Travel Time Reliability in Vehicle Routing and Scheduling with Time Windows

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Abstract This paper presents calibration of the Vehicle Routing and scheduling Problems with Time Windows-Probabilistic (VRPTW-P) model which takes into account the uncertainty of travel times. Probe vehicle data of travel times were obtained from usual operation of pickup-delivery trucks in South Osaka area. The optimal solution of the VRPTW-P model resulted in reducing total cost, running times and CO\textsubscript{2}, NO\textsubscript{x} and Particle Materials (PM) emissions compared with the usual operation. This is attributed to better routing of VRPTW-P to choose more reliable roads. Therefore, VRPTW-P can contribute to establish efficient and environmentally friendly delivery systems in urban area.

Keywords Urban freight transport · ITS · Optimisation · City logistics · Travel times

1 Introduction

Efficient and environmentally friendly urban freight transport systems are required for increasing the competitive power of industry as well as improving the environment, reducing the level of traffic congestion and the number of crashes, saving energy consumption in urban areas. These issues are complicated and difficult to be solved. Some researchers (Ruske, 1994; Kohler, 1997; Taniguchi and van der Heijden, 2000; Taniguchi et al., 2001, 2003; Taniguchi and Thompson, 2002, 2003, 2004; Crainic et al., 2004) have presented concepts and measures of City Logistics for tackling urban freight transport issues. These measures include: (a) application of ITS (Intelligent Transport Systems) or advanced information...
systems, (b) co-operative freight transport systems, (c) public logistics terminals, (d) load factor controls, (e) underground freight transport systems. Among these measures the application of ITS to vehicle routing and scheduling planning is most promising to establish efficient and environmentally friendly logistics systems. Taniguchi et al. (2000) pointed out that probabilistic vehicle routing and scheduling with time windows incorporating the uncertainty of travel times can reduce total costs as well as negative environmental impacts.

ITS allows us to obtain change of link travel times on road network. The historical travel time data can be used for probabilistic vehicle routing and scheduling. Recently, in Japan VICS (Vehicle Information Communication Systems) are available for providing traffic information on travel times, level of congestion, crashes and car parks. VICS are operated by regional road administrators. They have collected traffic information by many sensors like traffic counter and AVI (Automatic Vehicle Identification) camera. The collected data have been processed and information has been edited by the central operation center called by the VICS center. That information has been transmitted to drivers by radio beacons, optical beacons and FM multiplex broadcasting. Car navigation system can show such traffic information like travel times and level of congestion in real time for planning driving routes, taking a rest or deciding where to park. Traffic information has been updated every 5 min. Recently, those data became possible obtaining by out-of-car users. Accumulating data of link travel times on the road network can be a good source of historical travel times. However, travel times data by VICS are only available for 50–70% of all the major urban roads at large cities in Japan. Recently, a probe device with GPS (Global Positioning Systems) is installed on a vehicle and the location of vehicle can be precisely identified at every second. Measuring the location of vehicles provides travel times on each link of road network. The probe vehicle data on travel times can complement the lack of VICS data with appropriate calibration of both data.

A number of researchers (e.g., Solomon, 1987; Russell, 1995; Bramel and Simchi-Levi, 1996; Potvin et al., 1996; Taniguchi et al., 1998) have investigated vehicle routing problems with time windows (VRPTW). Other researchers have studied stochastic vehicle routing and scheduling problems (e.g., Jaillet and Odoni, 1988; Powell et al., 1995; Gendreau et al., 1996; Swihart and Papastavrou, 1999; Secomandi, 2000). Most research in this area has focused on dynamic routing and scheduling that considers the variation in customer demands. However, there has been limited research on routing and scheduling with variable travel times (Laporte et al., 1992; Malandraki and Daskin, 1992; Taniguchi et al., 1999, 2000; Kenyon and Morton, 2003; Taniguchi and Shimamoto, 2004). Most of papers have not fully incorporated the dynamically changing travel times within the urban road network. Some of papers presented models for maximising the probability to return to the depot within the designated time. In contrast, this paper presents a model for minimising the total costs incorporating the uncertainty of link travel times with the early arrival and delay penalty at customers who set up designated time windows. Moreover, this study performs experiments of operating pick-up delivery trucks on the real road network and compares the optimal solutions of probabilistic vehicle routing and scheduling with usual operation in terms of costs, total running times and environmental impacts.
2 Probabilistic Vehicle Routing and Scheduling Problem with Time Windows Model

