MODELLING THE EFFECTS OF URBAN CO-OPERATIVE FREIGHT TRANSPORT

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Abstract

Co-operative freight transport systems are among the key City Logistics initiatives with the potential for solving urban traffic problems. This paper focuses on multi-carrier joint freight transport systems with co-operative freight organisation within urban areas. A VRPTW-based simulation model is developed for investigating the effects and financial viability of such systems. This model has a three-stage calculation procedure involving the behaviour of three stakeholders: freight carriers, co-operative freight organisation and administrators (i.e. public sector). Applications of the model to hypothetical urban delivery problems showed that introducing co-operative freight transport systems could lead to significant reductions in total delivery cost and total travel time, whilst the effects and profitability for the co-operative freight organisation depend on the number and distribution of customers. Co-operative freight transport systems would not be profitable if the location of customers is widely dispersed within urban areas. Results also showed that access restrictions to the city centre would increase delivery costs as well as reduce total travel time on the whole road network.

Keywords: Co-operative freight transport systems; Vehicle routing and scheduling; Optimal location of logistics terminals; Access restrictions to the city centre
Topic Area: B5 Urban Goods Movement

1. Introduction

Urban goods movement using road-based vehicles has led to many urban traffic problems, including high levels of traffic congestion, high energy consumption and negative environmental impacts. A new area of transport planning has emerged called City Logistics (Taniguchi et al., 2001) to address these problems. Co-operative operation of freight transport systems are among the key City Logistics initiatives (Taniguchi et al., 2001). These systems offer a potential to satisfy the needs of companies (i.e. shippers and freight carriers) aiming at cost reduction as well as to reduce the total social and environmental costs for the whole community (Ogden, 1992; Ruske, 1994).

Several co-operative freight transport systems have been implemented in practice, such as co-operating in local pickup/delivery of Fukuoka in Japan (Nemoto, 1997) and co-operative goods delivery to the inner city of Kassel in Germany (Kohler, 1997). There have also been several researchers that have investigated co-operative freight transport systems that allow a reduced number of trucks to be used for collecting or delivering the same amount of goods (e.g. Ruske, 1994; Kohler, 1997; Taniguchi et al., 1999). These practices and researches identified that co-operative freight transport systems could reduce environmental pollution as well as logistics costs. However, in spite of these benefits to companies and the society at large, there have been few cases where the co-operative systems have been successfully implemented. This is largely due to a number of difficulties in introducing and operating them, relating to the costs required for implementing such systems, the number of companies participating and the amount of goods secured (Yamada et al., 1999).

This paper focuses on the effects and financial viability of multi-carrier joint freight transport systems with co-operative freight organisation within urban areas. The effects obtained from such systems will be compared to those obtained from other freight transport initiatives: Advanced Vehicle Routing and Scheduling Systems (AVRSS) and access restrictions of delivery vehicles to the city centre. These are investigated using a simulation model being developed on the basis of the Vehicle Routing and scheduling Problem with Time Windows (VRPTW) (e.g. Solomon, 1987). This model incorporates the possibility of using co-operative freight transport systems within the VRPTW. This model also explicitly provides the optimal location of logistics terminals required for the co-operative freight transport systems as well as determines the rates for the use of them. The rates for using the co-operative systems are optimised by considering the profitability of the co-operative freight organisation. The behaviour of three stakeholders is described in this model: freight carriers, co-operative freight organisation and administrators (i.e. public sector).

2. Model formulations

The structure of the model is illustrated in Figure 1. This model has a three-stage calculation procedure which describes the behaviour of the public sector (i.e. administrator) determining the optimal location of logistics terminals and the rates for using co-operative freight transport systems as well as that of freight carriers and co-operative freight organisation operating fleets of pickup/delivery vehicles.

