IMPACTS OF URBAN INFRASTRUCTURE IMPROVEMENT ON INTER-REGIONAL MULTIMODAL FREIGHT TRANSPORT*

by Jun T. Castro**, Tadashi Yamada*** and Bona Frazila Russ****

1. Introduction

Multimodal freight transport network planning is an absolute necessity for archipelagic countries to improve their passenger and goods movements. This paper describes a model that can be used as a tool for strategic level of planning, particularly in the development of freight-related infrastructure. It specifically investigates the impacts of urban infrastructure improvement on inter-regional multimodal freight transport conditions focusing on feasible actions for capacity expansion, which includes improving the existing infrastructure or building new roads, railways, sea links and freight terminals.

The model is developed within the framework of bi-level programming, where a multimodal multi-user assignment technique is described in the lower level problem, and the combination of actions, such that the freight-related benefit-cost ratio is maximized, is optimised using GA-based procedures in the upper level problem. The model is applied on the freight transport network in Java Island, Indonesia.

2. Modelling

(1) Lower Level Problem

The lower level problem involves user equilibrium conditions with a non-separable and asymmetric Jacobian matrix cost function among user types that can be stated as a variational inequality problem[1)] as follows: Find $x_a^{i*} \in \boldsymbol{\kappa}$ such that

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

where x_a^{i*} is the user equilibrium flow of link a for user type i, $\tilde{x}$ is a pn-dimensional column vector with the components $\{x_a^1,\ldots,x_n^1,\ldots,x_a^p,\ldots,x_n^p\}$ where n represents the number of links, and κ is defined as $\kappa \equiv \{\tilde{x} \mid$ satisfying the non-negative path flows and conservation of flow$\}$. $c_a^i(.)$ is the generalised cost on link a for user type i. The generalised freight cost is composed of a fare component and a time cost component (i.e. product of the time spent on the link and time value for each user type) expressed as:

$$c_a(x_a^i, y_a) = \rho_a^i + \alpha^i d_a^i(x_a^i, y_a) \tag{2}$$

where $c_a(x_a^i, y_a)$ is the generalised freight cost on link a for user type i, x_a^i is the flow on link a for user type i, y_a is the action implementation indicator (i.e. 1 if the action related to corresponding link a is implemented, and 0 if it is otherwise), ρ_a^i is the fare on link a for user type i, α^i is the time value for user type i, and $d_a^i(x_a^i)$ is the time spent on link a for user type i. To keep the link cost function monotonically increasing, the function for the time spent on the link function is converted to a continuous function in the form of polynomial approximation following Crainic *et al.*[2)]:

$$d_a^i(x_a^i, y_a) = t_{0a}\left[1 + \phi_1 x_a^i + \phi_2\left(\frac{x_a^i}{r_{0a} + y_a r_a}\right)^{\gamma}\right] \tag{3}$$

where t_{0a} is the free running time on link a, r_{0a} is the existing link capacity on link a, r_a is the added link capacity on link a if the action is implemented, and ϕ_1, ϕ_2, and γ are the parameters to be calibrated. Hence, the model incorporates the diagonalisation method[3)-5)] to solve this case of multi-user assignment problem.

---

* Keywords: multimodal freight transport, bi-level programming, discrete network design, genetic algorithms
** Member of JSCE, Dr. Eng., Dept. of Social and Env. Eng., Graduate School of Eng., Hiroshima University (Kagamiyama 1-4-1, Higashi Hiroshima-shi, Hiroshima, Japan, TEL: 0824-24-7771)
*** Member of JSCE, Dr. Eng., Dept. of Urban Management, Graduate School of Engineering, Kyoto Univ. (Sakyo-ku, Kyoto, 606-8501, Japan, TEL: 075-753-4787)
**** Student Member of JSCE, M. Eng., Graduate School of Eng., Hiroshima University (Kagamiyama 1-4-1, Higashi Hiroshima-shi, Hiroshima, Japan, TEL: 0824-24-7771)

(2) Upper Level Problem

The upper level problem optimises the combination of freight network improvement actions based on the ratio of reduced total generalised freight cost and the investment and operational cost incurred for implementing the actions, which is simply the benefit-cost ratio (BCR). Hence, the objective function is to maximise the BCR value of a combination of actions to be implemented, *z(y)*, as follows:

$$z(y) = \frac{\sum_{i\in F}\left(\sum_{a\in A_1\cup A_2} x_{0a}^{i*}c_a^i(x_{0a}^{i*}) - \sum_{a\in A_1} x_a^{i*}c_a^i(x_a^{i*}) - \sum_{a\in A_2} x_a^{i*}c_a^i(x_a^{i*}, y_a)\right)}{\sum_{a\in A_2} b_a y_a} \tag{4}$$

where:

