Optimization Model for Global Container Supply Chain: Imports to United States

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The Transpacific trade in container between Northeast Asia and North America is one of the world's highest volume arterial trade lanes. In comparison with Transpacific trade route, the Transatlantic trade route between Europe and North America is small and has been growing slow. Import container movement in these international trade lanes are the primary sources of United States container import activity. Container movements are heavily concentrated at a number of major gateways. The high concentration affects traffic and congestion at seaport as well as associated major transportation corridors. Concerns over potential long term congestion and large-ship draft restrictions have led shippers to seek alternatives. The all water routing through the Panama Canal to the East Coast is expected to grow to avoid potential congestion at West Coast. Canadian container ports are being developed and provide congestion free service and an interesting option for importers to reach U.S. markets. This paper analyzes the supply chain network with primary focus on import container to United States. An optimization model that integrates international trade and U.S. inland transport networks is developed. The supply chain channels include container import from Northeast Asia through the West Coast to U.S. inland markets of U.S. (defined by Business Economic Area), to East Coast of United States. via the Panama Canal, and European imports to U.S. markets through Gulf and East Coast. This study accounts for container imports to U.S. markets through existing and newly opened container ports in Canada. The model includes capacity restrictions at ports as well as capacities on the inland transport networks. The estimated container traffic flows are reflective of current traffic flows. Heavily concentrated corridors are indentified. Sensitivity analysis was performed to evaluate impacts of congestion on capacity constraints. The optimization model presents a framework for capturing impacts on the supply chain network due to underlying cost structure changes and potential infrastructure constraints.

INTRODUCTION AND BACKGROUND

A surge in global logistics trade has been driven largely by growth in global container trades. U.S. foreign container trades increased by 51 percent over last five years. In 2006, foreign container trades reached to 217 million metric tons which accounted for 15% of total waterborne trade. Container imports represent 61% of total U.S. foreign container trades (U.S. Transportation Department 2008). In 2006, container imports at U.S. West Coast ports amounted to about 10 million TEU (Twenty-foot Equivalent Units). Container imports at East Coast ports

reached to around 7 million TEU., whereas, container imports at U.S. Gulf Coast are about 0.7 million TEU, according to data sources from U.S. Maritime Administration (2008).

Asian imports are the main driver of North American container import activity. Northeast Asia is the largest sources of U.S. container imports. The top five overall U.S. containerized cargo trading partners in 2006 were all from Northeast Asia (U.S. Maritime Administration 2008). China (mainland) was the leading containerized merchandise trade partner and its dominance is expected to increase further. In comparison with trade from Asia, trade between Europe and United States is small and has been growing slow. Nevertheless, the Transpacific trade between Northeast Asia and North America and Transatlantic trade between Europe and North America are the primary sources of United States container import activities.

Transportation gateways for containers play critical roles in international merchandise trade. Import container traffic tends to be highly concentrated at a number of seaports and is becoming even more so as the use of larger vessels calls on ports that are capable of handling them. The top 10 U.S. container ports accounted for around 90 percent of U.S. containerized traffic in 2006. Five of the top 10 container ports in the United States are on the West Coast, four are on the East Coast, and one is on the Gulf Coast (U.S. Maritime Administration 2008). The ports of Los Angeles and Long Beach are the leading gateway for container imports. The large number of containers moving through U.S. seaports highlights the significance of container traffic. This results in pressure on the nation's transportation network and influences traffic of congestion in the areas surrounding the major U.S.-international water gateways. The demand for transportation is pressing the capacity of the nation's transportation systems as well. Challenges are due to the already highly congested U.S. transport corridors due in part to the large scale movement of container traffic (U.S. Department of Transportation 2007). The end result is an even greater tightening of rail capacity at a time when rail demand is increasing.

The consequences of strains in the logistics network are a diversion of traffic to other routes. Expansion of Panama Canal provides alternatives for all water East Coast routing to avoid potential congestion at West Coast. Canadian government, railways, and other private interests are contributing to initiate efficient Pacific trade gateways and congestion free transportation corridors (Allison Padova Economic Division 2006). The Container terminal at port of Prince Rupert is expected to create capacity for 500,000 TEUs per year by 2007. Implementation of the Canadian Pacific gateway strategy is expected to directly benefit international container movement and result in a substantial diversion from U.S. logistics system. Meanwhile, shippers appear to assess alternative's reliability before committing any active. There has been a recent publicity about container diversion from Los Angeles and Long Beach to Mexican ports and East ports via the Panama Canal (The Tioga Group, Inc).

Global economics is driving container import activities and these activities represent the questions commonly faced by organizations participated in global supply chain. The study of container shipment has been active area especially during the recent couple of decades with global booming trade. The Tioga Group, Inc. (2008) analyzes the trends and issues affecting North American intermodal container movements with primary focus on imports activity. Wilson and Benson (2008) analyze historical movement in world container trade and in U.S. container markets. Mercator Transport Group (2005) evaluates container vessel specifications and port calls with San Pedro. The report discusses global demand for containerized shipping services, world fleet development, main container trade lanes, Trans-Pacific services, and activity levels in the San Pedro Bay ports. Wilson and Dahl (2008a) reviews previous studies on container

shipping with a focus on infrastructure and projection and analyzes the current state of knowledge about port constraints and expansion possibilities and costs. Wilson and Sarmiento (2008) conduct a long term analysis of infrastructure demands and risks with toward a global forecast of container flows container model. A spatial econometric Tobit model is developed to analyze the cross-sectional demands for containers by Business Economic Area. Wilson and DeVuyst (2008) propose two alternatives i.e. cost minimization methodology and spatial price equilibrium model for analysis of competition and projections in case of container shipping. Luo and Grigalunas (2003) assess the potential demand for container ports and associated multimodal transportation facilities. The paper presents a spatial econometric multimodal container transportation simulation model. The core of the simulation model is the shortest path algorithm. Veldman and Buckmann (2003) develop a logit model to explain market share of a port's routings for each of traffic zones or regions. Leachman (2008) describes an economic optimization model for waterborne containerized imports from Asia to Unite States. The paper considers transportation, consolidation and inventory costs as well as lead time factors. Shintani et al. (2007) presents a study to decide optimal route, i.e. chose an optimal set of calling ports and associated calling sequence of ports. They employ genetic algorithm-based heuristic to solve the Knapsack problem. Fan (2008) conducts a study for the optimization and analysis of a global supply chain in container shipments. The study is detailed and captures impacts of potential congestion and short-term uncertainty to container supply networks.

The objective of this paper is to develop a methodology that can be used to determine optimal container flows from the point import to final consumption in the United States. The study intends to provide a framework for capturing impacts on the supply chain network due to underling cost structure changes and potential infrastructure constraints. The paper can be used to evaluate inter-port competitiveness and illustrates the impact of congestion on container flows as well as the impact of the new alternative routes and ports.

MODEL OUTLINE

The primary focus of this study is container imports to U.S. markets from origins in Northeast Asia and Europe. This is an integrated approach which optimizes both international water trade and inland transportation networks in North America. The problem of container imports to United States corresponds to the problem of minimizing total logistics costs, subject to a number of constraints over corresponding logistics channels. Given the demands at U.S. markets, the model considers the selection of routing options for import logistics channel.