In the first stage, vehicle routing and scheduling of freight carriers is described using the VRPTW-based model. Given a location pattern of logistics terminals and the rates for using the co-operative systems, each freight carrier determines either the amount of goods to be delivered directly to customers or to be transported to a logistics terminal to use the co-operative systems. It is assumed that freight carrier’s decisions are on the basis of them each minimising their total costs independently of the other carriers. The total costs are composed of three components: fixed costs of vehicles, vehicle operating costs being proportional to the time travelled and spent waiting at customers and early and delay penalty costs for specified pickup/delivery time at customers. The delay penalty cost is incorporated so that the accountability of transport service for shippers can be esteemed. The behaviour of each freight carrier for vehicle routing and scheduling can be formulated as follows:

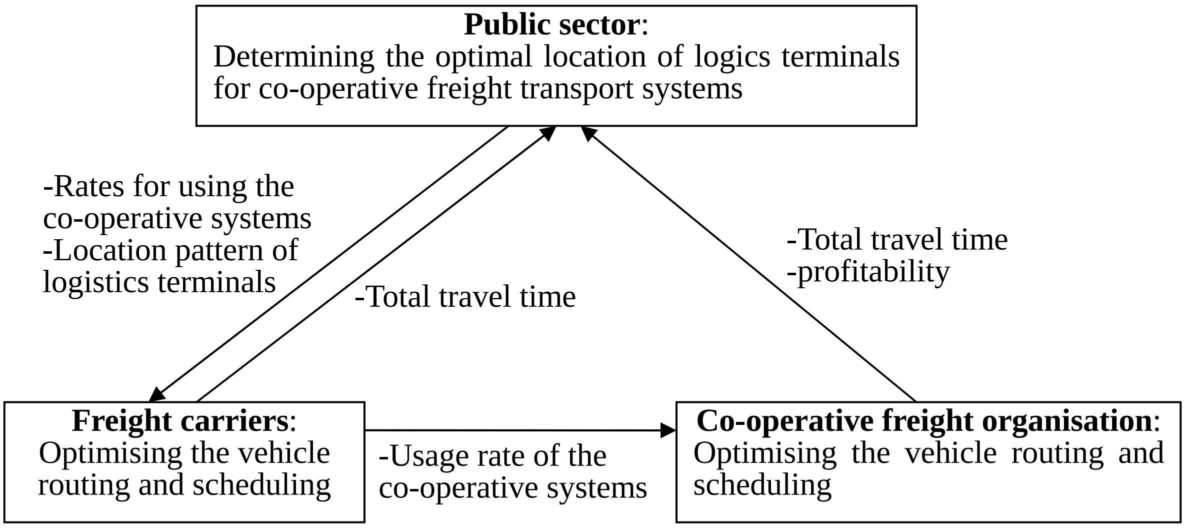

Figure 1. Model structure

$$\min TC\left(\mathbf{X},\boldsymbol{T}^{d},\boldsymbol{T}^{a},\boldsymbol{a}\right)=\sum_{l}\left\{a_l \times SC_l + (1-a_l)\times CC_l\right\} \tag{1}$$

where,

$$SC_l = FC_l(c_l^f,\ \mathbf{x}_l) + RC_l(c_l^t, D_{n(i)}, \mathbf{x}_l, \boldsymbol{t}_l^d, \boldsymbol{t}_l^a) + PC_l(c_l^p,\ t_{n(i)}^s,\ t_{n(i)}^e, \mathbf{x}_l,\ \boldsymbol{t}_l^d, \boldsymbol{t}_l^a) \tag{2}$$

$$CC_l = FC_l(c_l^f, \mathbf{x}_l) + RC_l(c_l^t, D_{n(i)}, \mathbf{x}_l, \mathbf{y}, \boldsymbol{t}_l^d, \boldsymbol{t}_l^a) + UC_l(D_{n(i)}, \mathbf{x}_l, \mathbf{y}, \mathbf{p}) \tag{3}$$

subject to

$$W_l\left(\mathbf{x}_l\right) \le W_l^c \tag{4}$$

$$\sum_l \sum_i n_l(i) = \sum_j n_j \tag{5}$$

$$\sum_l W_l\left(\mathbf{x}_l\right) = \sum_j D_j \tag{6}$$

$$t^d \le t_{l,n(i)}^d \tag{7}$$

$$t_{l,n(i)}^a \le t^a \tag{8}$$

where,

TC : total cost (yen)

l : vehicle number; given

N_l : total number of customers visited by vehicle l

$n_l(i)$: customer number for i th customer visited by vehicle l ($n_l(0)$ means the depot; $n_l(0) = n_l(N_l) = 0$)

m : maximum number of vehicles available; given

$\mathbf{X}$: assignment and order of visiting customers for all vehicles; $\mathbf{X} = \{\mathbf{x}_l \mid l = 1, m\}$

