MODELLING MULTIMODAL FREIGHT TRANSPORT NETWORK
TOWARDS FREIGHT TERMINAL DEVELOPMENT*

by Bona Frazila RUSS**, Tadashi YAMADA*** and Jun CASTRO****

1. Introduction

Indonesia is a vast archipelagic country composed of more than 17,500 islands. As such, freight movement using several modes is indispensable. However, relatively poor attention is given on the planning of a multimodal transport system particularly in the national level.

Inadequate quantity and quality of transport infrastructure are typical problems occurring in most regions of Indonesia. Moreover, the sole emphasis given on the road-mode has further worsened the transport system and has resulted in severe social and environmental impacts. Based on the national origin-destination survey in 2001, the share of other-than-road-mode in moving regional freight is less than 5% in the major island of Java where road density is relatively high. Even in regions with low road density, such as Sulawesi Island, Maluku and Irian Jaya Provinces, the share of other-than-road-mode is less than 50%. An integrated multimodal transport system could increase the utilisation of other-than-road-mode to attain a more efficient system that could ultimately reduce environmental impacts. This integration requires effective and efficient connectivity of multimodal terminals or transfer nodes. Recently, among 304 seaports and 3 dry ports that exist in Indonesia, only one port, Tanjung Priok in Jakarta, operates as a multimodal port.

Hence, for the purpose of strategic planning of freight networks, a predictive network model that sufficiently considers the effect of terminals is required. Furthermore, in cases where freight and passenger trips are less separated than other modes in using the infrastructure especially on the road network, the effect of freight movement on passenger trips, or vice versa, may be considered. Therefore, it should be worthy to include passenger trips in the predictive freight network model simultaneously.

2. Research Framework

(1) General

The general objective of the research is to develop a model that can be used as a tool for analysing interregional freight transport network, particularly freight terminal development. A bi-level programming approach is employed such that the model can be divided into two levels of problems (Figure 1). The prediction of freight volume and costs on links is performed in the lower level problem, while the optimal planning scheme, which provides the optimal system's objective function, is determined in the upper level problem.

This paper focuses on the lower level problem and discusses the model development of an aggregate multimodal freight transport network modelling in the strategic level of planning based on existing models[1]–[7]. The modelling framework is mainly based on available data and model structure (i.e. structure of bi-level programming). While the model should address competition among modes and routes, the available data, particularly the data of freight demand in Indonesia, only offer aggregate origin-destination matrices that can identify the mode shares of the total commodity but cannot provide information about the activities of individual shippers as well as that of carriers. Moreover, since most shipping companies in Indonesia are either medium or small companies[8] that only serve a small number of origin-destination pair at the same time, it can be assumed that freights are transported at minimum generalised path cost and a single shipper serves a certain origin-destination pair of freight movement. Therefore, in this case, the model with user equilibrium (UE) assignment would be appropriate.

* Keywords: multimodal freight transport, network modelling, assignment and modal split
** Student Member of JSCE, M. Sc., Graduate School of Engineering Hiroshima University
 (1-4-1 Kagamiyama, Higashi-Hiroshima, 739-8527 Japan, Fax: +81-82-424-7812
*** Member of JSCE, Dr. Eng., Graduate School of Engineering Hiroshima University
 (1-4-1 Kagamiyama, Higashi-Hiroshima, 739-8527 Japan, Fax: +81-82-424-7812
**** Member of JSCE, Dr. Eng., Graduate School of Engineering Hiroshima University
 (1-4-1 Kagamiyama, Higashi-Hiroshima, 739-8527 Japan, Fax: +81-82-422-7194
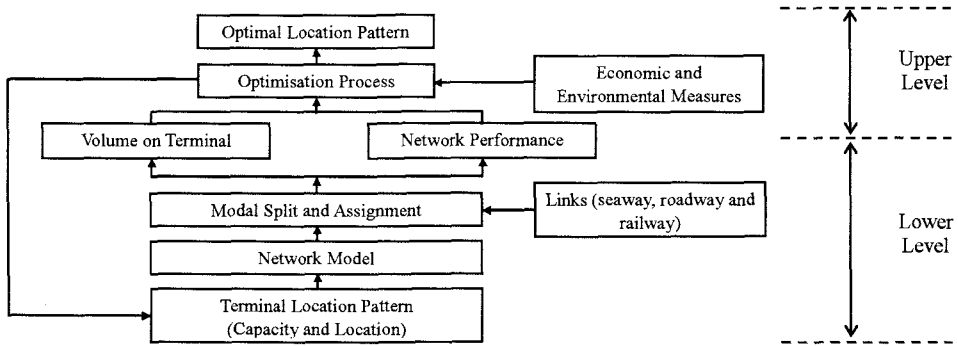
Figure 1: Modelling framework for investigating optimal freight transport systems