- y : set of freight network improvement actions
- F : set of user types for freight transport
- A_1 : set of existing links without modifications
- A_2 : set of existing links with implemented actions
- x^{i*}_{0a} : user equilibrium flow on link *a* for user type *i* without any action implemented (do-nothing case)
- x_a^{i*} : user equilibrium flow on link *a* for user type *i* with the combination of actions implemented
- b_a : investment/operation cost for link *a*

Genetic Algorithm (GA) is used to solve the upper level problem. A particular type of GA called Genetic Local Search (GLS) is applied[6)] where the local search operator is incorporated after crossover and mutation. This operator investigates other two variations of individuals and searches the best among them. Previous research[7)] showed that GLS provides better performance as compared to other GA-based procedures.

3. Model Application

(1) Description of Network and Actions Considered

The model is applied to the network of Java Island comprising 5 major cities: the capital city of Jakarta, Bandung, Semarang, Surabaya and Yogyakarta (Figure 1). Majority of the country's economic activities are generated in these areas. Total population is 12.2% of the total Java Island population, with Jakarta having the highest population (8.4M in year 2000), followed by Surabaya (2.6M), Bandung (2.1M), Semarang (1.3M) and Yogyakarta (0.4M). The transport network is represented by 93 zones with 405 nodes and 2318 links, comprising the national/provincial roads, expressways, railways, seaports and port-to-port connections.

