Macro-level Intermodal Capacity Modeling

by

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ABSTRACT

This report is presented in two parts: modeling and testing. In part 1, a summary of existing capacity models and speed/volume functions is presented in the following sections. An effort is made to organize it in a systemic and consistent way for easy reading and understanding. A critique of certain existing capacity models and relationship functions, where further development is possible, is also presented.

This report aims to demonstrate the comprehensive model that was discussed in the previous tasks to estimate the capacity of intermodal freight transportation. The estimation of capacities is conducted according to the previous proposed formulas for different transportation modes for freight transportation. Moreover, the model is going to be demonstrated in the case study of freight transportation analysis in the Hampton Roads Area. The optimization of freight assignment and routing in this region should reflect the validity of the model. The model identifies the bottlenecks in an intermodal network, as well as strategies to increase system-wide capacity for increased freight movement demand. Besides the current state analysis, this model is applied to forecast the necessity of expansion and improvement for specific choke points in order to face increased traffic volume after the expansion of the Panama Canal. Finally, this study uses what-if analysis for the condition that a few central links were disrupted in the transportation. The robustness of transportation system is evaluated for the Hampton Roads Area.

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SUMMARY OF CAPACITY MODELS

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HIGHWAY

The capacity of highway was studied using a variety of methods and techniques. Out of these numerous methods, there are only three models which can lead to an accurate estimate of the capacity.

Out of three methods, two commonly used highway capacity estimation methods are the Highway Capacity Manual (HCM) method using speed-volume-density relationship (Manual 2000), and the statistical method using observed traffic volume distribution (Chang and Kim 2000). A new dynamic method was proposed by Zunhwan, Jumsan & Sungmo(2005) which was intended to investigate the tendency of capacity over time.

HCM Highway Capacity Method

The HCM method executes the following: (1) collect 15 min-base traffic data (speed, volume, density), (2) establish speed-volume-density relationship using data from step (1), and (3) determine highway capacity. The results of HCM method are shown in Figure 1 and Figure 2.
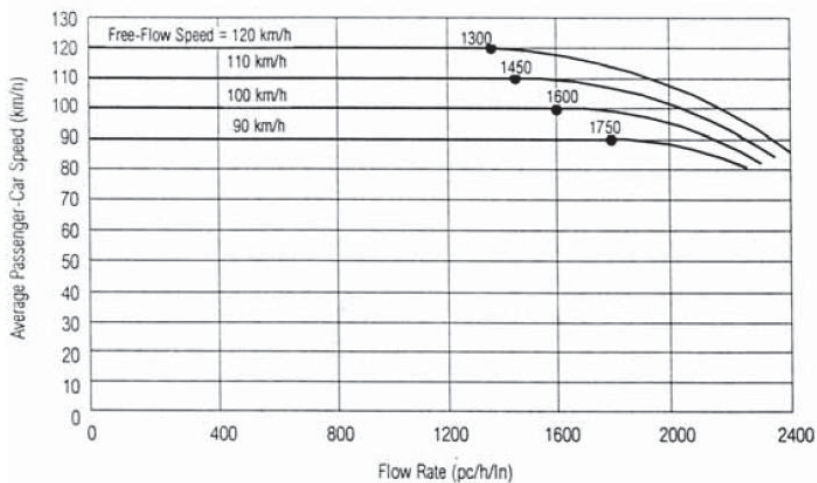
Figure 1. Speed-Flow Relationships for Basic Freeway Segments (Manual 2000)
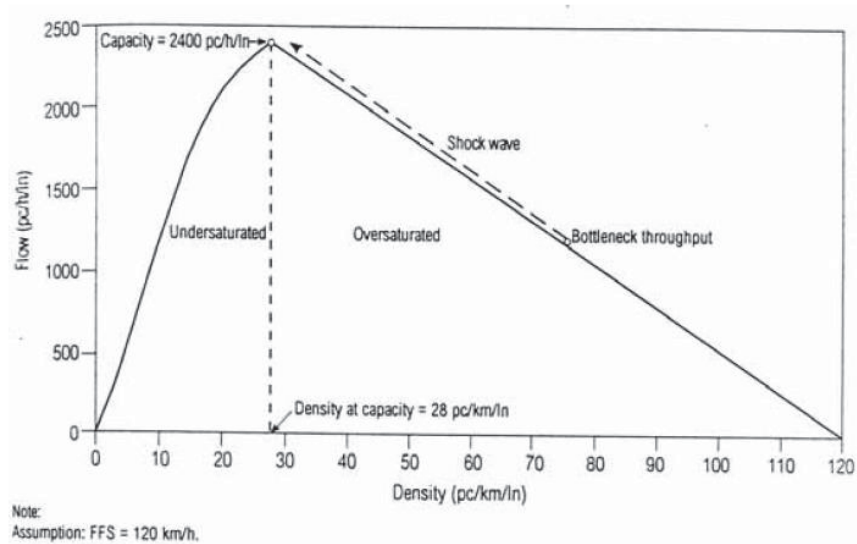
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Two Lane Highways

$$Annual\ Average\ Daily\ Traffic\ (AADT) = [2800 \cdot (v/c) \cdot Fd \cdot Fw \cdot Fg \cdot Fhv] \cdot PHF/K$$

where:
v/c = flow capacity ratio for selected level of service,
Fd = peak hour flow directional distribution factor,
Fw = lane and useable shoulder width factor,
Fg = factor for effect of grade on cars.

$$Factor\ for\ effect\ of\ grade\ on\ cars,\ Fg = 1/[1 + (Pp \cdot 0.02\{E - E0\})],$$

where:
Pp = proportion of cars in upgrade traffic stream,
E = base car equivalent for % and length of grade and speed,
Eo = base car equivalent for 0% grade and given speed.

Factor for effect of grade on trucks, $Fhv = 1/[1 + Phv(\{1 + [0.25 + Pt/hv][E - 1]\} - 1)],$
where:
Phv = proportion of total heavy vehicles in upgrade stream (trucks, buses etc.),
Pt/hv = proportion of heavy trucks among heavy vehicles in stream,
E = as defined above,
PHF = peak hour factor for Level of Service,
K = proportion of $AADT$ expected to occur in the design hour.

Two Lane Highways with Crawler Lane

Formulae are identical to above except to simulate the crawler lane, the effect of heavy vehicles on the upgrade has been virtually discounted with the factor Phv being selected as 1% and Pt/hv selected as 95% and with 40% "no passing" opportunities selected for the traffic stream.

Multi-Lane Highways

$$Annual\ Average\ Daily\ Traffic\ (AADT) = ([100 \cdot P] \cdot [5000 \cdot N])/(100 + T\{j - l\}) \cdot K \cdot D$$

where:
P = lane capacity base in passenger car unit (pcu) per hour for selected level of service (ranges between 2000 for expressways to 800 pcu for major highways with frequent "at grade" access),
N = total number of traffic lanes,
T = % of heavy trucks in traffic during peak hour,
j = pcu equivalent for trucks (= 2 for level terrain; 4 for rolling terrain and 7 for mountainous),
l = lane factor (= 1 for 3.75 m lane width; 0.97 for 3.5 m lane width),
K = % of $AADT$ expected to occur in the design hour,
D = % of one way traffic during peak hour in peak direction.

Statistical Highway Capacity Method

The objective of the statistical method was to determine the highway capacity determination by evaluating alternative approaches in developing capacity from the statistical distribution of observed traffic flow.

The statistical method executes the following: (1) detecting peak hour 1 minute base volume and average speed, (2) transferring 1 minute base data to 15 minute base, (3) finding time headway distribution using average volume, (4) determine highway capacity when confidence intervals are 99%, 95% and 90%.
The variance in the confidence interval obtained from this method greatly affects the result of highway capacity estimation. Chang and Kim (Chang and Kim 2000) found that the estimated highway capacity is 2200 $pc/h/l$ at the 95% confidence interval:
$$q = \frac{3600}{h},$$
where:
q = flow rate in an hour (vph),
h = average headway (second).
Finally, the highway capacity was calculated by the regressed relation of volume and headway which is illustrated in Figure 3.

Dynamic Estimation

The dynamic estimation of freeway capacity is based on a assumption that the roadway capacity is the function of the driver's and vehicle's conditions, vehicle speed, and time headway, as defined in
$$C_i = f(D, V, S, H)$$
where C_i = capacity of roadway, D = driver condition, V = vehicle condition, S = vehicle speed, H = time headway (seconds).
Unit time of highway capacity estimation is one hour.
$$C_i = \left\{ \frac{3600}{H} | H = g(D, V, S) \right\}.$$
If driver condition and vehicle condition follow certain distributions and set as error term,
$$H_{Ci} = g'(S) + \varepsilon,$$

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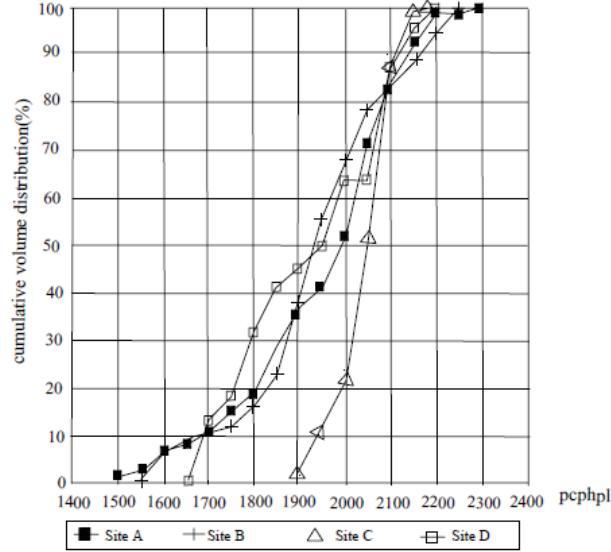
Figure 3. Cumulative volume dist. with 95% conf. headway interval (Chang and Kim 2000)

where H_{Ci} = time headway at Ci, ε = error term.
And then various capacities changed by speeds Cap_s are calculated by

$$Cap_s = \frac{3600}{H_{Ci}}.$$

Specific function type of $g(D,V,S)$ are studied and parameter values can be determined by statistical regression. The basic idea of this model is to adjust the capacity over time.

RAIL YARD

A macro-level capacity model may describe the relationship between the total dwell (put-through) time, expected values and variance, and the volume through a yard. In many studies, the dwell time at a yard is assumed to be fixed for railcars (e.g., Crainic, Ferland et al. 1984). Some studies considered the influence of train forming on the dwell time for a train. Thomet (1971) and Assad (1980), for example, assumed the dwell time of a train at a yard to depend on the number of railcar that the train has, as shown in (1). Their delay function at a given yard j for train i is

$$W_j + v_j x_{ij}, \qquad\qquad (1)$$

where W_j is the fixed delay for processing a train through yard j, v_j is the variable delay for one rail car at yard j, and x_{ij} is the number of railcars carried by train i. They did not consider the capacity of yards at all. At the same time, most recent rail routing papers consider a fixed capacity at each yard and assumed a fixed delay for each railcar (e.g., Barnhart (Barnhart, Jin et al. 2000); Liu (Liu, Ahuja et al. 2008); Jha (Jha, Ahuja et al. 2008); D'Ariano and Pranzo 2009). Their capacity model can be illustrated by Figure 4 with a constant dwell time and a fixed capacity at a yard, which is often measured by the number of railcars (Crainic, Ferland et al. 1984, Fernández L, De Cea Ch et al. 2004, Javadian, Sayarshad et al. 2011) or blocks (Barnhart, Jin et al. 2000).

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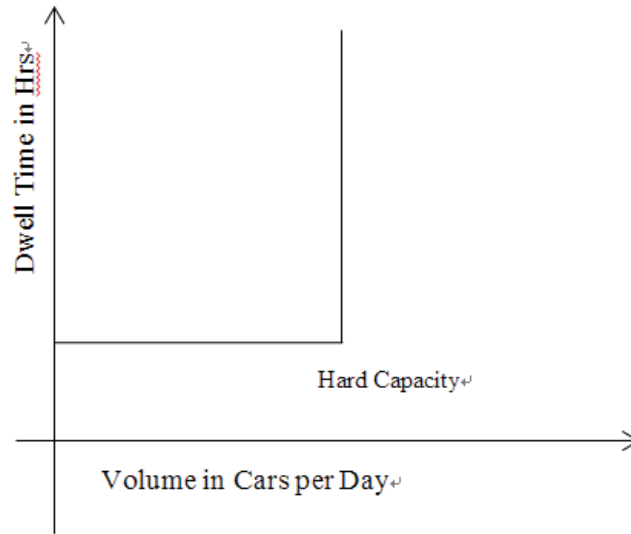
Figure 4. Yard Capacity Model with Fixed Dwell Time and Hard Capacity

In practice, however, the dwell time at a yard depends on the physical feature and operations, such as timetables of inbound and outbound trains, train connection standards, classification sequence, and block-to-train assignment, at a yard. Similar to the numerical example provided by Petersen (Petersen 1977), a sample capacity model is provided in Figure 4 to show the relationship between the average dwell time for railcars vs. the volume through a yard. Typically, the average put-through time almost keeps constant with very little increase at the beginning when the volume increases. When the volume passes some threshold value, the put-through time increases very quickly then the yard cannot handle any more railcars very soon. A capacity model illustrated in Figure 5**Error! Reference source not found.** has two major parameters: the average put-through (dwelling) time before the volume reaches its capacity and the capacity, measured by railcars per day. That threshold value can be defined as the capacity of the yard and is measured by railcars per day.
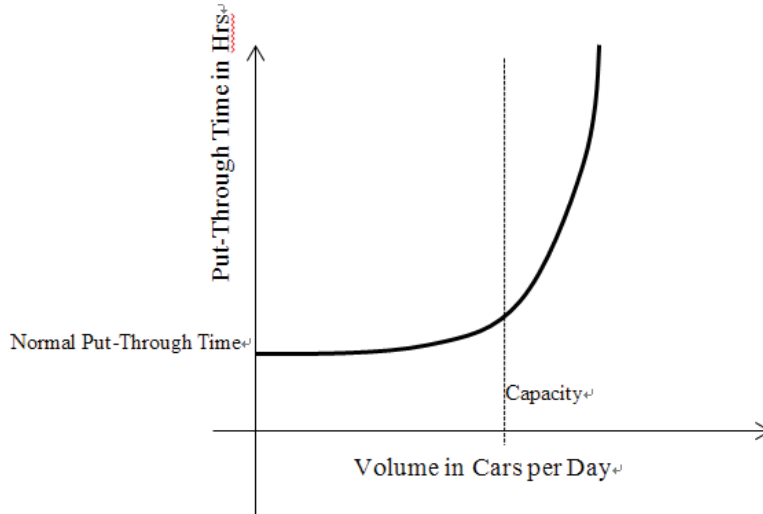
Figure 5. Yard Capacity Model with Fixed Dwell Time and Hard Capacity

The major operations for a railcar to go through a classification yard follow the sequence of

receiving and inbound inspection, classification, wait for connection, train assembly, and the outbound inspection and departure (Petersen 1977). After a train arrives, it is pulled into the receiving area if there is a track available. After necessary inspection, the train waits in the receiving area for classification. There are two major classification yards, hump yards and flat yards. In hump yards, which are the most common in the world, railcars are pushed by a shunting engine over a hump and roll through switches onto desired classification tracks. Flat yards have no humps so that they use switch engines to move railcars for classification. Railcars wait on classification tracks from the end of classification to the start of the train assembly because an outbound train has railcars from a number of inbound trains. An outbound train is assembled with railcars on one or more classification tracks picked up by a yard engine.

The receiving and departure along with their associated inspection often are not bottleneck in a yard and take relatively constant time. Most of time in a yard for a railcar is spent on the receiving tracks waiting for classification and on the classification tracks waiting for train assembly (Petersen 1977). A queuing model can be used to model the waiting line of trains or railcars for classification by assuming the inbound train arrivals are independent and there is only a shunting engine. Obviously, higher traffic, measured by the number of railcars, increases the waiting time for inbound trains in the receiving area. The train assembly process is complicated because it is influenced by both the timetable of the outbound trains and the availability of switch engines (Turnquist and Daskin 1982). Furthermore, the outbound train timetable of a yard may be influenced by traffic volume through the yard in order to form trains that are long enough. All other times can be considered constant. In summary, when the traffic through a yard is well under its capacity, the increase of the traffic will not significantly influence the total put-through time, as shown in Figure 6. However when the traffic reaches some critical point, maximum capacity, the put-through time for railcars increases very quickly so that very soon no more traffic can be routed through the yard.

We call the relationship between the put-through time and the put-though volume, illustrated in Figure 7, macro-level yard capacity models. The models heavily depend on the physical characteristics and management policies at the yard. Both analytical models and simulation models have been developed in a few studies. Those works will be discussed in more details later. Those macro-level models can be used for two major purposes at the strategic level and at the tactical level, as discussed in Section 2.

Both analytical models and simulation models have been used in literature to study rail yard capacity at the macro level. The two seminal papers by Petersen (1977a) and Petersen (1977b) build two queues for analyzing a classification yard, one for the waiting line for classification and one for the connection delay. He assumed that inbounded trains arrive at the yard following a Poisson process and wait for the humping service. For hump yards, he suggested $M/G/1$, $M/D/s$, or $M/M/s$ for the classification delays. If there is only one hump, the mean and variance of the waiting time for classification can be derived analytically. Turnquist and Daskin (1982) changed the modeling units of arrivals from trains to railcars because yard delay presented in Figure 8 is for railcars. Therefore, they considered a batch arrival queuing models and included the train length distribution into their model. They further derived the upper bound and lower bound of the expected values and variance of classification delays for different train length and service time distributions. They also analytically and empirically showed that the

Poisson assumption for train arrivals is reasonable. The connection delay is modeled as a bulk service queue by assuming that railcars arrive from classification waiting for connection following a Poisson process and is mainly determined by the departure pattern of outbound trains (Petersen 1977, Turnquist and Daskin 1982) . Both the expected value and variance of the time between two consecutive departures can heavily influence the connection delay. Another factor should be considered into the connection delay models is the various limits on outbound trains, such as length and weight limits of a train. However, both studies did not explicitly consider the impact of the traffic volume on the number of departing trains.

In practice, some railroads use cutoffs to decide which railcars should be assembled (Martland 1982).

- Inbound-based-cutoff: Cars with destination K arriving at time t should be connected to all outbound trains departing for destination K after time $t + C$.
- Outbound-based-cutoff: All cars with destination K arriving more than C hours before the scheduled (or actual) departure of an outbound train for destination K should make the connection.

Here, C is the cut-off time that defines the minimum scheduled time for the connection. The application of cut-off time can fundamentally change the connection delay calculation. Service rates influence the waiting lines of both queuing models for classification delay and for connection delay. Petersen (Petersen 1977) modeled the service rates based on the number of classification tracks, the configuration of switching leads, the available yard engines for connections, the marshaling rules, and the traffic intensities. With a FORTRAN program, he came up with the expected car put-through time by destination. One interesting capacity model illustrated in Figure 6 from Petersen (Petersen 1977) shows the impact of changes in a yard facility on its capacity of handling railcars. There are four scenarios,

- Base case of a single-ended yard with seven classification tracks;
- Expanded capacity of a single-ended yard with ten classification tracks;
- Expanded capacity of a double-ended yard with seven classification tracks; and
- Expanded capacity of a double-ended yard with ten classification tracks.