Moreover, to obtain a more elastic cost function influenced by passenger movement, particularly in the road mode, the origin-destination matrices of passengers are also assigned simultaneously. Freight and passengers are then treated as multi-class users[9] with asymmetric cost functions.

(2) Network and Terminal Representation

We consider an abstract mode network $\eta(N,A)$, where N is the set of nodes and A is the set of links. Nodes represent cities or junctions where there are no associated delays or costs. Links, which are the conduits for flow between two nodes, represent not only physical infrastructures (i.e. roads, railways), but also activities that cause delay/cost to the flow (i.e. links representing the loading process in the terminal).

Previous researches have represented terminals or transhipment links in several ways to take account of the cost and time of freight at terminals or mode transfer points (Figure 2). Tavasszy[3] proposed a simple transhipment link with fixed values of cost and delay time, while Guelat et al.[4] used a more specific transfer link that creates more links in the multimodal terminal. A more explicit representation of terminals in the network proposed by Southworth et al.[5] separates transhipment link into terminal access link and transfer link inside the terminal, although the application is for database and routing purposes only.

To determine the explicit effect of terminals, it is necessary to add more links representing the processes in the terminal. For a three-modal (multimodal) terminal, there would be loading-unloading activities, train spotting and switching, drayage, waiting for vehicles or storage including inspections and other administrative processes. However, it is necessary to make a simple representation of the terminal to avoid complicated calculation and inputs. Therefore, the terminal representation in Figure 3 is composed of the unloading link that represents unloading/discharging activity, and storage and loading link that represents loading and other activities in the terminal such as drayage, inspections and other administrative processes. Link way for mode, assumed to have limited vehicle availability for the sea and rail mode, includes waiting for the vehicle activity. This configuration is used due to the characteristics of the proposed cost and delay functions described in the following section.
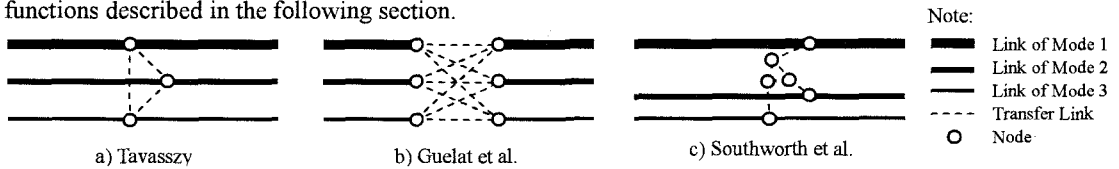

a) Tavasszy	b) Guelat et al.	c) Southworth et al.	Note:

Note:
- ▬▬ Link of Mode 1
- ▬ Link of Mode 2
- — Link of Mode 3
- ---- Transfer Link
- ○ Node

Figure 2: Examples of terminal representations

Note:
a_{ls} Loading link for sea mode
a_{us} Unloading link for sea mode
a_{lr} Loading link for rail mode
a_{ur} Unloading link for rail mode
a_{lh} Loading link for road mode
a_{uh} Unloading link for road mode
a_{ws} Link used by sea mode (including waiting for vehicle)
a_{wr} Link used by rail mode (including waiting for vehicle)
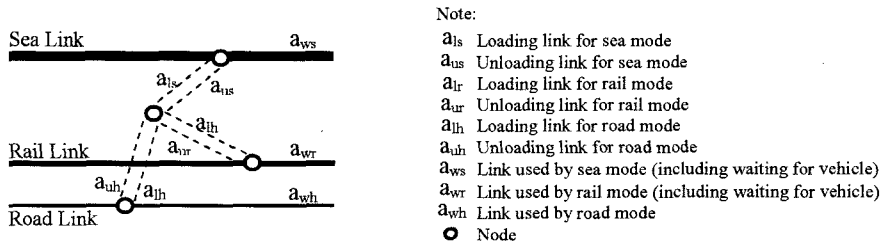a_{wh} Link used by road mode
○ Node

Figure 3: Links representing a multimodal terminal

Using this representation, the set of links A is composed of the unloading links (A_u), loading links (A_l), sea links (A_s), rail links (A_r), road links (A_h) and centroid connectors (A_c), such that $A=A_u\cup A_l\cup A_s\cup A_r\cup A_h\cup A_c$.