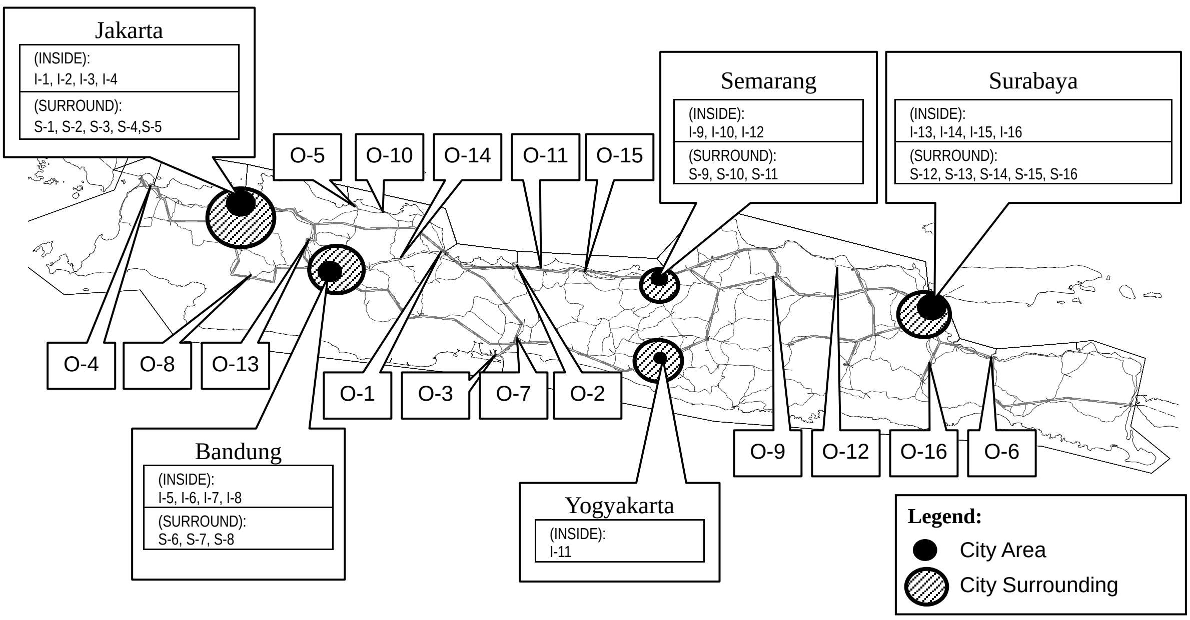

Figure 1 Location of major cities and actions considered

Table 1 Set of alternative actions

Set 1: Alternative actions inside the main cities (Inside)			
I-1 Sea port impvt in Jakarta	I-2 Rail terminal impvt in Jakarta	I-3 New expressway in Jakarta (WRR)	I-4 New expressway in Jakarta (ERR)
I-5 Rail terminal impvt in Bandung	I-6 Road widening in Bandung (Sukarno)	I-7 Road widening in Bandung (Surapati)	I-8 New expressway in Bandung (Soreang)
I-9 Sea port impvt in Semarang	I-10 Rail terminal impvt in Semarang	I-11 Rail terminal impvt in Yogyakarta	I-12 Road widening Semarang (North Rd)
I-13 Sea port Impvt in Surabaya	I-14 Rail terminal impvt in Surabaya	I-15 Road widening in Surabaya (Gresik)	I-16 Road widening in Surabaya (Mojoketo)
Set 2: Alternative actions in the surrounding area (Surround)			
S-1 Rail teminal impvt at Tangerang	S-2 Rail teminal impvt at Bogor	S-3 Road widening Jakarta-Bekasi	S-4 Road widening Jakarta-Tangerang
S-5 Road widening Jakarta-Bogor	S-6 Road widening Bandung-Sumedang	S-7 Road widening at Bandung-Garut	S-8 Road widening Bandung-Padalarang
S-9 Road widening Semarang-Kendal	S-10 Road widening Semarang-Demak	S-11 Road widening Semarang-Ungaran	S-12 Sea port impvt at Gresik
S-13 Rail terminal impvt at Sidoarjo	S-14 Road widening Surabaya-Lamongan	S-15 Road widening Surabaya-Sidoarjo	S-16 Road widening Surabaya-Mojoketo
Set 3: Alternative actions outside the main cities (Outside)			
O-1 Sea port impvt in Cirebon	O-2 Sea port impvt in Tegal	O-3 Sea port impvt in Cilacap	O-4 New sea port in Ciwandan
O-5 New port Karawang	O-6 Sea port impvt Probolinggo	O-7 Rail terminal impvt in Maos	O-8 Rail terminal impvt in Sukabumi
O-9 New rail terminal Blora	O-10 Road widening Jakarta-Cirebon	O-11 Road widening Cirebon-Semarang	O-12 Road widening Semarang-Surabaya
O-13 New exprswy Cikampek-Bandung	O-14 New expressway Bandung-Cirebon	O-15 New exprswy Cirebon-Semarang	O-16 New expressway Malang-Gempol
Set 4: Mixed-type set of actions (Mixed)			
I-1 Sea port impvt in Jakarta	I-4 New expressway in Jakarta (ERR)	I-5 Rail terminal impvt in Bandung	I-9 Sea port impvt in Semarang
I-8 New exprsway Bandung (Soreang)	S-2 Rail terminal impvt in Bogor	S-4 Road widening Jakarta-Tangerang	S-6 Road widening Bandung-Sumedang
S-9 Road widening Semarang-Kendal	S-15 Road widening Surabaya-Sidoarjo	O-4 New seaport in Ciwandan	O-8 Rail terminal impvt in Sukabumi
O-13 New exprswy Cikampek-Bandung	O-14 New expressway Bandung-Cirebon	O-15 New exprswy Cirebon-Semarang	O-16 New expressway Malang-Gempol

To investigate the impact of urban and surrounding network improvement on the regional freight transport condition, several sets of alternative actions by area are assessed. The actions are classified into three types, namely “inside”, “surround” and “outside” (Figure 1 and Table 1). Infrastructure improvements within cities are classified as “inside” actions (Set 1), while capacity improvements located just outside the cities are classified as “surround” actions (Set 2). Infrastructure improvements located outside the cities are grouped into “outside” actions (Set 3). Apart from the area-based set of actions, analysis for a mixed-type set of actions is undertaken to find possible improvements in the combination of actions from the “inside”, “surround” and “outside” areas as shown in Set 4 of Table 1.

4. Results

(1) Optimal Solution for Each Scheme

The computational results for the best set of actions by scheme are shown in Table 2. The term “benefit” indicates the difference between total freight cost for the do-nothing case and the total freight cost for the corresponding implemented scheme, while the term “improvement” suggests the percentage of benefit against the initial total freight cost (do-nothing scheme).

The best actions “inside” the cities are I-4 (new expressway in Jakarta) and I-9 (sea port improvement in Semarang) with a rather high benefit of 8,039 billion rupiah resulting in an improvement of 93.7% when compared to the initial condition. A high BCR value of 3.69 is also obtained. For the “outside” scheme, the best actions are O-8 (rail terminal improvement in Sukabumi) and O-13 (new expressway in Cikampek-Bandung) with a benefit of 5,151 billion rupiah corresponding to an improvement of 60% and a BCR value of 3.04. The “surround” scheme had the lowest benefit among the schemes. The best action of S-8 (road widening at Bandung-Padalarang) has negligible amount of benefit and BCR ratio. The rather low performance of the best action in the “surround” scheme may indicate that the assumed improvement level for road widening (i.e. 1.5 times of the existing capacity) may not be enough to offset the impacts of an already congested network. It can be hypothesized therefore that actions with higher capacity improvement levels such as construction of new road links and rail or port terminal improvements may be more effective in this case than road widening actions as can be seen from the results of the “inside” and “outside” schemes.