$\mathbf{x}_l$: assignment and order of visiting customers for vehicle l; $\mathbf{x}_l = \{n_l(i) \mid i = 0, N_l\}$

$\boldsymbol{T}^d$: departure time vector for all vehicles; $\boldsymbol{T}^d = \{\boldsymbol{t}_l^d \mid l = 1, m\}$

$\boldsymbol{t}_l^d$: departure time vector for vehicle l at each customer including the depot; $\boldsymbol{t}_l^d = \{t_{l,n(i)}^d \mid i = 0, N_l\}$

$t_{l,n(i)}^d$: departure time for vehicle l at customer $n(i)$

$\boldsymbol{T}^a$: arrival time vector for all vehicles; $\boldsymbol{T}^a = \{\boldsymbol{t}_l^a \mid l = 1, m\}$

$\boldsymbol{t}_l^a$: arrival time vector for vehicle l at each customer including the depot; $\boldsymbol{t}_l^a = \{t_{l,n(i)}^a \mid i = 0, N_l\}$

$t_{l,n(i)}^a$: arrival time for vehicle l at customer $n(i)$

$\boldsymbol{a}$: vector representing the possibility of using co-operative freight transport systems; $\boldsymbol{a} = \{a_l \mid l = 1, m\}$

a_l : =1; if vehicle l transports goods directly to customers
=0; if vehicle l transports goods via a logistics terminal for using co-operative systems

SC_l : cost incurred by vehicle l for transporting goods directly to customers (yen)

CC_l : cost incurred by vehicle l for transporting goods to a logistics terminal for using co-operative systems (yen)

FC_l : fixed cost for vehicle l (yen)

RC_l : operating cost for vehicle l (yen)

PC_l : penalty cost for vehicle l (yen)

UC_l : cost incurred for using co-operative systems by vehicle l (yen)

c_l^f : unit fixed cost for vehicle l (yen/vehicle/day); given

c_l^t : unit operating cost for vehicle l (yen/vehicle/min); given

c_l^p : unit penalty cost for vehicle l (yen/vehicle/min); given

$t_{n(i)}^s$: start of time window at customer $n(i)$; given

$t_{n(i)}^e$: end of time window at customer $n(i)$; given

$D_{n(i)}$: freight demand of customer $n(i)$ (ton); given

J : number of candidate sites of logistics terminals; given

D_j : freight demand of customer j (ton); given

$\mathbf{y}$: location pattern of logistics terminals; $\mathbf{y} = \{y_k \mid k = 1, J\}$

y_k : =1; if a logistics terminal is constructed at candidate node k
=0; otherwise

$\mathbf{p}$: vector of the rates for using co-operative systems (yen/ton); $\mathbf{p} = \{p_k \mid k = 1, J\}$

p_k : rates for using co-operative systems at candidate node k (yen/ton)
$W_l(\mathbf{x}_l)$: load of vehicle l (ton)
W_l^c : capacity of vehicle l (ton); given
n_j : customer number for customer j; given
t^d : earliest time for starting vehicle operations; given
t^a : latest time for completing vehicle operations; given

The mathematical model formulated by equations (1)-(8) involves incorporating co-operative systems into a VRPTW model which uses a single forecast value for predicting the travel time on each link in a road network (Taniguchi et al., 1999). Equation (4) represents the capacity constraint of vehicles, and equations (5) and (6) ensure that each customer is only visited by one vehicle. Equations (7) and (8) are constraints relating to the operating hours for a freight carrier.

This mathematical model represents the advanced vehicle routing and scheduling with lower costs and higher capacity utilisation of vehicles. Such advanced procedures are however, not always used in practice by freight carriers in their vehicle routing and scheduling. Practical vehicle routing and scheduling of freight carriers must therefore be represented for investigating the effects of co-operative freight transport systems. It can be undertaken by incorporating a constraint represented by equation (9) within the model represented by equations (1)-(8), since the value of load factor within urban areas in Japan is estimated approximately 30% (Giannopoulos and McDonald, 1997).

