
Intelligent Taxi Dispatch System for Advance Reservations

Hao Wang, Ningbo Institute of Technology, Zhejiang University

Ruey Long Cheu, The University of Texas at El Paso

Der-Horng Lee, The National University of Singapore

Abstract

This research proposes and tests a new taxi dispatch policy to improve the existing systems used by taxi companies in Singapore. The proposed method chains trips made by reservations at least 30 minutes before the customer pick-up times. In this paper, the taxi dispatching system, Singapore Taxi Advance Reservation (STAR), is defined. A novel trip-chaining strategy based on a customized algorithm of Pickup and Delivery Problem with Time Window (PDPTW) is proposed. The idea is to chain several taxi trips with demand time points that are spread out within a reasonable period of time and with each pick-up point in close proximity to the previous drop-off location. The strategy proposed has the potential to lower the taxi reservation fee in Singapore to encourage advance reservations that facilitate trip chaining, which translates to lower taxi fares for customers, higher revenue for taxi drivers, and lower fleet ownership cost for taxi companies.

Introduction

Taxis are a popular transportation mode in the compact city state of Singapore. With the high cost of private vehicle ownership, taxis play an important role in offering an alternative transportation service. Fast and efficient fleet dispatching is essential to the provision of quality customer service in a competitive taxi industry. Satellite-based taxi dispatching systems, which track taxis using Global Positioning System (GPS) technology, are currently deployed by taxi companies in Singapore. Taxis on the road network are tracked, located, and dispatched to customers in real-time.

Table 1 shows the related data of major taxi companies in Singapore. Based on the reservation fees (known locally as “booking surcharges”), there are generally two categories of taxi reservations in Singapore: current and advance. Current reservations are those in which customers request vacant taxis (i.e., taxis without passengers) to reach them in less than 30 minutes. Advance reservations (known locally as “advance bookings”) are requests made at least 30 minutes in advance. The focus of this paper is on advance reservations.

TABLE 1.
Major Taxi Companies in
Singapore and Their Fare
Structures

Taxi Company	Fleet Size (veh)	Current Reservation Fee	Advance Reservation Fee	Fare for 1st km	Meter Fare by Distance
Prime Taxis	731	SGD \$3.50	SGD \$5.00	SGD \$3.00	SGD \$0.20/385m between 1 km and 10 km; SGD \$0.20/330m after 10 km
Premier Taxis	2,436	SGD \$3.50	SGD \$8.00	SGD \$3.00	SGD \$0.22/400m between 1 km and 10 km; SGD \$0.22/350m after 10 km
Yellow-Top	1,090	SGD \$3.50	SGD \$8.00	SGD \$3.00	
CityCab	5,592	SGD \$3.50	SGD \$8.00	SGD \$3.00	
Smart Taxis	2,441	SGD \$5.00	SGD \$10.00	SGD \$3.00	
Comfort Taxis	15,200	SGD \$3.50	SGD \$8.00	SGD \$3.00	
Trans-Cab	4,230	SGD \$3.30	SGD \$6.50	SGD \$3.00	
SMRT Taxis	3,150	SGD \$3.30	SGD \$8.00	SGD \$3.00	

Note: SGD \$1.00 = US\$0.81 in May 2013; other fees such as peak hour surcharge, midnight surcharge, and airport surcharge, etc., are not included in this table.

The paper is organized as follows. Following this introduction, a description of the existing taxi dispatch systems in Singapore and their deficiencies are presented. The proposed taxi dispatch system to handle advance reservations is presented in the next section. This is followed by several sections that illustrate the computational methodologies of the new system, which includes the paired Pickup and Delivery problem with Time Window (PDPTW) models; a review of closely-related literature; the Singapore Taxi Advance Reservation (STAR) system with its special requirements; a customized two-phase trip-chaining solution algorithm; and the study network and Application Program Interface (API) programming for traffic simulations. The results of simulation experiments are subsequently presented, followed by a discussion on the performance of the proposed system. Finally, the benefits of the proposed system for customers, drivers, and taxi companies are highlighted in the conclusion.