Results for the mixed-type set of actions provided higher benefits than the area-based schemes. The best combination of actions are I-5 (rail terminal improvement in Bandung), O-8 (rail terminal improvement in Sukabumi) and O-13 (new expressway in Cikampek-Bandung). Total freight cost improvement is 95.0% with a high BCR ratio of 3.72. Hence, it can be observed that a mixture of actions from different schemes, i.e. “inside” and “outside” actions, would result in a more optimal solution.

(2) Impacts on the Major Urban Areas

The impacts on network performance for the five major cities in terms of total freight cost improvement of the best actions identified in each scheme are shown in Table 3.

For all five cities, all the schemes provided better performance than the do-nothing scenario. The mixed-type scheme gives the highest total freight cost improvement of 37.7% followed by the outside scheme with 24.8% and inside scheme with 18.9%. However, when the scope of analysis is shifted into individual cities, the result is quite different. The table shows that freight network improvements would not necessarily result in positive benefits for all the cities. As can be seen from the results of the "inside" scheme, not all the cities have positive total cost improvements. The negative value for Bandung implies that the total cost is increased by 105.7% due to the implementation of the best action in the "inside" scheme. On the other hand, the best actions for the "outside" scheme would result in unfavorable effects to Jakarta and Semarang with increased total freight costs of 8.7% and 18.3%, respectively. The mixed-type scheme would also result in increased total freight cost of 7.8% in Semarang. However, this scheme would have better positive effects (i.e. decreased total freight cost) in the big cities of Jakarta (5.1%), Bandung (12.8%), Yogyakarta (4.4%), and Surabaya (42.9%).

In general, the impacts of the combination of actions would vary according to the scope of analysis. The optimal solution for the entire Java Island which results in substantial amount of overall benefits may cause negative impacts in smaller-sized areas such as in cities. A trade-off between benefits and scope is therefore observed.

Table 2 Optimal solution for each scheme

Scheme	Best action	Freight Cost (B Rp)	Benefit (B Rp)	Improve ment (%)	Invest ment (BRp)	BCR
Initial	-	8,581	-	-	-	-
Inside	I-4, I-9	542	8,039	93.7	2,176	3.69
Surround	S-8	8,581	0.047	0.0005	81.3	0.0005
Outside	O-8, O-13	3,430	5,151	60.0	1,692	3.04
Mixed	I-5, O-8, O-13	426	8,155	95.0	2,192	3.72

Table 3 Total freight cost improvement for the five major cities

City	Scheme			
	Inside	Surround	Outside	Mixed
All	18.9%	0.01%	24.8%	37.7%
Jakarta	3.6%	0.01%	-8.7%	5.1%
Bandung	-105.7%	0.01%	24.2%	12.8%
Semarang	23.5%	0.00%	-18.3%	-7.8%
Yogyakarta	7.9%	0.00%	1.9%	4.4%
Surabaya	42.9%	0.00%	25.4%	42.9%

5. Conclusion

This paper described a model which can be used as a tool for strategic level of planning, particularly in the development of freight network in Java Island. The model investigated the importance of city and surrounding network improvements in optimizing the inter-regional freight network system of Java Island.

Results revealed that the best combination of actions is a mixed-type set of improvements located inside and outside the cities. In addition, the impacts of the combination of actions vary according to the spatial size or scope of analysis. The optimal solution resulting in substantial amount of benefits for the entire Java Island could cause negative impacts in terms of increased total freight costs in a particular area with a smaller scope or size. This is an area where additional analysis is needed to obtain a more improved solution that considers the trade-off between benefits and negative impacts.

References

1) Dafermos S.C.: Traffic equilibrium and variational inequality, Transportation Science, 14, pp. 43-54, 1980.
2) Crainic T. G., Florian M. and Leal J. A.: Model for the strategic planning of national freight transportation by rail, Transportation Science, 24(1), pp. 1-24, 1990.
3) Florian, M. and Spiess, H.: The convergence of diagonalization algorithms for assymetric network equilibrium problems, Transportation Research, 16B (6), pp. 477-483, 1982.
4) Sheffi, Y.: Urban Transportation Networks: Equillibrium Analysis with Mathematical Programming Methods, Prentice Hall, Englewood Cliffs, New Jersey, 1985.
5) Thomas R.: Traffic Assignment Techniques, Avebury Technical, England, 1991.
6) Goldberg, D. E.: Genetic Algorithms in Search, Optimisation, and Machine Learning, Addison-Wesley, 1989.
7) Russ, B.F, Yamada, T. and Castro, J.: Freight transport planning in Java Island: an optimisation model for terminal development and network expansion, SCIS & ISIS 2004, CD-ROM, 2004.