A COMPARISON OF ENVIRONMENTAL IMPACTS OF HARD TIME WINDOWS AND SOFT TIME WINDOWS USING EXACT ROUTING SOLUTION

Ali Gul Qureshi **, Eiichi Taniguchi*** and Tadashi Yamada****

1. Introduction

Transportation demand both in terms of freight and passengers is on an increase due to the increase in economic and industrial activities. As mostly these activities are concentrated in and around big cities, a high proportion of total goods movement occurs within cities[1)] and most of this movement is based on road transport. This results in bustling cities growing in size and with their economies on boom. All this of course do not come without some costs; big queues of vehicles in traffic congestion, noise, vibrations, generation of NOx, SPM, CO_2 and other environmental problems, accidents, loading and off-loading on streets are few of the typical costs to be paid. Road based freight transport in urban areas contributes a large proportion in these problems.

With the innovations in logistics, like Just-In-Time (JIT) systems and E-Commerce, urban freight related problems have further aggravated. Increase in E-Commerce, especially Business to Consumers (B2C) increases the negative effects on environment and traffic conditions, unless a major proportion of consumers use B2C, so that the reduced shopping trips may have considerable positive impact[2)].

Vehicle Routing Problem and scheduling with Time Windows (VRPTW) is a common tool used by the logistics firms to optimize their operations. Route optimization not only serves the logistics firms, it also advances the objectives of the other stakeholders of city logistics[1)] i.e. city administration, residents and customers. Route optimization would result in the least possible number of vehicle required to serve all the demands, traveling as minimum a distance as possible and decreasing the idling time of the vehicles. This would result in less pressure on the road network resources and less automobile related environmental problems. Thus, administrative get less traffic related problems, resident would get cleaner environment and customers would get faster deliveries. In Hard Time Windows (HTW), delivery is not possible outside the customer specified time windows $[a_i, b_i]$, where a_i, and b_i show the earliest and latest service start times. While in Soft Time Windows (STW) variant, any violation of time windows causes a penalty but the delivery is still possible. Practical logistic problems are mostly set in soft windows environment. Mostly heuristic (approximate) solutions of VRPTW are used in city logistics related research[3)-4)], where the solution is required within reasonable time. With the rapid increase in computer technology, the network handling capability and thus the importance of exact methods in vehicle routing is also increasing.

This paper is focused on to compare the environmental related effects of HTW and STW such as generation of NOx, SPM and CO_2. The STW is incorporated by relaxing the latest possible arrival time b_i to b_i' i.e. a vehicle can start service even if it arrives after the b_i (but not after b_i') by paying a late arrival penalty cost resulting in Vehicle Routing Problem and scheduling with Semi Soft Time Windows (VRPSSTW). Furthermore, waiting is only allowed if the path arrives earlier than the service start time a_i i.e. no waiting is allowed within the extended time windows $[a_i, b_i']$. Figures 1 and 2 show the penalty cost functions to be used for Vehicle Routing Problem and scheduling with Hard Time Windows (VRPHTW) and VRPSSTW, respectively. A very high penalty cost outside the time windows is used to model the hard time windows. Exact solution techniques would be used to solve both VRPHTW and VRPSSTW using real road network data. This would help in identifying the environmental problems generated on the each link of the road network used by the vehicles. As far as the authors are aware no such comparison is available to date, using exact solution techniques and real road network data. Qureshi *et al.*[3)] have reported such a comparison but using heuristic analysis and Solomon's test instances, whereas Ando and Taniguchi[4)] have calculated the environmental impacts using real road network data and heuristic solution of VRPSTW.

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** Student Member of JSCE, M.E, Doctoral Student, Faculty of Engineering, Kyoto University.
C-1 Kyotodaigaku Katsura, Nishikyo, Kyoto 615-8540, Tel. 075-383-3231, Fax. 075-950-3800.
*** Fellow Member of JSCE, Dr. Eng., Faculty of Engineering, Kyoto University.
C-1 Kyotodaigaku Katsura, Nishikyo, Kyoto 615-8540, Tel. 075-383-3229, Fax. 075-950-3800.
**** Full Member of JSCE, Dr. Eng., Faculty of Engineering, Kyoto University.
C-1 Kyotodaigaku Katsura, Nishikyo, Kyoto 615-8540, Tel. 075-383-3230, Fax. 075-950-3800.

