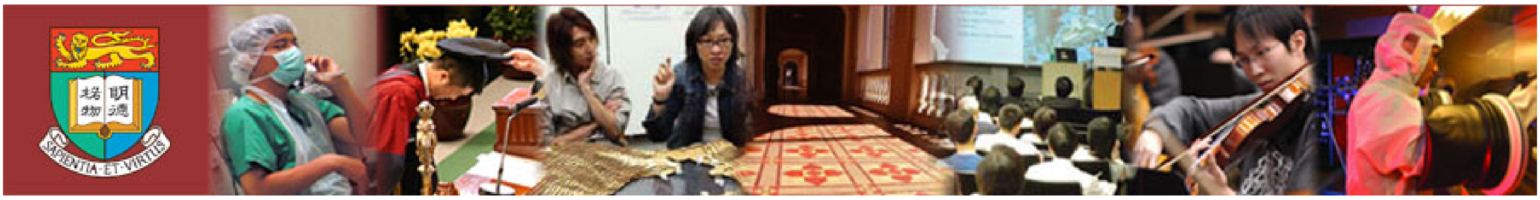

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A MULTIMODAL NETWORK DESIGN PROBLEM FOR DOMESTIC CONTAINER TRANSPORTATION WITH SHORT SEA SHIPPING

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ABSTRACT

With the growing importance of logistic in a green and environmental friendly way, it is widely accepted that short sea shipping (SSS) is a mean to divert the freight traffic from congested corridor in local communities as well as to reduce environmental costs. It can also relieve the problem of traffic congestion and investment on road construction and maintenance. This paper considers a multimodal transportation model for domestic container cargos, in which the flow of container cargos moving between foreign seaports and domestic cities can be transported via domestic seaports using SSS and inland by truck. We propose a two-level strategy in evaluating the various government policies to encourage or regulate the usage of SSS. While the objective of the freight carriers is to minimize its transportation cost, the government could internalize the external cost and invest on the transportation network with considering the cost to the society. A case study with the Taiwan network is performed to illustrate the benefit and performance of the model.

Keywords: Container Cargo, Intermodal Transportation, Short Sea Shipping, Trucking

INTRODUCTION

With the growing importance of logistic in a green and environmental friendly way, it is widely accepted that short sea shipping (SSS) is a mean to divert the freight traffic from congested corridor in local communities as well as to reduce environmental costs. It can also relieve the problem of traffic congestion and investment on road construction and maintenance. Recently, Lee et al. (2010) investigated an empirical study on the external cost of transportation of domestic cargos with SSS and trucking in Taiwan, showing a huge amount of external costs (including air pollution costs and climate change costs) by the truck transportation as compared to the SSS. This is due to the large amount of cargos between the North and South of Taiwan in consequence of mismatching between handling capacities of ports and demand and supply of cities.

The excess truck traffic on highways due to the asymmetric development of harbor ports in Taiwan are one of the concerns in developing short sea shipping. The Kaohsiung port in South Taiwan is the main import/export area for international trade containers, while Taipei (the capital) and most of the industrial centers are located on the North. However, the Keelung port, a well developed northern port in the past, has a limited capacity due to the geographic limitation, resulting in the long loading/unloading time and traffic congestion to/from the city. Therefore, most of the import containers have to be transported from the southern port to the northern cities via road transportation, while the export goods are moved from north to south. Furthermore, since the policy of dedicated berth, a shipping company remains to use the same port with priority regardless the final origin/destination of the containers. Chou (2005) showed that the North-to-South and South-to-North domestic container cargo movements reach a million TEU each year, incurring a direct transportation cost of 9.9 billion Taiwan dollars. Under the optimal situations, such container movements should only be 288 thousand TEU. Most of the container cargo between the ports and cities are moved by road transportation, mainly trucks through freeway, with only 10% by coastal shipping (Lee et al., 2009). The railway system is not utilized for cargo movements.

To solve the above problems, there is an interest to model the Taiwan situation by formulating the cargos movements with a transportation network modelling approach. A previous research by Kim et al. (2008) has investigated a multimodal transportation model in which the flow of container cargoes moving between foreign seaports and domestic cities were modelled with a Short Sea Shipping (SSS) formulation for the case of Korea. In their model, the flow of cargoes can be transported with ships and trains via domestic seaports and inland container depots (ICD). Assuming sufficient capacity at ports and depots, and there are limited number of vessels and trucks/trains available, a comprehensive mathematical formulation is developed with the objective of minimizing the total costs. The formulation will be adopted and modified for the problem stated in this paper.

Minimizing the costs is usually a common objective of the industry, but probably not the only objectives considered by the government. In the development of a country, the government is responsible to consider the cost and benefit to the society and environment, with allocating investment of limited resources at the right place. For instance, SSS has been widely discussed in Europe and America as a way to mitigate the traffic of cargoes from the roads to the sea, which relieves the problem of traffic congestion and investment on the constructions and maintenances of infrastructure (such as ports/depots, roads, or transit systems for cargoes at ports). The external cost of truck traffic on highways is a main concern in setting up a proper pricing policy to the truck transportation industry (see Mayeres et al., 1996; Piecyk and McKinnon, 2007; Ozbay et al., 2007; Berechman, 2009). It is widely accepted that SSS is a mean to divert the traffic from congested corridor in local communities as well as to reduce environmental costs. As discussed in Lee et al. (2010), over 90% container cargo movements between the ports in Taiwan are transported by trucking and less than 10% utilizes SSS. It is emphasized that, by charging the external costs caused by container transport, shifting freight from road transport to intermodal with SSS is considered to be one of the effective ways in solving the high environmental negative impacts of transporting freight.