For international logistics trade, two international container trade lanes are defined, namely Transpacific and Transatlantic trading lanes. The Transpacific trading lane serves the import container movement between Northeast Asia and North America, which further broken into routing from Northeast Asia through the West Coast to inland markets of U.S. and all water routing of Northeast Asia imports to Gulf or East Coast of U.S. via the Panama Canal. Transatlantic lane services container trade between Europe and North America. The model also takes into account alternatives for container imports to U.S. markets through Canadian seaports. Particular trade strings (or route), which are characterized by a sequence of port calls, are specified over each main trade lane, thus enable to reflect scenarios of container ship with multi-port calls.

The container ports ranked in top 50th North American container ports in year 2007 (American Association of Ports Authorities 2008) are included as primary water gateways in this

study. There are eight seaports in Pacific Coast, three in Gulf, and 17 in Atlantic Coast, including five Canadian container ports. Large containership with 8,000+ TEU has deployed in Transpacific trade. Some East Coast ports are expected to handle SuperPostPanamax container vessel after port expansion. However, most North American seaports are subject to water depth, channel constrained, and/or have a limited room for expansion. This study includes ten different container ship size ranged from 1,000 TEU (Feedermax) to 14,000 TEU (SuperPostPanamax).

Each port represents the origins for container imports from Northeast Asia and Europe respectively. Demand for container imports from Northeast Asia and Europe are specified individually, and there are not allowed to substitute for each other. The container supply chain is driven by demand and is not constrained by supply. Business Economic Areas (BEAs), the geographic groups of naturally contiguously located counties that are relevant for economic analysis, are specified as the container consumption markets. The BEAs that do not receive container shipment are most likely due to lack of intermodal terminal and assumed to receive container moved by truck from BEAs that have intermodal facility.

We use the following assumptions, based on data sources from Journal of Commerce[1] that reports the containerized import origins at U.S. corresponding coasts and incorporate the total import TEUs at various coasts[2]. In year 2006, 89% of U.S. West Coast imports come from Northeast Asia. Northeast Asian imports to East Coast and Gulf Coast ports accounts for about 23% of all volume. European imports accounts for 35% at East/Gulf Coast ports. There is very small amount of container shipped to West Coast ports of United States from Europe. The above estimates are comparable with other reports, e.g. port of Houston reveals that TEU imported from NE Asia and Europe account for 21% and 31% of its total volume respectively[3], the Tioga Group, Inc. (2008) predicted that in year 2005, container import from Asia shares 89% at West Coast, 31% at East Coast, whereas, Europe & Mediterranean account for 31% at East Coast and very small at West Coast of United States.

To identify the origin for container imports at U.S. BEAs, it is assumed that 89% outbound TEU from West Coast is imported from Northeast Asia and the same percentage comprises all the outbound rail shipments. Similar approaches apply to other U.S. coasts. The total demand at a specific inland BEA equals the sum of shipments through all U.S. coast ports plus the inflow from Canadian ports. The containers shipped by railway from Canadian West Coast/East Coast to U.S. markets are considered with origin from Northeast Asia/Europe, respectively. For container consumption at BEAs in U.S. coastal areas, the difference between inbound container by water and outbound by rail way plus inbound container by railway from other coasts ports is considered as amount of containers needed in coastal BEAs and vicinity BEAs, and assumed to be shipped by truck. Based on the these assumptions, container demands at U.S. BEAs are extracted and manipulated by incorporating data sources from U.S. Maritime Administration (2008) and the Surface Transportation Board Carload Waybill Sample (2006).

Figure 1 shows primary North American seaports and location of U.S.BEAs for container imports. We use the BEA codes defined in 1995, since the current Waybill Record follows old definition for BEA. Detailed procedures regarding demand estimation for import container is described in Fan (2008). Chicago-Gary-Kenosha (code 64) is the largest interior container demand markets, followed by Memphis (code 73), Dallas-Fort Worth (code 127), and Kansas City (code 99). Los Angeles-Riverside-Orange County (code 160)**,** New York-No. New Jersey-Long Island (code 10), and Houston-Galveston-Brazoria(code 131) dominate container consumptions at West Coast, East Coast, and Gulf Coast BEAs respectively.

Figure 1. Selected Container Seaports and BEA Locations for Import Container Activities.
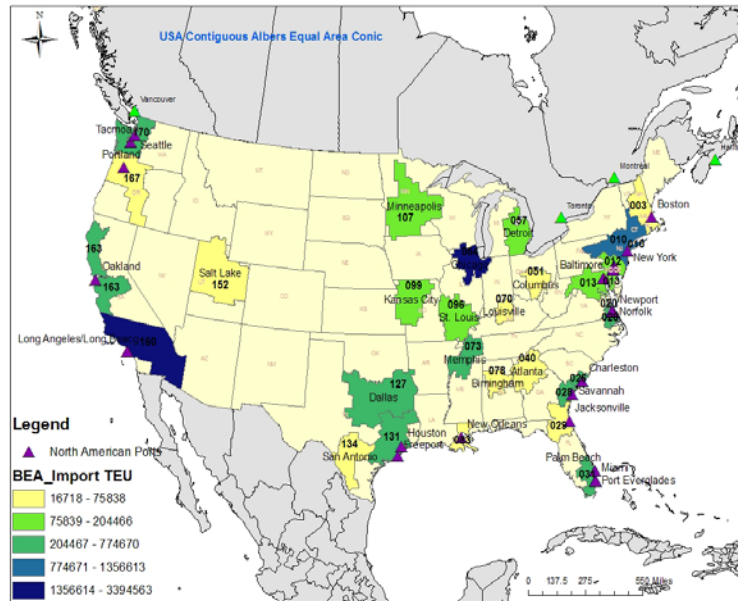

International container traffic currently represents about 60% of primary railroad's intermodal business (The Tioga Group, Inc. 2008). The primary railroads that serve container movements through U.S. inland transportation networks are BNSF Railway, CSX Transportation (CSXT), Norfolk Southern (NS), Union Pacific (UP), and two Canadian rail ways, namely Pacific Railway (CP) and Canadian National Railway (CN). About 94% of the container shipments are single-line, i.e. the originating railroads is the same as the terminating railroads (Wilson and Dahl 2008b).

To identify the railway shipping route for container imports, we use ArcGIS Network Analyst to find shortest route of primary railways that link seaports and terminating BEAs. The original GIS railway base map is obtained from National Transportation Atlas Databases (NTAD) 2006. The distances generated using ArcGIS are comparable to those reported on Waybill Record (2006) and predicated rail networks also fit well the primary corridors of each corresponding North American class-one railroads. The ArcGIS's network for North American primary rail ways is shown in Figure 2.