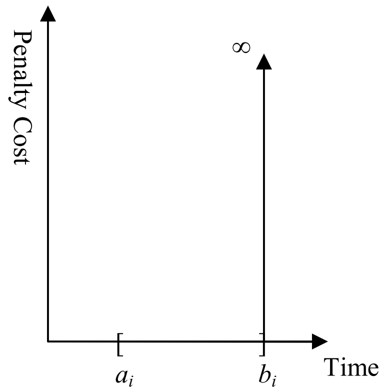

Fig.1 Penalty function for VRPHTW

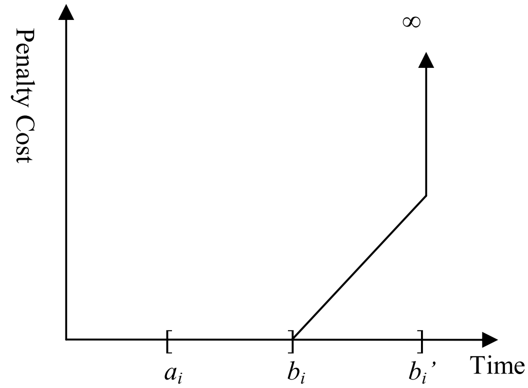

Fig.2 Penalty function for VRPSSTW

2. Vehicle Routing and Scheduling Problem with Time Windows (VRPTW)

VRPHTW is defined on a directed graph $G = (V, A)$. The vertex set V includes the depot vertex 0 and the set of customers $C = \{1, 2, \ldots\ldots, n\}$. K represents the set of identical vehicles with capacity q stationed at the depot. The arc set A consists of all the feasible arcs (i, j), $i, j \in V$. A cost c_{ij} and time t_{ij} is associated with each arc $(i, j) \in A$. A time t_{ij} includes the travel time on arc (i, j) and service time at vertex i, and a fixed vehicle utilization cost is added to all the out going arcs from the depot. With every vertex of V associated a demand d_i, with $d_0 = 0$, and a time window $[a_i, b_i]$ representing the earliest and the latest possible service start times.

Using the Dantzig-Wolfe decomposition VRPTW is formulated as

$$\min \sum_{p \in P} c_p y_p \tag{1}$$

subject to

$$\sum_{p \in P} a_{ip} y_p = 1, \qquad \forall i \in C \tag{2}$$

$$y_p \in \{0,1\} \qquad \forall p \in P \tag{3}$$

The above mentioned master problem consists of selecting a set of feasible paths of minimum cost generated by the Elementary Shortest Path Problem with Resource Constraints (ESPPRC). Where, y_p takes value 1 if the path p is selected and 0 otherwise. a_{ip} represents the number of times path p serves customer i. P is the set of all feasible paths. A vector of dual variables (prices) is also generated in the master problem represented by π_i.

The ESPPRC subproblem is solved on the same network as VRPHTW, with the arcs cost being reduced by the corresponding dual variables (prices) generated in the master problem by eq. (4).

$$\overline{c_{ij}} = c_{ij} - \pi_i \qquad \forall i \in V \tag{4}$$

Considering all identical vehicles and the reduced cost network, ESPPRC can be formulated as:

$$\min \sum_{(i,j) \in A} \overline{c_{ij}} x_{ij} \tag{5}$$

subject to

$$\sum_{i \in C} d_i \sum_{j \in V} x_{ij} \le q \tag{6}$$

$$\sum_{j \in V} x_{0j} = 1 \tag{7}$$

$$\sum_{i \in V} x_{ih} - \sum_{j \in V} x_{hj} = 0 \qquad \forall h \in C \tag{8}$$

$$\sum_{i \in V} x_{i0} = 1 \quad (9)$$

$$s_i + t_{ij} - s_j \le (1 - x_{ij}) M_{ij} \qquad \forall (i, j) \in A \quad (10)$$

$$a_i \le s_i \le b_i \qquad \forall\, i \in V \quad (11)$$

$$x_{ij} \in \{0, 1\} \qquad \forall (i, j) \in A \quad (12)$$

The model contains two decision variables x_{ij} which determines whether arc (i, j) is used in the solution ($x_{ij} = 1$) or not ($x_{ij} = 0$) and s_j that determines the service start time at vertex j by the vehicle. Objective equation (5) minimizes the reduced cost of the path. M_{ij} is a big constant. Constraint (6) is capacity constraint. Constraints (7), (8) and (9) are flow conservation constraints. Constraint (10) is time windows constraint specifying that if a vehicle travels from i to j, service at j can not start earlier than that at i. Constraint (11) specifies the service start time at all vertices must be within their specified time windows $[a_i, b_i]$. Note that the constraint (10) is the linearized form of the original non-linear constraint (13)

$$x_{ij}(s_i + t_{ij} - s_j) \le 0 \qquad \forall (i, j) \in A \quad (13)$$

For the VRPSSTW, the above mentioned ESPPRC model is extended to Elementary Shortest Path Problem with Resource Constraints and Late Arrival Penalties by replacing the constraint (11) with constraint (14) and by replacing the cost c_{ij} by c'_{ij} calculated as (15).