Taniguchi et al. (2001) formed Vehicle Routing and scheduling Problem with Time Windows-Probabilistic (VRPTW-P) model for minimising the total costs, which is comprised of fixed cost, operation cost and early arrival and delay penalty. Our research is to calibrate this model to actual urban distribution. The conditions for vehicle routing and scheduling are given below.

a) A vehicle is allowed to make multiple routes per day.
b) Each customer must be assigned to exactly one route of a vehicle and all the goods from each customer must be loaded on the vehicle at the same time.
c) The total weight of the goods for a route must not exceed the capacity of the vehicle.
d) A vehicle should be operated within the designated time of operation, for instance from 8 A.M. TO 5 P.M.

The problem is 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 model was formulated as follows.

Minimise

\[
C(t_0, X) = \sum_{l=1}^{m} c_{f,l} \cdot \delta_{l}(x_l) + \sum_{l=1}^{m} E[C_{t,l}(t_{l,0}, x_l)] + \sum_{l=1}^{m} E[C_{p,l}(t_{l,0}, x_l)]
\]

where,

\[
E[C_{t,l}(t_{l,0}, x_l)] = c_{t,l} \sum_{i=0}^{N_l} \left\{ T(t_{l,0}, n(i), n(i+1)) + t_{c,n(i+1)} \right\}
\]

\[
E[C_{p,l}(t_{l,0}, x_l)] = \sum_{i=0}^{N_l} \int_{0}^{\infty} p_{l,n(i)}(t_{l,0}, t, x) \left\{ c_{d,n(i)}(t) + c_{e,n(i)}(t) \right\} dt
\]

Subject to

\[
n_0 \geq 2
\]

\[
n(0) = 0
\]

\[
n(N_l) = 0
\]

\[
\prod_{l=1}^{m} \prod_{i=1}^{N_l} \{n(i) - k\} = 0 \quad \forall k = 1, 2, \cdots, N
\]
\[
\sum_{l=1}^{m} N_l = N
\]  
(8)

\[
\sum_{n(i) \in x_l} D(n(i)) = W_l(x_l)
\]  
(9)

\[
W_l(x_l) \leq W_{c,l}
\]  
(10)

\[
t_s \leq t_{l,0}
\]  
(11)

\[
t_{l,0}' \leq t_e
\]  
(12)

where

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

\(C(t_0, X)\): total cost (yen)

\(t_0\): departure time vector for all vehicles at the depot \(t_0 = \{t_{l,0}|l = 1, m\}\)

\(X\): assignment and order of visiting customers for all vehicles \(X = \{x_i|l = 1, m\}\)

\(x_l\): assignment and order of visiting customers for vehicle \(l\) \(x_l = \{n(i)|i = 1, N_l\}\)

\(n(i)\): node number of \(i\)th customer visited by a vehicle

\(d(j)\): number of depot (= 0)

\(N_l\): total number of customers visited by vehicle \(l\)

\(n_0\): total number of \(d(j)\) in \(x_l\)

\(m\): maximum number of vehicles available

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

\(\delta_l(x_l)\): = 1; if vehicle \(l\) is used, = 0; otherwise

\(C_{r,l}(t_{l,0}, x_l)\): operating cost for vehicle \(l\) (yen)

\(C_{p,l}(t_{l,0}, x_l)\): penalty cost for vehicle \(l\) (yen)

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

\(t_{l,n(i)}\): departure time of vehicle \(l\) at customer \(n(i)\)

\(\bar{T}(i_{l,n(i)}, n(i), n(i+1))\): 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 \(n(i)\)

\(p_{l, n(i)}(t_{l,0}, t, x_l)\): probability in which a vehicle that departs the depots at time \(t_{l,0}\) arrives at customer \(n(i)\) at time \(t\)

\(c_{d, n(i)}(t)\): delay penalty cost per minute at customer \(n(i)\) (yen/min)
The problem specified by Eqs. (1)–(13) involves determining the variable $X$, that is, the assignment of vehicles and the visiting order of customers and the variable $t_0$, the departure time of vehicles from the depot. Note, that $n(0)$ and $n(N_l+1)$ represent the depot in Eqs. (2) and (3).

