International Journal of ITS Research, Vol. 1, No. 1, December 2003

ITS Based Dynamic Vehicle Routing and Scheduling with Real Time Traffic Information

Eiichi Taniguchi[*1] Masatsugu Nakanishi[*2]
Professor, Department of Urban Management, Kyoto University [*1]
(Yoshidahonmachi, Sakyo-ku, Kyoto 606-8501 Japan, TEL: +81-75-753-4789,
E-mail: taniguchi@kiban.kuciv.kyoto-u.ac.jp)
Student, Department of Urban Management, Kyoto University [*2]
(Yoshidahonmachi, Sakyo-ku, Kyoto 606-8501 Japan, TEL:+81-75-753-4789,
E-mail: nakanishi@kiban.kuciv.kyoto-u.ac.jp)

Abstract: This paper presents a dynamic vehicle routing and scheduling with time window model that incorporates real time information of travel times. The model was applied to a test road network. Results showed that the dynamic model can reduce not only total costs but also total running times of trucks compared with a forecasted model that does not use real time information on travel times. In particular the dynamic model can reduce delay penalties at customers. This cost saving was attributed to successfully changing the visiting order of customers and the traffic links used between customers to avoid any congested links based on real time information on travel times.

Keywords: *Freight transport, Vehicle routing and scheduling, Travel time, Intelligent transport systems, Optimisation*

1. Introduction

Recently development and deployment of ITS (Intelligent Transport Systems) allows the use of traffic information on travel times in city logistics (Ruske [1], Kohler [2], Taniguchi *et al.* [3], Taniguchi and Thompson [4]). This paper focuses on vehicle routing and scheduling procedures using advanced information systems or ITS in urban areas. Freight carriers have depots and their pickup/delivery trucks depart from the depot and visit customers with designated time windows for collecting or delivering goods and returning to the depot. This paper presents a dynamic vehicle routing and scheduling model with real time traffic information, in particular variable travel times on road links. The uncertainty of travel times affects the identification of the optimal routes and schedules of pickup/delivery trucks on very congested urban roads. Recently the implementation of Automatic Vehicle Identification (AVI) systems using video based systems or Global Positioning Systems (GPS) allows freight carriers to use historical and real time travel time data on urban roads. This paper presents a model that can be used to quantify the benefits of considering the uncertainty of travel times in order to rationalise logistics systems and reduce the negative impacts of goods movement on the environment.

Travel time information based on ITS can be divided into three categories:

(a) Historical
(b) Real time
(c) Predicted

Historical travel times provide data relating to changes in travel times in the past. If travel times follow a normal distribution, it can be used to represent historical travel times on the links of road network. Probabilistic vehicle routing and scheduling procedures require historical travel time information for determining the optimal starting time and visiting order of customers. Real time travel times represent dynamic information relating to changes in travel times at the present time. In reality, for example, travel times 5 minutes before the current time will be typically provided by advanced information systems. Dynamic vehicle routing and scheduling procedures require real time travel time information. Predicted travel times are valuable for making vehicle operational plans taking into account the effects of sporting events, road construction work, etc. But techniques for accurately predicting future traffic conditions are required.

A number of researchers (e.g. Solomon [5], Russell [6], Bramel *et al.* [7], Taniguchi *et al.* [8]) have investigated vehicle routing problems with time windows (VRPTW). Other researchers have studied stochastic vehicle routing and scheduling problems (e.g. Jaillet and Odoni [9], Powell *et al.* [10] Gendreau *et al.* [11]). Most research in this area has focused on dynamic routing and scheduling that considers variations in customer demands. However, there has been limited research on routing and scheduling with variable travel times (Laporte *et al.* [12], Taniguchi *et al.* [13], Taniguchi and Thompson [14]).

The model in this paper assumes multiple depots. For a case of single depot, it is only possible to change the visiting order of customers and road links used with real time travel time information. But for a case of multiple depots, if a truck has difficulty to visit a customer due to traffic congestion, a truck from another depot can visit the customer in place of the truck originally assigned. This type of strategy is allowed in vehicle routing and scheduling for collecting goods based on multiple depots.

Actually for the real urban distribution of goods to retail shops, the routing and scheduling is periodically examined and changed every two or tree months, for example. However, if traffic information of real time travel times is properly given to freight carriers for collecting goods from offices or factories, they will have an opportunity to dynamically change their routing and scheduling based on the real time travel times. The dynamic change of routes is easier for collecting than delivering goods, since goods are normally loaded onto a truck considering the visiting order of customers.

2. Model

2.1. Framework

There are three types of models (Table 1):

(a) Forecasted vehicle routing and scheduling problem with time windows (VRPTW-F) model, which does not change the visiting order of customers nor the road links used by vehicles

(b) Forecasted and dynamic vehicle routing and scheduling problem with time windows (VRPTW-FD) model, which keeps the forecasted visiting order of customers and only changes the road links used by vehicles with real time information on travel times

(c) Dynamic vehicle routing and scheduling problem with time windows (VRPTW-D) model, which changes the visiting order of customers and the road links used by vehicles with real time information on travel times

Table 1. Three different models

Model	Use of real time information on travel times	Visiting order of customers	Road links used
VRPTW-F	no	no change	no change
VRPTW-FD	yes	no change	change
VRPTW-D	yes	change	change

The VRPTW model is defined as follows; a depot and a number of customers are defined for each freight carrier. A fleet of identical vehicles collects goods from customers and delivers them to the depot or delivers goods to customers from the depot. For each customer a designated time window, specifying the desired time period to be visited is also specified. For example, in the case of collecting goods, vehicles depart from the depot and visit a subset of customers for picking up goods in sequence and return to the depot to unload them. A vehicle is allowed to make multiple trips per day. Each customer must be assigned to exactly one route of a vehicle and all the goods from each customer must be loaded onto the vehicle at the same time. The total weight of the goods in a route must not exceed the capacity of the vehicle. This problem is used to determine the optimal assignment of vehicles to customers and the departure time as well as the order of visiting customers for a freight carrier. The VRPTW-D explicitly incorporates real time information on travel times for identifying the optimal routes and departure times of vehicles, whereas the VRPTW-F does not take this into account.