This paper considers a multimodal transportation model for domestic container cargos, in which the flow of container cargos moving between foreign seaports and domestic cities can be transported via domestic seaports using SSS and inland by truck. While the objective of the freight carriers is to minimize its transportation cost, the government could internalize the external cost and invest on the transportation network with considering the cost to the society. A case study with the Taiwan network is performed to illustrate the benefit and performance of the model.

MODEL FORMULATION

We present a two-level strategy in evaluating the various government policies to encourage or regulate the usage of SSS. A multimodal transportation model with short sea shipping is formulated to model the modal choices of freight carriers and cargo movements between foreign seaports and domestic cities. A government policy evaluation model is introduced to control various policy tools in affecting the carriers' decisions.

Multimodal transportation model with short sea shipping

We present a multimodal transportation model in which the container cargo movements are determined with the minimum shipper's total cost. The cargoes between foreign seaports and domestic seaports are transported by international vessels, and cargoes are transported by highways (i.e. trucks) between domestic seaports and cities. Since the distance via highways can be long, short sea shipping (SSS) could be used as a transfer mode between domestic seaports. As we are interested to see the reactions to the shippers with respect to the government policy against the environmental cost produced by each modes, a factor is introduced in the objective function to measure the amount of environmental cost that the shippers is responsible for. Therefore transportation cost and a fraction of environmental cost (due to pricing of government) are considered in the shipper's total cost. The formulation is presented below with the details described in subsections. The notations of variables are displayed in Table 1.

$$Minimize Z = TC + w \cdot EC \tag{1}$$

subject to constraint sets Ω_1, Ω_2, Ω_3, Ω_4, Ω_5, Ω_6 and Ω_7 defined later.

Objective functions and Cost components

In the objective function, transportation cost (TC) is the generalized cost consisting of the cost for trucks, short sea shipping and international vessels, and the environmental cost (EC) is the corresponding external cost of pollutant emissions to the environment. They are defined as

$$\begin{aligned} TC = & \sum_{j \in J} \sum_{k \in K} \left(c_{jk}^1 \left(DI_{jk} + \sum_{t \in J \setminus \{j\}} TI_{tjk} \right) + c_{kj}^1 \left(DE_{kj} + \sum_{t \in J \setminus \{j\}} TE_{kjt} \right) \right) + \\ & \sum_{j \in J} \sum_{t \in J \setminus \{j\}} \left(c_{jt}^2 \left(\sum_{k \in K} TI_{jtk} \right) + c_{tj}^2 \left(\sum_{k \in K} TE_{ktj} \right) \right) + \sum_{i \in I} \sum_{j \in J} \left(c_{ij}^3 SI_{ij} + c_{ji}^3 SE_{ji} \right) \end{aligned} \tag{2}$$

$$\begin{aligned} EC = & \sum_{j \in J} \sum_{k \in K} \left(e_{jk}^1 \left(DI_{jk} + \sum_{t \in J \setminus \{j\}} TI_{tjk} \right) + e_{kj}^1 \left(DE_{kj} + \sum_{t \in J \setminus \{j\}} TE_{kjt} \right) \right) + \\ & \sum_{j \in J} \sum_{t \in J \setminus \{j\}} \left(e_{jt}^2 \left(\sum_{k \in K} TI_{jtk} \right) + e_{tj}^2 \left(\sum_{k \in K} TE_{ktj} \right) \right) \end{aligned} \tag{3}$$

International vessels are excluded from the external cost as it is minor whichever domestic seaports are chosen. The unit cost components can be separated for import and export flow allowing for different routes from/to domestic sea ports to/from cites, and seaport costs are also included. The total transportation cost function c_{ij}^m for each TEU on each transportation link between port/city pair $(i, j) \in A$ and mode $m \in \{1,2,3\}$ can be determined by

$$c_{ij}^m = \left(h \cdot t_{ij}^m + p_{ij}^m \right), \text{ for } m = \{1\} \tag{4}$$

$$c_{ij}^m = \left(h \cdot t_{ij}^m + p_{ij}^m + thc_j \right), \text{ for } m = \{2,3\} \tag{5}$$

where h is the inventory holding cost per unit time (per TEU);

t_{ij}^m is the transit time of mode m from origin i to destination j;

p_{ij}^m is the transit cost per TEU, which corresponds to the inland transit cost by trucks for $m = \{1\}$, and to the sea freight rate for $m = \{2,3\}$

thc_j is the terminal handling charge (per TEU);

e_{ij}^{m} is the external cost (per TEU) using mode m from origin i to destination j.

The unit environmental cost e_{ij}^{m} can be determined by the avoidance cost approach, which elaborates the emission amounts of all environmental pollutants produced by the transportation mode. As suggested in Lee et al. (2010), it can be calculated for each TEU:

$$e_{ij}^{m} = l_{ij} \sum_{p} a_p \cdot k_p^m \tag{6}$$

where l_{ij} is the distance (in km) from *i* to *j*;

a_p is the avoidance cost of pollutant type *p*;

k_p^m is the emission factor of pollutant type *p* of mode *m* per TEU-km. For the shipping modes $m = \{2,3\}$, the factor depends on fuel type, engine type and consumption of fuel, and can be determined as $k_p^m = \sum_{l} f_l k_{lp}^m$, where f_l is the consumption amount of fuel type *l* and k_{lp}^m is the emission factor of pollutant type *p* by using fuel type *l* for the shipping mode.