The analysis can help strategic decisions regarding yard capacity expansion. The queuing models proposed by Petersen (1977[a,b]) were verified by two hump yards owned by the CN railroad to compare the estimated put-through time distribution and actual distribution. The results showed that the assumption of queuing models worked reasonably well regarding predicting put-through times for railcars for different destinations, perhaps because of the high variability in train and block lengths.

Rather than queuing models, Fernandez L. et al. (2004) used the following BPR type function (1), which was borrowed from highway capacity studies, to model classification delays at yards. The model is simple and in general follows the same shape as Figure 7**Error! Reference source not found.** with right calibration parameter values. However, they did not provide the details on
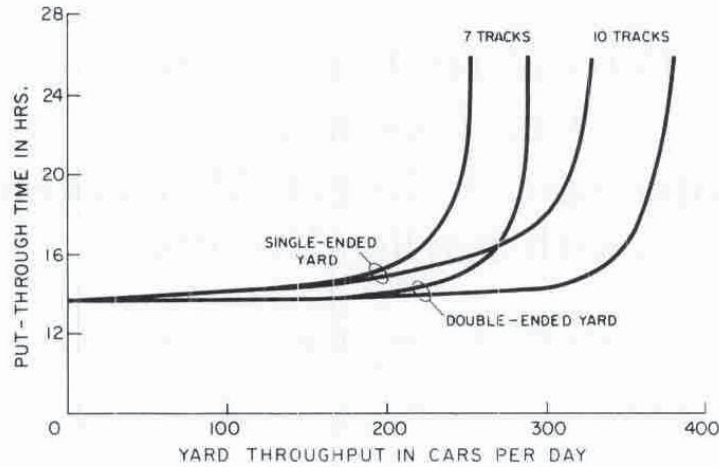
Figure 6. Effect of Yard Facilities on Put-Through Time (Petersen 1977[b])

how to obtain the values of all parameters for any specific yard. Another problem of (1) is that the flow can go infinity theoretically though it will push the delay very high. However, the flow through a yard is bounded in practice because a large volume will cause overflow in the queue and block the main line.

$$ClD_i = FClD_i + \beta_{Cli} \left(\frac{f_i}{CAP_i} \right)^{n_{Cli}} \tag{1}$$

Here,

ClD_i: Average classification delay for a freight car in yard i;

$FClD_i$:   Classification delay for a freight car in yard i, in free flow conditions when there is no congestion;

f_i: Flow of railcars in yard i during a period;

CAP_i: Capacity in yard i during a period in railcars; and

β_{Cli}, n_{Cli}:   Calibration parameters.

Though the analytical results from queuing models from late 70's and early 80's seem technically beautiful and have been verified by real-world data, they have not been well accepted by the railroad industry perhaps because of the following reasons.

1) The analytical models are complicated and require some mathematical background to understand. In some sense, the queuing models are so complicated that they are considered black boxes from the viewpoint of practitioners. Without a complete understanding, practitioners do not have confidence to utilize the analytical models.

2) Various assumptions are used during analytically modeling. Even though an assumption could be well justified based on theoretical analysis, practitioners often do not agree with the assumptions based on their real-world experience.

3) Even if a practitioner trusts all assumptions and the modeling procedures, the models are complicated for her to conduct an analysis and to reach any meaningful conclusion like the one shown in Figure 8. Furthermore, the analytical model does not have flexibility to incorporate changes.

4) The yard capacity results from analytical models may not be useful for other purposes such as network capacity analysis. The nonlinear function shown in Figure 4 needs to be

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further simplified to be used in rail traffic routing.

Therefore, a straightforward model to describe yard capacity and its connection with yard configurations and management policies are necessary to incorporate yard capacity into railroad network analysis and guide both strategic and tactical decisions for railroads.
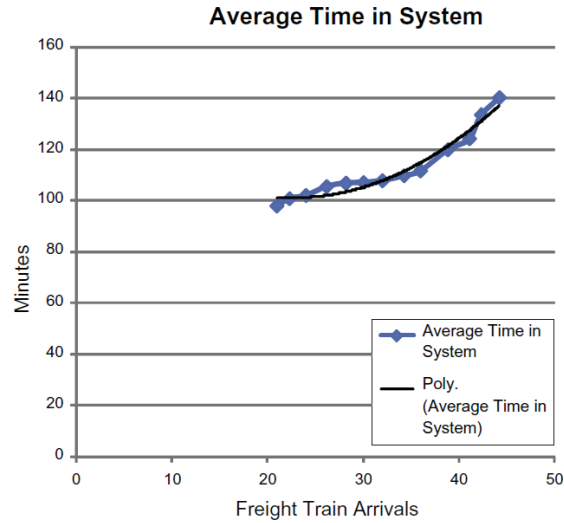
Figure 7. Put-Through Time vs. Traffic Volume in Trains (Marinov and Viegas 2009)
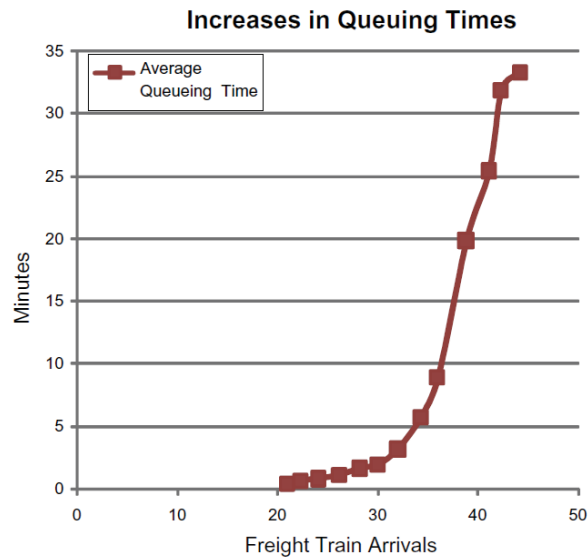
Figure 8. Waiting Time for Classification vs. Traffic Volume in Trains (Marinov and Viegas 2009)

To avoid above shortcomings of analytical models, simulation has been used in several recent studies. For example, Marinov and Viegas (Marinov and Viegas 2009) proposed a simulation modeling methodology for analyzing flat yards and implemented it with a discrete-even simulation package, SIMUL'8, for a sample yard. Figure 5 and Figure 6 show the capacity model for the yard under the study based on simulation results. It can be observed the yard

capacity model from the simulation results are close to the analytical one in Figure 4 in that they both show the put-through time does not increase a lot first but then grows very fast when the traffic is beyond some point called capacity.

Lin and Cheng (2011) from Norfolk Southern incorporated mechanical repairs and re-humps in a simulation model for a hump yard based on a simulation framework for rail yards proposed by them earlier (Lin and Cheng 2009). The simulation model also considered train schedule of inbound and outbound trains, trip plan of railcars, and train consist with performance measures of connection, outbound train on-time percentage, resource utilization, hump count and occupancy, humping and pullback process cycle time, track utilization percentage, and terminal dwell time. Similar to Dirnberger and Barkan (Dirnberger and Barkan 2007), the simulation model found out the pullback process, which pulls cars from the classification tracks to form outbound train in the forwarding yard, is a bottleneck. Their simulation also shows that the increased volume can hurt the quality of the classification area, also called bowl, as shown in Figure 9. Bowl quality is measured by the number of tracks with different states, which are defined as follows.

- A *clear* track is a classification track that has no cars on it.
- A *clean* track is a classification track that has only one block or class code or destination.
- A *layer* track is a classification track that has more than one block or class code, however, the cars are positioned in proper order following their train departure time. If blocks of cars will depart on the same outbound train, then blocks follow blocking standing order of the outbound train.
- A *dirty* track is a classification track that blocks of cars are not in proper order.

Higher volume often leads to more dirty tracks, which require more pullback efforts and therefore hurt the performance of the pullback (connection) process.
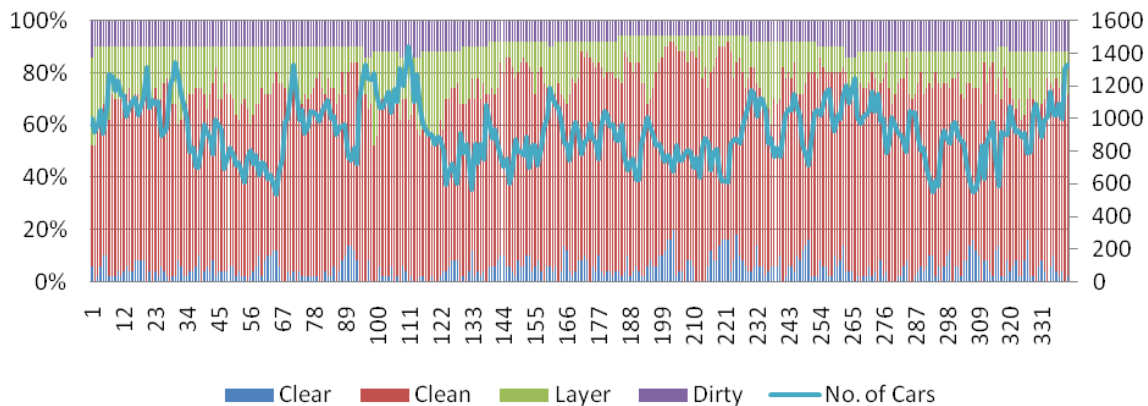
Figure 9. Bowl Quality vs. Bowl Volume (Lin and Cheng 2011)

Simulation models have strong flexibility to incorporating various factors and features at different yards and could fully consider variance without approximations. For one yard, once a simulation model is established, what-if analysis can be easily conducted by changing components in the model. However, significant efforts are involved in simulation model development for each yard. Furthermore, it is almost impossible to incorporate simulation

models in the analysis of one railroad network, which often includes multiple yards and other infrastructure.

In summary, the review of the macro-level yard capacity studies shows that there is a need to establish yard capacities models with the following features.

1) The models should represent the relationship between the dwell time (put-through) time and traffic volume in railcars in a simple way so that the capacity of yards can be incorporated into railroad network analysis.
2) The models should consider the major physical characteristics and operational management at yards in a reasonably straightforward way so that practitioners could estimate capacity lines easily for individual yards.

WATERWAY

The formulation of inland waterway links traffic capacity models has been conducted by various methodologies. Scholars utilized either theoretical or experimental method to achieve a measurement of the water traffic capacity not only in waterway links but the locks and ports as well. Some of the theoretical measurements were conducted in a macro level, which decompose the capacity by a number of influencing parameters and determine the value; however, another method was to calculate the capacity via queuing theory which assumed the waterway links and the facilities that work with them simultaneously were kind of servers with ships played as customers and pass through a routing of "workshops".

Both methods provide the researchers a theoretical result about the traffic capacity of inland waterway transportation systems. The parametric models require a database for coefficient values which ask for a large volume of physical test whereas the queuing theory models are in demand for the service time and arrival rate, which also need a support of data collection. The purpose of such study is to provide a convincible evidence for logistic operation system control or economic cost measure. Practical meaning of these researches can be foreseen in the future. We plan to compare and discuss both methods from various perspectives and intended to investigate the common and complimentary features of both.

It is known that the traffic capacity from the mathematical model is a theoretical value; however, a gap between the theoretical and practical values often appears in practical cases with the effect of estimation error or parametric value resilience. Analysis of factors affecting the traffic capacity of waterway links were conducted by some scholars as well (Liu and Wan 2008). The main purpose of their study was to find the estimation of the gap or the method of determining the parameter values in a proper way.

We will discuss the theoretical methods in a sequence of: 1) parametric decomposition method; 2) ship following theory; 3) queuing theory method; and 4) Other mathematical methods.

Parametric Decomposition Method

Plenty of researches focused on the decomposition of traffic capacity of waterway links. Most

models utilized product formulas to express the influence of environmental factors (Bian 2000, Liu and Wan 2008). These throughput capacity equations can be summarized into one generalized formula:

$$C = s \cdot T \cdot W \cdot V \cdot \frac{1000}{(1+m)L} \prod_{i=1}^{5} \beta_i,$$

where C is the waterway capacity ($ton/area$), s is the maximum allowed parallel ships on the cross section of the waterway links ($area^{-1}$), T is the available time for transportation each unit time (h), W is the average freight of shipment (ton), V is the velocity of the ship (km/h), m is the distance between ships, L is the length of each ship (m), β_1 is the reduce factor due to an increased density of traffic, β_2 is the reduce factor due to the unbalance of traffic control, β_3 is the coefficient of changes in draft marks, β_4 is the coefficient of average carrier capacity fulfillment, and β_5 is the reduce factor of traveling velocity due to traffic crossing and surpassing.

The above equation was argued to be subjective to and adjusted for various environments due to different waterway links or specific conditions, e.g. harbor and port capacity study. Early research of this parametric model limited in how to realize a closer measurement by achieving an improved parameter values. It is argued that such equation is subjective and not precise. The value of parameters are not enabling people either mathematical or operational insight. And such function is not considered to be mathematically rationalized because the parameters are out of human control (Dong, Jiang et al. 2007).

Therefore, scholars reported that the function needs further adjustment and improvement in regard of the gap between theoretical and practical throughput capacities (dong, Jiang et al. 2007). The researchers adopted the ship domain concept which was used for avoiding the collision of water traffic in the oceans or port canals (Tan and Otay 1999, Pietrzykowski and Uriasz 2009, Wang, Meng et al. 2009). Fuji domain (Deng and Liu 2009, liu, WanG et al. 2011) was the most discussed one of all models. After the introduction of the concept of ship domain, the research of waterway traffic capacity was improved to a more precise level. In doing so, some scholars focused on providing a closer estimation of theoretical capacity to the practical realized value via introducing various ship domain (Goodwin 1975, Szlapczynski 2006, Pietrzykowski and Uriasz 2009, Wang, Meng et al. 2009). Instead of numerical study, the adjusted model enabled people better operational insights of results. And the applications of the adjusted model were extended to the more of an economic element considered domain.

The study of adjusted capacity function firstly achieved the probability distribution function of freight and number of shipments per unit time. It was finally found that the two terms both followed the normal distribution and the capacity demand by number of traffics or freight can be estimated from the density distribution function. In their model, the traffic velocity was assumed to be piecewise linear to the density of traffic.
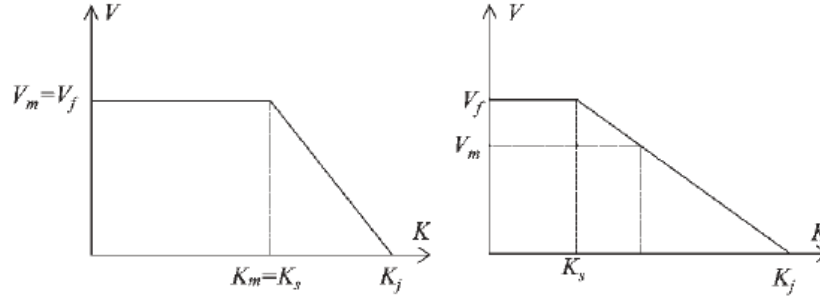
Figure 10. Piecewise Linear Relation between the Traffic Speed and Density (Dong, Jiang et al. 2007)

In Figure 10, v is the traffic velocity and K is the density whereas K_j is the blocking rate and K_s is the threshold rate above which the speed will reduce linearly. Upon the adjustment of the model and the corresponding value of parameters, the theoretical result of throughput capacity can be represented by:

$$C_m = s \cdot w \cdot t \cdot Q_{max}/10000,$$

where C_m is the theoretical result of capacity, s is the cross section capacity of the waterway link, w is the tonnage of a standard ship, t is available time per unit time and Q_{max} is the maximum traffic throughput volume which is related to the density and velocity of current water traffic.

Note that, in this model, the time unit was changed to days instead of hours. Utilized the adjusting coefficient, a practical result of capacity is available right away as:

$$C_p = C_m \cdot \beta_1 \cdot \beta_2 \cdot \beta_3 \cdot \beta_4,$$

where C_p is the practical realized capacity, β_1 is the reduce factor of traveling velocity due to traffic crossing and surpassing, β_2 is the rate of availability of the waterway links, β_3 is an adjusting factor due to different drivers, and β_4 is the night travel coefficient which reduces the capacity at night due to worse environment.

Similar to this work, Chen, Zhang et al. (2012) focused on the revise of the original equation as well. What he proposed verified Dong's motivation - the coefficient in the original equation required overwhelming subjective judgment on the transit traffic condition and the value of them vary significantly by time especially in the long run. Hence, the adjusted equation was proposed as:

$$Q_h = m_u (v_u - v_w)3600/\bar{l} + m_d (v_d - v_w)3600/\bar{l},$$

where Q_h denotes the traffic capacity per hour, m_u and m_d are the freight for upstream and downstream traffics respectively, v_u and v_d are the velocity of corresponding traffics, $\bar{l}$ is the longitude axis length of the ship domain, and v_w is the velocity of water.

The yearly traffic capacity was able to be derived from the above equation after taking into account the effect of blocking and yearly available time. Such calculation is more precise and controllable than the original formula. It provides the operators a deeper and better understanding to the capacity of the water links.

It is probable that different assumption on ship domain can influence the model to some extent. It

should be noted that the determination of ship domains presented by statistical or intelligent methods strongly depend on the statistical data and navigators' experience. Looking deeply at most of the existing typical ship domains, we find they were apt to be described by geometrical figures including circle, ellipse, polygon and other complex figures rather than in an analytical manner since it is difficult to analytically describe the ship domains derived from statistical data or navigators' experience. In addition, for a resultant shape type of ship domain, the model could be represented as stationary or dynamic corresponding to the variables affecting ship domains. So, the existing typical ship domains could be roughly distinguished as circular, elliptical and polygonal ship domains according to the resulting domain shape regardless of what method had been used (Wang, Meng et al. 2009).

Originally, the first elliptical ship domain was derived by Fujii and Tanaka (1971) from a mass of recorded data registering ships' positions and movement trajectories in Japanese waters by using statistical methods. In the 1980s, Coldwell (1983) established another elliptical ship domain by similar statistical methods for head-on and overtaking encounter situations in restricted waters. Recently, Kijima and Furukawa (2001) and,Kijima and Furukawa (2004) proposed a new ship domain modeled by "Blocking area" and "Watching area" which are defined as combinations of two ellipses.

Goodwin (1975) proposed a ship domain of which the boundary was divided into three sectors according to the arcs of a ship's sidelights and stern light. Subsequently, a modified circular ship domain, which made its modeling easier, was proposed by Davis, Dove et al. (1980) and Davis, Dove et al. (1982).

Later, Zhao et al. (1993) proposed a definition of fuzzy ship domain based on the Goodwin model using fuzzy sets theory, which determines a ship domain boundary and a fuzzy ship domain boundary. It was assumed that only if the area defined by the fuzzy ship domain boundary were to be interrupted, would the navigator's action be necessary. A concept of subjective ship domains based on neural networks has been presented by Zhu, et al. (2001).