Firstly, the VRPTW-F contains a dynamic traffic simulation that gives forecasted link travel times. Then vehicle routing and scheduling planning is undertaken on the previous day to identify the optimal departure time from a depot and visiting order of customers. On the current day vehicle operations are executed without changing the visiting order of customers and links used.

Secondly, the VRPTW-FD is based on the same vehicle routing and scheduling plan that was undertaken on the previous day. It keeps the visiting order of customers that was given on the previous day, but changes in the road links used can result with real time information on link travel times.

Thirdly, the VRPTW-D is also based on the same vehicle routing and scheduling plan that was undertaken on the previous day. However, plans are revised using real time information of present link travel times, whenever a vehicle arrives at a customer. This real time information is provided by dynamic traffic simulation based on the current conditions of the day. The VRPTW-D is therefore based on more accurate travel time data than the VRPTW-F. In particular if a road was blocked due to a crash or other traffic impediments, the VRPTW-D can give lower cost vehicle routing and scheduling plans than the VRPTW-F.

Note that the VRPTW-D model requires the optimal starting time to visit customers that is identified by vehicle routing and scheduling planning using VRPTW-F model from the previous day, while the visiting order of customers in the current day will be revised using real time information of present travel times.

Dynamic traffic simulation for VRPTW-F, VRPTW-FD and VRPTW-D provides the forecasted link travel times within a network. The simulation at the beginning of the calculation procedure is done using a normal traffic generation pattern for determining the average travel times on each link. Whereas the dynamic traffic simulation on the current day incorporates unexpected events on roads including road crashes. Here, a macroscopic block density model was adopted for the dynamic traffic simulation. This model estimates link travel times for one-minute intervals.

The VRPTW-F model represents conventional ways for routing and scheduling of freight carriers. They have made routing and scheduling plan on the previous day and never change their plan on the current day, although they may periodically change their plan in a couple of months. This was the case before ITS was deployed. However, today they can use real time traffic information of link travel times. Therefore, they should check the change of link travel times on the current day from forecasted ones on previous day. The VRPTW-FD and VRPTW-D models can help them to examine the benefits of changing their routing and scheduling based on the updated information. If they find that changing the original plan is substantially beneficial, they can follow the revised routing and scheduling plan.

2.2. VRPTW-F model

This section describes the mathematical model of the VRPTW-F that was introduced in the previous section. The model minimises the total cost of distributing or collecting goods with truck capacity and designated time constraints. The total cost is composed of three components; (a) fixed vehicle costs, (b) vehicle operating costs that are proportional to the time travelled and spent waiting at customers, and (c) early arrival or delay penalties for designated pickup/delivery times at customers.

The model formulation can be given:

Minimise

$$C(t_0,\mathbf{X}) = \sum_{l=1}^{m} c_{f,l} \cdot \delta_l(\mathbf{x}_l) + \sum_{l=1}^{m} C_{t,l}(t_{l,0},\mathbf{x}_l) + \sum_{l=1}^{m} C_{p,l}(t_{l,0},\mathbf{x}_l) \tag{1}$$

where,

$$C_{t,l}(t_{l,0},\mathbf{x}_l) = c_{t,l} \sum_{i=0}^{N_l} \left\{ \bar{T}(\bar{t}_{l,n(i)}, n(i), n(i+1)) + t_{c,n(i+1)} \right\} \tag{2}$$

$$C_{p,l}(t_{l,0},\mathbf{x}_l) = \sum_{i=0}^{N_l} \Big[c_{d,n(i)} \cdot \max\left\{0,\, t^{a}_{l,n(i)}(t_{l,0},\mathbf{x}_l) - t^{e}_{n(i)}\right\} + c_{e,n(i)} \cdot \max\left\{0, t^{s}_{n(i)} - t^{a}_{l,n(i)}(t_{l,0},\mathbf{x}_l)\right\} \Big] \tag{3}$$

Subject to

$$n_0 \geq 2 \tag{4}$$

$$n(0) = 0 \tag{5}$$

$$n(N_l + 1) = 0 \tag{6}$$

$$\prod_{l=1}^{m} \prod_{i=1}^{N_l} \{n(i) - k\} = 0 \qquad \forall k = 1, 2, \cdots, N \tag{7}$$

$$\sum_{l=1}^{m} N_l = N \tag{8}$$

$$\sum_{n(i) \in \mathbf{x}_{l,j}} D(n(i)) = W_l(\mathbf{x}_{l,j}) \tag{9}$$

$$W_l(\mathbf{x}_{l,j}) \leq W_{c,l} \tag{10}$$

$$t_s \leq t_{l,0} \tag{11}$$

$$t'_{l,0} \leq t_e \tag{12}$$

where,

$$t'_{l,0} = t_{l,0} + \sum_{i=0}^{N_l} \left\{ \bar{T}(\bar{t}_{l,n(i)}, n(i), n(i+1)) + t_{c,n(i+1)} \right\} \tag{13}$$

where,

$C(t_0,\mathbf{X})$: total cost (yen)

t_0: departure time vector for all vehicles from the depot

$t_0 = \{t_{l,0} \mid l = 1, m\}$

$\mathbf{X}$: 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

$\mathbf{x}_l = \{n(i) \mid i = 1, N_l\}$

$n(i)$: i th customer visited by a vehicle

$d(j)$: depot number (= 0)

N_l: total number of customers visited by vehicle l

n_0: total number of $d(j)$ in $\mathbf{x}_l$

m : maximum number of vehicles available

$c_{f,l}$: fixed cost for vehicle l (yen /vehicle)

$\delta_l(\mathbf{x}_l)$: = 1; if vehicle l is used,
= 0; otherwise

$C_{t,l}(t_{l,0},\mathbf{x}_l)$: operating cost for vehicle l (yen)

$C_{p,l}(t_{l,0},\mathbf{x}_l)$: penalty cost for vehicle l (yen)

$c_{t,l}$: operating cost per minute for vehicle l (yen /min)