(3) The Assignment Model

Denoting k as the path and K_ω as the set of all paths in the network connecting the origin-destination (OD) pair ω, where all OD pairs belong to the set Ω, and assuming user type i belongs to the set I with p types of users, then $f^i_{k\omega}$ can be defined as the flow of user type i on path k connecting ω, and x^i_a can be defined as the flow of user type i on link a. The following link flow conservation should then hold:

$$x^i_a = \sum_{\omega\in\Omega}\sum_{k\in K_\omega} f^i_{k\omega}\delta^i_{ak\omega} \quad \forall a \in A, \forall i \in I \tag{1}$$

where

$$\delta^i_{ak\omega} = \begin{cases} 1, \text{ if path } k \text{ connecting } \omega \text{ for user } i \text{ uses link } a \\ 0, \text{ otherwise} \end{cases}$$

Representing q^i_ω as the demand associated with OD pair ω, then the following OD flow conservation and non-negative path flow should also hold:

$$q^i_\omega = \sum_{k\in K_\omega} f^i_{k\omega} \quad \forall \omega \in \Omega, \forall i \in I \tag{2}$$

$$f^i_{k\omega} \geq 0 \tag{3}$$

Wardrop's user optimal principles state that the flow is distributed on the network such that the travel costs on all used routes between origin and destination are equal, while all unused route have equal or greater travel costs. This UE condition is a variational inequality problem. In the case when the Jacobian matrix of the link cost function is symmetric, UE flow may be obtained as the solution of an equivalent convex cost minimisation problem.

In this paper, freight and passengers are treated as multi-class users, with modal split and route choice carried out simultaneously by converting the multimodal network into a unimodal abstract mode network. Therefore, the UE problem to be dealt with is a non-separable and asymmetric Jacobian matrix cost function among user types. This can be stated as a variational inequality problem as follows:

Find $x^{i*}_a \in \kappa$ such that:

$$\sum_{i=1}^{p}\sum_{a\in A} c^i_a(\tilde{x}^*)\times(x^i_a - x^{i*}_a) \geq 0 \quad \forall\tilde{x} \in \kappa \tag{4}$$

Here, x^{i*}_a represents the link flow of each user type that is the solution for the user optimal equilibrium (UE) problem. $\tilde{x}$ is a pn-dimensional column vector with the components $\{x^1_a,...,x^1_n,..., x^p_a,...,x^p_n\}$ where n represents the number of links. κ can be defined as $\kappa \equiv \{ \tilde{x} \mid$ satisfying Equations (1), (2) and (3)$\}$.

By assuming that the marginal cost of freight transport using a particular mode is inelastic to the shared volume by mode, this multimodal assignment problem becomes a single modal assignment with various types of links. Since there is more than one user assigned, this case can be considered as a multi-class user equilibrium (UE) assignment problem with non-separable and asymmetric cost function. The asymmetry is due to the first order derivative of the cost function that is different for each user (i.e. between freight and passenger).

(4) Link Cost Functions

Cost on link a for user type i (except for the centroid connectors where the cost is neglected) is expressed as a generalised cost composed of a fare component and a time cost component. The time cost component consists of the product of the delay time and time value for each user type.

$$c_a(x^i_a) = \rho^i_a + \alpha^i d^i_a(x^i_a) \tag{5}$$

where
ρ^i_a : fare on link a for user type i (Rp)
α^i : time value for user type i (Rp/hr)
$d^i_a(x^i_a)$: delay time on link a for user type i (hr)

The fare component is a fixed value and does not depend on volume, while the time cost component, particularly the delay time, is a function of volume and differs by link type. For simplicity, it is assumed that the terminal is a series of (M/M/1) queue system. Therefore, the delay function for loading and unloading is derived from residence time (mean time an item spends in the system)[10] while administration and other processes are considered to be fixed values.