Figure 2. North America's Primary Railway Corridors for Container Imports.
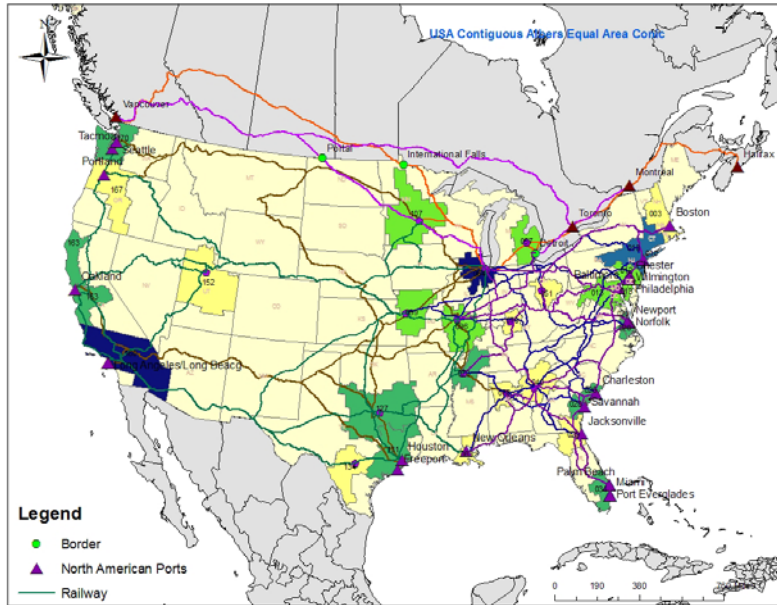
MATHEMATIC FORMULATION

The container import logistics system under consideration is presented in Figure 3. The problem of deciding optimal route, i.e. choosing an optimal of international water string, seaport, and associated inland rail lines, is formulated based on criteria of minimized total costs.

Figure 3. Global Supply Chain Networks for Container Imports to U.S.
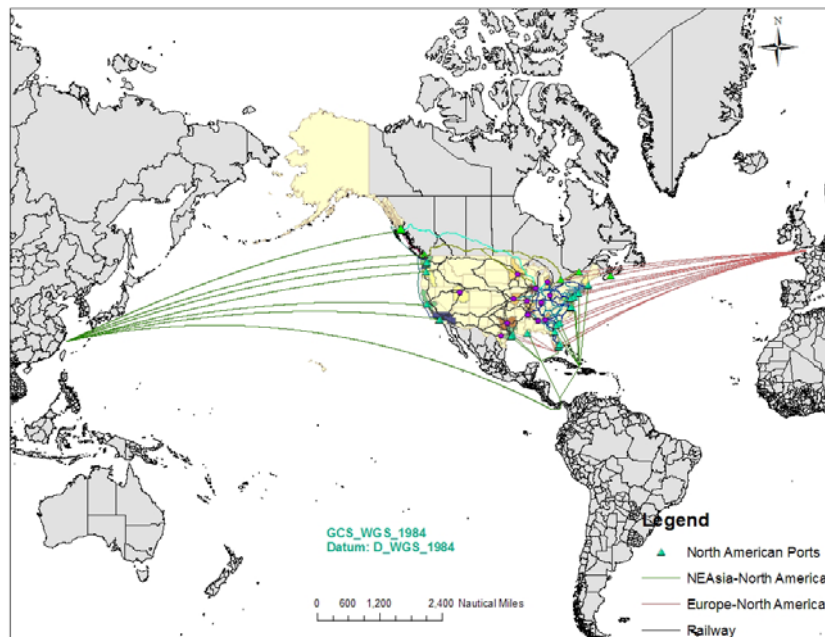
The logistics channels and interested originations involved in supply chain are defined in model formulation. Detailed approach for the sets, parameters, decision variables, and mathematic model is described below:

Sets:

F	= set of origin of container imports (Northeast Asia and Europe)
P^u	= set of container ports in Unite States
P^c	= set of container ports in Canada
E	= set of oceans carriers
V(e)	= set of container vessel type belong to ocean carrier $e \in E$
B	= set of Borders Crossing between Canada and Unite States
R^u	= set of U.S. class-one primary railways
R^c	= set of Canadian railways
Π_E^F	= set of strings (routes), i.e. selected sequence of ports *(i, j, k, …n)* over specified trade lane; $(i,j,k,..n) \subseteq F \cup P^u \cup P^c$, served by ocean carrier $e \in E$
$L^F(\pi_e^f)$	= set of lags *(i,j)* within string $\pi_e^f \in \Pi_E^F$
Π_E^A	= set of strings (routes) on trade lane via Panama Canal, $\Pi_E^A \subset \Pi_E^F$, served by ocean carrier $e \in E$
D	= set of BEAs located in interior areas of Unite States
O	= set of BEAs located in coastal areas of Unite states
$И^o$	= set of container flow arcs *(f,j,o)* from U.S. seaport *j* to coastal BEA *o* with import origin *f*; $И^o \subseteq \{f \in F, j \in P^u, o \in O \ \}$
Γ^r	= set of container flow arcs *(o,r,d)* from U.S. coastal BEA *o* via railway *r* to terminating BEA *d* ; $\Gamma^r \subseteq \{o \in O, r \in R^u, d \in D \cup O : o \neq d\}$
Γ^t	= set of container flow arcs *(o,r,t,d)* from U.S. coastal BEA *o* via railway *r* transit to railway *t* and to terminating BEA *d*; $\Gamma^t \subseteq \{o \in O, r \in R^u, t \in R^u, d \in D \cup O : o \neq d\}$
Γ^c	= set of container flow arcs *(j,r,b,d)* from Canadian port *j* by Canadian railway *r* through border crossing *b* and to terminating U.S. BEA *d* ; $\Gamma^c \subseteq \{ j \in P^c, r \in R^c, b \in B, d \in D\}$

Parameters:

Dem_d^f	= demand of TEU at BEA $d \in D \cup O$ with imports origin from $f \in F$
$VCap_v$	= the maximum of TEU that can be handled by a vessel of type $v \in V(e)$
$HCap_j$	= the maximum throughput capacity for container imports (TEUs) at North American ports $j \in P^u \cup P^c$

$VCapF_j$	= the maximum TEU of a container ship that can be handled at North American ports $j \in P^u \cup P^c$
$VCapM_j$	= the largest vessel type that can be handled at North American ports $j \in P^u \cup P^c$
$PCap$	= the largest vessel type that can go through Panama Canal
$PNCap$	= the maximum number of cruises (schedules) through Panama Canal
$VNCap_v$	= the available number of cruises (schedules) of vessel type $v \in V(e)$ of ocean carrier $e \in E$
$WCostA_v^{\pi_e^f}$	= operating cost (at sea) of a vessel of type $v \in V(e)$ over strings $\pi_e^f \in \Pi_E^F$
$IPCostA_v^{\pi_e^f}$	= operating cost (in port) of a vessel of type $v \in V(e)$ over strings $\pi_e^f \in \Pi_E^F$
$BCap_b$	= the throughput capacity of railway for container imports (TEU) at border crossing between Canada and United States $b \in B$
$RCapO_o$	= the throughput capacity of railway for container imports (TEU) at coastal BEA, $o \in O$
$RCapC_j$	= the throughput capacity of railway for container imports (TEU) at Canadian ports, $j \in P^c$
$URCapR_{ord}$	= the throughput capacity for container imports (TEU) over U.S. railway routes $(o, r, d) \in \Gamma^r$
$URCapT_{ortd}$	= the throughput capacity for container imports (TEU) over U.S. railway routes $(o, r, t, d) \in \Gamma^t$
$CRCap_{jrbd}$	= the throughput capacity for container imports over Canadian railway routes $(j, r, b, d) \in \Gamma^c$
$URCostR_{ord}$	= the shipping cost per TEU for container imports over U.S. railway routes $(o, r, d) \in \Gamma^r$
$URCostT_{ortd}$	= the shipping cost per TEU for container imports over U.S. railway routes $(o, r, t, d) \in \Gamma^t$
$CRCost_{jrbd}$	= the shipping cost per TEU for container imports over Canadian railway routes $(j, r, b, d) \in \Gamma^c$

