PDPTW based Taxi Dispatch Modeling for Booking Service

Hao Wang
Ningbo Institute of Technology, Zhejiang University, P.R. China
wanghao@nit.zju.edu.cn

Der-Horng Lee
Dept. of Civil Engineering, National University of Singapore, Singapore
dhl@nus.edu.sg

Ruey (Kelvin) Cheu
Dept. of Civil Engineering, University of Texas at El Paso, United States
rcheu@utep.edu

Abstract

This research involves a study of the existing taxi dispatch system employed by taxi operators in Singapore. Based on the booking surcharges, there are generally two categories of taxi bookings, current and advance. Current bookings are requests that taxi should reach the customer immediately or within half an hour, and advance bookings are requests made at least half an hour in advance. In this paper, a novel trip-chaining strategy for taxi advance booking based on a customized algorithm of Pickup and Delivery Problem with Time Window (PDPTW) was proposed. The idea is to chain several bookings with demand time points which are spread out within a reasonable period of time, and with each pick-up point coinciding with or being within close proximity to the previous drop-off location. Based on the experimental results, the proposed system has the potential to improve the taxi booking service currently operating in Singapore.

1. Introduction

Taxis play an important role in offering personalized service within Singapore's transport sector. Fast and efficient fleet dispatching is essential for the provision of quality customer service in a competitive taxi operation network.

A satellite-based taxi dispatching system, which tracks taxis using the Global Positioning System (GPS) technology for automatic vehicle locating, is currently widely-deployed in Singapore [1-3]. With the aid of the real-time GPS-based dispatching system, the vacant taxis on the road network are tracked in the prevailing taxi dispatch system.

Table 1 shows the related data of major taxi operators in Singapore [4-7]. Based on the booking surcharges, there are generally two categories of taxi bookings, current and advance. Current bookings are those where the customer makes a booking less than half an hour before the taxi is required to reach him or her (most current bookings require taxi companies to dispatch taxis immediately or as soon as possible). However, advance bookings are requests made at least half an hour in advance. The focus in this paper is on the advance bookings.

Table 1. Major Taxi Operators in Singapore

Taxi Company	Current Booking Surcharge	Advance Booking Surcharge
Comfort Taxis	SGD \$3.20	SGD \$5.20
Yellow Top	SGD \$3.20	SGD \$5.20
CityCab	SGD \$3.00	SGD \$5.00
TIBS Taxis	SGD \$3.20	SGD \$5.20

Note: 1 USD = 1.75 SGD approximately

2. The existing dispatch system and its deficiencies

Once an advance booking demand is made, the dispatching center broadcasts this booking information immediately to the island-wide taxi network in Singapore, to both occupied and empty taxis, since the advance bookings are services which should be fulfilled at least half an hour later. The job is assigned to the first taxi driver who bids for it.

Obviously, under this dispatch system, advance bookings are handled on a case-by-case basis; and booking demands and taxi assignments are treated independently. For instance, up to 100 different taxis might be assigned to fulfill an equal number of bookings. Hence, the taxi supply resource, in terms of occupancy time, may not be significantly utilized.

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At the same time, one advance-booking request usually affects a taxi's street pickup service. In fact, taxi drivers often face a dilemma when the time for an advance-booking job is approximately 30 minutes later. In other words, if a driver tries to pick up roadside passengers, then the booking job may not be fulfilled on time. Conversely, if the driver gives up all the street pickup business, then it is apparently a waste of time and vehicle resource. This situation has been used by taxi companies to justify why the surcharge for advance bookings is higher than that of current bookings in Singapore (see Table 1).

As a result, customers have to bear with an unreasonable price structure, which appears irrational with daily experiences elsewhere. For instance, certain discounts are usually offered for advance bookings of transportation services such as rental cars and air tickets. However, under the current taxi booking surcharge structure, it will cost more for a planned trip if a taxi booking is made earlier. To some extent, customers are encouraged to use taxi services at the last minute, either through street hailing or through current-bookings, to avoid paying higher advance-booking fees. However, it is known that this will cause the customer to be involved in risks such as taking a long time to find an empty taxi through street hailing. Finally, customers faced with time constraints have to give up waiting and switch to and pay for current-booking services. Nevertheless, the fact is that even the current-booking system cannot offer a hundred percent guarantee of obtaining a taxi service quickly during certain time periods.