$$a_i \le s_i \le b'_i \qquad \forall\, i \in V \quad (14)$$

$$c'_{ij} = \begin{cases} c_{ij}, & \text{if } s_j \le b_j \\ c_{ij} + c_l (s_j - b_j) & \text{if } s_j > b_j \end{cases} \quad (15)$$

(1) Column Generation

After the earlier work of Kolen *et al.* [5], the body of literature on VRPHTW has been increasing with time. Most of the research has taken along two optimal approaches namely Lagrangean Relaxation[6)-7)] and Column Generation[8)-12)]. Column generation or Dantzig-Wolfe decomposition, decomposes the VRPTW problem into a set partitioning master problem and in ESPPRC. ESPPRC is a NP-hard problem in strong sense[13)], but there exist some pseudo-polynomial dynamic programming labeling algorithms. Many researchers have worked with variety of subproblems as Desrochers *et al.*[9)] used 2-cycle elimination while solving shortest path sub-problem whereas Irnich and Villeneuve[10)] used k-cycle elimination with k>3. Feillet *et al.*[11)] and Chabrier[12)] used ESPPRC as the sub-problem. This study uses an adaptation of ESPPRC algorithms given by Feillet *et al.* [11)] and Irnich and Villeneuve[10)], to generate columns for a set covering master problem. To use ESPPRCLAP as the subproblem for VRPSSTW, ESPPRC algorithm was suitably extended.

3. Test Problems

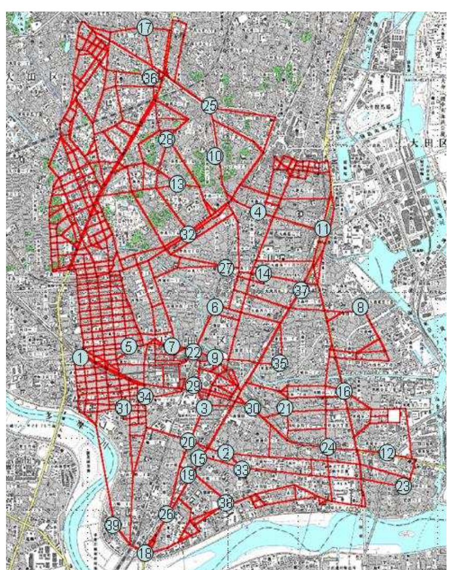

Fig.3 Test instance road network and customer location

The comparison of environment related indices such as NOx, CO_2 and SPM generation would be carried out by solving VRPTW instance derived from Tokyo Metropolitan Road Network data. The customer locations are a chain of convenience stores with their demands being known. Time windows are generated randomly and a fixed service time of 10 minutes is considered at every customer vertex. Figure 3 shows the study area along with customers' locations. The data input in the model is of the form of an origin destination matrix which is obtained from link based road network data. A shortest path was found from depot to all customers, between each pair of customers and between depot and customers, thus making an unsymmetrical travel time matrix using Dijkstra's algorithm.

4. Results and Discussions

Table 1 shows the partial analysis of VRPHTW and VRPSSTW solutions. VRPSSTW results in less number of vehicles but slightly more running time. On the other hand the waiting time (vehicle idling time) is reduced remarkably so as the total cost.

Table 1. Cost Components of Exact Solutions of VRPSSTW and VRPHTW

Instance	Vehicles	Waiting time	Running time	Running cost	Late Arrival Penalty	Total cost
TD1_39_djk_sstw	4	19.8	195.7	2743.71	1233.76	45647.5
TD1_39_djk_htw	5	119.5	176.8	2478.7	0	54566.2

**All costs are in Japanese yen.*

Use of real road network provides extra information such as speed on the link used. As generation of NOx, Co_2 and SPM are based on travel distance and speed. Hence a detailed link based analysis of the environment related issues is possible which will be presented at the conference.

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