Recently, some literature presented polygonal ship domains allowing the determination of dynamic dimensions of domains, which are mostly functions of ship dimensions and ship's speed in relation to other navigational objects (Smierzchalski and Michalewicz 2000, Smierzchalski 2001, Pietrzykowski and Uriasz 2004, Pietrzykowski and Uriasz 2006).

Ship-following Theory Method

Deviate from the previous thoughts, the study of water traffic can also introduce the concept from vehicle capacity models. Gazis, Herman and Post (19590 proposed a car-following model which described the static state flow of traffic. The car-following model was used to investigate traffic phenomena. One key investigation concerned the stability of a stream of traffic forming a platoon of cars following one another. It stated that the acceleration of the following car was proportional to the relative speed between the lead and following cars, with a time-lag between these two quantities. In other words, it was assumed that drivers were trying to catch up with a car pulling away, or slowing down while close to a car, but they did it after a certain time-lag which depended on their own reaction and the physical characteristics of their car (Gazis and Edie 1968, Gazis 2002, Mahmassani 2004).

In 2009, Zhu and Zhang (2009) proposed a model for water traffic capacity based on the adjustment of car-following model. The author provided an understanding of traffic capacity and critical water traffic spacing was derived from the dynamic differential equation.

The model can be expressed mathematically as

$$\ddot{x}_{n+1}(t + \tau) = \alpha \frac{[\dot{x}_{n+1}(t+\tau)]^m}{[x_n(t) - x_{n+1}(t)]^l} [\dot{x}_n(t) - \dot{x}_{n+1}(t)],$$

where $\ddot{x}_{n+1}(t + \tau)$ is the accelerated velocity of ship $n + 1$ at time $t + \tau$, $\dot{x}_{n+1}(t + \tau)$ denotes the velocity of ship $n + 1$ at time $t + \tau$, $\dot{x}_n(t)$ is the velocity of ship n at time t, $x_n(t)$ is the position of ship n at time t, and $x_{n+1}(t)$ is the position of ship $n + 1$ at time t. l and m are both constant while α is a characterization of maximum traffic flow which in the unit of m/s^2.

From the above equation, the relation between spacing and the velocity can be determined by solving the differential equation. And the critical velocity of ships under various conditions results in. Therefore, the traffic capacity of each condition can be written as:

$$C_{bh} = \frac{1000 \cdot v_c}{h} W,$$

where C_{bh} denotes the theoretical capacity, v_c denotes the critical velocity under each conditions, h is the water traffic head-to-head spacing, and W denotes the standard weight of the ship. Via enormous experiments, the parameter and constant value can be determined statistically.

There is one disadvantage of the above mentioned models, which is that the researchers can never reach an ideal state that enables them the knowledge of the gap between the theory and practical cases. Moreover, the theory is on the macro-level, even though they consider the micro-level behavior after the adoption of ship domain concept. The operators are lack of knowledge on the effects of facility or natural environments, e.g. locks, docks and floods. Therefore, the model need to be further improved and provide people more convincible insights to the nature of traveling time, throughput rate, and traffic capacity.

Statistical and Queuing Theory Method

Different from the parametric decomposition methods, the researchers who utilized queuing theory did not consider micro level condition of the traffics. Instead of that, they proposed the arrival and serving rate of the facility or waterway links (Lave and DeSalvo 1968) which were collected statistically, by which the available capacity can be calculated correspondingly. The arrival rates in these models are often assumed to follow Poisson distribution with the service time following exponential distribution family. Correspondingly, this method is mostly used in the study of lock capacity rather than waterway links capacity.

The advantage of such method is that the model can be verified by simulation models in Arena or any other user friendly software package. Further software development promised the model to be easily adopted by industry corporations (Dai and Schonfeld 1991, Ting and Schonfeld 1998, Kia, Shayan et al. 2002, Taylor, Whyte et al. 2005, Cortés, Muñuzuri et al. 2007, Almaz and Altiok 2012).

In 1960s, the earliest decade when such study can be found, the study of the capacity of waterway links were just started. An assumption was made that the bottleneck of the service level of one waterway section is determined by the lock within it. The service rate of the lock(s)

is represented by $\mu(b)$ which is determined by the number of barges in each tow (Lave and DeSalvo 1968). And the capacity of the waterway link can be calculated by:

$$K = \frac{8760}{1/\mu(b)},$$

where 8760 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). The relationship was assumed to have the shape shown in Figure 12.
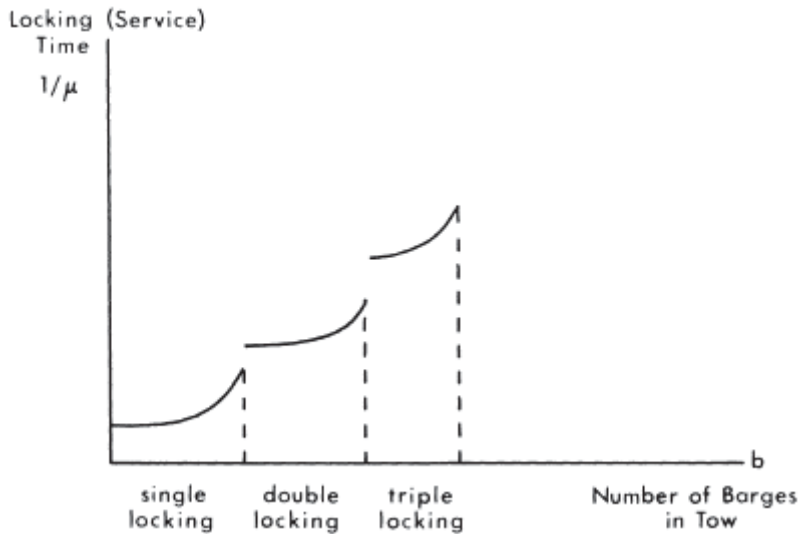
Figure 11. Service time as a function of the size of tow (Lave and DeSalvo 1968)

The number of barges can be served in one year can be got from the equation:

$$C = Kb,$$
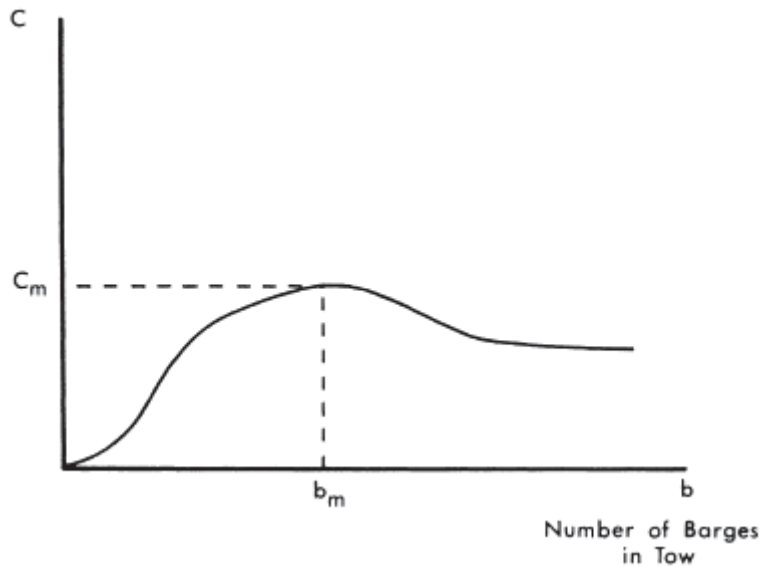
Figure 12. Waterway capacity as a function of the size of tow(Lave and DeSalvo 1968)

Since tows cannot be scheduled and it is costly to keep them waiting, one cannot expect that a tow will always be awaiting service at a lock. The physical capacity of a waterway, as shown in above equations, is an inappropriate measure from an economic standpoint and would never be

approached in actual operations. However, this physical measure is an input into the analysis of economic capacity. To determine the capacity of a waterway, one must also consider the randomness of arrivals and service times and the varying size of tows. The research of adapted such rough estimation and yield a function of lock time and waiting time:

$$T_{Lq} = \frac{\lambda}{\mu(\mu-\lambda)};$$
$$T_L = \frac{1}{\mu} + T_{Lq} = \frac{1}{\mu-\lambda},$$

where λ is the arrival rate of ships, T_{Lq} is the waiting time and T_L is the total lock time for one ship pass through the lock. The model can be further extended such that the result could be applied to multi-lock conditions.

Suppose that a total tonnage (upstream or downstream) of P per year is to be moved over a particular waterway. Suppose further that the average load of a tow is A tons. Consequently, an optimized utilization rate of the waterway links turns out to be:

$$\lambda^* = \frac{(1+p)P/A}{8760},$$

where $p \in (0,1)$ is the proportion of full tows that have an empty backhaul.

Since the capacity of inland waterway links were assumed to be bottlenecked by the operation efficiency of the locks, more studies focused on the optimization of lock control alternatives. In the study of DeSalvo and Lave (De Salvo and Lave 1968), they modeled lock operation as a simple single-server queuing process with Poisson distribution arrivals and exponentially distributed service times (i.e., M/M/1 queues). The model of Wilson (Wilson 1978) extended DeSalvo's by treating the service processes as general distributions (M/G/1 queues). Both models are designed for analyzing single lock delays. However, the assumption of exponentially distributed service times is not consistent with empirical data, and no exact queuing results are available for locks with tow chambers in parallel. Some scholars developed service times as a linear regression model based on tow size and direction from empirical data (Kim and Schonfeld 1995, Ting and Schonfeld 1996, Zhu, Schonfeld et al. 1999). Kim and Schonfeld (1995) proposed an artificial neural network approach to estimate the lock service time. Their artificial neural network model provided more accurate estimates of service times but required more computation time and information about tows than the models of Ting and Schonfeld (1996).

The queue dispatching discipline used in other simulation models (Dai and Schonfeld 1991, Dai 1993) is first-come first-served (FCFS). In other models, service times may, but do not normally, account for the directional effect when the consecutive tows are dispatched in the same direction or the opposite direction. Although FCFS seems fair to all the users, it is very unlikely to minimize the total system cost. The dispatching priority became a discussion focus of this field. Ting and Schonfeld (Ting and Schonfeld 1996) proposed and assessed two different dispatching rules, shortest processing time first (SPF) and maximum processing time saving first (SAVE), for both one-chamber and two-chambers locks.
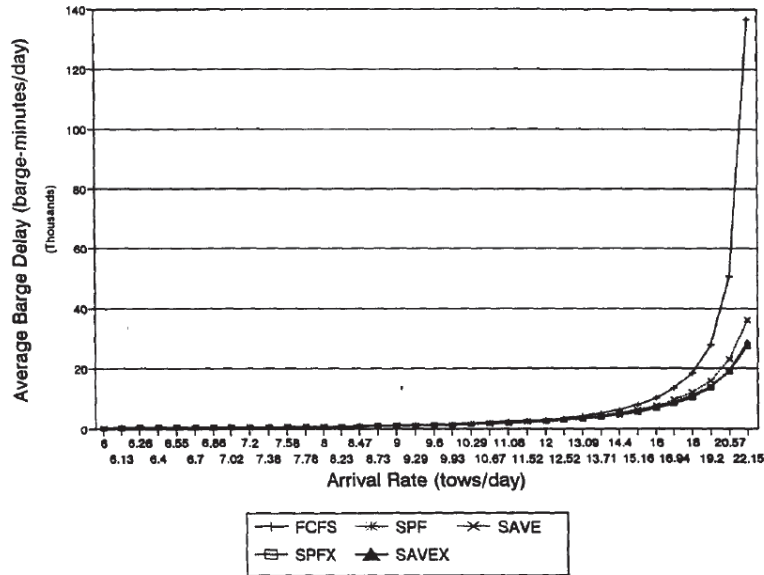
Figure 13. Average Barge Delay for Five Sequencing Methods (Ting and Schonfeld 1996)
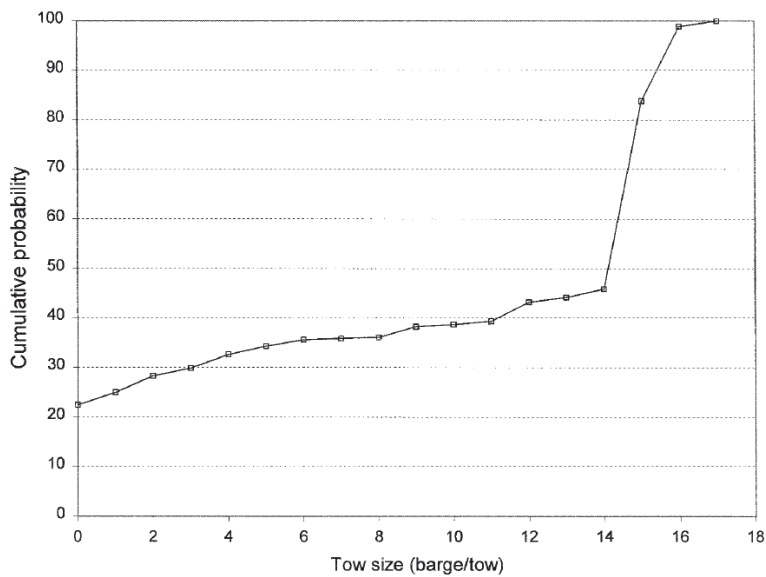
Figure 14. Tow Size Distribution at Mississippi River Lock 25 (Ting and Schonfeld 2001)

SIMULATION METHODS AND APPLICATION

One significant advantage of simulation model after introducing of the theory of queuing theory is that it enables scholars to integrate different functional parts in one section of waterway link. For example, in a harbor or inland port, docks, waterway links, stocking areas, and locks work simultaneously and corporately. Theoretical study encounters big challenge when integrating the sub models of working areas. It will make the effort of theoretical study in vain if any of those parts incorporate improperly. But statistical knowledge with queuing theory enables the simulation to meet the requirement of comprehensive study.

Several scholars have reported the simulation methods for an estimation of traffic capacity of inland waterway links. Related to the queuing theory, the researchers utilized optimized queuing discipline to improve the performance of simulation models. And the fields of application were further extended to port and lock capacity and utilization study.

The system simulation models were originally derived from Howe's microscopic model (Howe and Future 1969). Then independently, another model of waterway system simulation was developed jointly by Resources for the Future, Inc., and Pennsylvania State University. The model was derived from work done by Carroll (Carroll and Bronzini 1973) at the Tennessee Valley Authority on locking routines and from work done by Howe (Howe 1965, Howe 1967) on tow speed functions. This model was programed to simulate the movement of shallow draft barge tows. Inputs included tow characteristics, tow itineraries, and attributes of the waterway system. Model output included a variety of statistics concerning system operations such as tows processed, transit and delay times, queue lengths, and tonnages.

A further constraint imposed on the data conversion job is the 'balance principle': for each type of equipment in use on the waterway, input must equal output at every point. In summary the primary problem encountered in the preparation of the required itineraries and characteristics was to exhaust the origin-destination (OD) tonnage matrix for each commodity while simultaneously satisfying the balance principle. In response to this difficulty, work proceeded on developing the waterway systems simulation package. Operationally, the simulation model is divided into two parts. The first section is a tow generation program (Towgen), which produces a time-ordered list of tow arrivals into the system. This list is then processed by a waterway simulation program (Watsim).
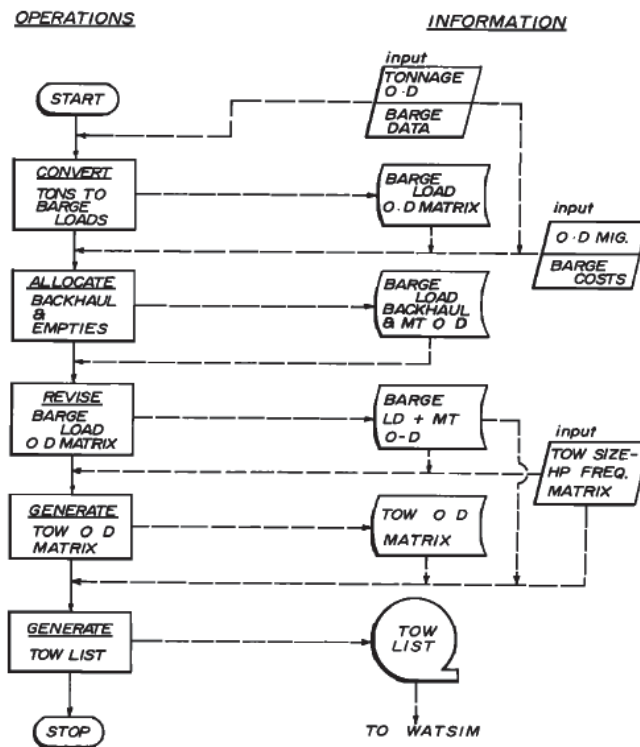
Figure 15. Logic Flow of Towgen (Carroll and Bronzini 1973)

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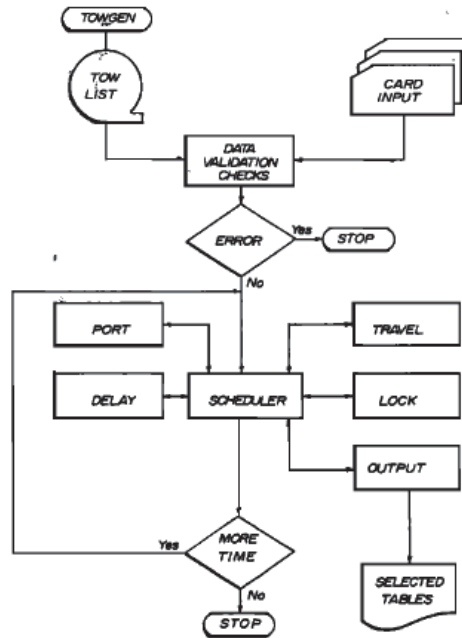
Figure 16. Logic Flow of Watsim (Carroll and Bronzini 1973)

Desai and Prock (1978) proposed a new model which programmed in FORTAIN language. This paper described a simulation study designed to identify methods of reducing delays at the locks. Factors used in the simulation were: lock utilization, tow mix, distance between locks, and sequencing rules. And the purpose of the model was to find a cost efficient way to operate the lock and arrange tow mix.