Equation (1) is the objective function of this model which composed with fixed cost of used vehicles, operation costs and early arrival and delay penalty at customers. Equation (2) means the operation costs of vehicles. It is calculated with average link travel times. Equation (3) expresses the early arrival/delay penalties at customers. Probability function may be expressed in any form. If it is assumed by normal distribution, it can be calculated faster, but real travel time distributions are used as it is in our research. Equations (4)–(6) show the constraint that every vehicle must start from and return to the depot. Equations (7) and (8) mean that every customer should be visited once. Equations (9) and (10) show that the total demand of the customers would not exceed the capacity of the vehicle. Equations (11) and (12) are the constraints that vehicle operation should not start before starting of operation time and should not finish after end of possible operation time. Equation (13) means the time when the vehicle returns to the depot.

Figure 1 shows the penalty for vehicle delay and early arrivals at customers. The time period $t_{n(i)}^c - t_{n(i)}^s$ of the penalty function defines the width of the soft time window in which vehicles are requested to arrive at customers. In this example, probability function of arrival time is assumed to be the normal distribution, but the function that we used in this research is the actual travel time distributions which does not follow normal distribution. If a vehicle arrives at a customer earlier than $t_{n(i)}^s$, 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 goods distribution to shops and supermarkets in urban areas. Multiplying the penalty function and the probability of arrival time as shown in Fig. 1 can identify the penalty of early arrivals and delay at customers for the probabilistic model.

The problem described herewith is a NP-hard (Non-deterministic Polynomial-hard) combinatorial optimisation problem. It requires heuristic methods to efficiently obtain a good solution. The model described in this paper uses a Genetic Algorithms (GA) to solve the VRPTW-P. GA was selected because it is a heuristic procedure that can simultaneously determine the departure time and the assignment of vehicles as well as the visiting order of customers. Designing the chromosome of GA carefully, GA can determine the optimal solution very efficiently.
3 Estimating Travel Times Based on Probe Vehicle and VICS Data

A probe device of PDA (Personal Digital Assistance) with GPS and antenna was installed on pick-up delivery trucks (loading capacity: 2 tons) for delivering electronic products in the South Osaka area in Japan. Figure 2 shows the probe device and Fig. 3 illustrates the probe system for measuring the location of vehicles. The probe system is composed of the probe device of PDA which is installed in vehicle, the data collecting terminal which is set up in the depot of freight carrier and the data analysing server which is set up at Kyoto University. The data collecting terminal and the data analysing server are connected each other via Internet. The probe device can record the location of vehicle (longitude and latitude) to memory card at every 1 s based on GPS signal. Whenever the vehicle returns to depot, the probe device automatically transmits data to the data collecting server.

Fig. 1 Early arrival and delay penalty

Fig. 2 Probe system

Fig. 3 Probe device
terminal via wireless LAN (Local Area Network). Then the data collecting terminal send all data of vehicle travelling to the data analysing server at Kyoto University via Internet. As drivers and workers at the depot do not need to do anything during the procedure, all data are automatically collected and transmitted to the data analysing server. This system allows required data to be collected at lower cost than other systems. In addition freight carriers can easily accept this system, since they need no extra work for collecting data.

This study used a pick-up delivery truck (loading capacity: 2 tons) as the probe vehicle which ran for 66 days from 13th March 2004 through 2nd June 2004 without 16 days which are Saturday, Sunday and Japanese national holidays. A road network was formed for analyses based on the actual routing of the probe vehicle. Figure 4 shows the road network. The network involves actual roads used by the probe vehicle and the location of customers. Moreover, bold lines of links in Fig. 4 represent roads where VICS information on travel times are presented. Table 1 shows outline of road network.

![Fig. 2 Probe device](image)

![Fig. 3 Probe system for measuring the location of vehicles](image)
The road network contains various types of roads including trunk roads as well as urban streets of small traffic capacity. Therefore, roads within the network were categorised into six groups by the characteristics and direction of roads as shown in Table 2, for example, trunk roads and urban streets for east–west, trunk roads and urban streets for north–south. After accumulating running data of the probe vehicle at each link, an analysis was performed on travel time distribution.

The maximum number of the probe vehicle passage which ran either direction of links within the road network of total data collecting period was 71 times and the average was 12.5 times. On the other hand there were 20 links where the probe vehicle did not run. Figure 5 shows an example of travel time distribution on link 5 (see Fig. 4), where the probe vehicle most frequently ran.