Set of constraints

The set of constraints below determines the feasible flow movement for import and export cargos. Ω_1, Ω_2 and Ω_3 specifies the cargo flow conservation whereas Ω_4, Ω_5 and Ω_6 are related to the operation issues of ports.

Import and export amount constraints, Ω_1:

$$\sum_{j \in J'} SI_{ij} = sf_i \text{ for all } i \in I \tag{7}$$

$$\sum_{j \in J'} DE_{kj} = sd_k \text{ for all } k \in K \tag{8}$$

$$\sum_{j \in J'} DI_{jk} = dd_k \text{ for all } k \in K \tag{9}$$

$$\sum_{j \in J'} SE_{ji} = df_i \text{ for all } i \in I \tag{10}$$

Flow conservation constraints, Ω_2:

$$\sum_{i \in I} SI_{ij} = \sum_{k \in K} DI_{jk} \quad \text{for all } j \in J' \tag{11}$$

$$\sum_{k \in K} DE_{kj} = \sum_{i \in I} SE_{ji} \quad \text{for all } j \in J' \tag{12}$$

Direct transport or transfer via Short Sea Shipping port, Ω_3:

$$DI_{jk} = AI_{jk} + \sum_{t \in J \setminus \{j\}} TI_{jtk} \quad \text{for all } j \in J' \text{ and } k \in K \tag{13}$$

$$DE_{kj} = AE_{kj} + \sum_{t \in J \setminus \{j\}} TE_{ktj} \quad \text{for all } k \in K \text{ and } j \in J' \tag{14}$$

Port capacity constraints, Ω_4:

$$\sum_{i\in I}\left(SI_{ij}+SE_{ji}\right)+\sum_{t\in J\setminus\{j\}}\left(\sum_{k\in K}TI_{jtk}+\sum_{k\in K}TE_{ktj}\right)\le a_j \quad \text{for all } j\in J \tag{15}$$

Determining the number of vehicles/ships with the amount of cargos, Ω_5:

$$AI_{jk}+\sum_{t\in J\setminus\{j\}}TI_{tjk}\le n_1\cdot VI^1_{jk} \quad \text{for all } j\in J \text{ and } k\in K \tag{16}$$

$$AE_{kj}+\sum_{t\in J\setminus\{j\}}TE_{kjt}\le n_1\cdot VE^1_{kj} \quad \text{for all } k\in K \text{ and } j\in J \tag{17}$$

$$\sum_{k\in K}TI_{jtk}\le n_2\cdot VI^2_{jt} \quad \text{for all } j\in J \text{ and } t\in J\setminus\{j\} \tag{18}$$

$$\sum_{k\in K}TE_{ktj}\le n_2\cdot VE^2_{tj} \quad \text{for all } t\in T \text{ and } j\in J\setminus\{t\} \tag{19}$$

$$SI_{ij}\le n_3\cdot VI^3_{ij} \quad \text{for all } i\in I \text{ and } j\in J \tag{20}$$

$$SE_{ji}\le n_3\cdot VE^3_{ji} \quad \text{for all } j\in J \text{ and } i\in I \tag{21}$$

Vehicle capacity constraints, Ω_6:

$$\sum_{k\in K}t^1_{jk}\cdot VI^1_{jk}\le u_j \quad \text{for all } j\in J \tag{22}$$

$$\sum_{j\in J}t^1_{jk}\cdot VE^1_{kj}\le u_k \quad \text{for all } k\in K \tag{23}$$

$$VI^2_{ji}\le v^2_{jt} \quad \text{for all } j,t\in J;\ j\ne t \tag{24}$$

$$VE^2_{tj}\le v^2_{tj} \quad \text{for all } t,j\in J;t\ne j \tag{25}$$

$$VI^3_{ij}\le v^3_{ij} \quad \text{for all } i\in I \text{ and } j\in J \tag{26}$$

$$VE^3_{ji}\le v^3_{ji} \quad \text{for all } j\in J \text{ and } i\in I \tag{27}$$

Non-negativity and integer constraints, Ω_7:

$$SI_{ij},SE_{ji}\ge 0 \quad \text{for all } i\in I \text{ and } j\in J \tag{28}$$

$$DI_{jk},DE_{kj}\ge 0 \quad \text{for all } j\in J'\text{and } k\in K \tag{29}$$

$$AI_{jk},AE_{kj}\ge 0 \quad \text{for all } j\in J \text{ and } k\in K \tag{30}$$

$$TI_{jtk},TE_{ktj}\ge 0 \quad \text{for all } j,t\in J \text{ and } k\in K \tag{31}$$

$$TI_{jtk},TE_{ktj}\ge 0 \quad \text{for all } j,t\in J \text{ and } k\in K \tag{32}$$

$$VI^1_{jk},VE^1_{kj}\ge 0 \text{ and integers for all } j\in J \text{ and } k\in K \tag{33}$$

$$VI^2_{jt},VE^2_{tj}\ge 0 \text{ and integers for all } j,t\in J\text{ , } j\ne t \tag{34}$$

$$VI^3_{ij},VE^3_{ji}\ge 0 \text{ and integers for all } i\in I \text{ and } j\in J \tag{35}$$

Constraints (7) – (10) in Ω_1 are the import and export amount constraints, which represents the total amount of cargos for the demand and supply of foreign seaports and domestic cities. For instance, (7) indicates that the cargo moving from a foreign seaport to all domestic seaports should be equal to the total supply of the foreign seaport, and (9) represents that the cargo moving from all domestic seaports to a city is the cargo demand of the city. Constraints (11)-(12) in Ω_2 are the flow conservation constraints, which ensure that the total amount of cargos moving from foreign seaports to a domestic seaport is equal to the corresponding total flows moving out to domestic cities. Note that for the above constraints domestic seaports here are defined for the international shipping where cargos are exported to and imported from a foreign seaport, and domestic transfer via short sea shipping transfer are considered in Ω_3. Constraints (13)-(14) in Ω_3 determines if the cargos moved from the domestic seaports to cities are transported by trucks directly or via a short sea shipping ports.