$t_{l,n(i)}$: departure time of vehicle l from customer $n(i)$

$\bar{T}(\bar{t}_{l,n(i)}, n(i), n(i+1))$: average travel time of vehicle l between customer $n(i)$ and $n(i+1)$ at time $\bar{t}_{l,n(i)}$

$t_{c,n(i)}$: loading/unloading time at customer $n(i)$

$c_{d,n(i)}(t)$: delay penalty cost per minute at customer $n(i)$ (yen/min)

$c_{e,n(i)}(t)$: early arrival penalty cost per minute at customer $n(i)$ (yen/min)

N : total number of customers

$D(n(i))$: demand of customer $n(i)$ (kg)

$t'_{l,0}$: last arrival time of vehicle l at the depot

t_s : earliest time for starting truck operations

t_e : latest time for ending truck operations

$W_l(\mathbf{x}_{l,j})$: load of vehicle l for j th traverse (kg)

$W_{c,l}$: capacity of vehicle l (kg)

The problem specified by equations (1) - (13) is to determine the variable $\mathbf{X}$, that is, the assignment of vehicles and the visiting order of customers and the variable $\boldsymbol{t_0}$, the departure time of vehicles from the depot. The first, second and third terms of equation (1) represent the fixed costs of vehicles, the vehicle operation costs and the early arrival or delay penalties, respectively. Vehicle operation costs are composed of the costs of travelling, waiting and loading/unloading goods at each customer that are given in equation (2). Equation (3) indicates the penalty of early arrival or delay at customers. Note that $n(0)$ and $n(N_l+1)$ represent the depot in equations (2) and (3).

Figure 1 shows the cost function for early arrivals and delays at customers. The time period $(t^e_{n(i)} - t^s_{n(i)})$ defines the width of the soft time window. If a vehicle arrives at a customer earlier than $t^s_{n(i)}$, it must wait until the start of the designated time window and a cost is incurred during waiting. If a vehicle is delayed, it must pay a penalty proportional to the amount of time it was delayed. This type of penalty is typically observed in Just-In-Time transport systems.

Equations (4) – (6) indicate that a vehicle must depart from the depot and return to the depot at the end of tour and can come back to the depot during the tour. Equations (7) and (8) indicate that a vehicle visits each customer exactly once. Equations (9) and (10) present the demand conditions that the load of a customer can be carried by a vehicle from a single visit and the total load of a vehicle cannot exceed the capacity of vehicle. Equations (11) – (13) indicate that the first departure time from the depot and last arrival time at the depot during the tour must be within the designated time period.

The problem described herewith is a NP-hard (Non-deterministic Polynomial hard) combinatorial optimisation problem. Heuristic methods are often used to obtain good solutions (e.g. Potvin [15], Taniguchi and van der Hijden [16]). This study adopts Genetic Algorithms (GA) for identifying the optimal solutions. In GA, sets of solutions (populations) with elements (genes) are combined (reproduced) to form new solutions (generations) using selection and multiplication operators. Solutions with better performance (fitness values) are given a higher chance of surviving. Crossover and mutation are applied to avoid being caught in local optimal solution.

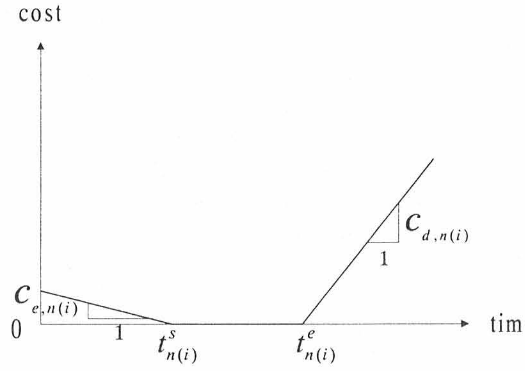

Figure 1. Cost functions for vehicle delays and early arrivals

After validation based on a number of test cases, the following parameters and procedures of the genetic algorithm were determined:

- Number of individuals (population) = 300
- Number of generations = 900
- Number of elite individuals = 30
- Crossover method for visiting order of customers: ordered crossover
- Crossover method for departure times = one point crossover
- Crossover rate = 0.7
- Mutation method: deletion and insertion
- Mutation rate = 0.03

2.3. VRPTW-D and VRPTW-FD model

The main difference between the VRPTW-D model and the VRPTW-F model is that the VRPTW-D model incorporates real time information of travel times while the goods are being delivered or collected during the current day. The optimal visiting order and road links used is updated with the latest information of travel times for each link whenever a pickup/delivery truck arrives at a customer. The optimisation method of the VRPTW-D model is almost the same as the VRPTW-F model, the only difference being that the VRPTW-D model uses the present (i.e. latest) travel times for identifying the shortest path between customers or between the depot and a customer. For the VRPTW-F model, the travel times for all links are based on the previous day of operating pickup/delivery trucks. On the other hand, with the VRPTW-D model, travel times are updated whenever a pickup/delivery truck arrives at a customer and are used to revise the optimal visiting order and road links used. Current travel times are used for estimating future travel times, since in reality current travel times on roads are provided through advanced traffic information systems.

The basic formulation for the VRPTW-F and the VRPTW-D models is exactly same. But there is a difference in the timing of optimisation; the VRPTW-F model tries to optimise the visiting order for all the customers on the previous day, while the VRPTW-D model tries to optimise whenever arriving at a customer for the rest of customers to be visited. Therefore, we revised the VRPTW-D model to have a function of re-optimising at a customer's node.

The VRPTW-FD model is between the VRPTW-F and the VRPTW-D models. The VRPTW-FD model follows the original visiting order of customers but it can choose optimal road links between customers by incorporating the updated real time travel times.

We have chosen a macroscopic approach, since vehicle routing and scheduling problems involve large scale urban traffic networks. A microscopic approach is not suitable for such large-scale networks due to long computation times.

2.4. Dynamic traffic simulation model

The dynamic traffic simulation model is based on a block density model that is essentially a macroscopic simple continuum model but because the origin and destination of each vehicle is defined, it is actually a hybrid macroscopic/microscopic model. Vehicles are assumed to choose the shortest path when they arrive at a node using an estimated average travel time. The block density model consists of two components, flow simulation and route choice simulation as shown in Figure 2. A sequence of blocks is used to represent each link in a network.