The relation of the maximum, minimum and average travel times and link distance of each link were plotted on graphs for each road group. A regression analysis was performed for examining the relationship between the maximum, minimum and average travel times and link distance. Figure 6 illustrate an example for road group 2. The maximum, minimum and average travel speeds for each road group can be determined by calculating the inclination of regression line. Let the link distance equal $l$ and the maximum, minimum and average travel speeds equal $v_{\text{max}}$, $v_{\text{min}}$, $v_{\text{ave}}$, respectively. The maximum, minimum and average link travel times are expressed by $t_{\text{max}} = v_{\text{max}} \cdot l$, $t_{\text{min}} = v_{\text{min}} \cdot l$, $t_{\text{ave}} = v_{\text{ave}} \cdot l$, respectively. Then the triangular travel time distribution of each link can be formed as follows; (a) each link travel times $t_{\text{min}}$, $t_{\text{ave}}$, $t_{\text{max}}$ represent values of horizontal

![Fig. 4 Road network at South Osaka](image)

Table 1 Outline of road network at South Osaka

| Number of nodes | 69 |
| Number of customers | 22 |
| Number of depot | 1 |
| Number of links | 218 |

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axis of apexes A, B, C in Fig. 5, respectively, (b) the probability of the average travel time $p_{ave}$ can be obtained by following equation.

If

$$t_{\text{max}} \neq t_{\text{min}}, p_{\text{ave}} = \frac{2}{t_{\text{max}} - t_{\text{min}}}$$

(14)

otherwise $p_{\text{ave}} = 1$

(c) lines AB and BC are expressed as follows;

$$\text{AB : } P = \frac{p_{\text{ave}}}{t_{\text{ave}} - t_{\text{min}}} (T - t_{\text{min}})$$

(15)

$$\text{BC : } P = \frac{p_{\text{ave}}}{t_{\text{ave}} - t_{\text{max}}} (T - t_{\text{max}})$$

(16)

<table>
<thead>
<tr>
<th>Road group</th>
<th>Travel speeds (km/h)</th>
<th>Fluctuation ((a)−(c))/(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max. (a)</td>
<td>Ave. (b)</td>
</tr>
<tr>
<td>1 (E–W st.1)</td>
<td>18.0</td>
<td>6.9</td>
</tr>
<tr>
<td>2 (E–W st.2)</td>
<td>21.2</td>
<td>11.0</td>
</tr>
<tr>
<td>3 (E–W st.3)</td>
<td>20.1</td>
<td>9.0</td>
</tr>
<tr>
<td>4 (E–W st.4)</td>
<td>11.3</td>
<td>6.8</td>
</tr>
<tr>
<td>5 (N–S st.1)</td>
<td>17.4</td>
<td>6.5</td>
</tr>
<tr>
<td>6 (N–S st.2)</td>
<td>21.3</td>
<td>10.7</td>
</tr>
</tbody>
</table>
Table 2 shows travel speeds for each road group and Fig. 5 includes the estimated triangular travel time distribution. The triangular travel time distribution can be used for the probabilistic vehicle routing and scheduling.

The results of the travel time distributions are significantly affected by the number of the samples obtained. As a small number of probe vehicle data were obtained, travel time distribution for both link direction and each hour of the day cannot be categorised. Therefore travel time distribution that was identified using probe vehicle data is only a function of link distance. As a result of such assumption, the numbers of obtained probe data for making distributions were from 64 to 362 for each road group. These were enough to get linear regression lines. If a lot of probe vehicle data were obtained in the future, it would be possible to determine the travel time distribution for each link direction and each hour of the day.

4 Effects of Using Several Travel Time Distributions for VRPTW-P

Travel time distributions which were obtained by probe vehicles for this study were not categorised, neither by link direction nor by hour of the day. On the other hand, VICS provides travel time information for major roads for every 5 min so that travel time distributions can be calculated. So in this study, the VRPTW-P model with several travel time distributions from different sources was studied by traffic flow simulation of the virtual traffic network.