$$W_l(\mathbf{x}_l)/W_l^c \leq W^{MAX} \quad (9)$$

where,
W^{MAX} : upper limit of load factor (=0.32); given

After the behaviour of individual freight carriers is described, the vehicle routing and scheduling of the co-operative freight organisation is performed using the VRPTW model. The optimal departure and arrival times as well as the order of visiting customers for all vehicles owned by the co-operative freight organisation are determined so that the total travel time for them can be minimised for alleviating the traffic congestion on the road network and reducing the environmental impacts. The objective function for the co-operative freight organisation is given below (superscript *cop* represents a variable relating to the co-operative freight organisation):

$$\min \ TT^{cop}\left(\mathbf{X}^{cop}, \boldsymbol{T}^{d,cop}, \boldsymbol{T}^{a,cop}\right) = \sum_{l'} RT_{l'}^{cop}(\mathbf{x}_{l'}, \mathbf{y}, \boldsymbol{t}_{l'}^{d,cop}, \boldsymbol{t}_{l'}^{a,cop}) \quad (10)$$

where,
TT : total travel time (min)
RT_l : travel time for vehicle l (min)
l' : vehicle number for the co-operative freight organisation; given

The constraints are identical to those of the vehicle routing and scheduling model for each freight carrier (i.e. equations (4)-(8)). The following constraint is also added for the profitability of the co-operative freight transport systems to be ensured.

$$\sum_{l'}(FC_{l'}^{cop}+RC_{l'}^{cop}+PC_{l'}^{cop})+LC(\mathbf{y},\boldsymbol{a})\le\sum_{u}\sum_{l}UC_{l}^{u} \tag{11}$$

where,

LC : logistics terminal cost (yen)

u : freight carrier number; given

The penalty cost is also incorporated within equation (11) in order to deliver consigned goods within designated time windows. Logistics terminal costs involve the construction, operation and management costs and depend on the land price and the amount of goods handled. The constraint represented by equation (9) is not involved in the formulation of vehicle routing and scheduling model for the co-operative freight organisation since the load factor would increase after implementing the co-operative systems.

Then, in the third stage, the optimal location of logistics terminals and the rates for using the co-operative systems are determined so that the total travel time of all vehicles (i.e. those owned by all the freight carriers and the co-operative freight organisation) can be minimised. Logistics terminals are required for implementing co-operative freight transport systems, and hence their location and the rates for using the systems strongly influence whether freight carriers utilise such systems. The rates for using them also rely on the location of logistics terminals (i.e. usage rate and land price). The objective function for this stage can be presented as follows:

$$\min\ TT(\mathbf{y},\mathbf{p})=\sum_{u}\sum_{l}RT_{l}^{u}(\mathbf{x}_{l},\mathbf{y},\mathbf{p},\boldsymbol{a},\boldsymbol{t}_{l}^{d},\boldsymbol{t}_{l}^{a})+\sum_{l'}RT_{l'}^{cop}(\mathbf{x}_{l'},\mathbf{y},\boldsymbol{t}_{l'}^{d,cop},\boldsymbol{t}_{l'}^{a,cop}) \tag{12}$$

Each of the above mathematical programming problems is complex and difficult NP-hard combinatorial problem, and the use of heuristic techniques is appropriate for obtaining optimal solutions. Genetic Algorithms (GA) were applied in this study to obtain good solutions within reasonable computational times. GA was selected because it can simultaneously determine the departure times and assignment of vehicles as well as the visiting order of customers (Taniguchi et al., 1999; Yamada et al., 1999).

In this paper, the simulation model developed is only applied to delivering goods in an urban area, though it can also be applied to collecting goods in an urban area and transporting goods between cities.

3. Test conditions

3.1 Road network

A test road network with uniform distances between nodes, shown in Figure 2, was used for the application of the model developed. Assuming a typical large city, distances between nodes for all links were set at 5 km (i.e. 20 km × 20 km). Link travel times on the road network vary depending on the time period (i.e. peak hours and off-peak hours). The shadowed portion of the road network represents the centre of city where the traffic conditions are relatively congested.

3.2 Logistics terminal

There are three candidate nodes for logistics terminals on the road network. One is located on candidate node 12 around the city centre, with its land price being higher than the others that are in the suburbs. Candidate node 23 is located on the concentration area of depots of freight carriers.

3.3 Freight carrier

Eight freight carriers were assumed to operate delivery trucks and join the co-operative systems, each with one depot. The depots were mainly located in the suburbs considering the actual location of depots within urban areas (Figure 2).