Constraint (15) in Ω_4 limits the physical capacity of the ports. Constraints (16)-(21) in Ω_5 determines the number of vehicles and ships required to transport the cargos, which are used together with constraints (22)-(27) in Ω_6 to bound if there is a maximum availability of trucks operators in the port area and if there is a maximum number of callings for ships between port pairs. Note that Ω_5 and Ω_6 are not binding in our examples, as in a planning mode the port throughput capacity Ω_4 is more essential than the operational condition Ω_6 which would be reviewed from time to time. Constraints (28)-(35) in Ω_7 is the non-negativity and integer constraints for the decision variables.

The model presented in this section is analogous to Kim et al. (2008) which studies the multimodal problem for the Korean case, and Chang et al. (2010) which discusses the external costs. Our model can be used for the Taiwan case (with the north and south imbalance development of ports). We also introduced the asymmetric cost functions and seaports characteristics, which permits some local ports operating for short sea shipping only.

Government policy evaluation model

The above multimodal transportation model is a deterministic model describing the decisions of shippers under optimal conditions to minimize their operating cost. With the promotion of green logistic and reduction of emissions, the government would consider regulation policy to restrict the usage of trucks and encourage SSS. The benefits of shifting truck traffic to the sea are two-fold. It reduces the emissions and thus environmental cost to the society, and the reduction of traffic in freeway corridor would relieve the traffic congestion as well as improve the road efficiency and safety. For this purpose, we propose a two-level framework to evaluate the policy issues. With the multimodal transportation model being a lower level model, an upper level evaluation model is proposed in this section.

In this model, we consider two factors that the government can control. The internalization factor of external cost *w* in Eq. (1) specifies the amount that the shippers should be responsible to environmental cost. This can be done by taxing the road freight transportation. For example, the external cost internalization ratio was estimated to be 88% for Britain (the highest in Europe) as compared to a lower ratio of 30% in Poland, Greece and Luxembourg in the study of Piecyk and McKinnon (2007). The external costs consists the environmental costs (emissions, pollutions and accidents) and congestion costs (travel delay to the other travellers), and infrastructure costs (road construction and maintenances) are also considered.

Measuring the external costs for truck transportation is not an easy task. While the environmental costs is reasonable to be measured on a per km-TEU basis, the congestion costs depend on the traffic conditions, share of truck traffic, and the value of time of drivers (Mayeres et al., 1996; Forkenbrock, 1999). It can also be estimated with a transportation network modelling approach (Ozbay et al., 2007). Furthermore a detailed estimation of environmental cost would also depend on the traffic conditions as the emissions and accidents rates vary with the traffic speed. Presenting a detailed estimation of externality is out of the scope in this paper, and it deserves another empirical study. In this study, such costs are simply approximated with the marginal costs approaches. For instance, Berechman (2009) investigated the marginal costs of truck traffic at the Port of New York and New Jersey. With presented cost functions, the externality (i.e. social cost) including congestion externality, accident costs, air pollution and noise costs were estimated.

Another factor that the government can affect the traffic movement pattern is the investment in ports and the associated policy. In the case of Taiwan, although the Keelung port at the Northern area is closed to the capital Taipei and has a good location advantage, it suffers from its physical limitations of size and road network. However, the Taipei port, positioning itself to be the auxiliary port of Keelung port for ocean-going container services and inbound bulky cargoes at this moment, is keep expanding. The second phase development for a total of seven wharves, with the capacity to accommodate container ships larger than 10,000TEU, is expected to be completed and in operation by 2014 on a BOT contract for 50 years. By that time, the container cargo movements and inter-port competition must be influenced. Once the Taipei port is fully functioned and operational, it would capture the container cargos from the Keelung port, which would lose its advantages and competitiveness, and Taichung port and Kaohsiung port would also suffer from losing its throughput. As suggested in Lee et al. (2010), one way to relieve the problem is to introduce an incentive policy to activate SSS service for less competitive ports.

Therefore we formulate the upper level problem to evaluate the total externality (i.e. social cost)

$$\underset{w, y_j}{Min} \quad SocialCost = EC + CC + IC \tag{36}$$

Subject to

$$\sum_j G_j \left(y_j \right) \le B$$

where

w = *internalization factor of external cost*
y_j = *capacity of port j to be expanded*
$G_j(y_j)$ = *cost function of capacity enhancement*
B = maximum budget to be allocated

which considers the environmental cost (EC), congestion cost (CC) of inland transportation and infrastructure cost (IC) (if any) needed for the port and highway expansion. EC is determined from Eq. (3); CC can be approximated by the product of the marginal cost of congestion and the amount of truck traffic movement in the network; and IC is determined from the capacity enhancement cost functions. Note that in general we can replace the decision variables y_j to be a collection of transportation projects and take the highway investment into account. Since the investment of ports will increase the development of the country, the associated benefit can also be introduced into the objective function.