4.1 Traffic Flow Simulation Using the Block Density Method

In order to apply travel time distribution data to the VRPTW-P model, we performed a traffic flow simulation on a test road network to represent urban traffic conditions. The test road network used in this research contains 25 nodes and 80 links as shown in Fig. 7. Every node on the road network represents a centroid that generates and attracts passenger cars. Every link is 4 km long and two types of free

Fig. 6 Travel times and link distance (road group 2)
running speeds are assumed to be either 20 or 15 km/h. The maximum density is assumed to be 150 vehicles/km. We generated about 495,000 vehicles on the road network for 30 days to simulate urban traffic conditions. The simulation presented link travel time distributions for 30 days. Based on these travel time distribution data, the optimal visiting order of customers and the starting times of vehicles were identified with VRPTW-P model. Then its delivering costs and early arrival and delay penalties of obtained optimal solution were calculated with travel time information of ten more days.

4.2 VRPTW-P Model with Several Travel Time Distributions from Different Sources

4.2.1 Assumption

In order to evaluate the effects of using travel time distributions from different sources on a link in VRPTW-P, four cases of travel time information as shown in Table 3 were used.

Table 3  Kinds of travel time distribution

<table>
<thead>
<tr>
<th>Kind of travel time distribution</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1  Average of 6 h</td>
<td>F</td>
</tr>
<tr>
<td>Case 2  Probe (distribution of 6 h)</td>
<td>P</td>
</tr>
<tr>
<td>Case 3  Probe (distribution of 6 h) + VICS (distribution of 5 min)</td>
<td>P</td>
</tr>
<tr>
<td>Case 4  VICS (distribution of 5 min)</td>
<td>P</td>
</tr>
</tbody>
</table>

F VRPTW-F, P VRPTW-P
In Case 1, an average of 6 h for each link was used for travel time information so that the optimal solution was obtained by the Vehicle Routing and scheduling Problem with Time Windows-Forecasted (VRPTW-F) model. VRPTW-F model uses a single value for each link travel time. In this case, VRPTW-F represents the traditional VRP in order to be compared its performance with that of VRPTW-P. In Case 2, the optimal solution was calculated by VRPTW-P with travel time distributions of 6 h for each link as distributions obtained by probe vehicles. In Case 3, the optimal solution was calculated by VRPTW-P with travel time distributions of 6 h for streets as distributions obtained by probe vehicles and 5 min for trunk roads. In Case 4, the optimal solution was calculated by VRPTW-P with travel time distributions of 5 min for each link as distributions obtained by VICS.

The VRPTW identified the optimal starting time at the depot and visiting order of customers under the following conditions.

a) Six pick-up delivery trucks (capacity: 2 tons × 2, 4 tons × 2, 10 tons × 2) are used.
b) Depot stands on node No5 and 24 customers without depot must be serviced.
c) The time windows for the customers are set at 2, 4 and 10 h randomly.

Results of calculation are shown on Table 4.

### 4.2.2 Results of Calculation

In Cases 2, 3 and 4 the total cost are reduced by 16.8, 23.1 and 25.1%, respectively, compared with Case 1 which used VRPTW-F with 6 h average for travel time information. The tendency of standard deviations of each case is the same as that of the total costs.

Reduction of total cost, which consists of operation cost, delay penalty and standard deviation, is proportional to the accuracy of information such as Cases 2, 3 and 4.

The simulation result implies that it is appropriate to use several sources of travel time distributions for VRPTW-P, such as probe information and VICS information.

<table>
<thead>
<tr>
<th></th>
<th>Fixed cost</th>
<th>Operation cost</th>
<th>Delay penalty</th>
<th>Early arrival penalty</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td></td>
<td>deviation</td>
<td>deviation</td>
<td></td>
<td>deviation</td>
</tr>
<tr>
<td>Case 1</td>
<td>20,835</td>
<td>15,882</td>
<td>12,015</td>
<td>341</td>
<td>49,073</td>
</tr>
<tr>
<td></td>
<td></td>
<td>293</td>
<td>6,922</td>
<td>130</td>
<td>7,104</td>
</tr>
<tr>
<td>Case 2</td>
<td>20,835</td>
<td>15,903</td>
<td>3,552</td>
<td>558</td>
<td>40,848</td>
</tr>
<tr>
<td></td>
<td></td>
<td>367</td>
<td>4,142</td>
<td>198</td>
<td>4,335</td>
</tr>
<tr>
<td>Case 3</td>
<td>20,835</td>
<td>15,442</td>
<td>1,184</td>
<td>254</td>
<td>37,715</td>
</tr>
<tr>
<td></td>
<td></td>
<td>379</td>
<td>3,447</td>
<td>139</td>
<td>3,695</td>
</tr>
<tr>
<td>Case 4</td>
<td>20,835</td>
<td>15,815</td>
<td>44</td>
<td>73</td>
<td>36,767</td>
</tr>
<tr>
<td></td>
<td></td>
<td>229</td>
<td>139</td>
<td>81</td>
<td>253</td>
</tr>
</tbody>
</table>
5 Case Study at South Osaka Area