Groups of vehicles flowing out of a block into the next block during the scanning interval represent flow on links. The movement of vehicles from a block to the next block can be given by the following equations.

$$\Delta n_{i,i+1} = \min \{ \Delta n_i^{OUT} , \Delta n_{i+1}^{IN} \} \tag{14}$$

$$\Delta n_i^{OUT} = \mathrm{NINT}\left(n \left(1-\frac{n}{n_i^J}\right)\right) \tag{15}$$

$$n = \min (n_i, n_i^C) \tag{16}$$

$$\Delta n_i^{IN} = \mathrm{NINT}\left(n' \left(1-\frac{n'}{n_i^J}\right)\right) \tag{17}$$

$$n' = \max (n_i, n_i^C) \tag{18}$$

where,

$\Delta n_{i,i+1}$: number of vehicles that move from block i to block $i+1$ (vehicles)

Δn_i^{OUT} : number of vehicles that need to flow out from block i (vehicles)

Δn_i^{IN} : number of vehicles that can be accepted into block i (vehicles)

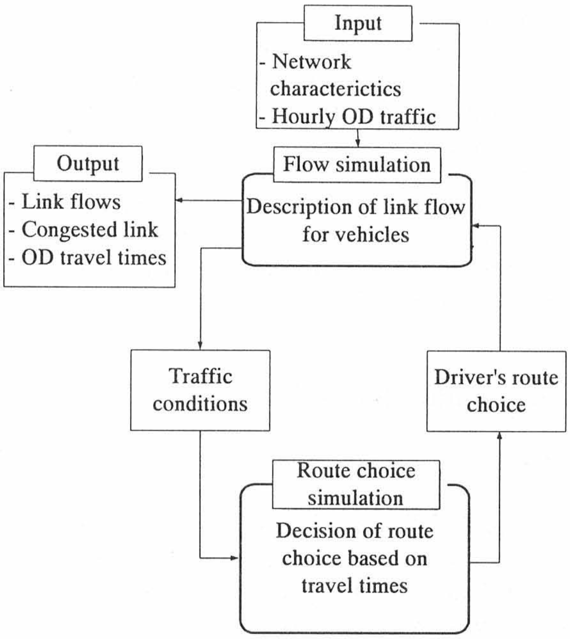

Figure 2. Structure of the block density model

n_i : number of vehicles in block i (vehicles)

Δn_i^J : number of vehicles in saturation in block i (vehicles) (i.e. maximum number of vehicles in block i)

Δn_i^C : number of vehicles at critical traffic density in block i (vehicles)

NINT: function of producing integer by counting fractions over 0.5 and cutting away the rest

We assumed the relationship between traffic volume and traffic density given by Greenshields [17] for deriving equations (15) and (17).

$$q = kv = kv_f \left(1-\frac{k}{k_j}\right) \tag{19}$$

where,

v : speed (km/h)

v_f : free speed (km/h)

k : traffic density (vehicle/km)

k_j : traffic jam density (vehicle/km)

The first-in-first-out (FIFO) rule was used in the flow simulation. Therefore, the order of vehicles on each link could always be maintained.

In the road link choice simulation, vehicles that arrive at each node search for the shortest path to the destination. The present travel time on each link is used for identifying the shortest path in this simulation.

Two stages of simulation were undertaken in this study. The first stage simulates normal traffic conditions and determines the optimal path for each vehicle. The second stage simulates changes in traffic conditions from the normal conditions due to traffic impediments. During the second stage all the vehicles except the pickup/delivery trucks will follow the same path as the first stage. This means that these vehicles are not informed of the current travel times on links. On the contrary the pickup/delivery trucks can use the real time information of updated travel times. This information allows trucks to avoid any delay due to heavily congested routes.

3. Case studies for test network

3.1. Test conditions

The model described in the previous section was applied to a test network with 25 nodes and 80 links as shown in Figure 3. This road network is comprised of two types of roads: trunk roads with free running speed of 40 km/h and streets with 30 km/h. These roads have 2 lanes with a traffic jam density of 120 vehicles/km/lane. Any node within the network can generate and attract passenger car traffic. These nodes are referred to as centroids and are also candidate nodes to be visited by pickup/delivery trucks. One freight carrier is assumed to operate multiple pickup/delivery trucks, 12 vehicles at maximum, within this network. The freight carrier has two depots whose location is shown in Figure 3 (Node 5 and 21). Each depot has 6 trucks of three different types, having a capacity of 2, 4 and 10 tons (2 trucks for each type). The operating cost for 2, 4 and 10 ton truck is 14.0, 17.5 and 23.3 Japanese Yen/min, respectively. The fixed cost for 2, 4 and 10 ton truck is 10,418, 11,523 and 13,790 Japanese Yen/day. These data are based on results from recent studies of truck operations in Japan. Twenty-three customers for the carrier were located randomly as shown in Table 2. The freight demand on each customer was 500 kg. The penalty cost was 87.7 Japanese Yen /min. In this study trucks only collect goods from customers and unload them at the depots.

The time windows at customers to be visited by pickup/delivery trucks were randomly generated between 9:00 –18:00 as shown in Table 2. The dynamic traffic simulation provides the distribution of travel times on each link for the scanning interval. A scanning interval of 1 minute was used in this study.

The dynamic traffic simulation requires information on passenger car behaviour. Passenger cars in this study include actual passenger cars and trucks other than those that are considered in the optimal routing and scheduling model. Passenger car Origin-Destination (OD) tables for every hour were estimated using traffic generation rates at each centroid and the probability of O-D choice. The number of passenger cars for each hour was generated using a temporal demand pattern based on the traffic census conducted in Hiroshima City.