The simulation model can be adopted by the operation of waterway links or the inland ports, the controller of which are interested to know the processing capacity of the harbor. Cortés, Muñuzuri et al. (2007) focused on the simulation of the freight transport process beginning with the movement through the whole estuary of the river and finishing with the vessels arriving to the port dependencies, where the logistic operators' load and unload processes take place. The simulation was carried out with Arena software. The navigation was simulated through the Guadalquivir estuary, the lock, the basins and the docks of the port, as well as the logistic activities in the berths. After testing several scenarios, it was stated that the capacity of facilities are quite clear which leads to an improvement objective.
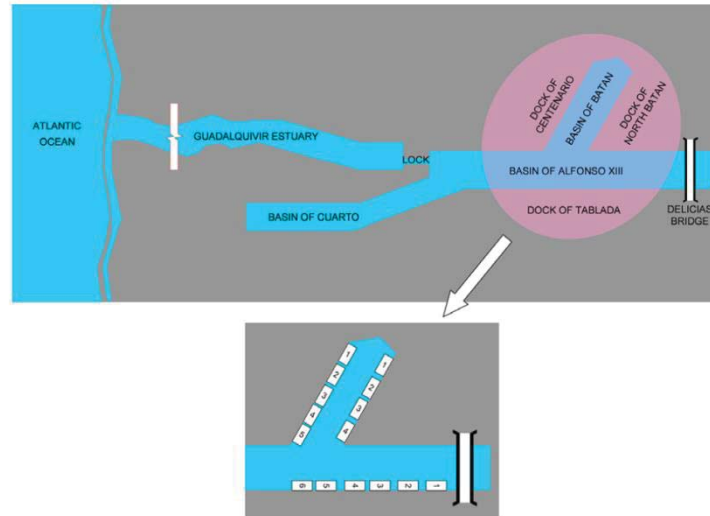
Figure 17 Simulation Scenario of Seville Port (Cortés, Muñuzuri et al. 2007)

In 1998, not applying simulation method in port waterway system, but inland river scenario, Thiers and Janssens (1998) reported a research in the simulation of port operation of Antwerp in Belgium. The simulation result told them the traffic and inbound capacity in current state and the necessity of further improvement, including extension of facility or a project of tunneling.

Differently, in 2005, a simulation based model was setup by Taylor, Whyte et al. (2005). They were intended to simulate the operation of inland waterway links in a scheduling perspective, which touched the layer of capacity. Specifically, the system assisted in the assignment of barge freight to boats. The simulation platform provided the ability to explicitly consider time-based cost trade-offs between barge handling requirements and equipment dwell time.

Smith, Sweeney et al. (2009) constructed a discrete-event simulation model to investigate the impact of alternative decision rules and infrastructural improvements to decrease traffic congestion in a section of the Upper Mississippi River navigation system. The model reveals that some improvement in performance (especially in peak periods) can be achieved by scheduling lock activity with priority given to vessels with shortest average processing and lock set-up times (affected by the time that vessels have spent in queue).

Consequently, in 2012, Ozhan Alper Almaz and Tayfur Altiok (2012) reported their work in the modeling of the vessel traffic in Delaware River. The purpose was to study the impact of deepening on the navigational efficiency in the River. The simulation model was specifically built to be able to perform scenario and policy analyses as well as a comprehensive risk analysis of the Delaware River and Bay area. The statistics tracked in this respect were the overall port and terminal utilization, port times and terminal calls, anchorage visits and delays based on various vessel visits, categories and movements.
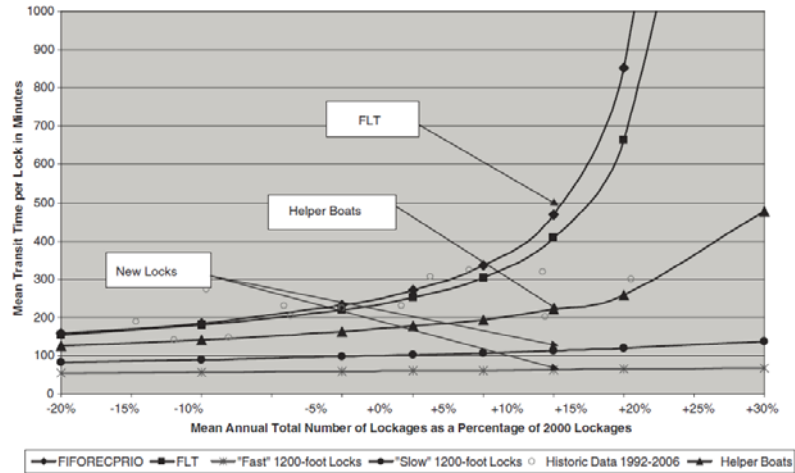
Figure 18. Effects of scheduling rules and infrastructural improvement (Smith, Sweeney et al. 2009)

The above simulation models for operations of locks, waterway links or ports, revealed people a broad application scope of the simulation method. However, the simplicity and robustness of the model are necessarily required for practical reasons. Moreover, the explicit result and convincible explanations of the result should be the most important purpose of the model. Otherwise, the model cannot be considered helpful.

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PART 2

DEMONSTRATION OF COMPREHENSIVE FREIGHT INTERMODAL TRANSPORTATION CAPACITY MODEL: CASE STUDY OF HAMPTON ROADS AREA

INTRODUCTION

This report aims to demonstrate the comprehensive model that was discussed in the previous tasks to estimate the capacity of intermodal freight transportation. The estimation of capacities is conducted according to the previous proposed formulas for different transportation modes for freight transportation. Moreover, the model is going to be demonstrated in the case study of freight transportation analysis in the Hampton Roads Area. The optimization of freight assignment and routing in this region should reflect the validity of the model. The model identifies the bottlenecks in an intermodal network, as well as strategies to increase system-wide capacity for increased freight movement demand. Besides the current state analysis, this model is applied to forecast the necessity of expansion and improvement for specific choke points in order to face increased traffic volume after the expansion of the Panama Canal. Finally, this study uses what-if analysis for the condition that a few central links were disrupted in the transportation. The robustness of transportation system is evaluated for the Hampton Roads Area.

Over the years, transportation has become increasingly important to not only regional economic development but also to global development. The basic problem derived from this growing transportation demand is the conflict between enlarged transportation volume and limited resources. Previous studies reported the problem arising from increasing congestion of road transport and the importance of rail transport scheduling, so that an improved capacity can be achieved. This report aims to demonstrate the comprehensive model that was discussed in the previous tasks to estimate the capacity of intermodal freight transportation. The estimation of capacities is conducted according to the previously proposed formulas for different transportation modes for freight transportation.

Conventionally, transportation is conducted in one of the following modes: road, rail, waterway, airline or pipeline. Any of these five transportation methods can effectively contribute to the growing transportation capacity. However, currently the continuously growing demand in transportation capacity has caused increasing congestion of road transport in and between urban areas. Unimodal seems to be unable to meet the requirements of transportation, which requires a reconsideration of a combination of different modes, namely intermodal transport. Intermodal transport is a highly discussed and studied topic in the transport industry. The purpose of

Intermodal Transportation Planning is to optimize the usage of all the transportation modes for both passengers and freight. Governments spare efforts to stimulate intermodal transport because it may contribute to a modal shift from road transport to rail and barge transport, which leads to an optimization in resource allocation (Trip and Bontekoning 2002).

Intermodal freight transport involves the transportation of freight within a standardized container or a specific vehicle, using at least two modes of transportation (rail, ship, and truck). In some circumstances it will not require the logistic employees to handle the freight itself when connecting one mode to another. This method reduces cargo handling and dwelling time in intermodal terminals. Reduced cargo handling also improves security, reduces damage and loss, and allows for faster transportation of standardized containers and vehicles. All these factors contribute to the reduced costs and increased efficiency and accuracy in logistic management, as well as reduced greenhouse gas emissions.

Figure 19 illustrates an example of a container terminal with an indirect transfer system, in which the freight is transshipped from waterway to road or rail transport. The excess freight is lifted to a storage area by yard crane. Transport through the waterway port consists of picking up containers directly from the vessel by quarry crane or from the storage area via yard crane. The movement of containers is not subject to unpacking and repacking of freight, which is more effectively operated and less overloaded by excess freight.
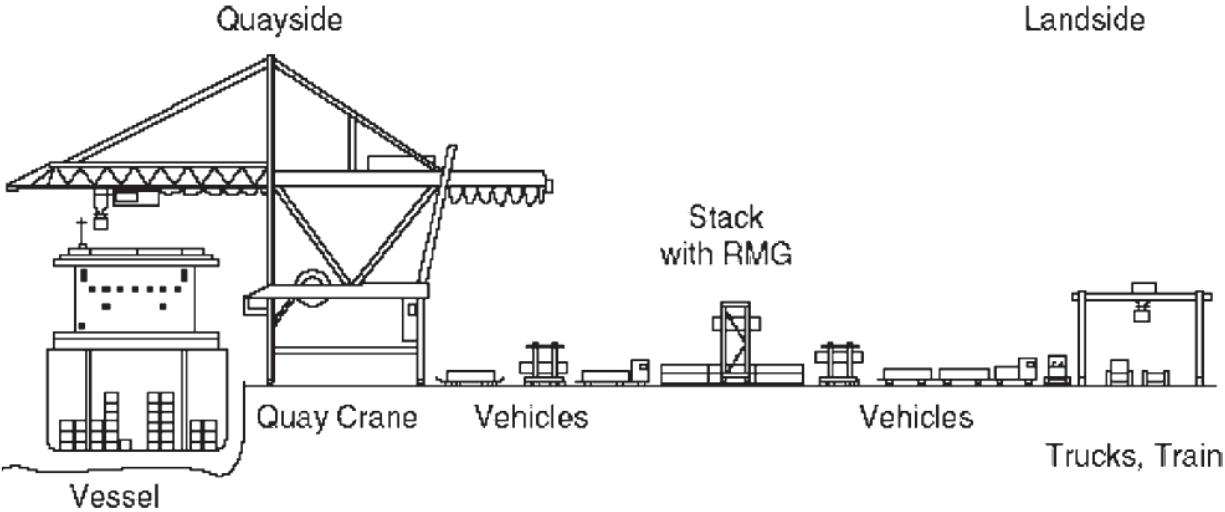
Figure 19. Transportation and Handling Chain of Intermodal Containers (Günther and Kim 2006)
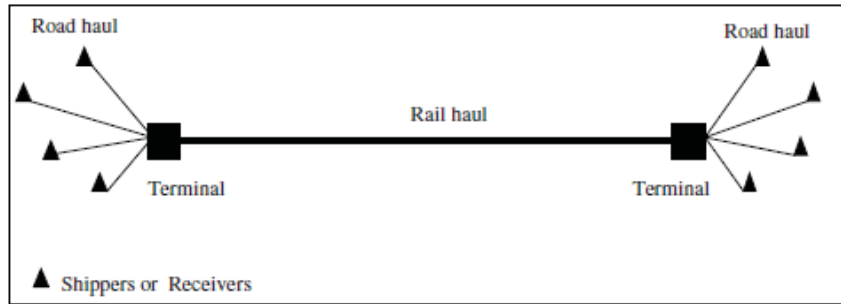
Figure 20. A typical representation of road–rail intermodal freight transport (Macharis and Bontekoning 2004)
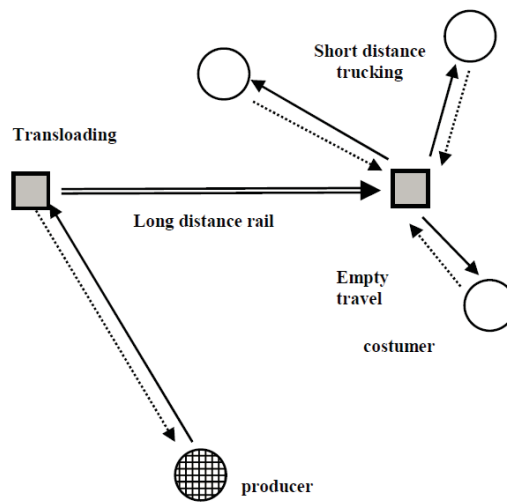
Figure 21. The loads transfer between truck and rail transportation mod (Mocuţa and Ghita, 2007)

Figures 20 and 21 provide a simple example of road–rail intermodal freight transport. A container of freight needs to be transported from a shipper to a receiver. The container is first transported by truck from the shipper's location to a transshipment terminal; it is then unloaded from truck and transferred to the second transport mode, which in this case is a train. Rail road freight transportation is known to be efficient in mid to long range large volume freight transportation. However, the limitation in the ability to reach the shipper and receiver indicates growing demand in corporation with other transport methods. The train transports between two rail road terminals in which the freight is transshipped either from rail to other modes or from other modes to trains. The transport between two local terminals is called the long haul in some previous pilot researches. At the other end of the transport the shipment is trans-loaded from train to truck and delivered by truck to the receiver. The trucking part of the transport chain is called drayage, pre-haulage and end haulage or pick-up and delivery. Instead of rail transport

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between the terminals, if terminals are connected by waterway, transport by barge is possible to substitute the rail road in this instance.

The concept of intermodal freight has been investigated intensively in recent years. Since 1990, a growing number of reports analyzing and addressing intermodal transport issues have appeared (Bontekoning, Macharis et al. 2004). To date, various intermodal freight transport decision problems and transport demand feeding models have been raised to help in the application of operation research techniques. However, the utilization of operation research (OR) in intermodal transport research is still limited. Unfortunately, the intermodal transportation problems are far more complicated than unimodal transportation problems and are more difficult to reach optimality. Intermodal freight transport is only just starting to be researched seriously and has yet to be adequately resolved. This provides very interesting and challenging tasks for the operation research practitioners to tackle.

The main purpose of this study is to develop a comprehensive model to estimate the capacity of intermodal freight transportation. Based on the estimation of capacities of different transportation modes for freight transportation, and the transfer capacity between modes, the model aims to identify the bottlenecks in an intermodal network. It also aims to identify strategies to increase system-wide capacity for increased freight movement demand.

This comprehensive model is intended to be demonstrated and applied in the area of the Hampton Roads region. Consisting of several important locations, including seaway transport and transshipment port group, the Hampton Roads region is considered to be the waterway gate of Virginia. Most of the seaway transport freight imports through the ports located in the Hampton Roads Area. In 2007, the Panama Canal was projected to expand, which consequently created demand for New Panamax ships. In 2016, this ongoing project is intended to double the capacity of the Panama Canal by creating a new lane of traffic. This new lane will not only allow for an increase of traffic, but also enable larger ships to traverse the canal. Once completed, a higher demand for transport and transshipment on the east coast, especially in the Hampton Roads Area, can be foreseen. The allocation of freight transport demand and scientific assignment of traffic needs to be processed in advance in order to optimize the system capacity of the Hampton Roads Area. This in turn could significantly contribute to the economic development of not only Virginia but the United States as a whole.

KEY FACTORS INFLUENCING INTERMODAL SYSTEMS CAPACITY

Intermodal freight transportation systems consist of various components that cooperate with each other. The function of each part of the system and the interactions between them form a key dimension of the intermodal system capacity study. In developing a comprehensive capacity

model for intermodal transportation, it is necessary to identify key influential factors that impact the theoretical and practical capacity of intermodal systems. Moreover, it is important to understand the relationships between these factors and capacity.

According to a previous study by Park, six core components deserve special attention. These components are known as the "VI-CORE model" in Park's research, though a wide variety of system elements exist: vehicles, infrastructure, customers, operations, regulations, and externalities (Park 2005). The referred factors are visualized in Figure 22. Each of the basic relationships is briefly described as follows.
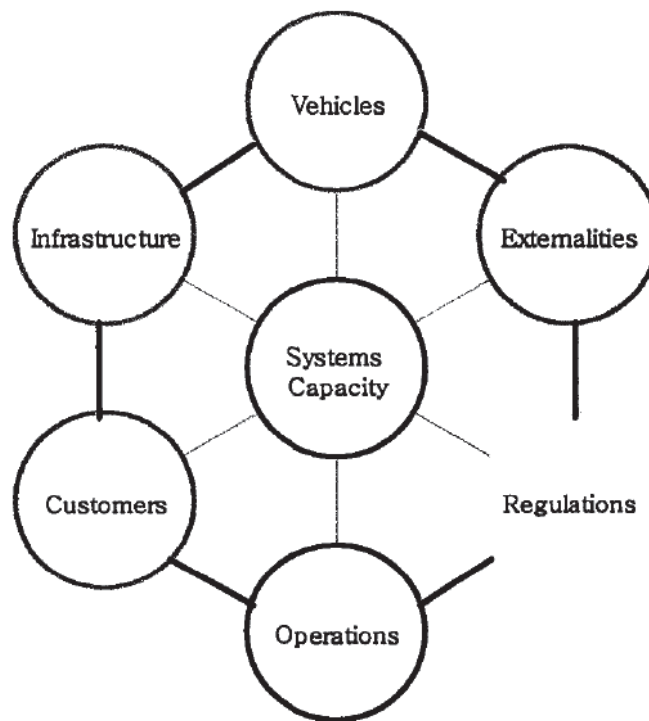
Figure 22. Six-Core Factors Affecting Multimodal Systems Capacity (Park, 2005)

Vehicles

As the first major component of an intermodal freight system, vehicles have different functional characteristics and purposes. This component represents the physical capability of transporting and containing resources that convey goods from place to place. Each mode leads to distinct characteristics of vehicles and different perceptions of users, which consequently lead to unbalanced levels of usage of vehicles. Moreover, studies explored different degrees of coordination and utilization of vehicles and lead to an evaluation of systems capacity. The primary determinants of systems capacity by vehicle include several factors: the number of

available modes, fleet size of each mode, and loading/unloading rate in connecting intermodal terminals.

Infrastructure

Even though some companies employ a huge number of vehicles, the capacity of constructed intermodal systems is actually limited by the service level of system infrastructure. Unlike the characteristics of vehicles, infrastructure expresses the fixed investment in intermodal systems. Highways, railroads, airports, ports and freight terminals are major elements of this dimension. The successive corporation of the infrastructure facilities practically defines the feasible capacity of freight movement in the intermodal network. In realistic cases, the physical condition and maintenance efforts essentially influence the operational performance of the service level of system infrastructure. It is important to maintain acceptable levels of mobility, which lead to different measuring results of system capacity. Usually, overall performance of intermodal systems is attributed to the degree of modal connectivity and maintenance. Thus special attention should be paid into this perspective.

Customers

Customers are generic but key participants involved in the process of freight transportation in intermodal transportation systems. Shippers and carriers are two major user groups with different objectives in the business of freight transportation of intermodal transportation systems. Shippers, including producers, wholesalers, retailers and individual consumers, represent all the parties involved in the decision-making processes of trip-making, origin and/or destination, and mode choices. Freight carriers, the actual service provider of the business, including trucking companies, railways, waterway and air lines, transport the freight in response to shippers' demands and possible requirements. Depending on the type of service provided, carriers are essentially engaged in the processes of resource allocation and routing and scheduling.

Operations

Operation refers to the set of procedures that organizers assign vehicles and shipments and guide the freight through the connection of physical facilities. Operation performance measures the difference between theoretical and practical realized capacity of the intermodal transportation system. Unlike passenger transportation, the capacity of containerized and non-containerized freight is more difficult to measure since the complexity of the mixture of multiple commodities, each of which has different attributes and requirements to be met and all of these factors must be carefully considered. The attributes of the commodities can be value, weight, size, packaging and other properties, for instances perishable or durable, fragility, temperature. Necessary attention

should be paid and different levels of transportation services may be required throughout the transportation process.

To be responsive to these diversified demands, vehicles and other physical or human resources are managed and operated in different means. Any changes in operations of these resources may have significant direct or indirect impacts on a systems operational performance. Therefore close coordination and precise optimization in operations of resources and handling of freight movements in consolidation will reduce the empty runs and improve the efficiency in utilizing existing capacity in the intermodal transportation systems.