Therefore, the above-mentioned direct or indirect problems are essentially due to available customers' advance-booking information that has not been well exploited by the existing dispatch system. Hence, new taxi dispatch systems that can deal with such problems become an urgent priority.

3. The proposed dispatch system for advance booking

Based on the data provided by local taxi operators in Singapore, nearly 40 advance-booking demands are made every five minutes during the peak hours (from 7:00 to 9:30 in the morning and from 16:30 to 19:00 in the evening). To take full advantage of the aforementioned taxi supply resource, chained trips may be planned and offered to taxi drivers as a package. This means that several bookings with demand times points that are spread out within a reasonable period of time can be chained, provided that each pick-up point coincides with or is within close proximity to the previous drop-off location. The shortest time paths as generated by the proposed dispatch system based on real-life traffic conditions for each job, could perhaps be linked up to form properly planned routes to be offered as a multiple-booking package to taxi drivers. This will help the drivers to minimize their empty cruising times, as the time will be spent fulfilling these advanced demands instead of cruising around in search of street-hailing customers.

4. Methodology for the proposed dispatch system

In this research, the heuristics for the Pickup and Delivery Problem with Time Window (PDPTW) was adapted to be deployed in the dispatch system for advance bookings.

4.1 Paired PDPTW models

Paired PDPTW models the situation in which a fleet of vehicles must serve a collection of transportation requests. Each request specifies a pair of pickup and delivery locations. Vehicles must be routed to service all requests, satisfying time windows and vehicle capacity constraints while optimizing a certain objective function such as the total number of vehicles used or the total distance traveled.

PDPTW is a generalization of the well-known Vehicle Routing Problem with Time Window (VRPTW). Therefore, PDPTW is also an NP-hard problem, since VRP is a well-known NP-hard problem [8].

Defining the Pickup and Delivery Problem with Time Windows (PDPTW) formally, let $G=(V,A)$ be a digraph, $V = P \cup \{v_0\}$ is the node set where $P=\{v_i \in V \mid i=1,2,...,n\}$ represents the customers, node v_0 denotes the depot where a fleet of vehicles is housed. For the paired PDPTW model, n is even. In addition, let $P^+ \subset P$ be the set of pickup locations and $P^- \subset P$ be the set of delivery locations. Therefore, $P = P^+ \cup P^-$, $|P^+|=|P^-|=n/2$. Each node $v_i \in V$ has an associated customer demand q_i, ($q_0 = 0$), a service time s_i ($s_0 = 0$) and a service-time window $[e_i, l_i]$. $q_i > 0$ for $v_i \in P^+$ and $q_i < 0$ for $v_i \in P^-$. For each pair of nodes $\langle v_i, v_j \rangle \{i \neq j, i, j = 0,1,2,..., n\}$, a nonnegative distance d_{ij} and a non-negative travel time t_{ij} are known.

Note that s_i represents the duration needed to serve customer i . Hence, if customer i is served starting from t and assuming that the following customer to be served is j , then the earliest time that j will be served is $t+s_i+t_{ij}$. If a vehicle reaches a customer v_i before e_i , it needs to wait until e_i in order to service the customer.

Depending on different contexts, the problem consists of minimizing several objectives, subject to a variety of constraints.

4.2 Related works in literature

PDPTW can be used to model many core problems arising from logistics and public transit. However, the multiple-vehicle pickup and delivery problem with time windows has received little attention. The only optimal algorithm developed by Dumas et al. [9] employed a column generation scheme with a shortest-path sub-problem with capacity, time window, precedence and coupling constraints. The algorithm can solve 1-PDPTW problems of up to 55 paired requests and multiple-vehicle PDPTW with a small number of paired requests per vehicle.

Recently, William and Barnes [10] proposed a reactive tabu search approach to minimize travel cost by using a penalty objective function in terms of travel time, penalty for violation of overload and time window constraints. The approach was tested on instances with sizes of 25, 50 and 100 customers. These test cases were constructed from Solomon's C1 VRPTW benchmark instances [11], which were solved optimally.