Existing Taxi Dispatch System and Its Deficiencies

In Singapore's taxi industry, taxi companies own the vehicles. Drivers rent taxis from companies by paying fixed daily fees. All the taxis subscribe to, and are part of, the company's dispatch system. When a customer requests a taxi in advance, either by phone or by Internet, the company's dispatch center broadcasts the trip information immediately to all taxis (with and without passengers) in its fleet. Since advance reservation is a service that should be fulfilled at least 30 minutes later, it is up to the taxi drivers to decide if they want to bid to serve this customer. Drivers do not have to pay for the bid; the dispatch system assigns the job to the first driver who bids for it.

Under this dispatch policy, trip demands and taxi assignments are distributed without any consideration of fleet or revenue optimization. For instance, up to 100 different taxis might be assigned to fulfill an equal number of reservations. Hence, the taxi supply may not be significantly used.

A commitment to a reserved trip usually affects a taxi's street pick-up service. Taxi drivers often face a dilemma when the time is approaching for a customer who has made an

advance reservation to be picked up. If a driver picks up a roadside passenger, he/she may not be able to subsequently pick up the customer who has made an advance reservation. Conversely, if the driver gives up the street pick-up business, this becomes opportunity cost for him/her to serve the customer with an advance reservation. This situation has been used by taxi companies in Singapore to justify why the advance reservation fee is more than two times than that of current reservations, in all except one company (see Table 1).

Taxi customers in Singapore have to bear an unreasonable price structure when making reservations. To some extent, customers are encouraged to shop for taxi services at the last minute, either through street hailing or through current reservations, to avoid paying higher fees. This cost-saving behavior causes the customer to take the risk of not being able to find a vacant taxi.

These problems are essentially due to the inability of the existing taxi dispatch systems to make full use of customer advance reservation information. Hence, a new and more intelligent taxi dispatch system that encourages advance reservations and makes better use of this information for fleet optimization is an urgent priority.

Concept of Trip Chaining

To take full advantage of advance reservation information, several trips may be chained to form a “route” and offered to a taxi driver as a package. This means that several reserved trips with spatial and temporal distributions of customer requests may be linked, provided that (1) each pick-up point is within close proximity to the previous drop-off location and (2) the pick-up time for the next customer must be later than the estimated drop-off time of the previous customer, but not too late. This will help the driver to minimize his/her vacant time (cruising around in search of roadside customers), as most of his/her time will be spent carrying passengers on board and generating revenue.

Computation Methodologies

In this research, the heuristics for the PDPTW were adapted to chain taxi trips in the proposed taxi dispatch system.

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 pick-up and delivery locations. Vehicles must be routed to serve all the requests, satisfying time windows and vehicle capacity constraints while optimizing a certain objective, such as minimizing 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 VRPTW is a well-known NP-hard problem (Savelsbergh 1995).

Related Works in Literature

PDPTW can be used to model and solve many problems in the field of logistics and public transit. As a special case of pick-up and delivery, dial-a-ride emphasizes human convenience (Cordeau and Laporte 2002)—for example, door-to-door transportation

services for older adults, or people who are sick or have disabilities (Borndorfer et al. 1997; Madsen et al. 1995; Toth and Vigo 1997) and shuttle bus services connecting airports and customer homes. Parragh et al. (2008a, 2008b) conducted a comprehensive survey on the topic of pick-up and delivery. In practice, transportation requests using dial-a-ride are usually booked at least one day in advance. Therefore, much research focuses on the static and deterministic version of this problem.

William and Barnes (2000) proposed a reactive Tabu search approach to minimize travel cost by using a penalty objective function in terms of travel time, a penalty for violation of overload, and time window constraints. The approach was tested on instances with 25, 50, and 100 customers. These test cases were constructed from Solomon's C1 VRPTW benchmark instances (Solomon 1987), which were solved optimally.

Researchers such as Lau and Liang (2002) and Li and Lim (2001) generated many test cases for PDPTW from Solomon's benchmark instances that were initially designed for VRPTW and proposed different versions of Tabu search embedded meta-heuristics to solve PDPTW.