Regulations

The construction of intermodal infrastructure demands enormous financial and invisible investment. The astonishing upfront cost is a crucial barrier to intermodal transportation companies. Some of the regulations may be connected with a more traditional role, such as construction of transportation infrastructure and subsidies to freight carriers, and public ownership of highways to maintain a comprehensive level of accessibility. They also take actions in the fulfilling of existing capacity. Government regulations raise public concerns in safety, environment and equity issues, and have become one of the important forces behind the underutilization of existing capacity. Consequently, investment and regulation of governments are closely related to the system capacity by directly and indirectly affecting the operational performance of the whole system.

Externalities

The transportation system itself cannot be considered without an awareness of interactions with other systems such as the economic or ecological system. In fact, this implies that capacity issues should be extended further to reflect the impacts of activities in other systems as well as the adverse external impact to the system capacity. From a system-wide point of view, economic development in regions primarily changes the pattern of freight distribution demands, which in turn results in a variation in traffic flow assignment in the network. It is also not difficult to observe that an increased freight activity impacts the society in traffic accidents and air contamination. Clearly, these impacts prevent the operator from complete utilization of available capacity from legislation or motivation perspective.

LITERATURE REVIEW

Over the years, an increasing number of studies have addressed the measurement of intermodal freight capacity. Two independent studies in 1993, Nijkamp, Vleugel et al. (1993) and Ahuja,

Magnanti et al. (1993) discussed the potential capacity with a consideration of network equilibrium and network flow. The concept of capacity management in infrastructure policy was developed. The papers examined the use of max-scenarios in capacity and operational management of infrastructure.

Morlok and Riddle (1999) made their calculation for intermodal freight capacity and compared the result with the capacity of unimodal transportation in each subdivision of the network. They argued that the overall capacity did not equal to the summation of all subdivisions. Consequently, in 2004, Morlok and Chang proposed the method to measure the flexibility of intermodal capacity, which is an extension of the previous work of Morlok and Riddle (2004). This paper aims to accommodate the measurement to changing demands and traffic patterns. The described measurements are implemented in a containerized freight rail network, as a method of testing their feasibility and potential value as descriptors of system characteristics. The uses of the measures in planning, investment, and policy-making are discussed.

In 2001, Lozano and Storchi discussed the potential capacity in intermodal freight transportation and estimated with network equilibrium methodology (Lozano and Storchi 2001). Another study summarized the previous studies and proposed a bi-level approach in order to calculate the potential capacity in multimodal freight transportation without considering the constraints in transporting time of the freight (Park 2005). Within a given intermodal network system, the problem at hand is to solve the feasible maximum flow of the network by all means. In intermodal systems, there exist different levels of decision makers, each with different objectives. In general, decision makers from the higher levels optimize their solution while taking into account the responses at the lower levels, in the form of constraints. The maximum flow in the network is affected by the level of current capacity utilization.
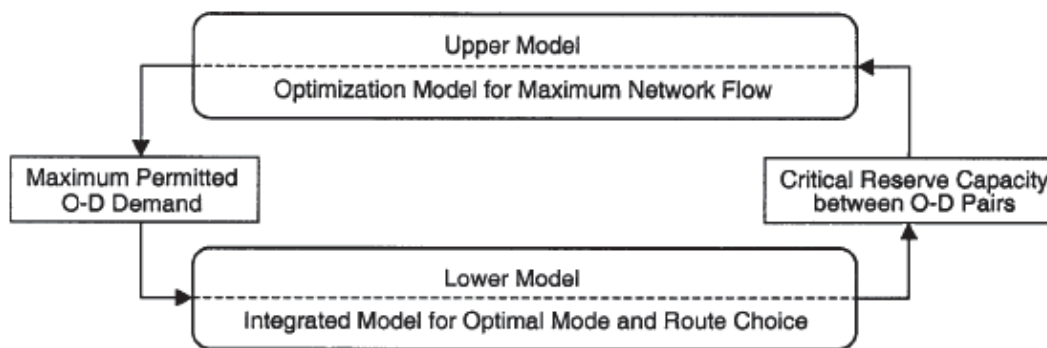
Figure 23. Conceptual Framework of Bi-Level Optimization Model

It also became clear that capacity should not only be considered in relation to a separate infrastructure segment, which in the past was widely accepted, but also as a feature of a multi-

layer and intermodal network. For example, capacity problems, for instance peak hour congestion in some modes may be overcome by intermodal substitution and complementarities. The identification of the optimal mix of necessary infrastructure modes in the perspective of attaining a given objectives is a major issue.

From the viewpoint of system-wide network optimization, it makes sense to pay particular attention to specific bottlenecks. An example of one of these bottlenecks is transshipment terminals, which connect different and independent transport modes. Possible variables in optimizing the available capacity at the system bottle necks can be interaction/communication speed, intermodal connection accessibility, information availability, peak load and capacity utilization, worker shift hours, the position of storage area and cranes, and standardization in transport systems technology. Improving intermodal transshipment performance, rather than physically expanding the whole infrastructure, will result in a much better use of existing capacity.

The conclusion from the above research reports is that there is a need for measurement of unitized capacity of intermodal system, so that a long-run sustainability criterion as a point of further improvement can be raised. This would also bring to light the potential improvement and analysis of the failure of operational management in crucial transport area.

MODEL

Most of the previous studies focused on the minimization of total transportation cost in intermodal network (Clarke 1995, Nozick and Morlok 1997, van Duin and van Ham 1998, Tsamboulas and Moraitis 2007, Chen and Schonfeld 2010); however, we are intended to provide a measurement of travelling time between two nodes in the network with an estimation of capacity and traffic volume.

In previous discussions, we have completed the summarization of capacity measurements with a relationship between travel and dwelling time and volume at rail road, highway and waterway links transportation modes. Consider a network with several subdivisions of unimodal freight transportation and connections between them, the total transportation time would be the sum of total transportation time within each subdivision and the transshipment processing time in container terminals and the waiting time in delay. The capacities of different freight transportation modes are listed as follows:

Highway (Manual 2000)

The free flow traveling speed is expressed as:

$$FFS = BFFS - f_{LW} - f_{LC} - f_M - f_A,$$

FFS	Free-flow speed (mph);
$BFFS$	Base free-flow speed, 60 mph is typically used;
f_{LW}	Adjustment for lane width (mph);
f_{LC}	Adjustment for right-shoulder lateral clearance (mph);
f_M	Adjustment for median type (mph);
f_A	Adjustment for access points (mph).

The average traveling speed is derived from the estimation on the flow rate:

$$s = FFS - \left[(\alpha_i \cdot FFS - \beta_i)\left(\frac{v_p - 1400}{\gamma_i \cdot FFS - \delta_i}\right)^{1.31}\right],$$

s	Average traveling speed (mph);
FFS	Free-flow speed (mph);
v_p	15-minute passenger-car equivalent flow rate (pc/ln/hr);
$\alpha_i, \beta_i, \gamma_i, \delta_i$	Calibration parameters according to environment condition.

where the adjust hourly volumes are calculated as:

$$v_p = \frac{v}{PHF \cdot N \cdot f_{HV} \cdot f_p},$$

v	Hourly volume (pc/hr);
PHF	peak hour factor;
N	Number of lanes in one direction (ln);
f_{HV}	Heavy-vehicle adjustment factor;
f_p	Driver population adjustment factor.

Therefore, the total traveling time through unit length of multilane highway could be estimated by:

$$t = \frac{l}{s} = \frac{l}{FFS - \left[(a \cdot FFS - b)\left(\frac{v_p - 1400}{c \cdot FFS - d}\right)^{1.31}\right]},$$

t	Total traveling time through unit length of multilane highway (hr);
l	Unit length of multilane highway (miles).

Rail Road (Fernández L, De Cea Ch et al. 2004)

$$t_i = d_i + \alpha_i \left(\frac{f_i}{C_i}\right)^{\beta_i}$$

t_i	Average classification delay for a freight car in yard i (hr);
d_i	Classification delay for a freight car in yard i, in free flow conditions when there is no congestion (hr);
f_i	Flow of railcars in yard i during a period (ton);
C_i	Capacity in yard i during a period in railcars (ton/hr);
α_i, β_i	Calibration parameters.

Intermodal Container Terminals

Uniformly converting these capacity estimations into hourly capacity or daily capacity, we are able to characterize the transportation modes in each subdivision, provided the information of arrival rate of traffic within unit of time. The center issue of this problem would be the measurement of waiting time and processing time in the container terminals, which connects two modes of transportation.

Park's model (Park 2005) focused on the two-level optimization of the system capacity, rather than the capacity of the single processing facility. Alternatively, we are aiming to provide a detailed estimation of processing time or system delay during transshipment between transportation modes.

Generally, similar to the rail yard capacity model, the total processing time can be recognized in two parts: storage time and processing time. The first part contributes to the time goods are stored in the warehouse or storage area, and the second part representing the trans-loading processing time. The total time in connection i due to transshipment can be measured by

$t_i = d_i + \alpha_i \left(\frac{f_i}{C_i}\right)^{\beta_i},$

t_i	Average classification delay for a freight car in yard i (hr);
d_i	Average storage time in connection i (hr);
f_i	Expected traffic arrival rate during a period in connection i (ton);
C_i	Capacity in connection i during unit of time (ton/hr);
α_i, β_i	Calibration parameters specific for connection i.

It is not hard to see that the dwelling time is related to the weight and the ability of trans-loading of the connection. Presumably, the capacities of the connections are different in maritime related terminals since most of the work is done by cranes. Therefore, the evaluation of the connection capacity is measured differently in maritime related transshipment and rail related transshipment.

Rail-Ship or Road-Ship Transshipment

For the capacity in terminals related to rail-ship or road-ship transshipment, the capacity of a facility is dependent on the availability of the equipment. The overall capacity could be further decomposed into a factoring formula (Mocuţa and Ghita, 2007):

$$C_i = CG_i + CM_i \times KUM_i,$$

CG_i	Capacity of gantry crane in connection i (ton/hr);
CM_i	Capacity of mobile crane in connection i (ton/hr);
KUM_i	Utilization factor of mobile cranes for transshipment in connection i (ton/hr).

There can also be a different assumption for the measurement of transloading capacity of waterway terminals, such as overall capacity depending on the availability of gantry cranes. It also yields a statistical estimation on the capacity of the transshipment facility.

Rail-Road or Road-Rail Transshipment

For rail-to-road or road-to-rail intermodal freight transportation, the transshipment efficiency is not dependent on the crane, but rather the length of the transshipment tracks so that the dwelling time due to trans-loading is measured as:

$$C_i = \frac{L_{Truck,i}}{L_{Wagon,i}} \cdot K_{LFi} \cdot K_{FFi} \cdot 2,$$

$L_{Truck,i}$	Length of transshipment tracks in connection i (m);
$L_{Wagon,i}$	Length of average wagon in connection i (m);
K_{LFi}	Load factor (ton/wagon);
K_{FFi}	Flow factor, the use of a track during the day (1/hr).

In doing so, by whichever method applied practically, the total dwelling time in connection, i, related by weight of the freight can be characterized mathematically. Taking into account of the delay in connection, i, the total traveling time and the transportation cost from original point to destination can be estimated theoretically. Moreover, an optimization with a combination of the capacities of the unimodal transportation is going to be conducted with above equations.

The overall objective of the problem is set to be minimization of traveling time from one terminal to another terminal. The optimization or path choices are subject to the constraints from freight transportation capacity and processing time in each candidate facility throughout the whole process of transportation.

The emphasis of the study will be put on the estimation on the constraints from freight transportation capacity and optimal path selection. A network representing the transportation paths will be set up and an optimal path are in picture to solve the best choice for transportation.

Beyond the optimal result, a theory of constraint will be deployed to attack the weak links between endpoints in order to improve the overall freight transportation capability of the target area.

CASE STUDY: HAMPTON ROADS AREA INTERMODAL FREIGHT TRANSPORTATION ANALYSIS

The proposed approach is applied to a case of interest: the intermodal freight transportation system analysis in the Hampton Roads Area, in Virginia. This area is located in the southeast region of Virginia and contains a body of water and a metropolitan area. This area is connected with the other parts of Virginia and other states with a number of Interstate Highway and railroad systems. From the systematical overview of Interstate Highways in Virginia, I-64, I-95, I-81, and I-77 undertake the major burden of the highway freight transportation. The current bottleneck of the highway transportation was found at the pink circled areas in Figure 24. Among these bottle necks, the Hampton Roads Area is one of the most important areas in Southeast Virginia where three international seaports and railroad network are located. The analysis of the intermodal freight transportation will take the first step towards the improvement of the Hampton Roads Area and the entire Virginia intermodal transportation system.
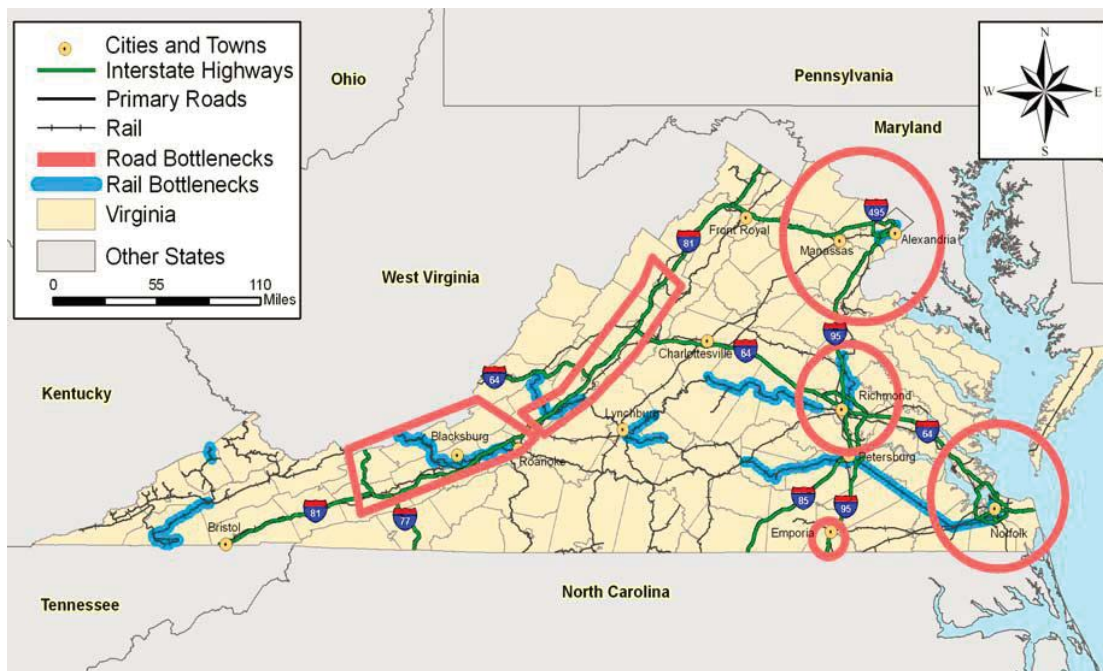

Figure 24. 4Captured Virginia Freight Bottlenecks (Cambridge Systematics)

The Hampton Roads Area consists of the Gloucester County, Isle of Wight County, James City County, Mathews County, York County, City of Chesapeake, City of Hampton, City of Newport

News, City of Norfolk, City of Poquoson, City of Portsmouth, City of Suffolk, City of Virginia Beach, and City of Williamsburg. Southeastern Virginia is connected with the western part of Virginia and other states through an extensive network of Interstate Highways. The included Interstate Highways are the Interstate 64, I-264, I-464, I-564, and I-664. Besides the mentioned Interstate Highways, the Hampton Roads Area extends the connection with New England States
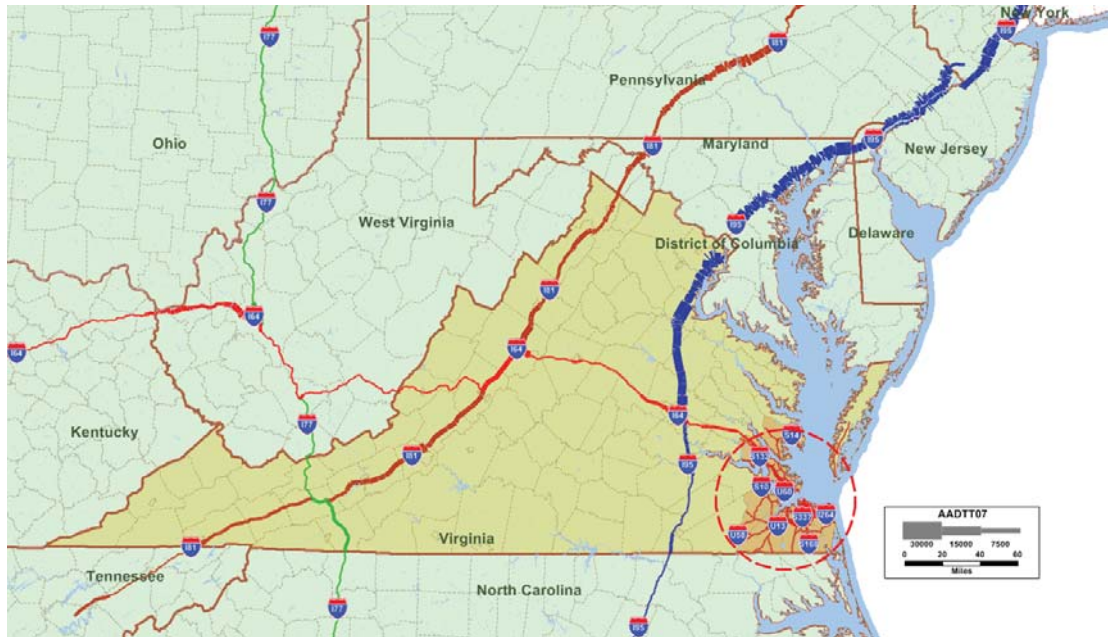
Figure 25. Measurement of Truck Volume in 2007 (Red circled is the analysis area - Hampton Roads Area)

by U.S. Highway 17, U.S. Highway 60, and U.S. Highway 13. U.S. Highway 13 could also connect Hampton Roads Area to the West Virginia and other western States. Moreover, to the south of the Hampton Roads Area, U.S. Highway 17, U.S. Highway 158, and U.S. Highway 58 are able to connect this area with North Carolina and other southeastern regions. The freight transportation from these mentioned highways contribute to the outbound, inbound, throughput and international freight transportation demands.