Decision Variables:

$anp_{v\pi_e^f}^{ij}$	= the number of TEU shipped over leg$(i, j) \in L^F(\pi_e^f)$ by ocean carrier $e \in E$, using vessel type $v \in V(e)$
$anp\_u_{v\pi_e^f}^{ij}$	= the unused capacity on leg$(i, j) \in L^F(\pi_e^f)$ by ocean carrier $e \in E$,

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$$\text{by vessel type } v \in V(e)$$

$anp\_V_{v\pi_e^f}$ = the number of cruises (schedules) on string $\pi_e^f \in \Pi_E^F$ by ocean carrier $e \in E$, using vessel type $v \in V(e)$

suo_{jo}^f = the number of TEU delivered over flow arcs $(f, j, o) \in И^o$

$sut\_R_{ord}^f$ = the number of TEU delivered over U.S. rail routes $(o, r, d) \in \Gamma^r$ with import origin $f \in F$

$sut\_T_{ortd}^f$ = the number of TEU delivered over U.S. rail routes $(o, r, t, d) \in \Gamma^t$ with import origin from $f \in F$

$sct\_R_{jrbd}^f$ = the number of TEU delivered over Canadian rail routes $(j, r, b, d) \in \Gamma^c$ with import origin $f \in F$

Objective Function:

Minimize total cost =

$$\sum_{e \in E} \sum_{v \in V(e)} \sum_{\pi_e^f \in \Pi_E^F} (WCostA_v^{\pi_e^f} + IPCostA_v^{\pi_e^f}) * anp\_V_{v\pi_e^f} + \sum_{f \in F} \sum_{(ord) \in \Gamma^r} URCostR_{ord} * sut\_R_{ord}^f$$

$$+ \sum_{f \in F} \sum_{(ortd) \in \Gamma^t} URCostT_{ortd} * sut\_T_{ortd}^f + \sum_{f \in F} \sum_{(jrbd) \in \Gamma^c} CRCost_{jrbd} * sct\_R_{jrbd}^f \qquad (1)$$

The cost components of the objective function comprise operating costs of different type of vessel deployed on global trade lanes and the railway shipping rate per TEU on the specific inland corridor served by different North American class-one railroads. The handling cost per TEU is assumed to be constant cross North American seaports, thus is not included in the model.

Subject to:

$$anp_{v\pi_e^f}^{ij} \le VCapF_j * anp\_V_{v\pi_e^f}$$
$$v \in V(e), \ e \in E, \ \pi_e^f \in \Pi_E^F, \ (i,j) \in \{L^F(\pi_e^f) : j \in P^u \cup P^c\} \qquad (2)$$

$$anp_{v\pi_e^a}^{ij} + anp\_U_{v\pi_e^a}^{ij} \le PCap_{\pi_e^a} * anp\_V_{v\pi_e^a} \ \ v \in V(e), \ e \in E, \ \pi_e^a \in \Pi_E^A, \ (i,j) \in L^A(\pi_e^a) \qquad (3)$$

$$anp_{v\pi_e^f}^{ij} + anp\_U_{v\pi_e^f}^{ij} \le VCapM_j * anp\_V_{v\pi_e^f}$$
$$v \in V(e), \ e \in E, \ \pi_e^f \in \Pi_E^F, \ (i,j) \in \{L^F(\pi_e^f) : j \in P^u \cup P^c\} \qquad (4)$$

$$\sum_{\pi_e^f \in \Pi_E^F} anp\_V_{v\pi_e^f} \le VNCap_v \qquad v \in V(e), e \in E \qquad (5)$$

$$\sum_{e \in E} \sum_{v \in V(e)} \sum_{\pi_e^a \in \Pi_E^a} anp\_V_{v\pi_e^a} \le PNCap \qquad (6)$$

$$anp^{ij}_{v\pi^f_e} + anp\_U^{ij}_{v\pi^f_e} = VCap_v * anp\_V_{v\pi^f_e} \qquad v \in V(e),\ e \in E,\ \pi^f_e \in \Pi^F_E,\ (i,j) \in L^F(\pi^f_e) \qquad (7)$$

$$\sum_{e\in E}\sum_{v\in V(e)}\sum_{\pi^f_e\in\Pi^F_E}\sum_{\{i:(i,j)\in L^F(\pi^f_e)\}} anp^{ij}_{v\pi^a} - \sum_{e\in E}\sum_{v\in V(e)}\sum_{\pi^f_e\in\Pi^F_E}\sum_{\{k:(j,k)\in L^F(\pi^f_e)\}} anp^{jk}_{v\pi^f_e} \le HCap_j$$

$$j \in P^u \cup P^c \qquad (8)$$

$$\sum_{e\in E}\sum_{v\in V(e)}\sum_{\pi^f_e\in\Pi^F_E}\sum_{\{i:(i,j)\in L^F(\pi^f_e)\}} anp^{ij}_{v\pi^a} - \sum_{e\in E}\sum_{v\in V(e)}\sum_{\pi^f_e\in\Pi^F_E}\sum_{\{k:(j,k)\in L^F(\pi^f_e)\}} anp^{jk}_{v\pi^f_e}$$

$$= \sum_{\{(r,b,d):(j,r,b,d)\in\Gamma^c\}} sct\_R^f_{jrbd} \qquad j \in P^c,\qquad f \in F \qquad (9)$$

$$\sum_{e\in E}\sum_{v\in V(e)}\sum_{\pi^f_e\in\Pi^F_E}\sum_{\{i:(i,j)\in L^F(\pi^f_e)\}} anp^{ij}_{v\pi^a} - \sum_{e\in E}\sum_{v\in V(e)}\sum_{\pi^f_e\in\Pi^F_E}\sum_{\{k:(j,k)\in L^F(\pi^f_e)\}} anp^{jk}_{v\pi^f_e}$$

$$= suo^f_{jo} \qquad\qquad (f,j,o) \in И^o \qquad (10)$$

$$\sum_{\{j:(fjo)\in И^o\}} suo^f_{jo} + \sum_{\{(pr):(pro)\in\Gamma^r\}} sut\_R^f_{pro} + \sum_{\{(prt):(prto)\in\Gamma^t\}} sut\_T^f_{prto}$$

$$= \sum_{\{(rd):(ord)\in\Gamma^r\}} sut\_R^f_{ord} + \sum_{\{(rtd):(ortd)\in\Gamma^t\}} sut\_T^f_{ortd} + Dem^f_o \qquad o \in O, f \in F \qquad (11)$$

$$\sum_{f\in F}\sum_{\{(jrd):(jrbd)\in\Gamma^c\}} sct\_R^f_{jrbd} \le BCap_b \qquad b \in B \qquad (12)$$