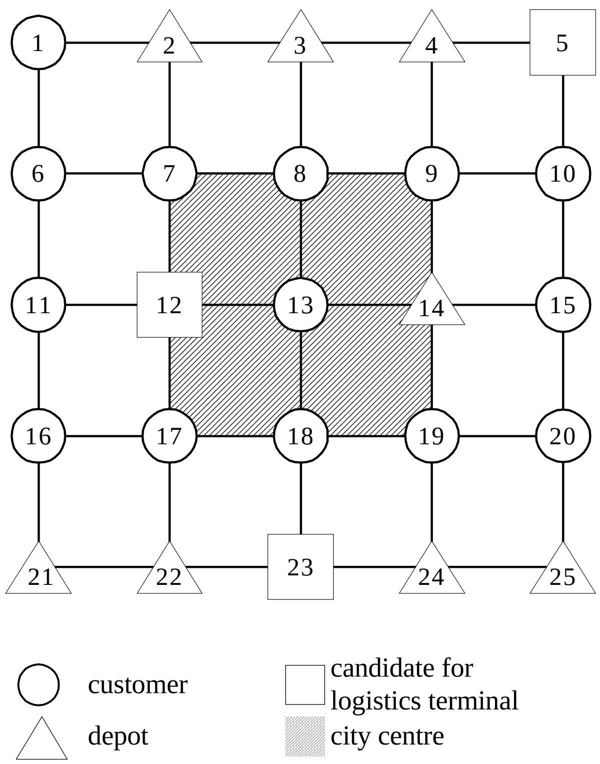

Figure 2. Test road network

3.4 Customer

Two different types of distributions of customers were defined for investigating the influence of customer location on the effects and profitability of co-operative freight transport systems. Figure 3 displays the difference in customer distribution between these two types:

Type A: customers are mainly distributed within the city centre.

Type B: customers are widely dispersed within an urban area

The six types of problems were set by the distribution and number of customers (Table 1). Table 2 shows an example of customer data used in problem (ii). Freight demand is larger for customers that are located closer to the centre of city. Designated time windows are categorised into 3 types, time windows of two hours length, time windows for a.m. (8:00-12:00) or p.m. (13:00-17:00) and no time window.

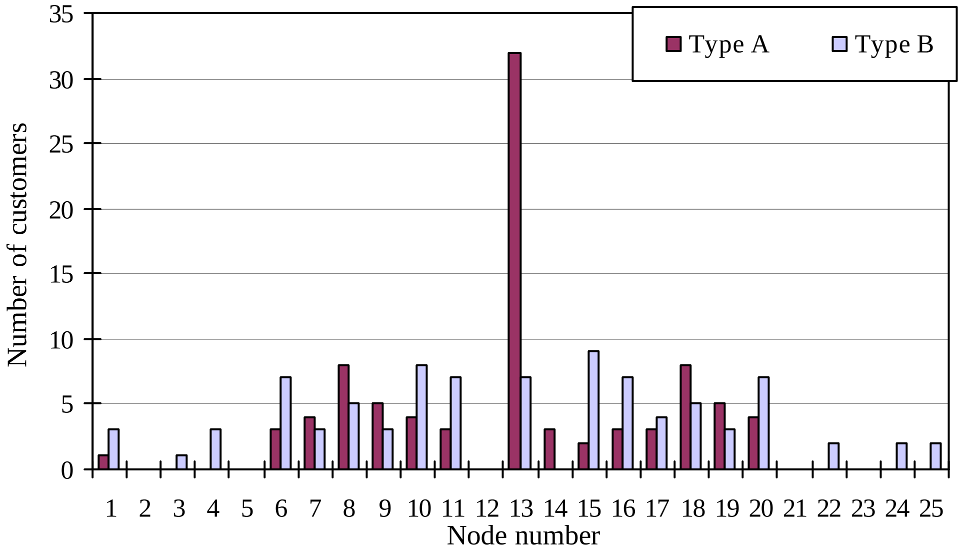

Figure 3. Difference in customer distributions

Table 1. Problem types

No.	Customer distribution	Number of customers
i	Type A	5
ii	Type A	11
iii	Type A	20
iv	Type B	5
v	Type B	11
vi	Type B	20

Table 2. Example of customer data (Problem (ii))