From a transportation perspective, some of the outlying area in Hampton Roads forms a natural interconnectivity terminal for the potential intermodal transportation. Consisting of several important locations including seaway transport and transshipment port group, Hampton Roads is considered to be the waterway gate of Virginia. Out of the possible forms of intermodal transportation, waterway transportation is regarded as the most cost efficient mode in large volume freight movements. Most of the seaway transport freight imports through the ports located in the Hampton Roads Area. Commodities from other eastern states or foreign origins could be transported via seaway or waterway to the port area. It incorporates the international

waterway terminal in the mouth of the Elizabeth River, Nansemond River, and James River with several smaller rivers and empties into the Chesapeake Bay. After that, the unloaded freight is trans-loaded to either a truck or rail. The highway and railroad system perform a time efficient delivery to the destinations.
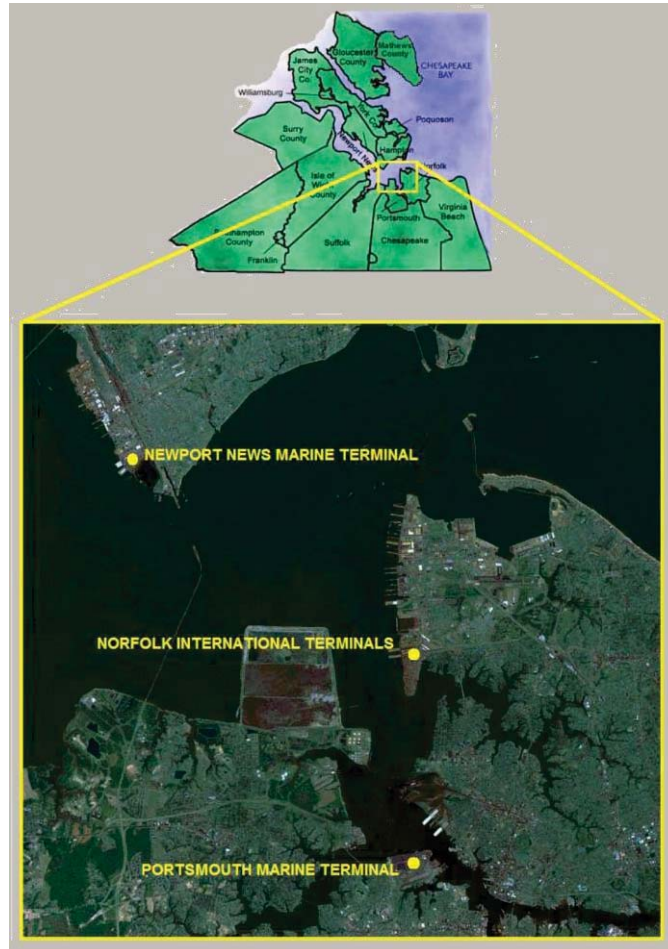
Figure 26. Major In-use Marine Terminals in Hampton Roads Area (Rondorf, Wilkins et al.)

As of 2015, the highway transportation volume is 232,297 kton, meanwhile the railroad transportation within the Hampton Roads Area is recorded as 287,843 kton. In 2007, the Panama Canal was projected to expand so that the upgraded canal is expected to create demand for New Panamax ships. In 2016, this ongoing project is intended to double the capacity of the Panama Canal by creating a new lane of traffic. This new lane will not only allow for an increase of traffic, but also enable larger ships to traverse the canal. Once completed, a higher demand for transport and transshipment on the east coast, especially in the Hampton Roads Area, can be foreseen. The allocation of freight transport demand and scientific assignment of traffic is needed to be processed in advance in order to optimize the system capacity of the Hampton Roads Area. This in turn could significantly contribute to the economic development of not only Virginia, but

the United States as a whole. Therefore the transportation volume by truck and railroad are projected to increase by more than 50%, eventually increasing by three fold, by 2040.

TABLE 1		
HOT AND COLD: RANKING U.S. PORTS BY SIZE (TEUs, 2008)		
Port	Container TEUs 2008	Percent Growth Rate, 1998-2008
Los Angeles	7,849,985	132.4
Long Beach	6,350,125	55.0
New York/New Jersey	5,265,058	113.5
Savannah	2,616,126	258.1
Oakland	2.236.244	42.0
Hampton Roads	2,003,278	66.4
Tacoma	1,861,352	161.0
Houston	1,794,309	87.1
Seattle	1,704,492	10.4
San Juan	1,684,883	-15.4
Charleston	1,635,534	28.0
Port Everglades	985,095	39.9
Miami	828,349	1.7
Jacksonville	697,494	-8.0
Baltimore	612,887	25.9
U.S.	42,827,594	63.7

Sources: American Association of Port Authorities and the Old Dominion University Economic Forecasting Project

Figure 27. Ranking of U.S. Ports by Size (2008)
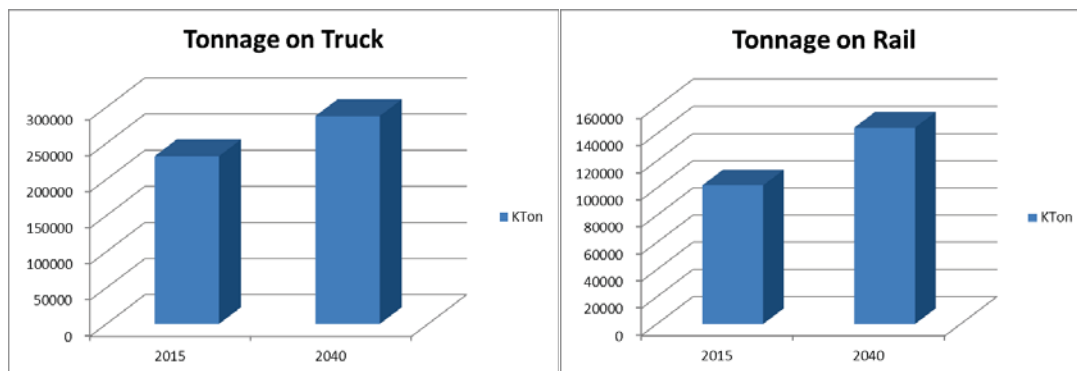
Figure 28. Tonnage within Hampton Roads Area in 2015 and 2040, respectively

Freight analysis framework (FAF) is the main data source for this study. It provides all major freight data, such as commodity flow survey (CFS). The CFS data and additional sources are integrated and recorded by FAF[3] from a number of sources to generate a comprehensive picture of commodity flow among states and major FAF specific analysis zones by all modes of transportation. The database provides traffic volume, highway capacity, peak hour traveling

time, etc., for 2007 to 2015 and a projection of those terms for the year of 2040. Also included are state-to-state flows for these years plus 1997 and 2002, summary statistics, and flows by truck assigned to the highway network for 2015 and 2040. The record of transportation provides the existing commodity flows for the year 2007 and forecasts through 2040. The generated flows and forecasts include tonnage, value and domestic ton-miles by region of origin and destination, commodity type, and mode selection. In this database, the information is tabulated for 123 domestic zones and 8 foreign zones regarding the shipments. We applied the given data to the Hampton Roads Area and analyzed the performance of highway along with an interconnected evaluation of performance after Panama Canal expansion. In doing so, the comparisons of traffic assignment and congestion analysis of the truck and rail networks are conducted in TransCAD 6.0.

The case study will be structured in three sections. In section 5.1, we will introduce the transportation demand on highway system in the Hampton Roads Area. Section 5.2 will introduce the current state traffic assignment. In section 5.3, the impact of the expansion of the Panama Canal will be discussed. In section 5.4, the influence of rerouting is studied when a major transportation infrastructure is disrupted. Finally, in section 5.5 and 5.6, the transportation of railroad will be analyzed in the similar manner. The case study results will be conducted and displayed by TransCAD to show the routing and traffic assignment for defined scenarios.

Transportation Demand on Highway in Hampton Roads Area

The Hampton Roads Area consists of 14 counties and cities. All the freight trips originated from and routed to this area are selected as the scope of work. The tonnage of shipments from and to this area is computed with FAF[3] database. The data beyond the region scope were eliminated from the dataset. As illustrated in Figure 29, 11 boundary highway endpoints are selected in order to disaggregate the transportation data from and to the Hampton Roads Area, and they are indexed from A to K. In railroad transportation analysis, only B, E, F, J, and K are kept due to network structure difference. Within the boundary, the specific transportation volumes to each city and county are disaggregated according to the population proportions. We only focus on the truck and rail as they represent the dominant share of freight movement. The transportation mode for both domestic and foreign shipments in the original database is categorized into three modes: truck, rail, water. Additionally, all waterway freight shipments are disaggregated according to the capacity ratio of the three marine international terminals. After that, the freight is transloaded to either truck or rail and shipped to the destination. Because of this, the truck and railroad transportation can be the representative of the whole intermodal freight transportation system.

Estimation of original-destination (O-D) matrix of freight transportation on truck and rail in the Hampton Roads Area are computed and partially shown in Tables 1 and 4. The traffic volumes

in O-D matrixes are measured in minute. The O-D matrix represents the truck shipment data for 11 boundary points and 15 centroids as well as 3 marine terminals.
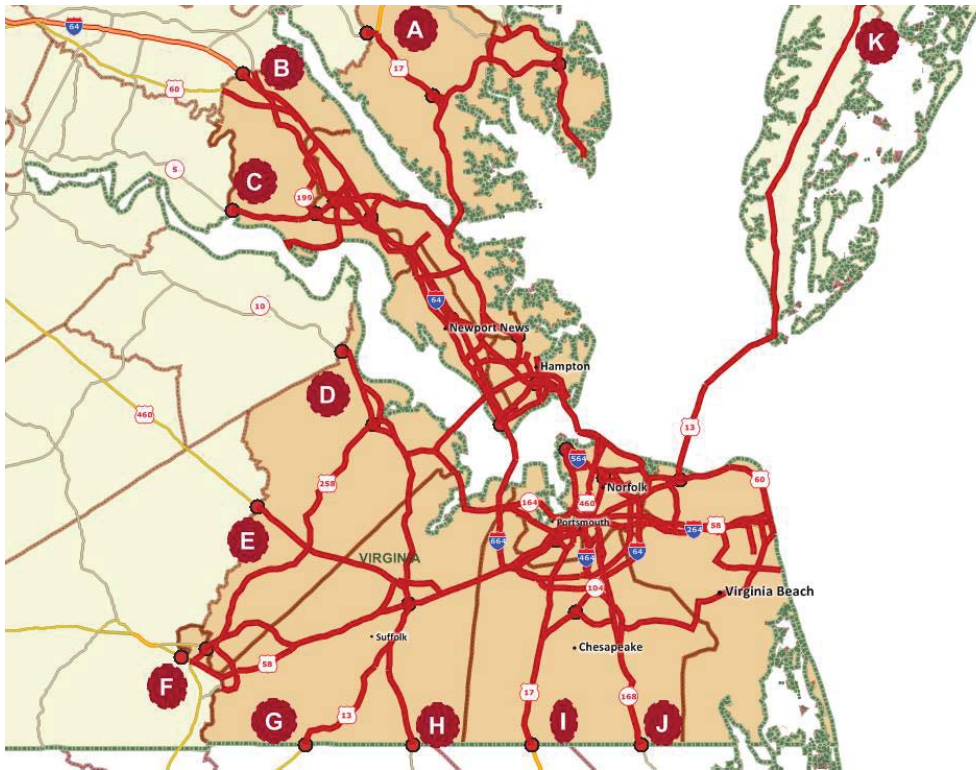
Figure 29. Highway Map of Hampton Roads Area

Table 1. Original-Destination Matrix of Freight Transportation on Truck in the Hampton Roads Area.

	A	B	C	D	E	F	G	H	I	J	K
Poquoson	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chesapeake	0.00	0.06	0.06	0.06	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Suffolk	0.00	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Newport News	0.00	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Hampton	0.00	0.03	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Norfolk	0.00	0.06	0.06	0.06	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Williamsburg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Portsmouth	0.00	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Franklin	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Virginia Beach	0.00	0.11	0.11	0.11	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Gloucester	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Isle of Wight	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
James City	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Mathews	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
York	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Current State Traffic Assignment Analysis for Freight Movement on Truck
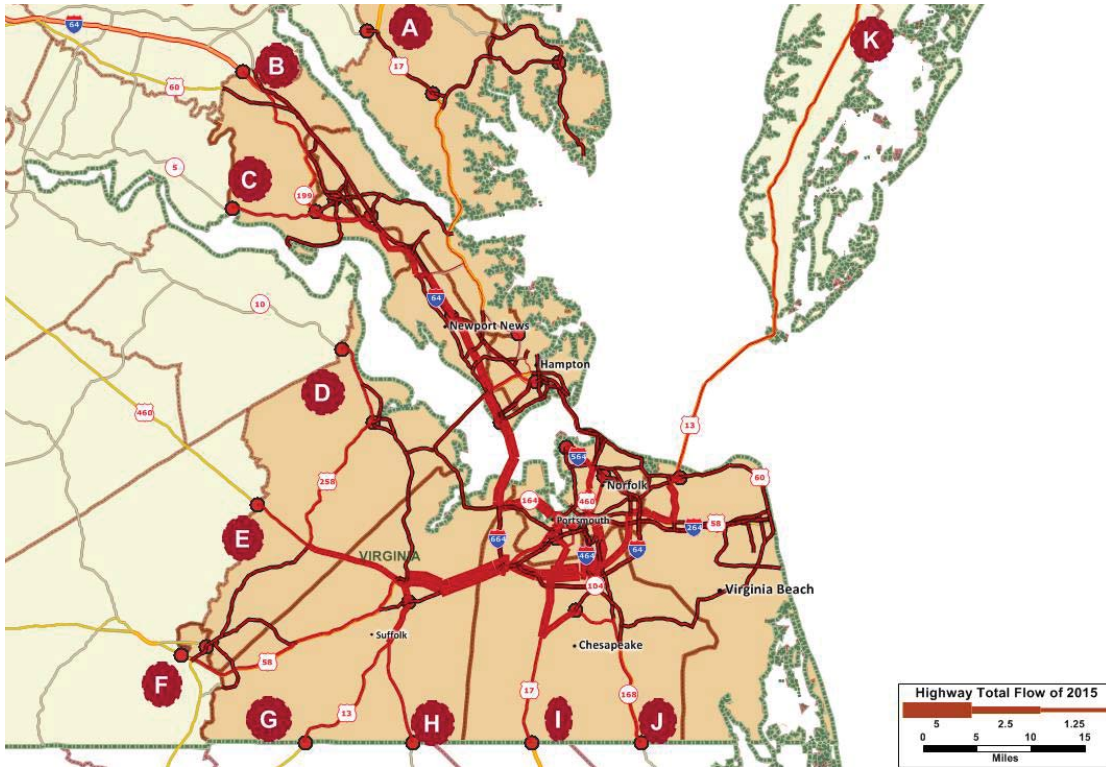
Figure 30. Highway Traffic Flow in 2015

The Hampton Roads Area has already been found to be the most congested and that the I-64 corridor has significant congestion problems as well. The traffic flow map is shown in Figure 30. It could be found that the most traffic flow is distributed on I-64 from Newport News to Portsmouth and Norfolk segment, also significant amount of traffic is traveling on U.S. Highway 13 between Suffolk and marine terminals.

Based on the information described above, data on the most heavily used highway segments, the consistent result could be illustrated by volume to capacity ratio (VOC) and volume dependent delay (VDF) map in Figures 31 and 32. It has been reported that the major problem or bottleneck most often criticized was highway congestion. (Cambridge Systematics)

The usage of highways near marine terminals in Norfolk and the surrounding area were found to be significantly higher in the region. Also, the corridor of U.S. Highway 13 is proved to be contributing to the congestion of East-West truck Transportation. U.S. 13 runs parallel with U.S. Highway 58 and U.S. Highway 460. Both of these corridors connect the Hampton Roads Area to

the Western Virginia and other states. There are no true parallel facilities to U.S. Highway 13. However, it accesses other major corridors, especially within the Hampton Roads area, where it accesses Interstate 64 and its auxiliary routes, including I-664, the Hampton Roads Beltway, and I-264 in multiple locations. It also accesses U.S. 58, U.S. 460, and U.S. 17, all components of Corridors of Statewide Significance. Freight transportation from New England to the Hampton Roads Area is mainly assigned to U.S. Highway 13 and also I-64. Both highway segments contributing to the significant delays are near the northeast part of Hampton Roads.

The improvement of U.S. 460 to interstate quality between Hampton Roads and Richmond is reported to be a high priority project in the coming 6-10 years. The combination of Portsmouth Marine Terminal and Craney Island Marine Terminal will result in the majority of the more than six million cargo movements occurring on the Portsmouth side of the Elizabeth River. U.S. 460, I-664 and U.S. 13 are expected to transfer this cargo efficiently to the western part of the transportation systems.
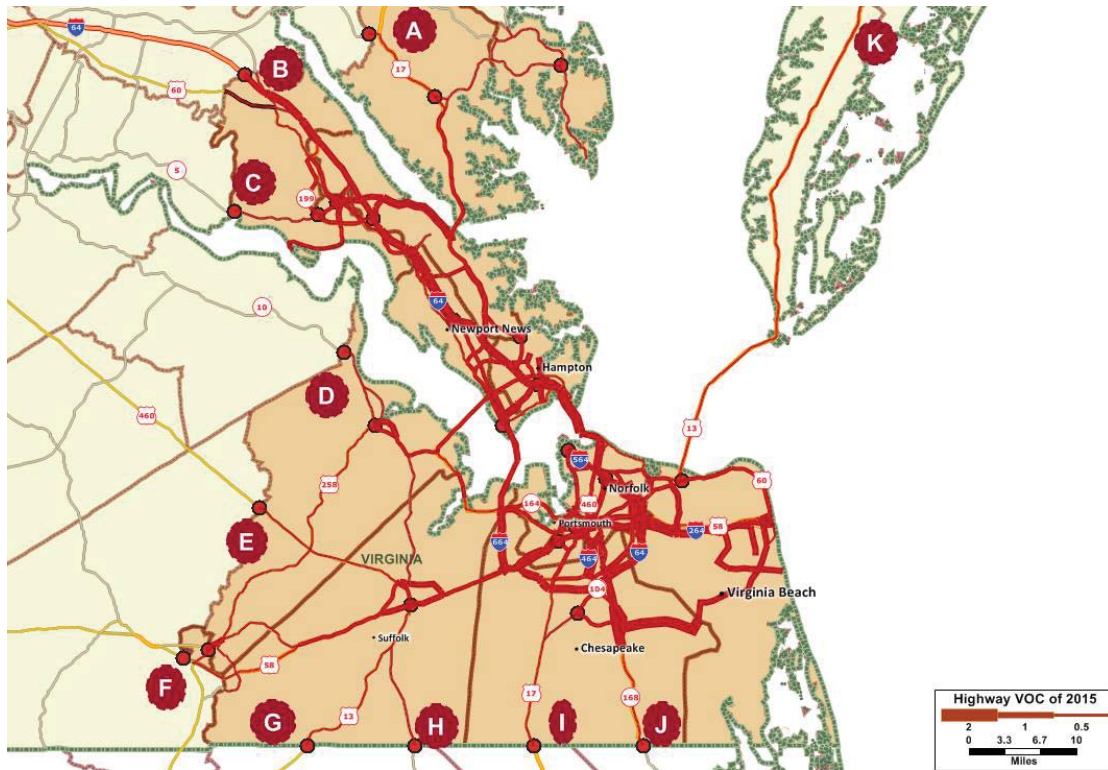
Figure 31. Volume to Capacity ratio (VOC) of Truck Transportation in Hampton Roads Area
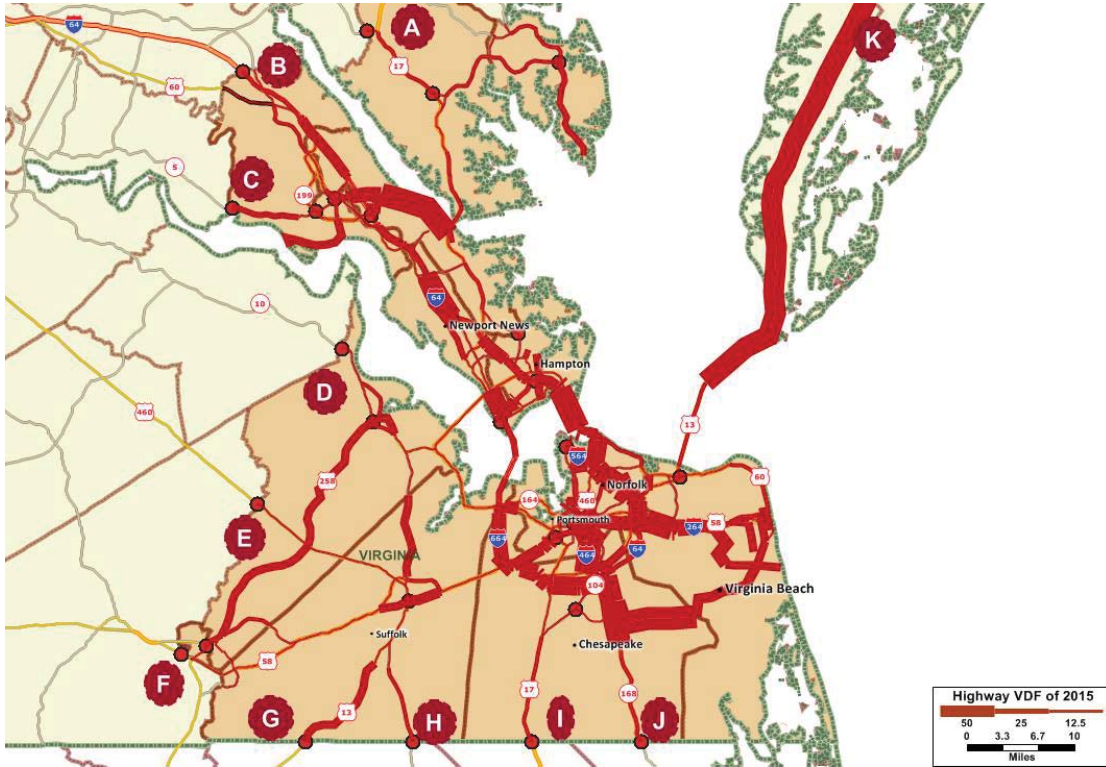
Figure 32. Volume Dependent Delay (VDF) of Truck Transportation in Hampton Roads Area