$$\sum_{f\in F}\sum_{\{(rd):(ord)\in\Gamma^r\}} sut\_R^f_{ord} + \sum_{f\in F}\sum_{\{(rtd):(ortd)\in\Gamma^t\}} sut\_T^f_{ortd} + \sum_{f\in F}\sum_{\{(pr):(pro)\in\Gamma^r\}} sut\_R^f_{pro}$$

$$+ \sum_{f\in F}\sum_{\{(prt):(prto)\in\Gamma^t\}} sut\_T^f_{prto} \le RCapO_o \qquad\qquad o \in O \qquad (13)$$

$$\sum_{f\in F}\sum_{\{(rbd):(jrbd)\in\Gamma^c\}} sct\_R^f_{jrbd} = RCapC_j \qquad j \in P^c \qquad (14)$$

$$\sum_{f\in F} sut\_R^f_{ord} \le URCapR_{ord} \qquad (o,r,d) \in \Gamma^r \qquad (15)$$

$$\sum_{f\in F} sut\_T^f_{ortd} \le URCapT_{ortd} \qquad (o,r,t,d) \in \Gamma^t \qquad (16)$$

$$\sum_{\{(or):(ord)\in\Gamma^r\}} sut\_R^f_{ord} + \sum_{\{(ort):(ortd)\in\Gamma^t\}} sut\_T^f_{ortd}$$

$$+ \sum_{\{(jrb):(jrbd)\in\Gamma^c\}} sct\_R^f_{jrbd} = Dem^f_d \qquad d \in D, f \in F \qquad (17)$$

Constraint Descriptions:

Constraint (2) takes into account the maximum TEU of a loaded containership that can be accommodated by North American seaports. This constraint considers the scenario that some ports have difficulty handling full-loaded large ships (8,000+ TEU) as first-inbound calls, because of relatively small marine terminals, inefficient rail/transit infrastructure to handle high volume container incoming, or not enough channel depth to allow fully loaded large container ships to access. Large ships are allowed to access at second or third call and so forth.

      The Panama Canal constraint (3) ensures that the ship size cannot exceed Canal restriction. This constraint will only apply to the strings from Northeast Asia to Gulf/Atlantic Coast trade lane. The current vessel size that Panama Canal can handle is Panamax with 4,400 TEU. The Panama Canal is in the process of expansion and will allow vessels up to 12,000 TEU. Likewise, constraint (4) defines the largest container ship type that can be handled by North American seaports. Most North American ports cannot handle large containership due to water depth restriction. This constraint differs from constraint (2), which specifies the restriction for maximum TEU number of a loaded vessel that can be handled. Constraint (5) takes into account number of cruises (schedules) of each type of container vessel available by corresponding ocean carriers. Constraint (6) considers the maximum number of container vessels allowed through Panama Canal. Constraint (7) states the delivered TEU number plus unused capacity of vessel v on each $\text{leg}(i,j) \in L^F(\pi_e^f)$ equals the specified TEU capacity of vessel type $v \in V(e)$. Constraint (8) specifies total inbound TEUs by vessels at port $j \in P$ cannot exceed port handling ability.

      The set of constraints (9) and (10) represent equilibrium of container flow at seaports. Constraint (9) state that the sum of inbound TEUs at Canadian seaports equal the sum of outbound TEUs for destined to U.S. markets. In terms of U.S. seaports, constraint (10) defines the sum of inbound TEUs at U.S. seaports equals the sum of outbound TEUs to U.S. coastal BEAs. Constraint (11) assures the total TEU inflows at coastal BEA, which are shipped by water mode and rail mode from other coasts, equal the sum of outbound TEU for destined to U.S. markets plus the demand consumed by coastal BEA itself. Equation (12) presents throughput restriction for import container at border crossing between Canada and Unite States. This constraint only applies to Canadian railroads. Equation (13) represents rail capacity through coastal BEA of United States. Constraint (14) states rail capacity to serve Canadian seaport. The set of equations (15) and (16) specify railway capacity for container shipment on each individual railway route. The last equation (17) ensures that TEU demands at U.S. interior markets are met.

Costs Estimations

The costs components included in the model comprise vessel operating costs at sea and in port, tariffs at Panama Canal, and shipping rates on inland railways. Estimation for ocean shipping costs (at-sea and in-port) for containership is based on prototypical model by Wilson and Dahl (2008b) and cost estimation for large container vessel extended by Fan (2008). Their research use U.S. Army Corps of Engineers (ACE) Aggregated Vessel Operating Cost model as a point of departure and supplemented with market information from Clarkson. The ship sizes reported in Wilson and Dahl (2008b) are for 600 TEU to 8,000TEU capacities. Fan (2008) extrapolates amongst values which ship size up to 8,000 TEU capacities to derive costs for larger vessel up to 14,000 TEU. We assume that daily operating costs of container vessel (at-sea and in-port) are the same cross all ocean carriers deployed on Transpacific and Transatlantic container trade lanes.

At-sea Cost   The operating cost of each type of containership is derived for specific strings or routes over Transpacific or Transatlantic trade lanes, based on how many days it spends at sea. The total operating cost of a vessel of type *v* on specific route equals the vessel daily cost of at-sea multiplied by days that vessel spends on this route. The point to point distance matrix is derived from ACE model, which consists of major container ports in the world and the North American container ports. To estimate actual distance for specific strings, we incorporate distances amongst multiple post calls in North American container ports into international water route. The distances between ports calls at North American coasts are calculated using ArcGIS Network Analyst, which the base U.S. water-way GIS map is from NTAD 2006. Further detail is given in Fan (2008).

In-port Costs In-port operating costs of containership depends on how many days that vessel has to stay in port, thus directly related to port handling capacity and land access. To account for all these factors requires detailed port information. For simplicity, we consider that in-port time is primarily related to number of cranes and crane productivity. On average, the effective maximum rate of a crane is 25 cycles per hour after accounting for stoppages and idle time (NCHRP 399 1998). Container productivity is particularly critical for ports that frequently receive large vessels, which require a fast container-handling speed to minimize the time spent at dock. Container terminals that can operate with approximately 28 to 35 moves per crane per hour (Le-Griffin and Murphy 2006) and higher rates of up to 40 crane moves per hour are possible at some North American ports[4]. To capture the relevant spatial component of in-port costs in the optimization model and based on investigation to various ports, we make assumptions that three cranes with 35 moves per crane per hour are used to serve large containership, e.g. SuperPostPanamax, three cranes with 30 moves per crane per hour for PostPanamax, and two cranes with 20 moves per crane per hour for small containership e.g. SubPanamax, whereas the high rate would require more cranes when necessary. The assumptions are the same across all ports. It is realized the above assumptions may not be realistic and it is expected to be reconciled from the industry.

Rail Shipping Rate Estimation Wilson and Dahl (2008b) present an econometric model to analyze the rail rate structure for loaded/empty container and trailer shipments. Fan (2008) develops a regression model with specific dealing with rail shipping rate for loaded import container shipments. The panel data set is derived from public Waybill Record (1996-2006). We use results from Fan (2008) to predicate rail shipping rates, such as corridors from Canadian new opened port of Prince Rupert to various U.S. inland markets, which is not reported by Waybill Record to days. For most rail routes, we use the shipping rates from public Waybill Record. Waybill Record dose not provide information regarding shipping rate for each individual railroad. We assume that shipping rates are the same over two railroads, if there are two railroads that can serve the container movement from the same seaport to designated BEAs and the corresponding rail distances are comparable. In addition, there is no discrimination in rail shipping rate for ocean carriers.