Freight carrier number	Depot node number	Customer node number	Freight demand (ton)	Time window
I	2	6	0.1	a.m.
		7	0.5	no time window
		8	0.5	no time window
		11	0.1	15:00-17:00
		13	1	9:00-11:00
		13	1	9:00-11:00
		13	1	9:00-11:00
		13	1	9:00-11:00
		16	0.1	no time window
		17	0.5	p.m.
		18	0.5	9:00-11:00

3.5 Vehicle

Two different types of trucks, having a capacity of 2 and 4 tons respectively, can be used by the co-operative freight organisation, whilst each freight carrier can only operate 2-ton trucks. The operating costs and fixed costs for each type of delivery trucks are based on the results from recent studies of truck operations in Japan. Unit fixed costs were set at 10418 (yen/vehicle/day) for 2-ton trucks and 11523 (yen/vehicle/day) for 4-ton trucks. Unit operating costs were also set at 14.0 (yen/vehicle/min) for 2-ton trucks and 17.5 (yen/vehicle/min) for 4-ton trucks. Unit penalty costs were distinguished for both early and late arrivals. Unit penalty costs for early arrivals were assumed to be equivalent to the above unit operating cost, while those for late arrivals were set at 5 times the unit operating cost for 4-ton trucks. This type of penalty is typically observed in Just-In-Time transport systems in Japan.

3.6 Logistics Systems

Different types of logistics systems should be compared with each other for investigating the effects of the co-operative systems. This paper focuses on the following five types of logistics systems:

Case (a) : All goods are delivered directly to customers by individual freight carriers without the co-operative systems and AVRSS. Vehicle routing and scheduling for each carrier can be represented using an optimisation problem with equations (1)-(9). This case represents current logistics systems, and therefore is used as a benchmark for investigating the effects of other systems.

Case (b) : The co-operative systems are introduced in conjunction with Case (a). Equation (11) allows profitability to be considered in the vehicle routing and scheduling for the co-operative freight organisation.

Case (c) : The AVRSS is introduced in conjunction with Case (a). In this case, equation (9) is not considered.

Case (d) : Both the co-operative systems and AVRSS are introduced in conjunction with Case (a).

Case (e) : Access restrictions of delivery trucks to the city centre are introduced in conjunction with Case (b).

4. Results

4.1 Financial viability

The model was applied to the six types of problems given in Table.1 for Case (b). The co-operative freight transport systems were successfully implemented in only two problem types (Table. 3). For the other types of problems, no freight carriers used the co-operative systems, since the costs of delivering goods directly to the customers were lower than that of consigning the goods delivery to the co-operative freight organisation under the high price of using the systems that allowed the profits of the co-operative freight organisation to be ensured.

Comparing the results obtained from the problem (i)-(iii) where the Type A was adopted for the customer distribution, it is found that the co-operative systems were not successfully implemented in only problem (i) with five customers. This result reveals that the financial viability of co-operative freight transport systems depends on the number of customers.

4.2 Optimal location

The detailed results in Case (b) are presented in Table 3 for the two problem types where the co-operative systems are successfully introduced. Optimal solutions are encircled with thick line in this table. This table also shows other good solutions.

Constructing logistics terminals only in candidate node 12 is the optimal location of the problem (ii) and there is not much difference in the reduction of travel times between two solutions for problem (iii). These results indicate that it is desirable to construct logistics terminals around the centre of city for decreasing total travel time considering the profitability of the co-operative freight transport systems. Such logistics terminals can allow the co-operative freight organisation to efficiently deliver the consigned goods due to better accessibility to the city centre

4.3 Case comparison

Applications of the model to all the logistics systems (i.e. Case (a)–(e)) were then undertaken for investigating the effects of introducing co-operative systems. Figure 4 displays the total travel times on the whole road network and the average total costs of freight carriers were estimated in Figure 5 for the five cases.

The effects of co-operation can be seen from the results of Case (b), but it is smaller than that of AVRSS (i.e. Case (c)). The average load factor was 31% in Case (a) due to the low utilisation of trucks delivering goods many times within the urban area. Compared to Case (a), goods were efficiently delivered with only one truck in Case (c). The load factor was therefore increased by approximately 52%. In Case (c), the total cost was reduced by around 40 % and the total travel time was also reduced by about 30%. This result indicates that the AVRSS could offer benefits to the whole community as well as to freight carriers.