DATA COLLECTION AND NUMERICAL EXAMPLE

In this section, a case study is used to demonstrate the optimal cargo flow in Taiwan based on the model Eq. (1)-(35). All data are obtained from the transportation research statistics data published by the government (MOTC, 2007, 2008, 2009) and the harbour bureaus. The export and import amount of container in Taiwan cities is obtained from MOTC (2008) and shown in Table 2. The travel distances and times between domestic cities and ports are extracted from a web-based GIS system, and shown in Table 3. The capacity of ports is displayed in Table 3. Since the selection of incoming/outgoing domestic ports is not sensitive to the origin/destination of foreign seaports, we simply assume the foreign seaport to be a single source/sink in this example.

On the cost functions, the transit cost p_{ij}^m and terminal handling charge thc_j are taken from the data announced by the corresponding harbour. On average, the transit cost of truck from Kaohsiung to Keelung is about 8000 NT$/TEU, meaning a unit cost of 20 NT$/TEU-km for long distance transport. Since the transportation time is short within Taiwan, the inventory holding cost h is relatively small in the overall cost and neglected here. The marginal environmental cost is adopted from Lee et al. (2010) and displayed in Table 5. In the initial setting, the internalization factor of external cost w is set to be zero. The marginal external congestion cost is not available in empirical study for Taiwan, to be best known of the authors. We estimate this value to be to be NT$ 138.9 (or NT$ 0.74 for each TEU-km) with the analysis in Appendix A. Indeed, this value is relatively insignificant as compared to the marginal environmental cost.

The model is solved with the commercial package CPLEX. In this study we focus on the reaction and modal choices of freight carriers between trucks and SSS under various government policies. For this reason, a series of scenarios of such policy changes are computed, rather then a single solution point. The government policy evaluation model is not directly solved, but we show the changes of objective values with decision parameters, i.e. external cost internalization ratio w and harbour capacity at the Northern area.

The solution of the base case shows that there is no short sea shipping flow and all incoming and outgoing cargos are sent to/from cities by trucks, resulting in total truck traffic of 35.3 million TEU-km in the road network. If the external cost is internalized to the freight carriers and they are responsible for part of the environmental cost produced, it is expected that SSS would be more attractive as they can save cost. Figure 1 shows the change in truck traffic and short sea shipping traffic against the factor w. There is a modal shift from trucking between port and cities to the intermodal SSS-trucking when the trucking freight cost increases over the intermodal option between an origin-destination pair of port and city. At 10% of internalization rate, 23% of import and export cargos will traverse by SSS rather than direct port-to-city by trucking, resulting a reduction of the truck traffic to 76% of the base case. It is noted that the sum of the two percentage values is not necessary to be 100%, as trucking is still used for the “last mile” transportation from SSS port to cities. The SSS usage ratio and reduction of truck traffic settles at 28% and 71% respectively when w reaches 0.5, and further increases in w has no effect on the modal choice and cargo movement pattern. Noting that in our calculation the road capacity and the truck availability is not binding at the solution. This implies that, under the given supply and demand pattern of cities, only 28% of cargos can be transported with a lower cost with intermodal transportation, and the rest of the cargos are already transported in their optimal mode choice and distribution in the base scenario.

As mentioned in the last section, the Taipei port being expanded will attract the throughput of the other ports in the future. Since most of the industrial centres are located at the north and middle of Taiwan, which also have a high population, there is a very strong in demand for import and export. As the Taipei port opens for full operation, it can see from Figure 2 that the northern ports will absorb the container traffic from the Kaohsiung port up to 6.1 million TEU. However, this figure does not yet account for the increases in the total throughput of Taiwan for imports, exports as well as transhipments in the future with the improved port capacity.

From Figure 1, we assume that efficient internalization factor is taken to be 0.2. We would like to see under this circumstance what will happen to the amount of short sea shipping flow. Figure 3 shows the amount truck traffic and short sea shipping flow with the port capacity at w = 0.2. We can see that the SSS throughput (mainly from Kaohsiung port) decreases from 3.5 million TEU to zero when the northern port capacity increases up to 6.1 million TEU. As concluded from Figure 2, the international container cargos originated or terminated at the north and central Taiwan will choose the Taipei port directly as it expands, and there is no need for the transfer via short sea shipping. As a result the truck traffic increases although the overall transportation cost for the freight carrier is still decreasing.

CONCLUDING REMARKS

In this study we present a model to estimate the optimal cargo movement pattern with intermodal transportation model of trucking and short sea shipping (SSS). SSS has been argued to be a user-friendly way of transportation when we take the external cost such as environmental and congestion cost into account. Internalization of external cost to the truck industry has been extensity considered and implemented in European countries. An empirical study is done for the Taiwan case, and it demonstrates that an internalization rate of 20% may reduce the overall truck traffic on freeway by one fourth. This conclusion is highly depending on the demand and supply pattern in the hinterland of Taiwan, as it was found that there is a large amount of cargo traffic between the north and south of the island due to the unmatched port development and also the dedicated berth policy. As suggested in Berechman (2009), promotion (such as subsidization) of short sea shipping operations, railway expansion, and efficient pricing to trucks are possible solutions to mitigate the truck traffic problems.