MODEL IMPLEMENTATION

Computational Traffic Flow for Container Imports

The optimization model is programmed using A Modeling Language for Mathematical Programming (AMPL) of Fourer et al. (2003) with lpsolve solver that interfaces to AMPL. The

demands of U.S. markets are derived from Waybill Record and summarized according to criteria explained in previous section. Since the most recent data available from Waybill Record is of year 2006, we employ all relevant data sources for year 2006. The constraints of the number of vessel type over specific trading lane are relaxed. The container traffic at U.S. seaports in year 2006, which are incorporated waterborne container imports volume reported by Maritime Administration (2008) and import origin share, is used as reference points for port handling ability constraints. The water depth of North American seaports is specified based on current port configurations. The classifications of containership by ACE and Clarkson Research Service Limited are used to define the vessel TEU capacity. In addition, we assume that ocean carriers operate under Vessel Sharing Agreements. Containership with capacity up to 4,400 TEU is defined as current capacity restriction through Panama Canal. Current traffic of import container on specific railway transportation routes and gateways, which are derived from Waybill Record, are considered as benchmark to represent corresponding constraint parameters. Complete description of model's data and parameter can be founded in Fan (2008).

The estimated global supply chain for container shipment to U.S. markets is mapped in Figure 4 and very reflective of current traffic situation. The model shows that Transpacific West Coast trade lane is dominating logistics channel for U.S. interior container demand markets. Transpacific Panama Canal all-water lane is major channel for container with import origin from Northeast Asia to be consumed in East and Gulf Coast areas, and also serves BEAs areas at east regions, such as Atlanta, Columbus, and Louisville. Transatlantic logistics channel serves container trade with origin from Europe to most U.S. interior markets as well as East and Gulf Coast markets. For container demand with Europe as origins and to be moved to West Coast and West interior regions, i.e. BEAs at Los Angeles-Riverside-Orange County, San Francisco-Oakland-San Jose, and Salt Lake City-Ogden, Transatlantic Gulf Coast trade lane is main logistic channel.

Figure 4. Computational Traffic Flow for Container Imports to United States.
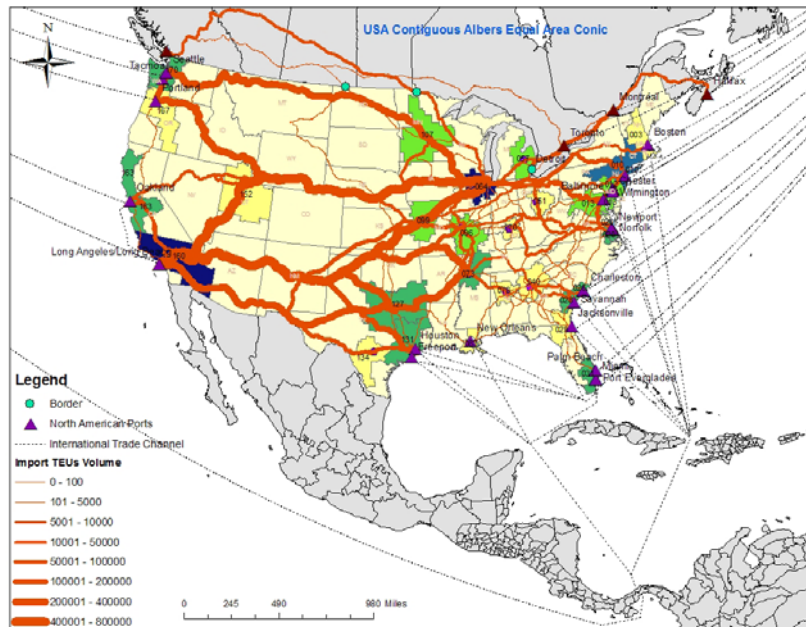
Figure 5 shows the model estimate and actual traffic for container through the U.S. ports. Container flows at U.S. ports tend to be highly concentrated. Dominance of ports of Log Angeles/Long Beach are still significant in West Coast, likewise, Ports of New York and Houston are main gateways at East and Gulf Coast. Most ports of West Coast in United States can accommodate vessel with capacity up to 6,000 or 8,000 TEU. Large vessel calls with capacity of up to 14,000 TEU occur at ports of Los Angeles and Long Beach. The port of Oakland, whose infrastructure is considered currently inadequately to allow large vessel to access ports fully loaded, receives first vessel call with capacity up to 8,000 TEU and handle large containership as second port call. The type of vessels on transpacific all-water path is Panamax with capacity less than 4,400 TEU, because of restriction of Panama Canal. In East Coast, ports of New York, Norfolk, and Newport can accommodate 8,000 TEU vessels. Canadian port of Halifax has deep water to receive Super Post-Panamax large container vessel.

Figure 5. Comparison the Actual Volumes and Estimated Results for Container Imports at U.S. Seaports.
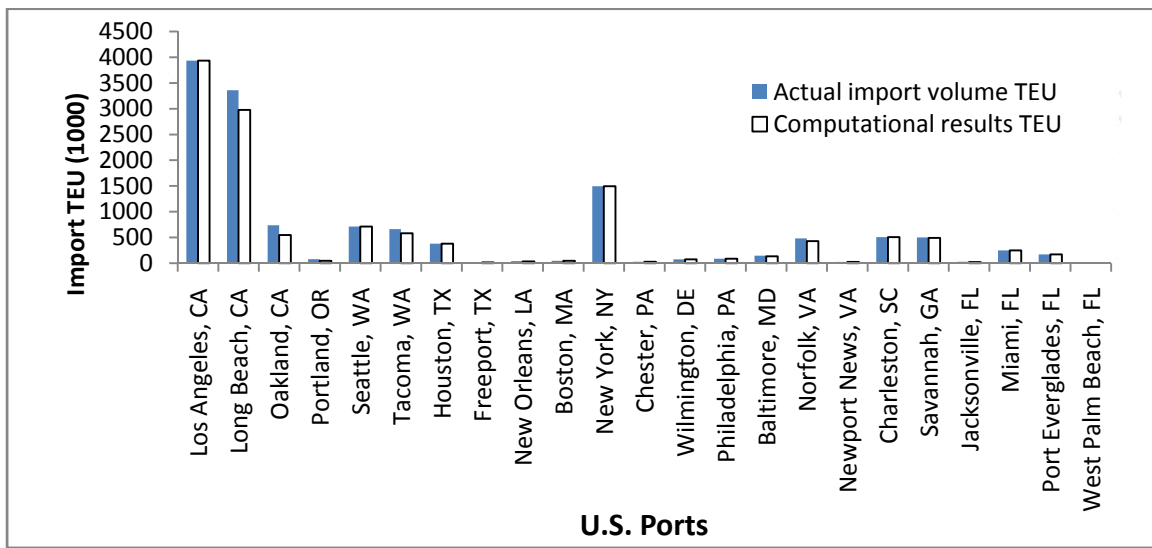
The West Coast ports are the primary gateways to move container imported from Northeast Asia to interior U.S. markets. About 50% of inflow TEUs at ports of Los Angeles/Long Beach, 70% of inflow TEUs at ports of Seattle/Tacoma, and 30% at port of Oakland are moved out by rail to inland markets. East and Gulf Coast ports handle containers imported from both Europe and Northeast Asia. 40% of inbounded TEUs at port of Houston is moved out by rail. Imports through the East Coast ports are mainly consumed by coastal BEA markets. About 90% of the TEUs through the Port of New York is consumed locally. The ports of Norfolk and Newport News, which outbound volume accounts for 23% of inflow TEUs, are the relevant main gateways in East Coast for container destined to interior markets