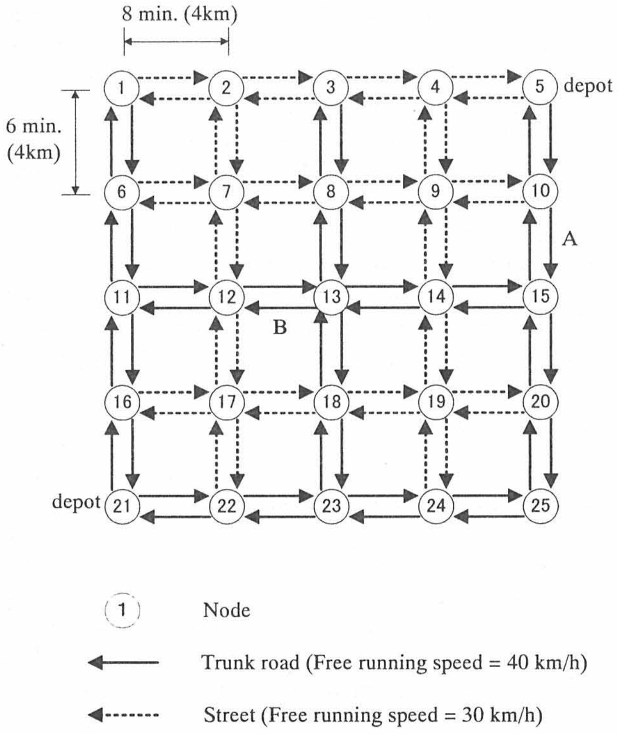

Figure 3. Test road network

Table 2. Location of customers

Customers at node	Time windows
1	9:00 ~ 12:00
2	9:00 ~ 12:00
3	12:00 ~ 15:00
4	15:00 ~ 18:00
6	12:00 ~ 15:00
7	9:00 ~ 12:00
8	9:00 ~ 12:00
9	15:00 ~ 18:00
10	12:00 ~ 15:00
11	9:00 ~ 12:00
12	15:00 ~ 18:00
13	9:00 ~ 12:00
14	9:00 ~ 12:00
15	12:00 ~ 15:00
16	15:00 ~ 18:00
17	12:00 ~ 15:00
18	9:00 ~ 12:00
19	15:00 ~ 18:00
20	9:00 ~ 12:00
22	9:00 ~ 12:00
23	12:00 ~ 15:00
24	15:00 ~ 18:00
25	12:00 ~ 15:00

As described above, the first stage simulates the normal traffic conditions, whereas the second stage simulates cases where there are very congested conditions. When link A or B (Figure 3) was blocked for two hours due to traffic impediments such as crashes, the capacity of each link was reduced to 1/2, 1/5 and 1/10 of its original capacity. The starting time of this blockage was 9:00 a.m. at link A and 11:00 a.m. -1:00 p.m. at link B and it lasted for two hours.

3.2. Test results

Table 3 shows the total costs of VRPTW-F, VRPTW-D and VRPTW-FD models for the case where link A in Figure 3 was blocked. This table indicates that the VRPTW-D model can substantially reduce total costs for these three cases where capacity was reduced to 1/2, 1/5 and 1/10 of its original value. The total cost decreased by over 10% compared with VRPTW-F for the reduction to 1/5 and 1/10 of capacity. In particular, delay penalty was greatly reduced for VRPTW-D, which leads to better service to customers in terms of punctuality of arrival time. This is due to the VRPTW-D model taking into account the real time travel times generated benefits of reducing total costs.

The VRPTW-FD model in Table 3 also resulted in the reduction of total cost for the reduction to 1/5 and 1/10 of capacity. It means that using real time information of travel times can generate benefits for vehicle routing, even if the visiting order of customers was fixed.

Table 4 shows the total running time without waiting time for the case that link A was blocked. The VRPTW-D model can also reduce total running time for these three cases in reduction of capacity to 1/2, 1/5 and 1/10 its original value. Therefore, the VRPTW-D model is beneficial not only for cost saving but also for running time saving. This will cause positive effects for alleviating traffic congestion within the network.

Table 3. Total costs (Link A blocked)

Model	Reduction of capacity	Total cost	Fixed cost	Operation cost	Delay penalty	Early arrival penalty
VRPTW-F	1/2	35,947.3	23,046.2	12,725.7	0.0	175.4
VRPTW-FD	1/2	36,046.9	23,046.2	12,737.6	87.7	175.4
Change(%)		0.28	0.00	0.09	-	0.00
VRPTW-D	1/2	35,374.3	23,046.2	11,766.8	0.0	561.3
Change(%)		-1.59	0.00	-7.53	0.00	220.00
VRPTW-F	1/5	41,249.0	23,046.2	13,414.3	4,648.1	140.3
VRPTW-FD	1/5	38,077.4	23,046.2	13,101.8	1,754.0	175.4
Change(%)		-7.69	0.00	-2.33	-62.26	25.00
VRPTW-D	1/5	36,824.5	23,046.2	11,813.8	877.0	1,087.5
Change(%)		-10.73	0.00	-11.93	-81.13	675.00
VRPTW-F	1/10	42,620.8	23,046.2	13,558.4	5,875.9	140.3
VRPTW-FD	1/10	38,076.2	23,046.2	13,100.6	1,754.0	175.4
Change(%)		-10.66	0.00	-3.38	-70.15	25.00
VRPTW-D	1/10	36,821.7	23,046.2	11,811.0	877.0	1,087.5
Change(%)		-13.61	0.00	-12.89	-85.07	675.00

Unit: Yen

Table 4. Total running time without waiting time (Link A blocked)

Model	Capacity Reduced to	Total running time (min)
VRPTW-F	1/2	725.5
VRPTW-FD	1/2	726.2
Change(%)		0.09
VRPTW-D	1/2	670.9
Change(%)		-7.53
VRPTW-F	1/5	764.8
VRPTW-FD	1/5	747.0
Change(%)		-2.33
VRPTW-D	1/5	673.5
Change(%)		-11.93
VRPTW-F	1/10	773.0
VRPTW-FD	1/10	746.9
Change(%)		-3.38
VRPTW-D	1/10	673.4
Change(%)		-12.89