Impact of Expansion of the Panama Canal on Highway Transportation in 2040

The aggregate level of transportation data for Hampton Roads Area is shown in Tables 2 and 5Error! Reference source not found.. As depicted in Figure 33, it is easy to observe a remarkable growth in tonnage in both plots. This significant increase in tonnage could be mostly attributed to the expansion of the Panama Canal. After the expansion, the export and import tonnage are both doubled, this is greater than the increase in domestic transportation. Therefore, an increasing volume of traffic could be foreseen near the international marine terminals and the highways connect the marine transloading terminals to other states.

Table 2. Comparison of Tonnage in 2015 and 2040 on Truck

2015		2040	
Truck	Tonnage (k-ton)	Truck	Tonnage (k-ton)
Domestic Outbound	109181	Domestic-Outbound	133603
Domestic Inbound	103804	Domestic-Inbound	108454
Export	9240	Export	23107
Import	10071	Import	22680
Total	232297	Total	287843

Table 3. Original-Destination Matrix of Freight Transportation on Truck in Hampton-Roads Area

	A	B	C	D	E	F	G	H	I	J	K
Poquoson	0.00	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Chesapeake	0.00	0.43	0.43	0.43	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Suffolk	0.00	0.17	0.17	0.17	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Newport News	0.00	0.35	0.35	0.35	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Hampton	0.00	0.27	0.27	0.27	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Norfolk	0.00	0.52	0.52	0.52	0.57	0.57	0.57	0.57	0.57	0.57	0.57
Williamsburg	0.00	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Portsmouth	0.00	0.19	0.19	0.19	0.21	0.21	0.21	0.21	0.21	0.21	0.21
Franklin	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Virginia Beach	0.00	0.86	0.86	0.86	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Gloucester	0.00	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Isle of Wight	0.00	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.08
James City	0.00	0.13	0.13	0.13	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Mathews	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
York	0.00	0.13	0.13	0.13	0.15	0.15	0.15	0.15	0.15	0.15	0.15

The estimation of O-D matrix for truck in the Hampton-Roads Area in 2040 are computed and partially shown in Table 3. Additionally, the flow map, VOC, VDF measurements are shown in Figure 33, 34 and 35, respectively.

Figure 33. Highway Traffic Flow in 2040

Table 2 and Figure 33 show the growth of annual truck volume in the projected future, respectively. After 35-years growth estimation, the projected annual truck volume in the Hampton Roads Area appears to be growing heavily along I-264, I-64 and I-664, U.S. Highway 13 between Suffolk and Portsmouth and the interstate to the south of Chesapeake. The main growth comes from the areas surrounding the port. The increased freight volume contributes also to the raised truck volume to the interstate highway or freeway connecting this area to the neighboring states. Compared to that, Figures 34 and 35 illustrate the comparison in volume to capacity ratio and the volume dependent delay in this area. The growth does not seem to be as significant as what was shown. Only difference between these two groups of figures is that remarkable delay was found at the east part of Norfolk. This phenomenon was also found in the base case in 2015. With a significantly increased traffic volume, especially the export and import volume, Figures 34 and 35 imply that the capacity is constraint in the area near marine transloading terminals. In this area, the necessity of expanding the highway or providing alternative choices can be expected to increase in the future.

There were more than 1.1 million trips go beyond the international marine terminal gates in 2006. Within the "last mile" truckloads originating or terminating at VPA terminals head to connection points along I-64, I-664, I-164, and U.S. 58. Due to this growing necessity, VDOT has included projects to expand capacity to I-64 from Airport Drive in Henrico County to
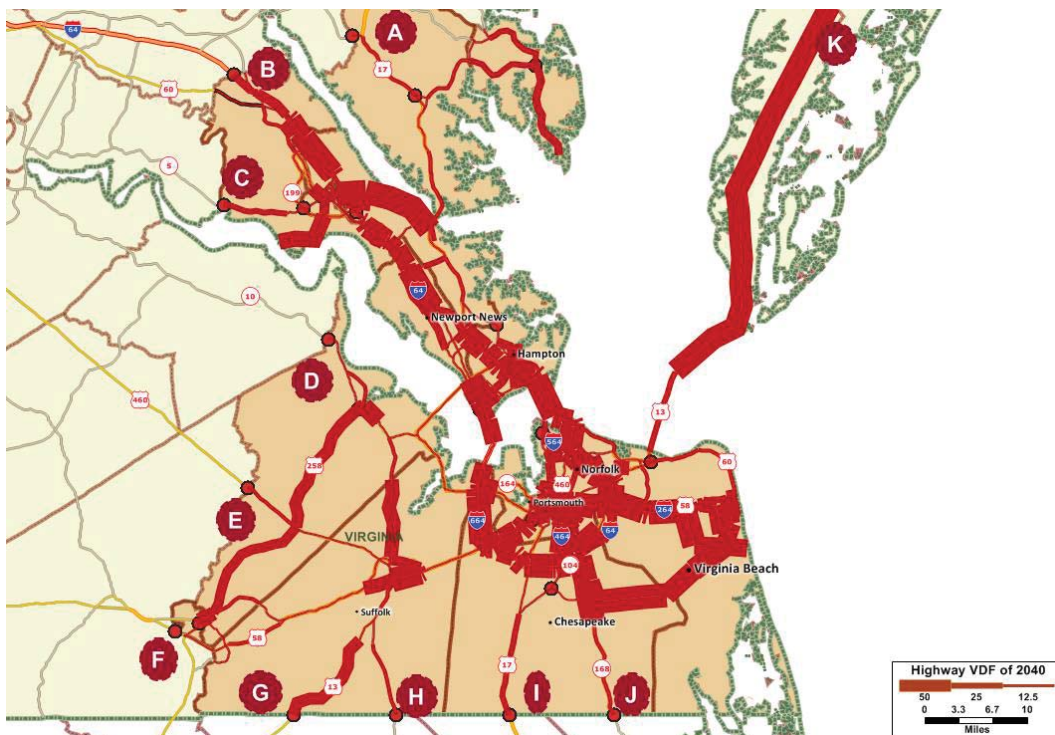

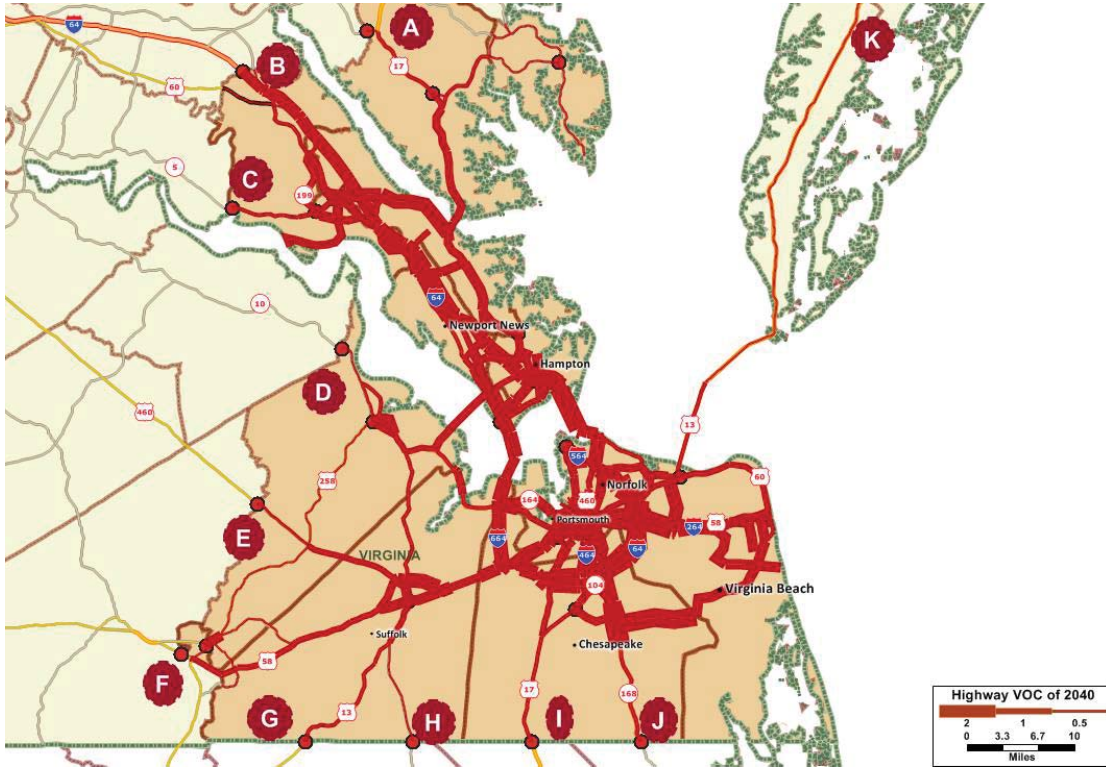Figure 34. Volume to Capacity ratio (VOC) of Truck Transportation in 2040

Figure 35. Volume Dependent Delay (VDF) of Truck Transportation in 2040

Jefferson Avenue/Route 143 in Newport News. I-564 provides interstate access close to but not directly to Norfolk International Terminal (NIT), which could facilitate the intermodal freight transportation.

Impact of Traffic Disruption in Hampton Roads Area

According to the shown traffic flow, the heavy use of a few Interstate Highways or U.S. Highways may imply a significant impact when a disruption due to accident or natural disasters happens. The disruption may cause an alternation in capacity of highway links or endpoints and therefore make a shift of traffic flow to other connecting links. The cost of this shift should be evaluated regarding the volume dependent delay. The evaluation will indicate several choke points in case of the accidents or natural disasters. In this condition, the new traffic flow will be shown on the TransCAD map in order to display the potential necessity of maintenance and expansion of highway capacity.

In the previous study, I-664 contributes to the freight transportation between the north and the south of the waterway. In our study, we choose to disable the Hampton Roads Beltway between Newport News Creek and the south of the waterway, which is also known as Monitor Merrimac Memorial Bridge Tunnel. In doing so, we are intending to find out the second choice for

transportation between north and south in the Hampton Roads Area.

Moreover, part of the U.S. Highway 13 from Portsmouth to Suffolk is also disabled to study the alternatives for freight movement between the intermodal marine terminals and Western Virginia. From Figures 36 and 37, we can see that the volume dependent delay on Highway 60 (Hampton Roads Bridge Tunnel) between Hampton to North Norfolk increased remarkably, which indicates that the freight shifts to Highway 60 rather than taking advantage of the James River Bridge. However, from previous discussions we found that the usage of Highway 60 already exceeds its capacity and that the James River Bridge could not perform as the secondary choice for the I-664, which plays a key role in connecting Newport News to Norfolk. The reason for this shift is because part of the commodities need to be transported to Norfolk International Terminal and very few detour possibilities are provided for the trips at this point. This may imply a necessity for construction of a secondary choice, other than Highway 60.

Some news about the secondary choice has been reported as the Hampton Roads Third Crossing that includes the Craney Island Connector and a new bridge-tunnel that would connect I-564 and I-664. This project is intended to construct a third tunnel in the Hampton Roads Area. The proposed alignment would substantially benefit freight transportation to and from the marine terminals in Newport News, Portsmouth and Norfolk.
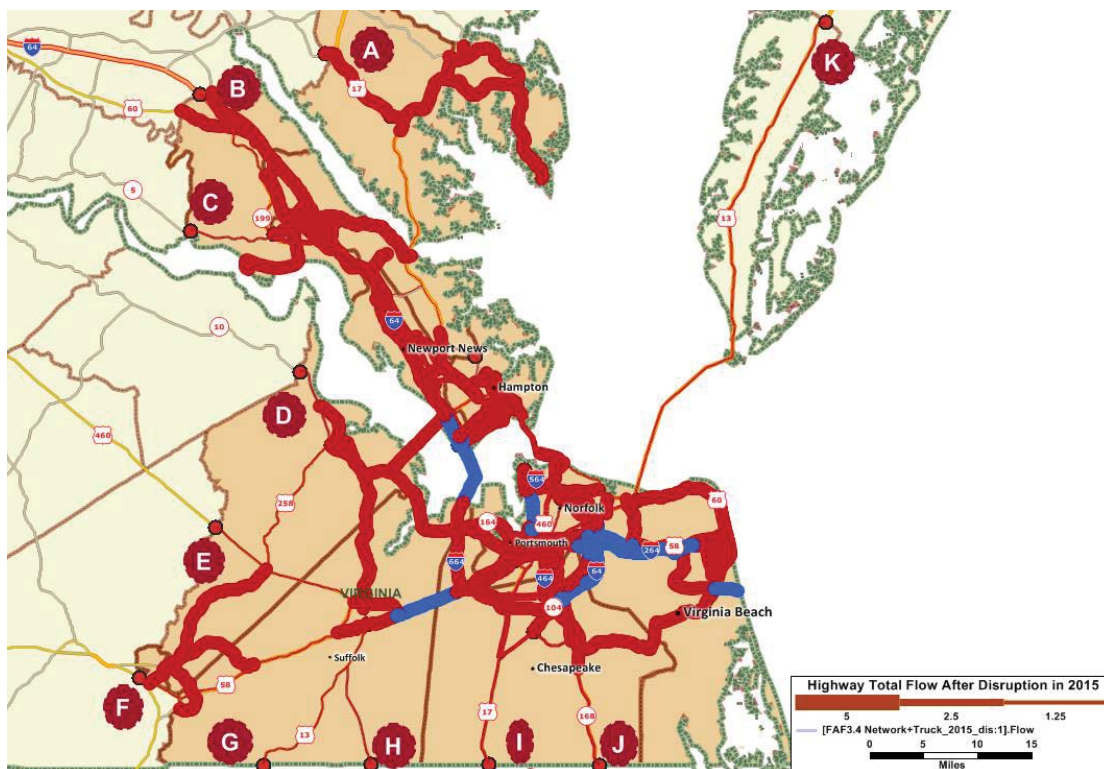

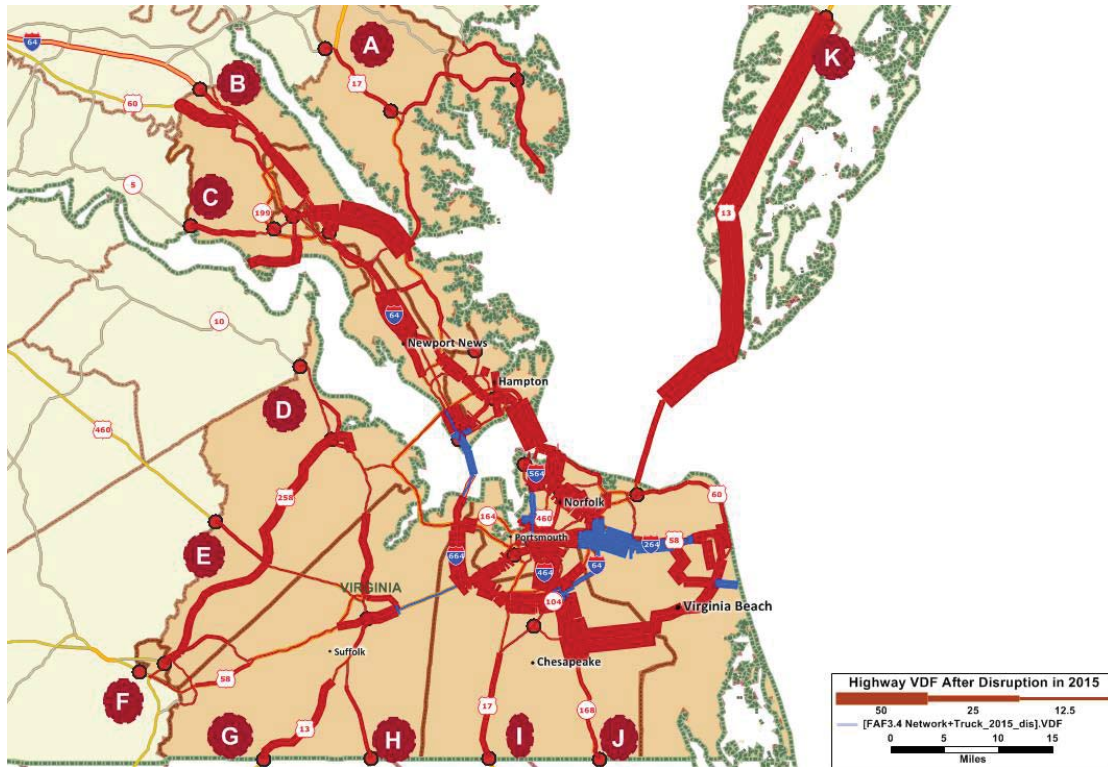Figure 36. Highway Traffic Flow after Disruption in 2015

Figure 37. Volume Dependent Delay (VDF) of Truck Transportation after disruption in 2015

Except for the previously mentioned disabled links, we also tried to put the restrictions on Hampton Boulevard in Norfolk. This is the preferred route for many truckers to the Norfolk International Terminal. We were looking for the impact the restrictions had on this efficient link. It was found that the constraint of this link contributed to the congestion of U.S. 460 and other connected links. This is especially significant after the expansion of Panama Canal. The delay on south I-664 and the intersection with U.S. 460 increased remarkably and induced heavy congestion nearby.