In order to keep the link cost function monotonically increasing, the delay for the administration process is attached to the loading process, while the function for the waiting process is attached to the link ways of sea and rail modes. Therefore, the delay function for the unloading and loading links follows Equation (6) and (7) respectively, while the delay function for the links used by sea and rail mode follows Equation (8).

$$d_a^i(x_a^i) = \frac{\tau_a}{1 - \frac{x_a^i}{\psi_a \mu_a}} \qquad \forall a \in A_u \tag{6}$$

$$d_a^i(x_a^i) = \theta_a + \frac{\tau_a}{1 - \frac{x_a^i}{\psi_a \mu_a}} \qquad \forall a \in A_l \tag{7}$$

$$d_a^i(x_a^i) = \frac{l_a}{S_a} + \frac{\zeta_a}{1 - \frac{x_a^i}{o_a v_a}} \qquad \forall a \in A_s, A_r \tag{8}$$

where

$d_a^i(x_a^i)$: delay time on link a for user type i (hr)
θ_a : delay time on link a for inspections, administration, drayage, etc. (hr)
τ_a : unloading/loading time on link a (hr)
μ_a : unloading/loading capacity on link a (ton/hr/berth or passengers/hr/ berth)
ψ_a : number of berths on link a (unit)
l_a : travel distance on link a (km)
S_a : average speed on link a for sea and railway links (km/hr)
o_a : frequency of vehicle arrivals on link a (veh/hr)
v_a : average vehicle capacity on link a (ton/veh)

For the links used by the road mode, the delay equation is adopted from the Indonesian Highway Capacity Manual 1997[11], with the following basic form:

$$d_a^i(x_a^i) = \frac{2t_{oa}}{1 + \left(1 - \frac{x_a^i}{r_a}\right)^{0.5}} \qquad \forall a \in A_h \tag{9}$$

where

t_{oa} : travel time or delay time on link a at flow equal to 0 (hr)
r_a : capacity of road link a (pcu/hr)

The above delay time equations (Equations (6)-(9)) can be used to determine delay time $d_a^i(x_a^i)$ in the cost function $c_a^i(x_a^i)$ of Equation (5). However, these functions have asymptotic behaviours that require special procedures particularly when the magnitude of flow is about the total capacity, which can lead to a complex objective function. Therefore, in order to evade that complexity or non-singularity of solution, polynomial approximation proposed by Crainic et al.[1] is used for all link type, as follows:

$$d_a^i(x_a^T) = t_0 \left(1 + \phi_1 x_a^T + \phi_2 \left(\frac{x_a^T}{r_a^T} \right)^\gamma \right) \tag{10}$$

where

x_a^T : total flow on link a (veh)
$r_{,a}^T$: total capacity of link a (veh)
ϕ_1, ϕ_2, γ : parameters to be calibrated

(5) Solution Method

A method widely used for solving this case of assignment problem is diagonalisation[12]. Essentially, this method keeps interaction effects constant while solving the assignment problem by a descent direction algorithm. When updating the flow of one user type in the next iteration, the other user type is considered constant.

This can simultaneously be undertaken until no significant changes on the flows are obtained. Based on Sheffi[13] and other diagonalisation results in Thomas[12], the basic condition for reaching convergence is that the link cost is only dominated by the flow on it. Even if the condition is violated, the satisfactory result could still be obtained as long as the link cost is Jacobian positive definite.

3. Model Application

(1) Test Conditions

The proposed model is applied using available data from the two major islands of Indonesia - Sumatra and Java, where all transport modes are commonly utilised. These islands are divided into 15 provinces consisting of about 206 cities covering 32% of the total Indonesian land area and are inhabited by around 80% of the total population. The current transport system in these areas and their surroundings (Figure 4) is composed of 38,058 kms of national-provincial roads (52% of Indonesian total), 508 kms of toll roads, and 5,042 kms of railway tracks with 45 commercial seaports and 83 non-commercial seaports.