Table 3. Effects and profitability of co-operative freight transport systems

No.	Optimal location (y_k ; k=5,12,23)	Rates for using the systems (yen/ton)	Profitability*	Ratio of decreased total travel time**	Usage rate of the systems***
ii	0,1,0	7000	101.8%	15.4%	33.8%
	0,0,1	7500	114.1%	11.2%	24.2%
iii	0,1,0	7000	104.2%	14.4%	18.1%
	0,0,1	7000	108.7%	15.1%	17.3%

* defined as $$\sum_u \sum_l UC_l^u \Big/ \left(\sum_{l'} (FC_{l'}^{cop} + RC_{l'}^{cop} + PC_{l'}^{cop}) + LC(\mathbf{y}, \boldsymbol{a}) \right)$$

** compared with the results from Case (a)

*** ratio of the amount of goods consigned to the co-operative freight organisation to the total amount goods to be delivered to customers

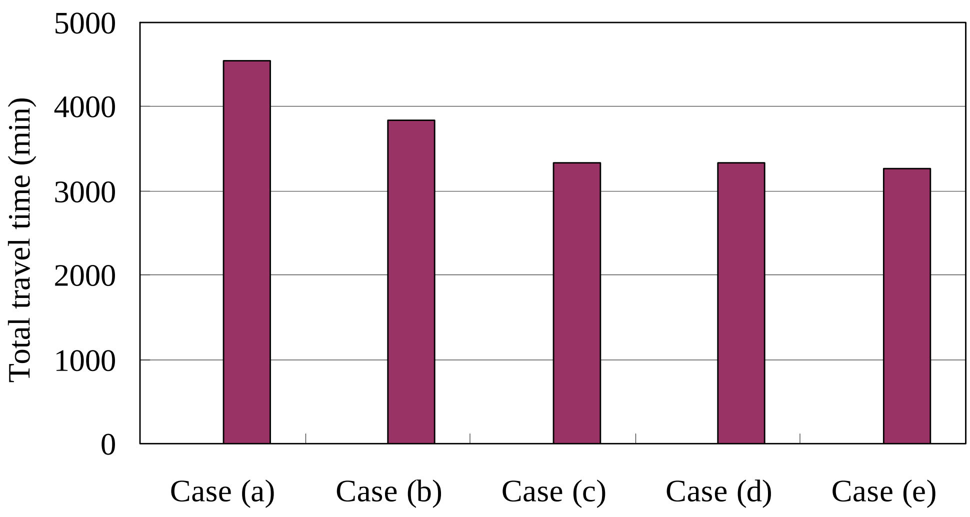

Figure 4. Total travel times (Problem (ii))

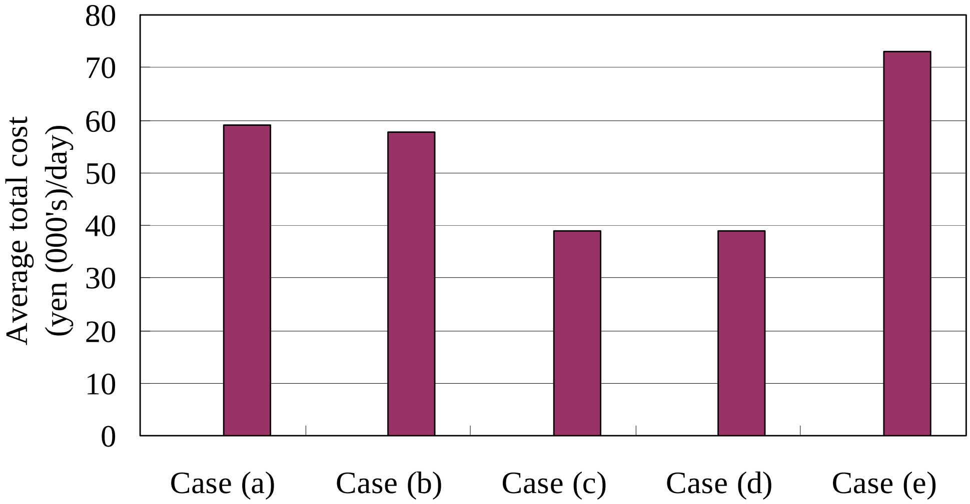

Figure 5. Average total costs (Problem (ii))

The co-operative systems were not profitable for all the problem types in Case (d). This is a normal result, because the delivery costs incurred by freight carriers decrease using AVRSS and therefore they do not need to use the co-operative systems. The decrease in total travel time and total costs in Case (d) is therefore attributed to the AVRSS, and hence the effects are identical to those obtained from Case (c).