APPENDIX A

The marginal congestion cost measures the time losses of all other road users due to the reduction of speed caused by an additional truck on the road networks. In Taiwan, most of the container cargos are transported through National freeway between north and south, whereas trailer flow along provincial highway is relatively insignificant.

Table A1 displays the traffic statistics through the freeway toll stations. On average, tractor trailers contributes 7% of traffic by number of vehicles and 14% by the number of passenger car units (PCU). On some toll stations near the ports, it contributes up to 30% of traffic by PCU. It is noted that some studies adopted a passenger car equivalent of 3.0 to 4.0 for trucks and tractor trailers in their estimation of marginal costs, it is generally valid for urban arterial where traffic stream is moving at slower speed and possible stop and go. At higher traffic speed this value can be lower, and a PCE of 2.0 for trucks and buses and 2.5 for tractor trailers are chosen in the published statistics. Therefore, a higher contribution of tractor trailers to traffic congestion is expected for congested road sections.

Without the usage of traffic simulation model, a reasonable way to estimate the congestion cost is to construct a congestion function and its marginal function (see Mayers et al, 1996; Ozbay et al., 2007; Berechman, 2009). Adopted from Ozbay et al. (2007), a general form of congestion function for freeway using the BPR function is:

$$CC(Q) = Q \cdot \frac{d}{v_0}\left(1+\alpha\left(\frac{Q}{C}\right)^{\beta}\right)\cdot VOT$$

$$MCC(Q) = \frac{d}{v_0}\left(1+\alpha\left(\frac{Q}{C}\right)^{\beta}\right)\cdot VOT + \frac{d}{v_0}\left(\alpha\beta\left(\frac{Q}{C}\right)^{\beta}\right)\cdot VOT$$

where

$Q =$ traffic volume (veh/hr)
$C =$ road capacity of the freeway (veh/hr)
$d =$ length of the road section (km)
$v_0 =$ free flow speed (km/hr)
$VOT =$ value of time (NT$/hr)
$\alpha, \beta =$ model parameters

$CC(Q)$ is the congestion cost (i.e. equivalent cost of total travel time spent) of all drivers along a section of the freeway, and $MCC(Q)$ is the corresponding marginal cost. The first term on the right hand side of the MCC is the internal cost occurred to the additional vehicle, and the second term is the external cost to the other vehicles, which is of interest. To measure the additional cost to a particular vehicle type, the VOT value for the corresponding user group has to be chosen.

We assume a free flow speed of 100 km/hr for freeway and average trip length of truck of 93.71 km (MOTC, 2009). For freeway, α and β are commonly taken to be 0.15 and 4. The value of flow/capacity ratio Q/C measures the congestion level, meaning a 15% increase on the average travel time when flow reaches its design capacity. Although the change of traffic flow with composition of vehicles can be found in the statistics, the average traffic speed is not part of the data to be recorded, detailed estimation of the congestion function is not possible, and this value is different for different road sections. For demonstration, Q/C= 1 is chosen in the calculation. To determine the external cost to private cars, the value of time of car users is used. Laih et al. (2002) estimated the value of times of auto-commuters for queuing time to be NT$ 98.8/hr in Taiwan. Substituting all values into the equation derived above, the marginal internal congestion cost of a tractor trailer can be computed to be NT$ 266.2, and the marginal external congestion cost to be NT$ 138.9 (or NT$ 0.74 for each TEU-km). Note that the tractor trailer contributes 2.5 PCU to the traffic. Finally, we emphasize that the above calculation fairly depends on the estimation of Q/C ratio, as one may notice the marginal cost drops to its 41% for a road section with Q/C = 0.8, and increases up to 207% for Q/C = 1.2.

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LEGENDS FOR TABLES AND FIGURES

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Table 1 Notations of variables

Nomenclature	
Set	
I	Set of foreign seaports
J	Set of domestic seaports
J'	Set of domestic seaports for international vessels, $J' \in J$
J''	Set of domestic seaports for short sea shipping (but not for international vessels), $J'' \in J$, such that $J' \cap J'' = J$ and $J' \cap J'' = \varnothing$
K	Set of domestic cities
A	Set of feasible links between seaports and cities
M	Set of transportation mode, where $m = \{1,2,3\}$ with 1 for truck, 2 for short sea shipping and 3 for international vessels
Parameters	
sf_i	supply amount from foreign seaport i
sd_k	supply amount from domestic city k
df_i	demand amount at foreign seaport i
dd_k	demand amount at domestic city k
a_j	capacity of domestic seaport j
n^m	capacity (i.e. number of TEU) of mode m
u_j	total available time of trucks at seaport j
v_{jt}^m	number of available calls of transport mode m from j to t
t_{ij}^m	transit time of mode m from origin i to destination j
c_{ij}^m	transportation cost (for each TEU) using mode m from origin i to destination j
e_{ij}^m	external cost (for each TEU) using mode m from origin i to destination j
w	internalization factor of external cost
Decision variables	
SI_{ij}	import amount from foreign seaport i to domestic seaport j
SE_{ji}	export amount from domestic seaport j to foreign seaport i
DI_{jk}	import amount from domestic seaport j to domestic city k
DE_{kj}	export amount from domestic city k to domestic seaport j
AI_{jk}	import amount directly transported from j to k
AE_{kj}	export amount directly transported from j to k
TI_{jtk}	import amount transported from j to k via t
TE_{ktj}	export amount transported from k to j via t
VI_{jk}^m	number of vehicles/vessels of mode m to transport import cargoes from j to k
VE_{kj}^m	number of vehicles/vessels of mode m to transport export cargoes from k to j