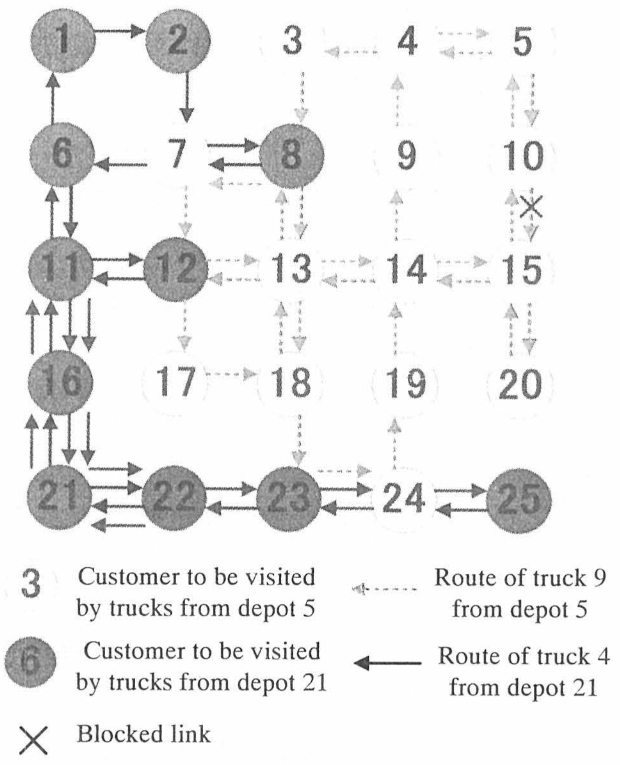

Figure 4(a). Truck routes for VRPTW-F (Link A blocked)

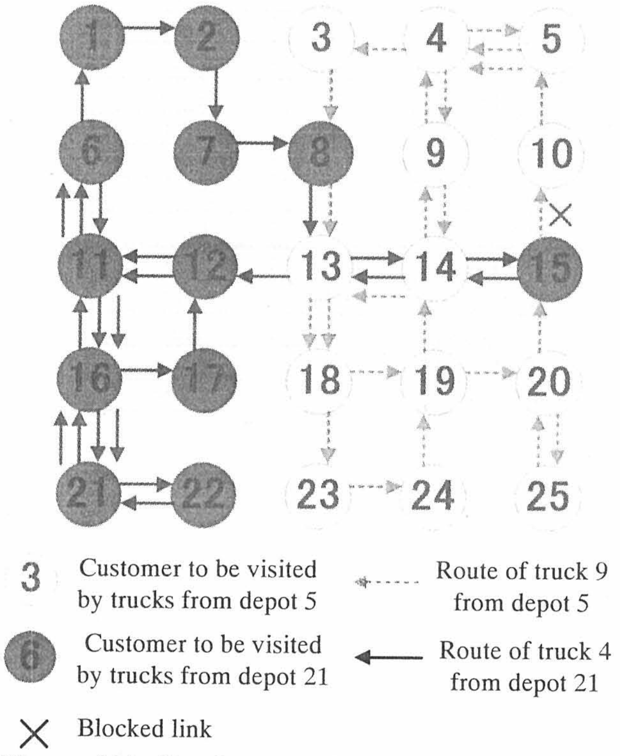

Figure 4(b). Truck routes for VRPTW-D (Link A blocked)

Table 5(a). Visiting order of VRPTW-F (Link A blocked)

Truck	Customer	Arrival time	Departure time	Time window	
4	21(depot)		10:18		
	22	10:24	10:34	9:00 ～ 12:00	
	11	11:53	11:03	9:00 ～ 12:00	
	1	11:16	11:26	9:00 ～ 12:00	
	2	11:34	11:44	9:00 ～ 12:00	
	8	12:00	12:10	9:00 ～ 12:00	
	6	12:27	12:37	12:00 ～ 15:00	
	23	13:09	13:19	12:00 ～ 15:00	
	25	13:32	13:42	12:00 ～ 15:00	
	21(depot)	14:32	14:32		
	12	14:52	15:10	15:00 ～ 18:00	
	16	15:24	15:34	15:00 ～ 18:00	
9	5(depot)		10:14		
	20	11:09	11:19	9:00 ～ 12:00	
	14	11:33	11:43	9:00 ～ 12:00	
	13	11:50	12:00	9:00 ～ 12:00	
	18	12:07	12:17	9:00 ～ 12:00	delay
	7	12:40	12:50	9:00 ～ 12:00	delay
	15	13:18	13:28	12:00 ～ 15:00	
	10	13:34	13:44	12:00 ～ 15:00	
	5(depot)	14:12	14:12		
	3	14:28	14:38	12:00 ～ 15:00	
	17	15:06	15:16	12:00 ～ 15:00	delay
	24	15:40	15:50	15:00 ～ 18:00	
	19	15:58	16:08	15:00 ～ 18:00	
	9	16:26	16:36	15:00 ～ 18:00	
	4	16:45	16:55	15:00 ～ 18:00	

Table 5(b). Visiting order of VRPTW-D (Link A blocked)

Truck	Customer	Arrival time	Departure time	Time window	
4	21(depot)		10:18		
	22	10:24	10:34	9:00 ～ 12:00	
	11	10:53	11:03	9:00 ～ 12:00	
	1	11:16	11:26	9:00 ～ 12:00	
	2	11:34	11:44	9:00 ～ 12:00	
	7	11:52	12:02	9:00 ～ 12:00	
	8	12:10	12:20	9:00 ～ 12:00	delay
	15	12:40	12:50	12:00 ～ 15:00	
	6	13:24	13:34	12:00 ～ 15:00	
	21(depot)	14:17	14:17		
	17	14:31	14:41	12:00 ～ 15:00	
	12	14:50	15:10	15:00 ～ 18:00	
	16	15:24	15:34	15:00 ～ 18:00	
9	5(depot)		10:14		
	14	10:38	10:48	9:00 ～ 12:00	
	13	10:54	10:04	9:00 ～ 12:00	
	18	11:11	11:21	9:00 ～ 12:00	
	20	11:37	11:47	9:00 ～ 12:00	
	25	11:53	12:10	12:00 ～ 15:00	
	10	12:29	12:39	12:00 ～ 15:00	
	5(depot)	13:05	13:05		
	3	13:21	13:31	12:00 ～ 15:00	
	23	13:58	14:08	12:00 ～ 15:00	
	24	14:15	15:10	15:00 ～ 18:00	
	19	15:18	15:28	15:00 ～ 18:00	
	9	15:47	15:57	15:00 ～ 18:00	
	4	16:06	16:16	15:00 ～ 18:00	