Inter-regional freight and passenger movement data (origin-destination matrices) are obtained from the 2001 National OD Survey. Only internal movements between Sumatra and Java are included in model implementation. Figure 5 shows the total freight movements exceeding 10 thousand tons per day for all the transport modes in the two islands. Data concerning road characteristics of national and provincial roads are obtained from the database of Interurban Road Management System (IRMS) of the Department of Public Works while data concerning toll roads are acquired from the Indonesian toll road operator PT. Jasa Marga. Railway data and related information are obtained from the Department of Communications and the semi-private railway company, PT. KAI. Port information and other sea network data are collected from the Directorate General of Sea Communication under the Department of Communications.
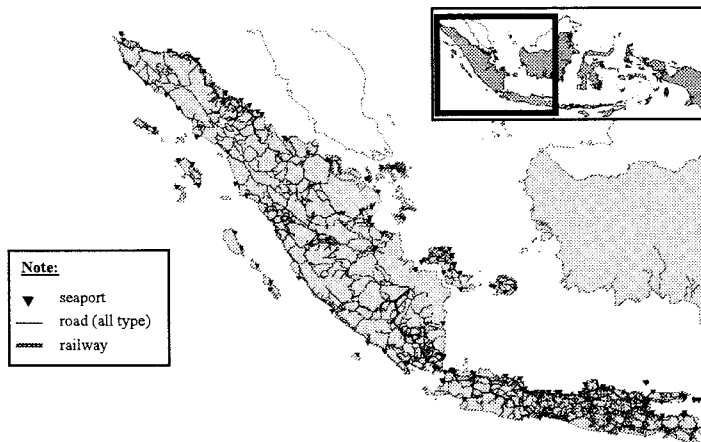
Figure 4: Transport infrastructure in Sumatra-Java island and surroundings
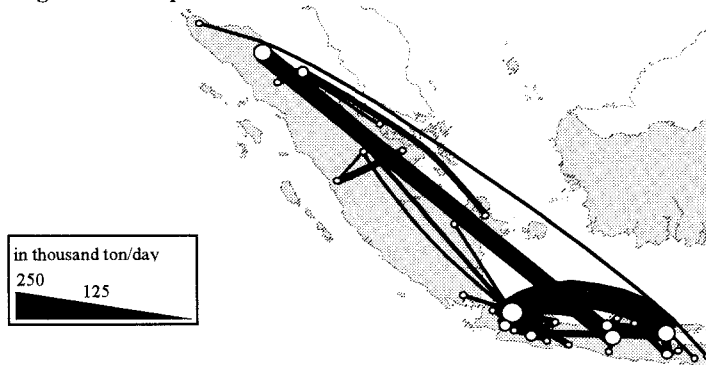
Figure 5: Origin-destination freight movements exceeding 10 thousand ton/day in Sumatra-Java Islands

The transport network is modelled into 166 zones consisting of 767 nodes and 2082 links, comprising the national, provincial and toll roads, railways, 30 seaports (12 strategic seaports, 4 ferry ports and 14 other commercial seaports), and port-to-port connections including ferry routes. In addition, 147 loading links and an equal number of unloading links were included in the transport network.

(2) Validation and Results

Crainic et al. provided a heuristic method for parameter calibration of the link delay function by plotting the original equations, setting the total capacity and fixing the γ value. The value of ϕ_2 is then estimated by fitting

$$d_a^i * (x_a^T) = t_0 \left(1 + \phi_2 \left(\frac{x_a^T}{r_a^T} \right)^\gamma \right) \tag{11}$$

for values of x_a^T higher than the total capacity. ϕ_1 is estimated by adjusting Equation (10) using small values of x_a^T (i.e. 0.2 of total capacity) and using the ϕ_2 value previously obtained. Some values of γ are evaluated for the best-fit polynomial. The value of γ can be typically represented with small integers.

Example for parameter calibration result for each link type is presented on Table 1. Road link data are adopted from the IRMS data base, with the total capacity equal to the capacity of the road and the ratio of distance to the average speed. The average speed for the rail mode is set at 60 km/hour and at 12 km/hour for the sea mode, and frequency and vehicle capacity values are averaged from the available yearly trip statistics. Capacities for loading/unloading links are derived from the ship handling capacities of several ports/terminal. Other delay times such as time of inspection, inventory, administrations on terminals are assumed, ranging from 6 to 48 hours depending on terminal type. The number of berths are derived from the port's berth length and the average ship length for loading/unloading at sea terminals, while for rail terminals, it is equal to the number of yards.