Case (e) represents the conditions where the co-operative freight transport systems are simultaneously implemented with the access restrictions of delivery trucks to the city centre. Freight carriers are then forced to use the co-operative systems for delivering goods to customers located within the city centre. This implies that the co-operative freight organisation can only operate delivery trucks within the city centre (i.e. the shadowed portion of the road network in Figure 2). In this case, co-operative freight organisation can force up the rates, since freight carriers have to use the co-operative systems. The optimal solutions of the model were therefore determined by gradually lessening the rates so that the profits for co-operative freight organisation could barely be ensured with total travel time being smaller than that experienced in Case (a).

Logistics terminals were optimally located on the candidate nodes 5 and 23 in Case (e). The candidate node 2 was not optimal, since the access restrictions deteriorate the access to the centre of city from freight carrier’s depots. Two candidate nodes were selected in this case in contrast to the results in Case (b). Reasons for this includes that the allotment of consigned goods among several logistics terminals can lead to the reduced travel times due to the larger amount of goods consigned to the co-operative freight organisation. Here, the usage rate of co-operative systems was 90%.

However, the use of co-operative freight transport systems with the access restrictions to the city centre causes the loss of chance of efficiently routing and scheduling vehicles for freight carriers. Delivery costs therefore increase, though total travel time significantly decreases (Figure 4 & 5). Access restrictions of delivery vehicles to the city centre offer the potential to substantially reduce total travel time within urban areas. Such initiatives are however likely to make freight carriers in financial difficulties due to the increased expenses.

4.4 Potential benefit

Co-operative freight transport systems were not viable in cases where freight carriers have fewer customers or customers are widely dispersed within urban areas. Potential benefits for total travel time being gained from the co-operative systems were then investigated in Case (b) by disregarding profits for the co-operative freight organisation. In this case, equation (11) is not taken into account in the mathematical programming problem associated with the co-operative freight organisation.

The optimal solutions were obtained when the logistics terminals were constructed at all candidate nodes and the rates for using the systems were free. The system usage rate was 100%, that is, all freight carriers consigned their goods delivery to the co-operative freight organisation. Both the total costs and travel time were much smaller than those in Case (c). This result indicates that co-operative systems can provide great effects, though it is not realistic that freight carriers can use the systems free of charge. Co-operative freight transport systems would offer benefits to the city as a whole by decreasing the total time travelled as well as to freight carriers by reducing their total costs, if the monetary assistance for the co-operative freight organisation could be granted.

Table 4 shows the reduction in total travel time for each problem type in this case, compared to the results from Case (a). Problems (i)-(iii) where customers are mainly distributed within the city centre provide significant reductions in total travel time. However, in problems (v) and (vi) where customers are typically located in the suburbs, the co-operative systems cannot offer so much effects in total travel time, even though the profitability of the co-operative freight organisation is disregarded. It can also be seen from Table 4 that total travel time is not reduced in problem (vi). This result implies that the co-operative systems cannot always lead to the reduction in total travel time on the whole road network in case that freight carriers have a number of customers with their location being widely dispersed.

Table 4. Total travel time reductions

No.	Ratio of decreased total travel time*
i	42.4%
ii	42.8%
iii	35.5%
iv	18.1%
v	1.1%
vi	0%

*compared with the results from Case (a)

5. Conclusions

This paper has investigated the effects and profitability of multi-carrier joint freight transport systems with co-operative freight organisation using a simulation model. This model was developed on the basis of the VRPTW. This model was then applied to an urban delivery problem. Applications of the model showed that co-operative freight transport systems could offer benefits to the city as a whole by decreasing the total time travelled as well as to freight carriers by reducing their total costs, though the financial viability of such systems relies on the number and distribution of customers.

Different types of logistics systems were also compared with each other for investigating the effects of implementing co-operative freight transport systems. The results indicated that freight carriers as well as the whole community could gain substantial benefits by introducing advanced vehicle routing and scheduling procedures. It was also found that access restrictions of delivery vehicles to the city centre would increase total delivery costs in spite of significant reductions in total travel time.

These results were however obtained through a limited number of applications. Further investigation will be necessary using the simulation model developed, under a variety of conditions relating to the nature of road network and the range of designated time windows.

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