Table 2 Export and Import amount of container in Taiwan cities (unit: TEU)

	Cities	Import	Export
1	TP	5,833	8,656
2	KH	679,483	458,436
3	TPC	600,559	399,231
4	YLC	176,520	153,976
5	TYC	487,238	608,118
6	HCC	171,911	179,608
7	MLC	92,555	166,109
8	TCC	1,842,948	1,608,678
9	CHC	1,013,725	1,016,487
10	NTC	172,124	123,704
11	YUC	210,161	80,793
12	CYC	205,127	101,107
13	TNC	271,576	463,128
14	KHC	249,974	298,080
15	PTC	50,749	388,601
16	TTC	728	0
17	HLC	43,553	79,789
18	KL	195,185	107,670
19	HC	11,529	0
20	TC	148,303	253,978
21	CY	3,268	6,731
22	TN	24,566	98,256
	Subtotal	6,657,615	6,601,136

Note:
1 TP: Taipei City; 2 KH: Kaohsiung City; 3 TPC: Taipei Country; 4 YLC: Yilan Country;
5 TYC: Taoyuan Country; 6 HCC: Hsinchu Country; 7 MLC: Miaoli Country; 8 TCC: Taichung Country;
9 CHC: Changhua Country; 10 NTC: Nantou Country; 11 YUC: Yunlin Country; 12 CYC: Chiayi Country;
13 TNC: Tainan Country; 14 KHC: Kaohsiung Country; 15 PTC: Pingtung Country; 16 TTC: Taitung Country;
17 HLC: Hualien Country; 18 KL: Keelung City; 19 HC: Hsinchu City; 20 TC: Taichung City;
21 CY: Chiayi City; 22 TN: Tainan City.

Table 3 Travel distance and time between cities and ports

		Distance (km)			Time (hr)		
	Cities	KLH	KSH	TCH	KLH	KSH	TCH
1	TP	24.7	371	171	0.5	5.7	2.8
2	KH	374	18.1	204	5.4	0.9	3.2
3	TPC	44.3	396	196	1.2	6.3	3.3
4	YLC	75.3	427	227	1.7	6.8	3.8
5	TYC	68.8	326	126	1.2	5.1	2.1
6	HCC	107	310	110	1.9	5.0	2.0
7	MLC	163	277	78.6	2.9	4.7	2.0
8	TCC	208	260	61.1	3.8	4.7	1.9
9	CHC	212	182	40.9	3.3	3.0	1.1
10	NTC	277	270	103	4.9	5.1	2.6
11	YUC	246	158	75.6	3.9	2.9	1.7
12	CYC	294	139	131	4.6	2.7	2.3
13	TNC	316	90.8	146	5.1	2.0	2.5
14	KHC	412	88.9	242	6.4	2.3	4.1
15	PTC	408	47	238	6.1	1.7	3.8
16	TTC	382	241	432	11.4	7.6	9.9
17	HLC	238	320	239	6.9	9.1	7.4
18	KL	7.5	389	190	0.3	6.0	3.0
19	HC	103	294	90.8	1.8	4.7	2.4
20	TC	186	208	22.7	2.9	3.4	0.9
21	CY	274	128	104	4.1	2.4	1.9
22	TN	332	67.3	162	4.9	1.7	2.7

Note: KLH: Keelung Harbour; KHH: Kaohsiung Harbour; TCH: Taichung Harbour.

Table 4 Capacity of ports in TEU

Port	Port capacity (TEU)
Keelung port	2,500,000
Kaohsiong port	13,000,000
Taichung port	1,500,000

Table 5 Emission factor and avoidance cost of pollution types for truck and SSS

Pollutant type	Emission factor			Avoidance cost (US$/ton emission)
	Truck (g/veh-km)	SSS (kg/ton)		
		Heavy oil	Diesel oil	
PM_{10}	1.5	1.2	7.6	375888
NO_X	20.3	57	87	4992
VOC	1.3	2.4	2.4	1390
SO_2	0.6	10	54	13960
CO_2	554	3170	3170	26

Table A1 Traffic statistics at freeway toll stations (at 2006)

Vehicle type	No. of vehicle passage	Percentage share in Vehicle	Percentage share in PCU
Small automobiles	480,594,647	84%	70%
Buses & Trucks	55,241,451	10%	16%
Tractor Trailers	38,877,139	7%	14%
Subtotal (vehicles)	574,713,237	100%	
Subtotal (PCU)	688,270,397		100%

Note: Tractor trailer is the term in the report for vehicles carrying container cargos.