Figure 4 and Table 5 illustrate optimal visiting order of customers for the VRPTW-F and VRPTW-D models. Trucks 4 (capacity = 4 ton) and 9 (capacity = 4 ton) visited customers for both cases VRPTW-F and VRPTW-D, but the visiting order was slightly different. Truck 9 for VRPTW-F departed from depot at 10:14 and arrived at customer 20 at 11:09 via link A, which was blocked during 9:00-11:00, since the route was fixed. Truck 9 had to go through the heavily congested link A and this caused delayed arrival at customers 18, 7 and 17 as well as increased running times. In contrast, truck 9 for the VRPTW-D first visited customer 14 instead of customer 20 to avoid congested link A based on real time traffic information. This manoeuvre made it possible to arrive earlier at customers and decrease running time and result in a cost saving. Moreover, for VRPTW-F truck 9 arrived late at customer 7 by 40 minutes. However, for VRPTW-D truck 4 in place of truck 9 visited customer 7. This strategy minimised the effects of the traffic impediment on vehicle routing.

Tables 6 and 7 show the total cost and total running time for the case where link B was blocked during 11:00-13:00. This case also indicates that substantial reduction in costs and running time was achieved. In this case VRPTW-D achieved larger cost savings compared with the case where link A was blocked. This is attributed to link B being located in the centre of network and blockage of that link affects the traffic conditions in a wider area of network. So the information on real time travel time can be more effectively used.

The study in this paper actually used the present travel time as the real time information on travel time. The present travel time means the travel time that vehicles that arrived at their destinations experienced. However, the travel time that would be experienced when a vehicle departs from the origin is required. From this point of view, we compared the results of using perfect information on travel times with the case of using the present travel times. Perfect information on travel times provides the actual travel times that we would be experience by vehicles travelling between customers. It is impossible in reality to estimate this, but for comparison, we calculated the case where perfect information was assumed to be available (VRPTW-DP).

Table 6. Total costs (Link B blocked)

Model	Reduction of capacity	Total cost	Fixed cost	Operation cost	Delay penalty	Early arrival penalty
VRPTW-F	1/2	35,937.3	23,046.2	12,715.7	0.0	175.4
VRPTW-FD	1/2	35,956.7	23,046.2	12,735.1	0.0	175.4
Change(%)		0.05	0.00	0.15	-	0.00
VRPTW-D	1/2	35,424.8	23,046.2	12,045.3	0.0	333.3
Change(%)		−1.43	0.00	−5.27	-	90.00
VRPTW-F	1/5	41,055.9	23,046.2	13,624.7	4,385.0	0.0
VRPTW-FD	1/5	36,228.3	23,046.2	12,883.9	263.1	35.1
Change(%)		−11.76	0.00	−5.44	−94.00	-
VRPTW-D	1/5	35,360.3	23,046.2	11,682.7	0.0	631.4
Change(%)		−13.87	0.00	−14.25	−100.00	-
VRPTW-F	1/10	42,695.2	23,046.2	14,036.2	5,612.8	0.0
VRPTW-FD	1/10	36,559.3	23,046.2	13,250.0	263.1	0.0
Change(%)		−14.37	0.00	−5.60	−95.31	-
VRPTW-D	1/10	35,902.8	23,046.2	12,260.2	0.0	596.4
Change(%)		−15.91	0.00	−12.65	−100.00	-

Unit: Yen

Table 7. Total running time without waiting time (Link B blocked)

Model	Reduction of capacity	Total running time (min)
VRPTW-F	1/2	724.96
VRPTW-FD	1/2	726.06
Change(%)		0.15
VRPTW-D	1/2	686.73
Change(%)		−5.27
VRPTW-F	1/5	776.78
VRPTW-FD	1/5	734.54
Change(%)		−5.44
VRPTW-D	1/5	666.06
Change(%)		−14.25
VRPTW-F	1/10	800.24
VRPTW-FD	1/10	755.42
Change(%)		−5.60
VRPTW-D	1/10	698.99
Change(%)		−12.65

Table 8. Comparison of total cost for perfect information

	Blocked link	Reduction of capacity	Total cost	Fixed cost	Operation cost	Delay penalty	Earty arrival penalty
VRPTW-D			35,374.3	23,046.2	11,766.8	0.0	561.3
VRPTW-DP	A	1/2	35,374.3	23,046.2	11,766.8	0.0	561.3
Change(%)			0.00	0.00	0.00	-	0.00
VRPTW-D			36,824.5	23,046.2	11,813.8	877.0	1,087.5
VRPTW-DP	A	1/5	36,823.3	23,046.2	11,812.6	877.0	1,087.5
Change(%)			0.00	0.00	-0.01	0.00	0.00
VRPTW-D			36,821.7	23,046.2	11,811.0	877.0	1,087.5
VRPTW-DP	A	1/10	36,820.4	23,046.2	11,809.8	877.0	1,087.5
Change(%)			0.00	0.00	-0.01	0.00	0.00
VRPTW-D			35,424.8	23,046.2	12,045.3	0.0	333.3
VRPTW-DP	B	1/2	35,382.7	23,046.2	12,003.3	0.0	333.3
Change(%)			-0.12	0.00	-0.35	-	0.00
VRPTW-D			35,360.3	23,046.2	11,682.7	0.0	631.4
VRPTW-DP	B	1/5	35,343.3	23,046.2	11,630.6	0.0	666.5
Change(%)			-0.05	0.00	-0.45	-	5.56
VRPTW-D			35,902.8	23,046.2	12,260.2	0.0	596.4
VRPTW-DP	B	1/10	35,886.4	23,046.2	12,208.7	0.0	631.4
Change(%)			-0.05	0.00	-0.42	-	5.88

Unit:Yen

Table 8 shows the comparison of total cost for VRPTW-DP and VRPTW-D. It is interesting that the total costs for VRPTW-D are almost same as the case of perfect information VRPTW-DP. Therefore, in this case using the present travel time does not lead to significantly higher costs than if exact values of travel times were available for optimising vehicle routes and schedules.