After some trial, it is determined that $\gamma = 5$ provides the best-fit polynomial. Setting x_a^T as $\Sigma \beta^i x_a^i$, where β^i is the flow adjustment (to convert unit of flow into the same unit with that of capacity), $c_a^i(x_a^i)$ can be transformed into the following equation:

$$c_a^i(x_a^i) = \rho_a^i + \alpha^i t_{0,a} \left(1 + \phi_{1,a} \sum_i^p \beta^i x_a^i + \phi_{2,a} \left(\frac{\sum_i^p \beta^i x_a^i}{r_a^T} \right)^\gamma \right) \qquad \forall a \in A \tag{12}$$

By applying this equation to all links, the multimodal and multi-type links network is then converted to a single abstract mode network.

Parameter values of fare at the links are equal to the average tariff (in Rp./ton/km) standardised by the government. The time value of freight used a single value of 5.05 Rp./ton/hour that is derived from a previous research[7]. It should be noted that this value is not obtained from an actual study since a nationwide time value study in Indonesia has not been conducted yet.

The model was validated using data from various sources. Details of these data types are explained below:
- road mode data is composed of the traffic count data, which forms part of the IRMS database, available in the form of daily traffic volumes by vehicle type and direction, and converted into tonnage unit for freight vehicles and number of passengers for passenger vehicles
- railway mode data is terminal-to-terminal flow related to National OD Survey data
- sea mode data is composed of the port-to-port flow related to National OD Survey data

Table 1: Example of parameter calibration results

Link Type	Data Input (Hourly)							Parameter Calibration Result			
	Distance	Capacity	Ave Speed	Freq.	Other Delay	Vehicle Capacity	No. of Berth	Total Capacity	t_0	ϕ_1	ϕ_2
	d	c_r, μ_u, μ_l	S	q	D_e	c_v	N	c_t			
Road link	88.8	1207.1	47.1	-	-	-	0.0	1207.1	1.885	2.181E-04	8.983E-01
Sea/rail link	70.1	-	60.0	0.21	-	384.9	0.0	80.2	1.182	5.923E-05	1.196E+00
Unloading link		115.4	-	-	-	-	1.0	115.4	0.009	2.220E-02	2.690E+03
Loading link	-	115.2	-	-	12.0	-	1.0	115.2	12.009	1.610E-07	1.946E-02

Road mode, R²=0.82   Rail mode, R²=0.84   Sea mode, R²=0.79
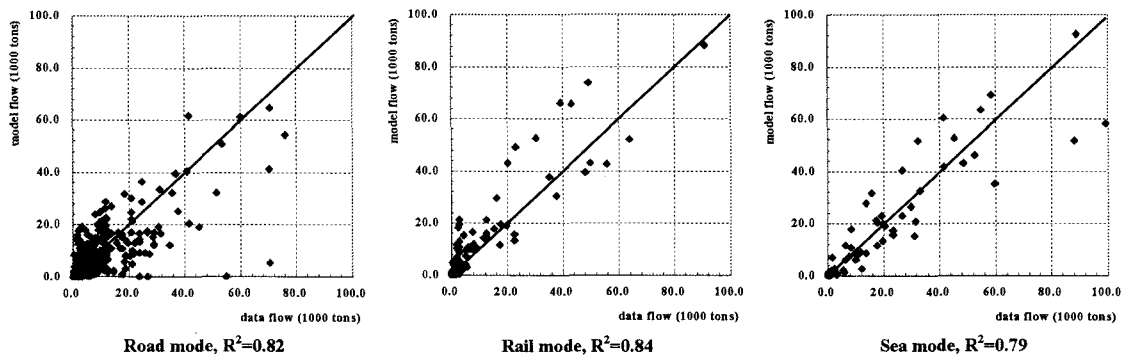
Figure 6: Comparison of flow distribution patterns

It can be seen from Figure 6 that the proposed assignment model, as expressed in the form of flow ratio (i.e. model ratio refers to the ratio of individual link flows to the total link flows by mode as calculated from the model and data ratio is similarly calculated except that the values are from the actual data), performed well. Estimated values from the model have a strong correlation with the actual values from the available data set as indicated by the high correlation coefficients ranging from 0.79-0.84.

4. Conclusions and Future Tasks

This paper proposed a model that can be used as a tool for strategic level of planning, particularly in the development of freight terminals. It presented a freight network assignment model that incorporates the various processes within the terminal. The model was applied to the actual freight transport network in Sumatra and Java, Indonesia. Results revealed that the model adequately represents the freight network behaviour and sufficiently predicts the major freight flows in accordance with available data.