More recently, researchers such as Lau and Liang [12], Li and Lim [13] have generated many test cases for PDPTW from Solomon's benchmark instances initially designed for VRPTW and proposed their different versions of Tabu-Search embedded Meta-Heuristics to solve PDPTW, each with good results.

4.3 The problem and its special requirements

This section analyzes the problem as defined by the authors of this paper as the Singapore Taxi Advance Reservations (STAR) problem. Based on the characteristics of the taxi booking service currently operating in Singapore, the differences between the STAR as addressed here, and the normal PDPTW in literature, are as follows:

1. Multiple vehicles are made available all over the street network instead of starting from a central depot.
2. Pickup and delivery jobs are paired and directly connected without any interruption from other pickup or delivery jobs.
3. Hard and extremely narrow-time window, i.e. a desired pickup time point with few deviations, has to be satisfied instead of a time window with earliest and latest allowable pickup time. Usually, a desired pickup time point is requested by a customer. A customer will complain if he is forced to wait for more than 2-3 minutes beyond the pickup time point for the taxi that has been booked by him in advance.
4. Vehicle capacity constraint is automatically respected by the customers. In real life a customer will consider this constraint when specifying the number of taxis to be booked.
5. Short response time for the solution.

To adopt a PDPTW model for the solution of the STAR problem, the computational cost is a critical factor, since customers cannot wait for more than a few minutes to receive a confirmation on his/her booking request, and the algorithm is supposed to be implemented in a dynamic environment intended for on-line scheduling.

At the time of the planning, the following information was available:

1. A number of requests for taxi service are identified in advance at each planning horizon.
2. For each customer the following information is known:
   a. The pickup location requested by the customer
   b. The delivery destination of the trip
   c. The desired pickup time.
3. The driving distances between the above-mentioned locations are well understood. Furthermore, the driving times between each Origin-Destination pair are based on data calculated through microscopic traffic simulations.
4. The average service time is based on daily statistics data, i.e. the time consumed when customers get on board, pay for the bill and alight from the vehicle.

There are a wide variety of objective functions for PDPTW. In the problem of STAR, the following were considered:

1. Minimizing the number of vehicles, which is the most dominant part of the costs for taxi operators.

2. Minimizing travel time/distance, i.e., the sum of the driving times or the length of all the routes in the plan, which is usually the main input of fuel consumption.

To model the duo-objective of minimizing (a) the total number of vehicles and (b) total travel time/distance as a linear function, a coefficient for each objective was multiplied and then added together. Since the number of vehicles is more important than the total travel time of a plan, the cost of each vehicle (route) is penalized with a coefficient C, which is set to be greater than the maximum possible total travel time. Hence, the objective function of the problem is:

$$\text{Minimize } C \times m + f(R)$$

Where, m is the total number of taxi used, and R is a pickup and delivery route plan, $f(R)$ is defined as the total travel cost (driving time or distance). The first term in the above objective function may be considered as the fixed cost and the second term as the variable cost.

4.4 The two-phase method

It has been shown that a successful approach for solving PDPTW is to construct an initial set of feasible routes that serve all the customers (construction phase) and subsequently improve the existing solution (improvement phase) [14-16]. This is known as the two-phase method.

In contrast to the common PDPTW problems, the time windows of taxi booking demands are extremely narrow; i.e., customers who make an advance booking usually specify the time 'point' instead of the time 'window'. Hence, the construction heuristics in the literature may not be efficient for solving such problems as taxi dispatching. In the first phase, the earliest time window insertion algorithm was proposed for the 'ad hoc' problem of taxi dispatching:

1. Let all vehicles have empty routes (with no booking assignments initially).
2. Let *L* be the list of unassigned requests.
3. Take a job pair v in which the requested passenger pickup time is the earliest from the current list of L.
4. Insert v in a route at a feasible position.
5. Remove v from L.
6. If L is not empty, go to 3.

The initial feasible solution is then improved in the improvement phase using tabu search. In this study, the steepest decent search was applied. A move in this approach corresponds to one of the traditional vehicle-routing move operations. In this paper, the focus was on two types of move operations, namely exchange and relocate.

4.5 The study network

Instead of using centroids and constant travel costs between pick-up and drop-off locations as was reported in literature, a customized microscopic simulation model, PARAMICS [17], was adopted to model real-street-network traffic conditions. A portion of the Central Business District (CBD) area in Singapore, which is bounded by the Electronic Road Pricing (ERP) gantries, covering an area of approximately 3.0 km by 2.5 km, was used for the simulations conducted in this research.