5.1 Outline

A case study on goods distribution was performed at South Osaka area. A freight carrier there delivers electric products to many customers. The distance between customers is several kilometres and a pick-up delivery truck visits about ten customers per day. The average running distance per day is about 30 km.

The case study adopted an actual delivery to 11 customers who set up soft time windows to be visited by pick-up delivery trucks. The optimal solution of VRPTW-P model given in the previous section was identified for the delivery using link travel time distribution. In the experiment two pick-up delivery trucks started from the depot at the same time. One truck followed the actual operation route and the other truck followed the optimal route given by VRPTW-P. Both trucks were equipped with probe device for recording the running route at every 1 s. The actual operation is based on experiences of drivers and does not use traffic information systems such as VICS. The comparison was made for these two truck operation in terms of costs for delivery as well as environmental impacts.

5.2 Assumptions for VRPTW-P

In this study the travel time distribution by VICS was used for links where VICS information on travel times are available (see Fig. 4). Estimated travel time distribution by probe vehicle was used for the other links. The historical data on travel times of VICS during 1st February 2001 and 31st March 2002 were used. The data period of VICS was different from the probe vehicle data because of the restriction of availability of VICS data. It is better that the data period of both methods is the same. Tendency of link travel time of urban road network is assumed not to be changed in this research. Note, that the travel time distribution by VICS from 9 A.M. to 2 P.M. was used, which is same in terms of time period of the probe vehicle operation.

The travel time distributions of VICS and probe vehicle are different. Therefore, correction was made to let the average of travel times by VICS to be same as the average travel time by the probe vehicle and the shape of distribution of VICS was preserved. That is, distribution of VICS is shifted to where its average would be equal to the average of probe data of the same link keeping its shape. The reason is that travel time by the probe vehicle is more reliable than VICS data, since the probe vehicle actually measures travel times by running a road link, while VICS estimates travel times based on the measurement of vehicle running speed at a point using traffic detector.

It is expected that the calibrated distribution would be biased, since the morning traffic should be very different from the evening traffic pattern. It must be better to use multiple distributions for each time period on VRPTW-P. But one distribution was used in this research because of restrictions of availability of travel time information, especially probe data. And the effect on variation of duration of distributions was evaluated on hypothetical network in 4.2. The difference between
6 h and 5 min in duration of distribution was 11.1% in total costs comparing Case 2 with Case 4.

The case study compares the optimal solution of VRPTW-P and usual operation of pick-up delivery trucks. The VRPTW-P identified the optimal starting time at the depot and visiting order of customers under the following conditions.

d) A single pick-up delivery truck (capacity: 2 tons) is used.

e) The designated departing time at depot is 10 a.m. and the returning time is 1:30 p.m. The time windows of customers are 10–11 a.m., 11 a.m.–noon and noon–1 p.m. (Table 5)

f) The travel time distribution during the delivery is constant.

In order to compare the optimal solution of VRPTW-P and usual operation of pick-up delivery trucks, two probe vehicles ran the routes of VRPTW-P and usual operation, respectively, for 5 days, 5th, 6th, 12th, 13th, 14th October 2004 when were weekdays and not sequent because of preparation of trucks for experiments. Based on the probe vehicle routing, total costs, total running time and environmental impacts were calculated under the following conditions.

a) The measured travel times during the experiment can be used.
b) The loading/unloading time at all customers is 8 min.

Table 5 Time windows

<table>
<thead>
<tr>
<th>Customer</th>
<th>Time windows</th>
</tr>
</thead>
<tbody>
<tr>
<td>28, 42, 44, 63</td>
<td>10 to 11 A.M.</td>
</tr>
<tr>
<td>47, 64, 65</td>
<td>11 A.M. to noon</td>
</tr>
<tr>
<td>14, 16, 24, 39</td>
<td>Noon to 1 P.M.</td>
</tr>
</tbody>
</table>

Fig. 8 Routing of usual operation

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c) The unit time cost is 14.02 yen/min, the unit delay penalty is 70.1 yen/min, which is five times as large as the unit time cost and the fixed cost is 10,417.5 yen/day based on survey to a freight carrier.