This study used a lattice shape road network. On the realistic road network that is different from lattice shape, it may be hard to find alternative link to avoid the blocked link by traffic impediment. For that case if a freight carrier operates multiple trucks based on multiple depots, it may be wise to use a truck that departed from another depot for visiting the customer in place of the originally assigned truck. We need further study for indicating that the optimisation strategy given in this paper based on multiple depots be effective for any shape of road network. It is important that this type of flexible strategy is only allowed for freight vehicle operations and not for passenger cars.

This study focused on the cases that the link capacity was considerably reduced by traffic impediments. The VRPTW-D model was effective for these cases. It can be pointed out that the smaller the fluctuation of travel times is, the lower become benefits of using VRPTW-D model with real time travel times. For cases of small fluctuation of travel times without any road crashes or special events within the network, VRPTW-D model may not effectively generate cost reduction.

4. Conclusions

This paper presented a dynamic vehicle routing and scheduling with time windows (VRPTW-D) model that incorporates real time, travel time information. Application of model to a test road network provided the following findings.

(a) The VRPTW-D model that uses real time information on travel times achieved substantial savings in total costs compared with the VRPTW-F model that does not use real time information. In particular, the VRPTW-D model can reduce delay penalties, which gives better service to customers.

(b) The VRPTW-D model can also reduce the total running time of trucks compared with the VRPTW-F model. Therefore, using real time information on travel times in VRPTW-D model is beneficial both for freight carriers in terms of cost savings and for society at large in terms of alleviating traffic congestion.

(c) The VRPTW-D model successfully changed visiting order of customers to avoid heavily congested links using real time information on travel times. In addition, for the VRPTW-D model, if a truck cannot visit a customer, another truck based at another depot can complete the transport task instead of the truck originally assigned the task.

(d) In this study there was no significant difference between total costs of the VRPTW-D model that uses the present travel times and the VRPTW-DP model that uses perfect information on travel times.

For further study, the models presented here need to be applied to more realistic and large-scale networks with real traffic information.

References

[1]Ruske, W. City logistics --- Solutions for urban commercial transport by cooperative operation management. *OECD Seminar on Advanced Road Transport Technologies*, Omiya, Japan, 1994.

[2]Kohler, U. An innovating concept for city-logistics. *4th World Congress on Intelligent Transport Systems*, Berlin, Germany, CD-ROM, 1997.

[3]Taniguchi, E., Thompson, R.G., Yamada, T. and van Duin, R. *City Logistics - Network Modelling and Intelligent Transport Systems*, Pergamon, Oxford, 2001.

[4]Taniguchi, E., Thompson, R.G.(Eds.). *Innovations in Freight Transport,* WIT Press, Southampton, 2002.

[5] Solomon, M. M. Algorithms for the vehicle routing and scheduling problems with time window constraints. *Operations Research* **35**, 254-265, 1987.

[6] Russell, R.A. Hybrid heuristics for the vehicle routing problem with time windows. *Transportation Science* **29**, 156-166, 1995.

[7]Bramel, J. and Simchi-Levi, D. Probabilistic analysis and practical algorithms for the vehicle routing problem with time windows. *Operations Research* **44**, 501-509, 1996.

[8] Taniguchi, E., Yamada, T., Tamaishi, M. and Noritake, M. Effects of designated time on pickup/delivery truck routing and scheduling. *Urban Transport and the Environment for the 21st Century IV*, WIT Press, 127-136, 1998.

[9] Jaillet, P. and Odoni, A.R. The probabilistic vehicle routing problem. In B.L. Golden, A.A. Assad (eds.), *Vehicle*

routing; Methods and studies, North-Holland, Amsterdam, 293-318, 1998.
[10] Powell, W.B., Jaillet, P. and Odoni, A. R. Stochastic and dynamic network and routing. In M.O. Ball, T.L. Magnanti, C.L. Monma, G.L. Nemhauser (eds.). *Network Routing,* North-Holland, 141-295, 1995.
[11] Gendreau, M., Laporte, G. and Seguin, R. Stochastic vehicle routing. *European J. Oper. Res.* **88**, 3-12, 1996.
[12] Laporte, G., F. V. Louveaux and H. Mercure The vehicle routing problem with stochastic travel times. *Transportation Science* **26**, 161-170, 1992.
[13]Taniguchi, E., Yamada, T. and Tamagawa, D. Probabilistic vehicle routing and scheduling on variable travel times with dynamic traffic simulation. In: E. Taniguchi and R.G. Thompson (eds.). *City Logistics I,* Institute of Systems Science Research, Kyoto, 85-99, 1999.
[14]Taniguchi, E., Thompson, R.G. Modelling city logistics, *Transportation Research Record*, No.1790, pp.45-51, 2002.
[15]Potvin, J.-Y., Kervahut, T., Garcia, B.-L. & Rousseau, J.-M. The vehicle routing problem with time windows; Part I: tabu search, *INFORMS Journal on Computing* **8**, 158-164, 1996.
[16]Taniguchi, E. and van der Heijden, R.E.C.M. An evaluation methodology for city logistics. *Transport Reviews* **20(1)**, 65-90, 2000.
[17]Greenshields, B.D. A study in highway capacity. *H.R.B. Proceedings,* **14**, p.468, 1935.

Eiichi Taniguchi is a professor of transport and logistics at Kyoto University. He has performed intensive research on modelling city logistics and ITS based urban freight transport. He recently published a book entitled "City Logistics – Network Modelling and Intelligent Transport Systems" with three co-authors. He also organised international conferences on city logistics at Cairns, Australia in 1999, at Okinawa, Japan in 2001 and at Madeira, Portugal in 2003.

Masatsugu Nakanishi is a student of master course at University of Tokyo. After investigating dynamic vehicle routing and scheduling under the supervision of Prof. Taniguchi at Kyoto University, he moved to University of Tokyo in 2003.

Received: 6 April 2003
Revised: 19 July 2003
Accepted: 27 July 2003
Editor: Masao Kuwahara