Future tasks for model development and implementation are as follows:

- collection of supplementary data, particularly data for validation processes and model improvement parameters
- development of models in the upper level problem to solve for optimal terminal location and performance and its application
- further model application and validation for other areas to obtain a better picture about the fitness of the model applied in Indonesia in particular
- development of models that incorporate the interaction of carrier and shipper explicitly that might provide a better simulation of freight movement

References

1) Crainic T. G., Florian M., Leal J.: A Model for The Strategic Planning of National Freight Transportation by Rail, Transportation Science 24(1), pp.1-24, 1990.
2) Friesz T. L., Tobin R. L. and Harker P. T.: Predictive Intercity Freight Network Models: The State of The Art, Transportation Research A, vol. 17A (6), pp. 409-417, 1983.
3) Tavasszy L. A.: Modelling European Freight Transport Flows, PhD Thesis, T. U. Delft, 1996.
4) Guelat J., Florian M. and Crainic, T. G: A Multimode Multiproduct Network Assignment Model for Strategic Planning of Freight Flows, Transportation Science 24(1), pp. 25-39, 1990.
5) Southworth F. and Peterson, B. E.: Intermodal and International Freight Modeling, Transportation Research Part C 8, pp. 147-166, 2000.
6) Lubis H. A., Sjafruddin A. and Frazila, R. B.: Port Planning with Multimodal Analysis, Report of Group Activities on Marine Transportation Engineering, JSPS Marine Transportation Program, Hiroshima University, Japan, pp. 238-260, 2002.
7) Lubis H. A., Sjafruddin A., Putra A.I. and Pramono, D.: Developing Eastern Indonesia Multimodal Freight Transport Network, Report of Group Activities on Marine Transportation Engineering, JSPS Marine Transportation Program, Hiroshima University, Japan, pp. 311-325, 2003.
8) Kateru A. K.: Development of Domestic Shipping in Indonesia, Report of Group Activities on Marine Transportation Engineering, JSPS Marine Transportation Program, Hiroshima University, Japan, pp. 410-426, 2003.
9) Dafermos S. C.: The Traffic Assignment Problem for Multiple-user Transportation Networks, Transportation

Science 6(1), pp. 73-87, 1972.

10) Stallings W.: Queuing Analysis, WilliamStallings.com/StudentSupport.htm, 2000.
11) Directorate General of Highway, Department of Public Works, Republic of Indonesia: Indonesian Highway Capacity Manual, 1997.
12) Thomas R.: Traffic Assignment Techniques, Avebury Technical, England, 1991.
13) Sheffi, Y.: Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods, Prentice Hall, Englewood Cliffs, New Jersey, 1985.

Modelling Multimodal Freight Transport Network towards Freight Terminal Development*

By Bona Frazila RUSS**, Tadashi YAMADA*** and Jun CASTRO****

Efficient provision and suitable location of freight terminals such as ports, rail and truck terminals are necessary to establish a multimodal freight transport system. This paper proposed a model that can be used as a tool for strategic level of planning, particularly in freight terminal development. It presented a freight network assignment model that explicitly incorporates the various activities within the terminal taking into account not only freight flows but also passenger flows. Model application to actual transport network in Sumatra and Java, Indonesia revealed that the model adequately represents the freight network behaviour and sufficiently predicts the major freight flows in accordance with available data.

物流ターミナル整備のためのマルチモーダル輸送網分析*

ルス・ボナ・フラジラ**・山田忠史***・カストロ・ジュン****

貨物のマルチモーダル輸送体系を確立するためには，港湾・鉄道駅・トラックターミナルなどの物流ターミナルの効率的な整備・配置が重要である．本研究では，インドネシアにおける物流ターミナルの最適配置計画を念頭に置き，その第一段階として，既知の物流ターミナル配置下における輸送機関分担・配分の推定手法を構築した．構築されたモデルは，従来の手法に比べて，物流ターミナル内での活動を詳細に考慮している点に特徴がある．また，このモデルでは，貨物の流動だけでなく，旅客の流動も考慮されている．構築したモデルをインドネシアのスマトラ・ジャワ地域に適用した結果，モデルのパフォーマンスが良好であることが確認された．