Transportation Demand on Railroad in Hampton Roads Area

The freight rail network in Hampton Roads is comprised of tracks, bridges, sidings, and terminals. The network is centered at the three international marine terminals and mostly privately owned and operated. Norfolk Southern and CSX Transportation are the largest owners of rails. The operating railroad network connects the east and west part of Hampton Roads Area so that the lines are used most likely to serve the freight movement between Hampton Roads and West Virginia/Kentucky/Tennessee. Along with the major lines, the freight transportation on the railroads is served with an extensive network of yards and intermodal terminals. Freight from intermodal terminals is enabled to transfer between seaway and waterway to rail whereas the transfer between trucks and rail is rare in this area.
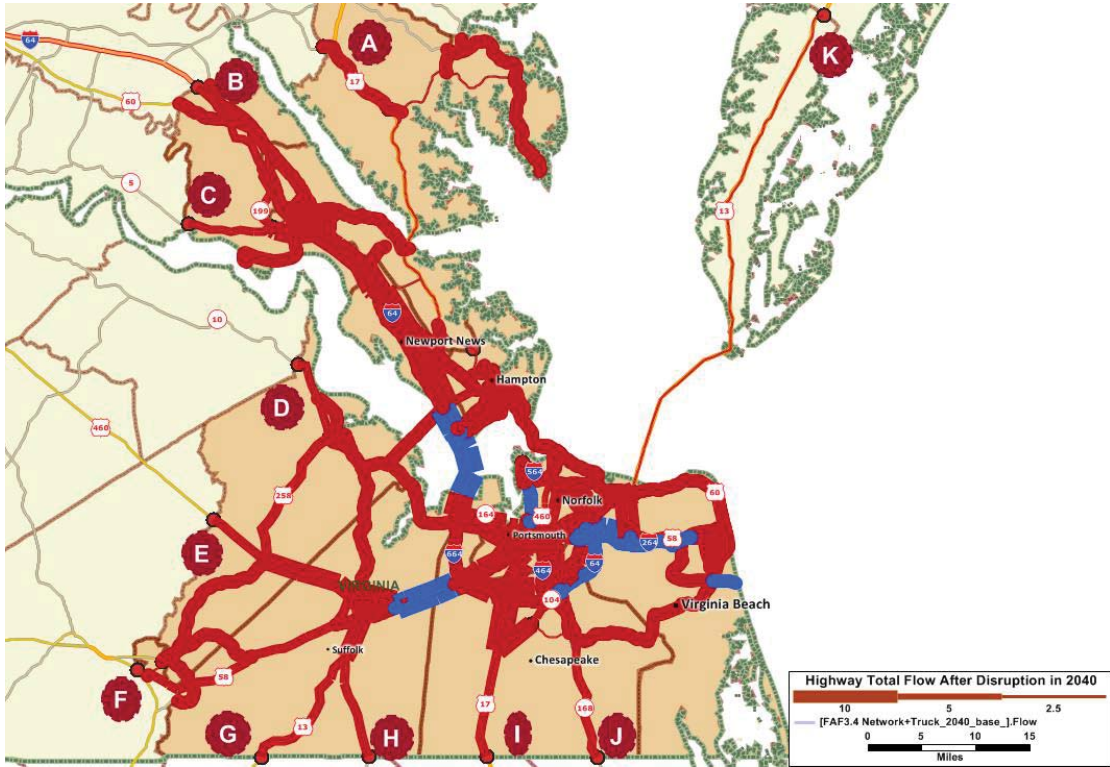
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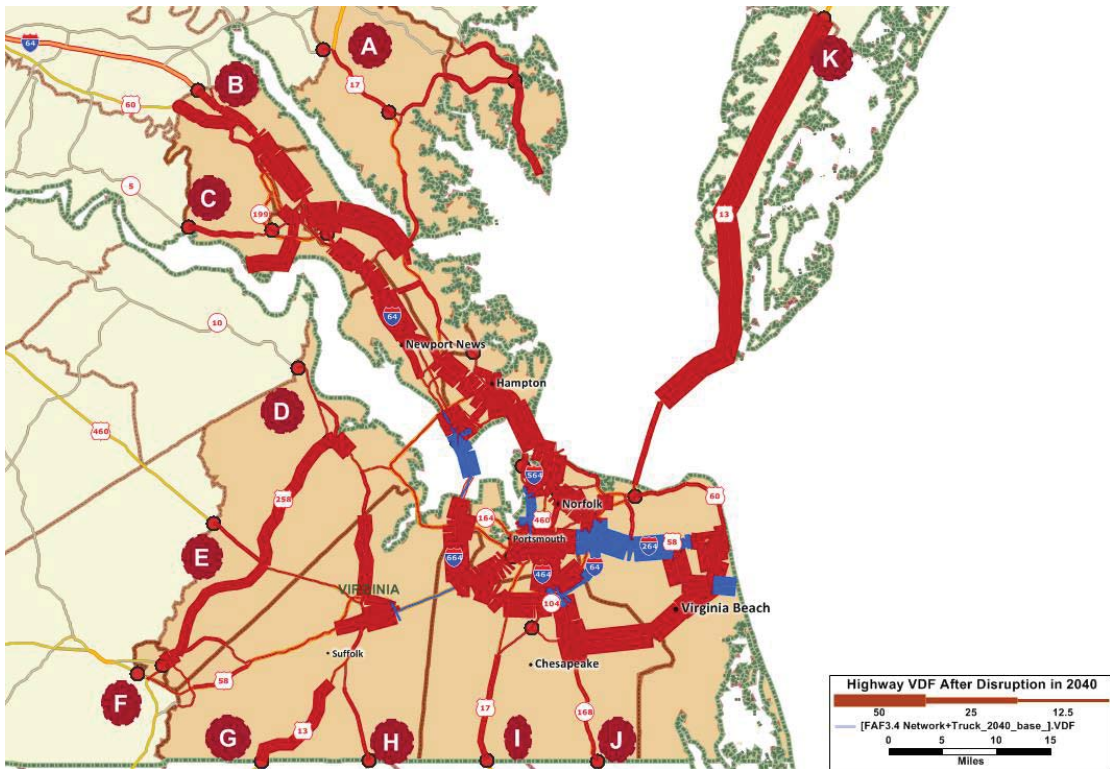Figure 38. Highway Traffic Flow after Disruption in 2040

Figure 39. Volume Dependent Delay (VDF) of Truck Transportation after disruption in 2040

Table 4. Original-Destination Matrix of Freight Transportation on Rail in Hampton-Roads Area

	B	E	F	J	K
Chesapeake	0.02	0.02	0.02	0.02	0.02
Suffolk	0.01	0.01	0.01	0.01	0.01
Newport News	0.02	0.02	0.02	0.02	0.02
Hampton	0.01	0.02	0.02	0.02	0.02
Norfolk	0.00	0.01	0.01	0.01	0.01
Williamsburg	0.00	0.00	0.00	0.00	0.00
Portsmouth	0.01	0.01	0.01	0.01	0.01
Franklin	0.00	0.00	0.00	0.00	0.00
Virginia Beach	0.04	0.05	0.05	0.05	0.05
Isle of Wight	0.00	0.00	0.00	0.00	0.00
James City	0.01	0.01	0.01	0.01	0.01
York	0.01	0.01	0.01	0.01	0.01

Table 5. Comparison of Tonnage in 2015 and 2040 on Rail

Rail	Tonnage (k-ton)	Rail	Tonnage (k-ton)
Domestic Outbound	14555	Domestic Outbound	13634
Domestic Inbound	28877	Domestic Inbound	35802
Export	57853	Export	93453
Import	826	Import	1735
Total	102110	Total	144623

Table 6. Original-Destination Matrix of Freight Transportation on Rail in Hampton-Roads Area

	B	E	F	J	K
Chesapeake	0.03	0.03	0.03	0.03	0.03
Suffolk	0.01	0.01	0.01	0.01	0.01
Newport News	0.02	0.03	0.03	0.03	0.03
Hampton	0.02	0.02	0.02	0.02	0.02
Norfolk	0.00	0.00	0.00	0.00	0.00
Williamsburg	0.00	0.00	0.00	0.00	0.00
Portsmouth	0.01	0.01	0.01	0.01	0.01
Franklin	0.00	0.00	0.00	0.00	0.00
Virginia Beach	0.05	0.06	0.06	0.06	0.06
Isle of Wight	0.00	0.01	0.01	0.01	0.01
James City	0.01	0.01	0.01	0.01	0.01
York	0.01	0.01	0.01	0.01	0.01

We checked the data record for import and export in the FAF[3] data base. The data record showed that the international seaway freight was mostly trans-loaded from rail for export but transferred

to truck from import. From the flow map in Figure 41, we see that the major lines connecting the Norfolk Marine Terminal are heavily used. The major use of the railroad in Hampton Roads is to transport the export and part of the import freight between the terminal and the other states. The lines to the east, south and west states are the most heavily used. There has been reported a necessity of improving facilities to accommodate anticipated growth.
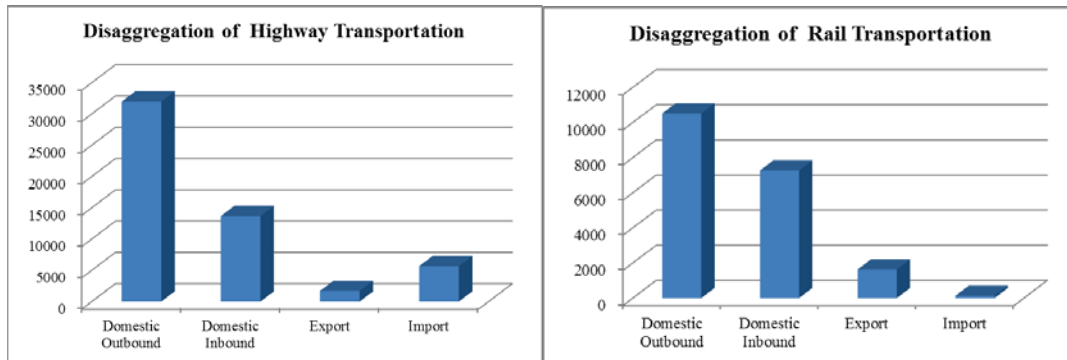

Figure 40. Disaggregation of Highway Transportation (Left) and Rail Transportation (Right)

The companies and logistic transportation entities has been looking to use more rail going to western Virginia or states from the Port of Norfolk. The proposed way for large volume freight transportation for mid or long distance is proved to be travelling economic. Therefore the connection between Norfolk and Suffolk in the Hampton Area should be ready for improvement and safety maintenance in order to provide a more transportation efficient major line.

The Impact of Expansion of the Panama Canal on Rail Transportation in 2040

Due to the expansion of the Panama Canal and a remarkable increase in export and import volume, the demand of freight transportation by railroad is expected to grow. From Figure 42, we can see an increase flow along the major lines directing to the marine terminals. The growing demand on the major lines proves that the major use of Virginia railroads is east-west, in order to connect some neighbor states with New England or the source of freight at international marine terminals.

There are 300,000 recorded containers trans-loaded between the rail yard and marine terminals of Virginia Port Authority. Additionally, about 10 percent of the truck movements shuttle between the terminals and rail yards. A growing need for connectivity between terminals and rail yards will be seen in the future. (Cambridge Systematics)
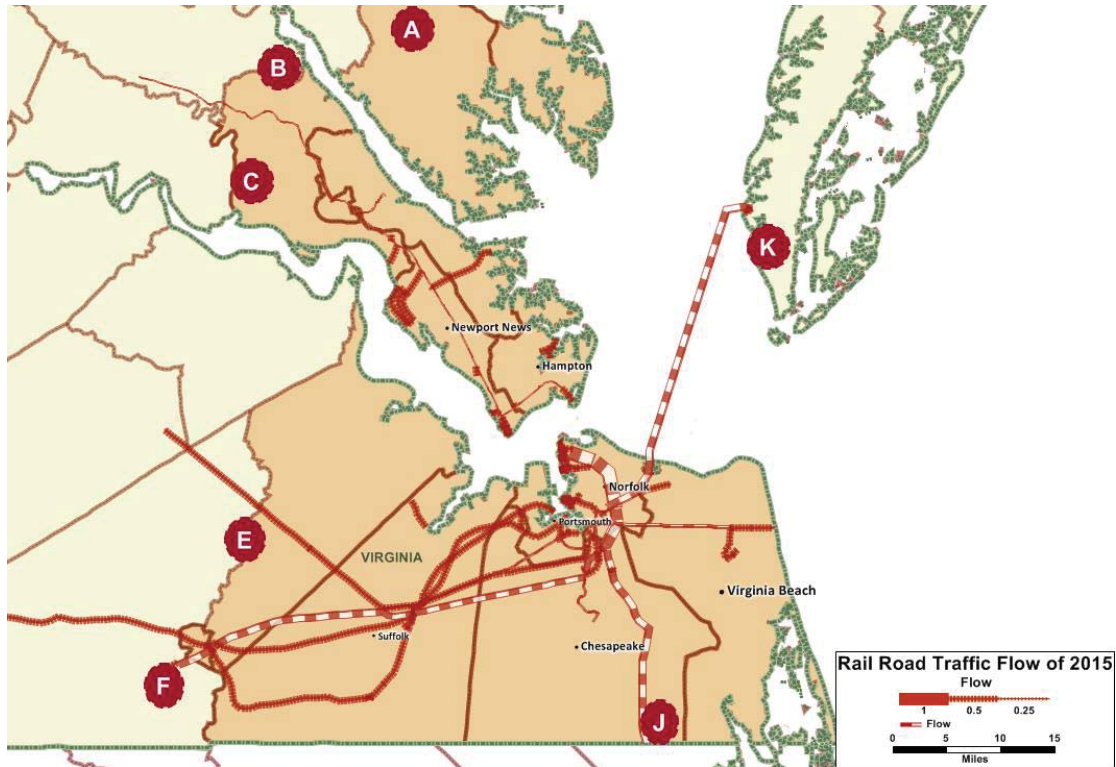
Figure 41. Railroad Traffic Flow in 2015

Currently, the rail system infrastructure in the Hampton Roads Area is providing inadequate freight capacity. This will be especially significant after the expansion of the Panama Canal. Also, the access to the heavily used marine terminal facilities appears to be very critical for intermodal trans-loading. Additionally, the links between marine terminals and connected warehouse, or storage area, also have to be enforced to face the increasing pressure in export and import freight movement demand.

CONCLUSION

In this paper, we developed a comprehensive model to estimate the capacity of intermodal freight transportation. The estimation of capacity was integrated for intermodal transportation. The case study in the Hampton Roads Area was conducted. According to the result of traffic assignment, we were able to find the congestion situation and the choke points. The most heavily used highway segments are the one close to the international marine terminals in Norfolk and Newport News. I-64 in north-south and U.S. 13 in east-west are the critical link of the whole system network. Also, I-664 and U.S. 337 (Hampton Blvd.) play an important role as alternatives for highway freight movement.
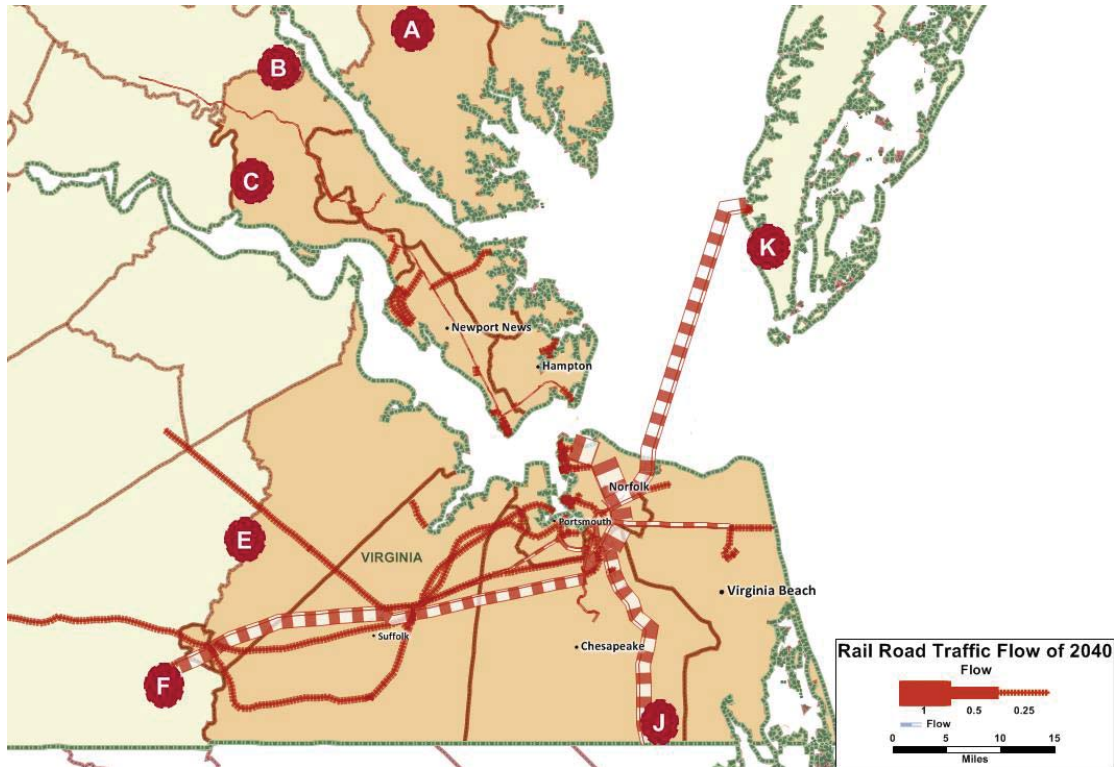
Figure 42. Railroad Traffic Flow in 2040

Additionally, the secondary choice needs to be provided for Hampton Roads Bridge Tunnel and Monitor Merrimac Memorial Bridge Tunnel. The increasing transportation demand in export and import intermodal shipment indicates the necessity for Hampton Roads Third Crossing project. Suggestion about maintenance and improvement were provided after the comparison of the case after the expansion of Panama Canal and disruption what-if analysis.

The analysis also proved the demonstrated necessity of integration of waterway/seaway to rail and truck transportation in order to face the increasing pressure in export and import volume. The usage of rail will grow to be an increasingly critical source in the intermodal transportation system of the Hampton Roads Area.

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