For the inland container movements, BNSF and UP are dominating rail lines to serve container flow from West Coast to U.S. interior markets. UP also serves the container flow through Gulf Coast. The primary railway corridors are from West Coast to BEAs areas at Chicago-Gary-Kenosha, Memphis, Dallas-Fort Worth, and Kansas City. Los Angeles/ Long Beach to Chicago are by far the most heavily concentrated corridors in United States. The

container traffic in East and Gulf regions is small in comparison with west region. NS and CSXT are main rail lines to move container at east regions. The busiest movement in east region is from ports of New York, Norfolk, and Newport News to Chicago. The border crossing at Detroit (MI) handles around 140,000 TEU shipped from ports of Halifax, Montreal, and Toronto to BEA at Chicago-Gary-Kenosha and Detroit-Ann Arbor-Flint. A small proportion of container imported from Northeast Asia is shipped via Canadian port of Vancouver to Chicago through the border crossing at Portal (ND) and International Falls (MN) by Canadian CN and CP railroads.

Identification of Potential Infrastructure Strains

Capacity constraints and potential congestion at logistics channels are identified using dual theory. If the dual value in the ith constraint is greater than zero or the slack value is near zero, it implies the ith constraint is binding or near binding, that means corresponding system or infrastructure is operating at capacity. The parameters defined in the model are based on assumptions. The predefined constraints might not reflect actual system capacity. However, it motivates our study for analyzing container traffic flow through global supply chain network, enables to capture current container traffic situations, and easily conducts sensitivity analysis.

For simplicity, the dual and slack values of corresponding constraints for the major logistics channels are selected and shown in Table 1. The rows in the table contrast potential strains on logistics channels from water gateways to interior markets, i.e. port handling constraint versus rail capacity. Dual value or shadow price of corresponding constraint is the amount by which the optimal objective value is improved (decreased in min problem), if corresponding constraint is increased to handle each extra TEU, under the condition that current basis remains optimal.

For Transpacific-West Coast logistics channels, Los Angeles and Seattle are operating at capacity. Negative dual value of rail constraint indicates that the capacity tightness is primary due to potential congestion on the heavily concentrated rail way linking West Coast gateways to the major interior BEAs. There are substantial strains on capacity over most primary transport corridors in west region, which embodied in both UP and BNSF. For East Coast, the port of New York is at capacity. The negative dual value suggests relaxing that constraint would reduce system costs. Most rail corridors in east region appear less congested than west region. Dual value of constraint at Houston implies handling capacity of port is the bottleneck of logistics channel through Gulf Coast. The results for imported container traffic over U.S. inland rail networks are consistent with other study such as by Cambridge Systematics, Inc. (2007), which shows the primary rail corridors at west region are more congested than those at east regions.

Table 1. Dual and Slack Values of Corresponding Constraints for the Major Logistics Channels.

Constraint at Port $HCap_j$		Constraint on Railway $URCapR_{ord}$					
Port	**Dual (Slack) Value**	**Rail Roads**	**Interior BEAs**				
			Chicago	**Memphis**	**Dallas**	**Kansas**	**St. Louis**
			Dual (Slack) Value				
Los Angeles Long Beach	0(0) 0(382410)	BNSF UP	-107(0) -107(0)	-232(0) -232(0)	0(0) 0(61960)	-118(0) -118(0)	-129(0) -129(0)
Oakland	0(188942)	BNSF UP	0(81960) 0(63974)	-164(0) -164(0)	-3(0) -3(0)	-49(0) -49(0)	-84(0) -84(0)
Seattle Tacoma	0(0) 0(80504)	BNSF UP	-93(0) -93(0)	-147(0) -147(0)	- 0(2640)	- 0(15306)	0(8120) 0(882)
New York	-169(0)	CSXT NS	0(0) 0(21467)	0(1560) 0(1560)	- -	- 0(4623)	0(2080) 0(2080)
Savannah	0(10017)	CSXT NS	0(560) 0(560)	0(2640) 0(2640)	- -	- -	0(40) 0(40)
Norfolk	0(51686)	CSXT NS	0(3360) 0(59720)	0(120) 0(120)	- -	- 0(2880)	0(0) 0(4952)
Charleston	0(634)	CSXT NS	0(1440) 0(1440)	-21(0) -21(0)	- -	- 0(680)	- -
Houston	-135(0)	UP	0(13200)	0(4290)	-	-5(0)	-56(0)

Canadian Port of Prince Rupert

Prince Rupert's proximity to Northeast Asia, deep water, and lack of congestion served by Canadian CN railroad give it potential advantages for imports with container for U.S. inland markets. Importers appear to be assessing its reliability before committing volume (The Tioga Group, Inc. 2008). A recent report by Lloyd's List states that Canadian port of Prince Rupert has announced a sharp rise in box traffic since Cosco vessels began calling at the newly-built container terminal. In the period to end September, 2008, import container from Asia for North American destination amounted to 62,365 TEU and ship size has increased up to about 1,2000 TEU[5].

To account for this option, we generate railway distances from Prince Rupert to various U.S. markets using ArcGIS Network Analyst. The railway shipping rate is estimated based on econometric model by Fan (2008). BEA areas at Chicago-Gary-Kenosha, Memphis, and Detroit-Ann Arbor-Flint are considered to be served by port of Prince Rupert. More interesting options can be assessed using similar approaches. We conduct sensitivity analysis to evaluate the impacts due to Prince Rupert involved in container supply chain. The data and parameters are all the same as described above except inclusive of Canadian new water gateway and association rail corridors.

The results indicate that there are about 40,000TEU shipped through port Prince Rupert to U.S. BEA areas at Chicago-Gary-Kenosha and Memphis. The diversion of containers from U.S. water gateways to Canadian ports and associated corridors is shown in Table 2. Container vessels with a capacity up to 12,000 TEU are deployed on trade strings of Asia-Prince Rupert

and Asia-Prince Rupert-Seattle. The ports of Seattle service large-containership as second calls on latter string (see Figure 6).

Table 2. Diversion of Containers from U.S. Logistics System to Canadian Water Gateways

Original Port	Diverted to Canadian Port	BEAs	TEUs
Oakland	Prince Rupert	Chicago	18000
Vancouver	Prince Rupert	Chicago	6800
Los Angeles/Long Beach	Vancouver	Minneapolis	6800
Portland	Prince Rupert	Memphis	7800
Charleston	Prince Rupert	Memphis	8500

Prince Rupert provides an alternative, or new logistics channels for container imported from Northeast Asia to major U.S. interior markets. However, model estimate is less than volume as reported by Lloyd's List. The primary container movements to Chicago-Gary-Kenosha and Memphis with origin from Northeast Asia are via Transpacific to U.S. West Coast trade lane. The dual values in Table 1 shows that most of constraints of transport corridors that serve these channels are tight. In addition, the study by Cambridge Systematics, Inc. (2007) shows that some rail ways served container movements on these corridors are currently operating near or at capacity, especially, the corridor from the port of Oakland to Memphis and Dallas-Fort Worth is operating at capacity.