Traffic condition of read network had been very congested and truck drivers were asked to drive moderately and obey traffic rules so that driving behaviours of each truck drivers could be assumed to be equal.

5.3 Results in Terms of Costs and Delay Times

Figures 8 and 9 compare the route of optimal solution of VRPTW-P and the usual operation. Table 6 shows the visiting order of customers. These visiting order of customers and road used for two methods are different.

Table 7 shows the average and standard deviation of total costs for 5 days. The fixed cost in Table 7 is same for usual operation and VRPTW-P, since a single pick-up delivery truck (capacity of 2 tons) was used for both cases. The average of operation cost for VRPTW-P was reduced by 4.0% and the standard deviation was also reduced by 61.2%. The average of delay penalty for VRPTW-P was considerably reduced by 46.2% and the standard deviation was also reduced by 77.5%. This is attributed to the characteristics of the VRPTW-P model that tends to avoid any delay which is demonstrated in Fig. 1. The average of total cost for

![Fig. 9 Routing of optimal solution of VRPTW-P](image.png)

**Table 6 Visiting order of customers**

<table>
<thead>
<tr>
<th>Visiting order of customers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rout of usual operation</td>
</tr>
<tr>
<td>Optimal route of VRPTW-P</td>
</tr>
</tbody>
</table>
VRPTW-P was reduced by 4.1% and the standard deviation was reduced by 75.1%. The reduction of standard deviation means that the VRPTW-P model can provide more reliable routing in terms of costs than usual operation without any information on travel times. The results indicate that the historical data of travel times contributed to not only reduce average of total costs but also stabilise the fluctuation of costs.

Table 8 compares the arrival time at customers for VRPTW-P and usual operation on 5th October, when the discrepancy of delay penalty between VRPTW-P and usual operation was maximum. The vehicle arrived late at customers 44, 65 and 14 in usual operation, while the vehicle only arrived late at customer 28 for VRPTW-P. The total delay time for VRPTW-P was reduced by 62.6% compared with the usual operation.

Table 9 shows the total delay time of each day during 5 days. This table indicates that the total delay times of usual operation greatly fluctuate and the operation was unreliable, although the total delay times of usual operation was smaller than

<table>
<thead>
<tr>
<th>Time window</th>
<th>Visiting order of usual operation</th>
<th>Arrival time (hour : minute : second)</th>
<th>Visiting order of VRPTW-P</th>
<th>Arrival time (hour : minute : second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 A.M.</td>
<td>Depot</td>
<td>10:00:00</td>
<td>Depot</td>
<td>10:00:00</td>
</tr>
<tr>
<td>10 to 11 A.M.</td>
<td>42</td>
<td>10:14:42</td>
<td>42</td>
<td>10:13:52</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>10:37:04</td>
<td>44</td>
<td>10:34:33</td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>10:48:52</td>
<td>63</td>
<td>10:53:44</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>11:05:29</td>
<td>28</td>
<td>11:08:04</td>
</tr>
<tr>
<td>11 A.M. to noon</td>
<td>47</td>
<td>11:21:04</td>
<td>65</td>
<td>11:25:42</td>
</tr>
<tr>
<td>Noon to 1 P.M.</td>
<td>64</td>
<td>11:43:28</td>
<td>64</td>
<td>11:39:14</td>
</tr>
<tr>
<td>Noon to 1 P.M.</td>
<td>65</td>
<td>12:02:35</td>
<td>47</td>
<td>11:56:10</td>
</tr>
<tr>
<td>Total delay time</td>
<td>00:34:33</td>
<td></td>
<td></td>
<td>00:12:55 (−62.6%)</td>
</tr>
<tr>
<td>Delay penalty (yen)</td>
<td>2,422</td>
<td></td>
<td></td>
<td>905 (−62.6%)</td>
</tr>
</tbody>
</table>
VRPTW-P for 2 days. The drivers of usual operation have decided their route based thoroughly on their experiences. This result implies that their experiences were not objectively based on the average or distribution of link travel time but they could be based on the radical experience which they could run in short travel time. As a result of it, those links have been not stable in travel time and it may be not always a correct decision. On the other hand, optimal solution of VRPTW-P is calculated with travel time distributions so that obtained visiting order of customers and links used are to minimise the expectations of total cost. The result of experiment also showed that VRPTW-P is more reliable in terms of total delay times, which can provide better service to customers. The best in urban delivery is always less delay as possible. But the average and standard deviation of delay time of VRPTW-P were smaller than that of usual operation so that it could be also considered good service to customers. Constant delay can be reduced by relaxing the time windows. But at least an occasional big delay makes urban delivery unstable and unreliable.