Figure 1 Change of truck traffic and short sea shipping traffic against the external cost internalization factor

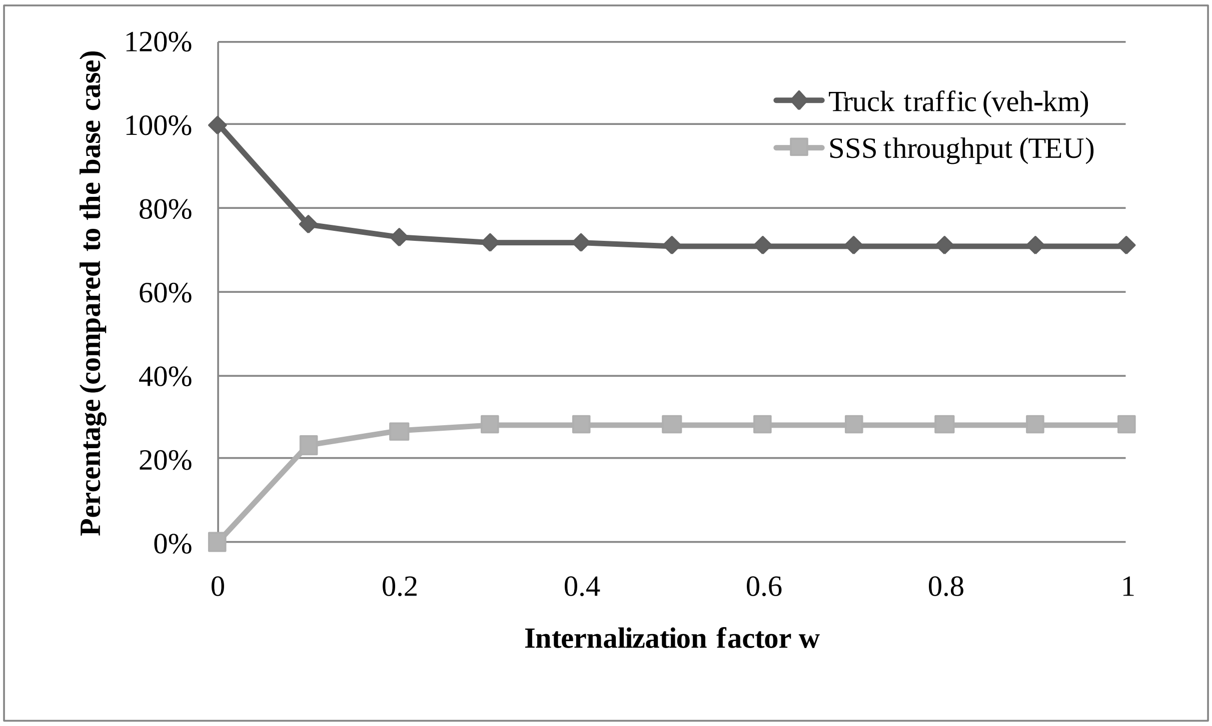

Figure 2 Throughput of the three ports against capacity expansion of the harbours at the Northern area

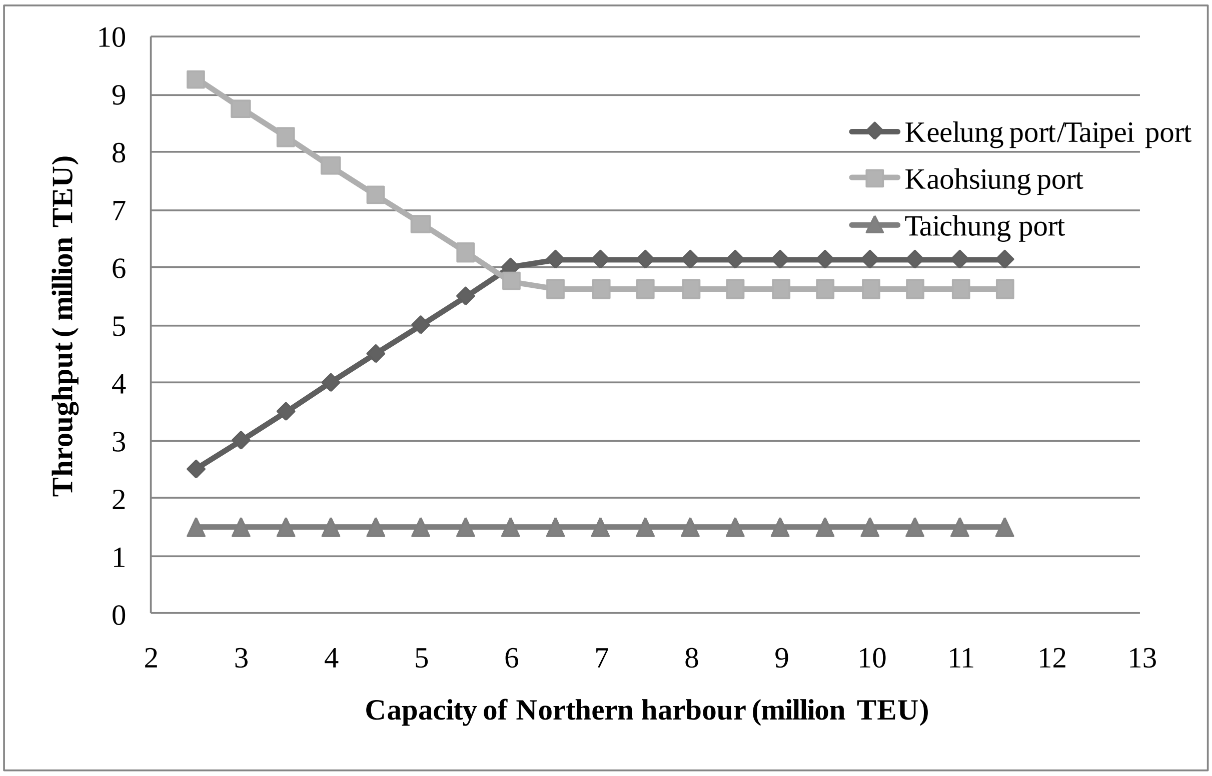

Figure 3 Truck traffic and short sea shipping throughput against capacity expansion of the harbours at the Northern area at w = 0.2