To evaluate potential diversion of container traffic from U.S. West Coast ports due to potential congestion of infrastructures, the rail shipping rate for transport corridor from Oakland to Memphis is increased and higher than shipping rate from other West Coast ports to Memphis. The simulated result shows that CN railway will take over these shipments via Prince Rupert to Memphis. The total container volume through Canadian new water gateway reaches around 111,000 TEUs. It appears that Canadian logistics channel has potential threats to diversify container flow from U.S. system, if it can initiate efficient Pacific trade gateways and congestion freed transportation corridors.

Figure 6. Container Traffic through Canadian Port of Prince Rupert to U.S. Interior Markets at Chicago and Memphis.
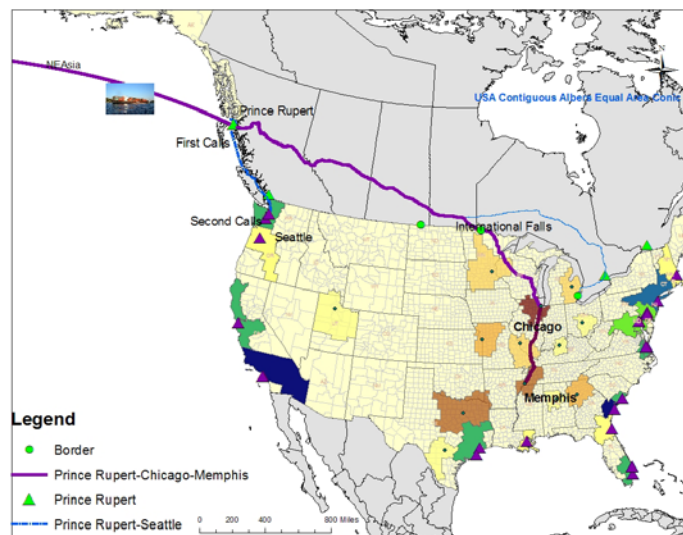
Panama Canal

The Panama Canal route is an all-water option for transpacific container destined to the Gulf and East United States. The Canal's current maximum containership size is 4,400 TEU and the expansion will allow it to handle large vessel up to 12,000 TEU. A major issue regarding the continued growth through the Panama Canal has been the uncertainty of its future capacity. To assess the capacity through the Canal, we use the same approaches as mentioned before, but without port of Prince Rupert. The results indicate about 1.6 million TEUs with origin from Northeast Asia go through Panama Canal to U.S. Gulf and East Coast. Major demand markets for containers through the Panama Canal are of coastal BEAs in East Coast of the United States. A small portion of movements originated from Northeast Asia via Panama Canal to BEAs at East interior regions, including Atlanta, Louisville, Columbus, and Memphis.

To evaluate the impacts of expansion of Panama Canal to traffic flow over all-water trade lane, we relax Canal vessel size constraint to 12,000 TEU and include additional Panama Canal fee[6] to the all-water string. The largest vessels through Canal increase to up to 80,000 TEU, since East Coast ports cannot currently handle container vessel with capacity over 80,000+TEU. The TEUs traffic through Panama Canal increase slightly. A small amount of TEUs that originally shipped from Portland to Memphis is diverted through East Coast. It reveals that West Coast trade lane has cost advantages over most East Coast for container shipments from Northeast Asia to U.S. interior markets, assuming no congestion. For those logistics channels that appear to have competitive edge against West Coast, e.g. by all water Panama Canal channel via ports of Houston and some East Coast ports to interior BEAs, have potential strains on either ports or associated transportation corridors. The changes of TEU demands at Gulf/East areas also present impacts to traffic flow through Canal.

The port of Houston appears to be a great potential water gateway for container movement to U.S. interior markets, such as at Memphis and Dallas-Fort Worth. Expansion of Bayport complex at Houston port is conceived to create an opportunity to nearly triple the port's overall container handling capacity[7]. We use the scenario that takes into account port Prince Rupert and effects of congestion over corridor from Oakland to Memphis. Capacities of port of Houston and associated corridor are increased enough to compete with Canadian port of Prince Rupert. The results show that Houston will dominate container movement with origin from Northeast Asia to Memphis.

CONCLUSIONS AND FURTHER RESEARCH

We developed a comprehensive and integrated optimization model framework that covers primary international container trade channels between United States and foreign partners, as well as potential infrastructure constraints through supply chain networks. The major components of model are defined in term of logistics channels. It could easily be extended to incorporate additional cost elements as well as infrastructure constraints that are of interests to decision makers. The underlying assumptions motivate our study for investigating container shipping and logistics activities of United States. This research is considered to be appropriate for strategic planning at a national level, however, should be also of beneficial to organizations in global container supply.

The results show that Transpacific West Coast trade lane is dominating logistics channel for U.S. interior container demand markets. The Transpacific Panama Canal all-water lane is the major channel for container with import origin from Northeast Asia to East and Gulf coastal

BEAs. Transatlantic trade lane serves container trade with origin from Europe to most East and Gulf Coast markets as well as U.S. interior markets. Dominance of ports of Log Angeles/Long Beach is significant in West Coast. Ports of New York and Houston are main gateways at East and Gulf Coast. Container imports tend to be highly concentrated at a number of logistics channels. The model estimated traffic flows are reflective of current traffic situation and provide an overall insight to container import supply chain. The study also shows that Canadian ports will present a substantial diversion from U.S. ports, due to the potential infrastructure strains over U.S. logistics system. If the more detailed data set were reflected in the model, the solutions will have been more insightful.

The results in this study and the process of building the model suggest a number of areas for future research. First, data and parameters in the existing model could be refined. Most important would likely be data regarding operations and constraints at ports and associated transport corridors. Second, we are expanding the model to evaluate the impacts of congestion costs on container supply chain. It would be of interest to perform more detailed sensitivity analysis and to identify the potential diversified flow from heavily concentration logistics channel due effects of congestion. This will provide additional benchmarks for the developed procedures and more interesting information to organizations in supply chain. Third, the model presented in this paper assumes a deterministic environment. The nature of demand for containers suggests there is substantial risk and uncertainty. We are expanding the model to capture effects of short-term uncertainty in future demand to logistics network flows.

Interest in West Coast Mexican container ports depends on container diversions from U.S. West Coast ports. Potential strains at Southern California may provide motivation for Mexican ports. More research is needed to account for the expanding Mexican container ports. Large import/export container movements have posed challenges to U.S. transportation networks both at seaports and associated inland transport corridors. But, overall, U.S. transportation infrastructures handle more TEUs of imports than exports. The deficit of U.S.-international container traffic may result in unbalanced traffic in U.S. primary gateways and corresponding corridors. A comprehensive formulation and analysis is needed to incorporate import and export movements in global supply chain.

Endnotes

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