5.4 Results in Terms of Environmental Impacts

Figure 10 reflects the effects of VRPTW-P on the environmental impacts compared with the usual operation. The environmental impacts like CO$_2$, NOx and PM (Particle Materials) are not only proportional to travel distance but also depend on running speed of vehicles. Usually, objective function of VRP must be the total

<table>
<thead>
<tr>
<th>Date</th>
<th>Usual operation</th>
<th>VRPTW-P</th>
</tr>
</thead>
<tbody>
<tr>
<td>5th October</td>
<td>34 min, 33 s</td>
<td>12 min, 55 s</td>
</tr>
<tr>
<td>6th October</td>
<td>2 min, 53 s</td>
<td>5 min, 42 s</td>
</tr>
<tr>
<td>12th October</td>
<td>18 min, 8 s</td>
<td>7 min, 51 s</td>
</tr>
<tr>
<td>13th October</td>
<td>15 min, 54 s</td>
<td>5 min, 15 s</td>
</tr>
<tr>
<td>14th October</td>
<td>1 min, 7 s</td>
<td>7 min, 22 s</td>
</tr>
<tr>
<td>Average</td>
<td>14 min, 31 s</td>
<td>7 min, 49 s</td>
</tr>
<tr>
<td>St. dev.</td>
<td>13 min, 31 s</td>
<td>3 min, 03 s</td>
</tr>
</tbody>
</table>

Table 9 Total delay times

![Environmental impacts](image)
distances of vehicles but that of our model is the sum of the fixed costs, the operation costs and early arrival and delay penalty. As a result of experiments, it becomes clear that the optimal solution can achieve not only the reduction of total distance but also increasing travel speeds. Figure 10 indicates that the VRPTW-P model is better than the usual operation in reducing the total running times by 6.8%, CO$_2$ emissions by 7.6%, NOx emissions by 6.9% and PM (Particle Materials) by 8.0%. In VRPTW-P model, a freight carrier tried to minimise their costs and such behaviour resulted in reducing the total running times and negative environmental impacts. Therefore, considering the uncertainty of travel times in the probabilistic vehicle routing and scheduling can contribute not only to decrease costs but also to alleviate traffic congestion and improving the environment. As a whole, the VRPTW-P model with variable travel times can establish efficient and environmentally friendly urban freight transport systems.

6 Conclusions

The followings were derived from this study.

a) The probe vehicle technique was used for urban pick-up deliver trucks equipped with probe device. It allows obtaining the precise travel time data by recording the running behaviour of vehicles and analysing them.

b) A methodology was proposed for estimating the travel time distribution for each road group by analysing travel time data of probe vehicles. The travel time distribution that was determined using this method can be applied to the VRPTW-P model.

c) The optimal solution was identified for the VRPTW-P model using historical travel time distribution given by the probe vehicles and VICS. The total costs of optimal solution of the VRPTW-P model was reduced by 4.1% compared with the usual operation. In particular, the delay penalty was decreased by 46.2%. Moreover, the standard deviation of total costs of the VRPTW-P model was also considerably reduced by 75.1%. It means the VRPTW-P model can provide better service to customers and more reliable solution considering the uncertainty of travel times.

d) The negative environmental impacts were also reduced by using the VRPTW-P model in terms of CO$_2$, NOx and PM emissions. Therefore, the VRPTW-P model can contribute not only to reduce the total costs but also improve the environment.

Further researches are required on the following points.

a) This study only employed a single depot with a single pick-up delivery truck in a small scale. It is needed to conduct a large scale experiment using multiple depots with multiple trucks to examine the effectiveness of the VRPTW-P model.

b) The development of ITS allows to obtain real time travel times. Therefore, dynamic vehicle routing and scheduling with real time traffic information should be examined with the comparison of usual operation in the field test.
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