Figure 1. CBD Network in Singapore

The CBD network was chosen because it has the highest concentration of offices and commercial activities, making it a densely-populated area within Singapore island. The commercial buildings serve as the generators and attractors for taxi service, especially during peak hours, which is otherwise relatively uncommon in other road networks such as expressways and suburban areas.

For network coding, the details of the geometry and physical layout of the roads were collected via field surveys, and included such information as the number of lanes (mid-block and at intersections), turning restrictions, post speed limit, etc. The data on signal timing, origin-destination (OD) and information on the demarcation of zones in the CBD area was collected from related transportation authorities [18-20].

The CBD network consists of a total of 894 nodes and 2,558 links. The 100 traffic analysis zones in this network were defined according to the traffic demands of each zone, which were allocated according to the acquired OD data. Figure 1 provides an overview of the CBD network.

4.6 Application program interface (API) program for traffic simulation

An API program was developed to collect the travel time of each link along the CBD network through traffic simulations. A link-to-link shortest path algorithm was embedded into the API program to search for the shortest time paths for each origin-destination pair.

Forty pairs of pick-up and drop-off locations were selected at major trip generators, e.g., shopping malls, hospitals and convention centers. Twelve sets of booking demands were randomly generated with pickup time points between the afternoon peak hours and midnight of the same day, and pickup and drop off locations distributed among the forty pairs of trip generators. Each demand set represents the advance-booking requests that the dispatch system receives in five minutes. For each demand set, the time deviation is defined as $\sum_{i=1}^{n} | T_i - \bar{T} | / n$, where T_i is the desired pickup time point and $\bar{T}$ stands for the average pickup time. Twelve demand sets were then randomly generated, with the average deviation of requested pickup time for each booking set varying from a few minutes to one hour.

5. Experimental results

The computation works were carried out in a personal computer with a Pentium IV 1.8 GHz CPU and 512 MB of RAM. The computation times of these construction heuristics were always less than one second to get the initial solution with a problem size of forty booking jobs in this study. Then each of these initial solutions was improved by using the same Tabu search procedure within the same computation time of five seconds (pre-set maximum computation time for the improvement phase). The results are shown in Table 2.

On the whole, the larger the booking time deviation, the fewer were the taxis required. However, the deviation defined as $\sum_{i=1}^{n} | T_i - \bar{T} | / n$ only indicated the average deviation from the average booking time, and a large value of deviation did not necessarily mean that the booking demands were almost evenly distributed along the time space that could guarantee obtaining a solution in which fewer taxis were involved.

The proposed earliest time window insertion algorithm could generate good initial solutions efficiently, without significant improvements after a limited computation time in the second phase. Hence, for an online service with a strict time constraint, this initial solution could even be adopted as a sensible solution where the improvement phase was omitted so as to entertain customers more quickly without losing too much solution quality.

Table 2. Experimental Results

Deviation (min)	Taxi Used		Travel Cost (min)	
	initial	improved	initial	improved
4.5	22	21	217.5	213.1
5.2	19	19	228.2	215.6
6.1	17	16	240.1	222.3
7.3	14	14	261.0	248.2
8.0	15	14	250.1	241.6
9.2	12	12	265.3	255.8
15.1	10	9	283.1	267.2
23.6	7	7	286.2	275.4
30.6	7	6	286.2	283.3
46.4	5	5	304.7	283.0
59.5	4	4	297.2	288.0
64.1	5	5	292.2	279.0

6. Conclusion

This research identifies and explores the potential employment of a new taxi dispatch system modeled after a customized PDPTW problem. A two-phase method was adopted and an earliest time window insertion algorithm to efficiently generate the initial solution for this 'ad hoc' problem was also proposed. Experimental results show the efficiency of the proposed taxi dispatching system.

Although this study was motivated by a practical problem faced by taxi operators in Singapore and did not intend to make a contribution with regard to the algorithm initially, it did raise the STAR problem, which is a special version of the normal PDPTW, discussed its characteristics and requirements, and proposed a particular construction method to better solve this 'ad hoc' problem.

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