Recently, Parragh et al. (2009) used a variable neighborhood search heuristics coupled with path relinking to jointly minimize transportation cost and average ride time for a dial-a-ride system with multiple service criteria. In addition, many authors, such as Beaudry et al. (2010) and Jorgensen et al. (2007), incorporated quality-of-service considerations into the solution of the dial-a-ride problem. However, few papers modeled after real-world applications with large-scale sample size have been found in published literature.

The STAR Problem and its Special Requirements

This section analyzes the problem as defined by the authors as the STAR problem. Based on the characteristics of the taxi dispatch service for advance reservations, the differences between STAR and the normal PDPTW are as follows:

1. Multiple vehicles are available throughout the street network instead of starting from a central depot.
2. Pick-up and delivery jobs are paired and directly connected without any interruption from other pick-up or delivery jobs.
3. There is a hard time window—customers will complain if the taxi is late by more than three minutes. Therefore, the pick-up time window becomes $[-\infty, \text{pick-up time as specified by the customer}]$.
4. Vehicle capacity constraints are automatically respected by customers—in real life, customers will consider this constraint when specifying the number of taxis to be booked.
5. There is a short confirmation response time—after submitting an advance reservation request, customers usually expect to receive a confirmation (by phone call, text message, or email) with a taxi's license plate number, pick-up time, and location in less than five minutes; therefore, "real-time" route planning is highly desirable.

During route planning (chaining of trips), the following information is available:

1. Requests for taxi service are identified in advance at each planning horizon.
2. For each customer, pick-up location (origin), delivery location (destination), and desired pick-up time are known.
3. Driving distances between these locations are well understood, and driving time between each origin-destination (O-D) pair is known.
4. Average service time, i.e., time consumed after customers get on board, pays, and alights from the vehicle, is based on historical statistics.

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

1. Minimizing the number of vehicles, the highest cost component for a taxi company.
2. Minimizing the travel time or distance, which usually translates into minimizing fuel consumption, the highest component of operating cost for drivers.

To model these objectives, the following function has been considered:

$$\text{Minimize } C \times m + f(R) \quad (1)$$

where, m is the total number of taxis used, R is a pick-up and delivery route plan, $f(R)$ is the total travel cost (converted from driving time or distance), and C is a coefficient set to penalize the high cost of vehicle. The first term in the above objective function may be considered as the fixed cost and the second term the variable cost.

The Two-Phase Solution Heuristics for the STAR Problem

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 (known as the construction phase) and subsequently improve the existing solution (known as the improvement phase) (Gendreau et al. 1994; Glover and Laguna 1997). However, the characteristics and requirements of the STAR problem preclude straightforward implementation of most algorithms that have been developed for the normal VRPTW or PDPTW. In this section, a two-phase approach for solving the STAR problem is proposed.

Construction Phase

The nearest-neighbor heuristic adds on the closest customer for extending a route. A new vehicle is introduced when no more customers can be accommodated by the current vehicle in use (Toth and Vigo 2000).

1. Let all the vehicles have empty routes (with no customer assignment).
2. Let L be the list of unassigned requests.
3. Take a trip v from L in which the requested pick-up location is the nearest from the previous drop-off location of a route.
4. Insert v to extend the abovementioned route (if v satisfies all the constraints).

5. Remove v from L .
6. If L is not empty, go to step 3; otherwise stop.

The earliest time insert heuristic always inserts the trip with the earliest pick-up time instead of the nearest pickup location.

The sweep heuristic builds routes by using a sweep technique around a certain location. The sweep heuristic for VRP is shown below:

1. Let O be a site (usually the depot) which serves as a central point, and let A be another location, which serves as a reference.
2. Sort the jobs by increasing angle $\angle AOJ$, where J is the pickup location. Place the result in a list L .
3. The jobs in L will be allocated to taxis in the above order as long as constraints are respected.

The initial feasible solution is then improved in the improvement phase.

Improvement Phase

In the improvement phase, two types of move operations—exchange and relocate—are combined with Tabu search to improve the solution. A move in this approach corresponds to one of the traditional vehicle-routing move operations. In this study, the steepest descent search was applied.

An exchange operation swaps trips in two different existing routes, whereas in a relocation operation, a customer is removed from an original route, inserted into another route, or reinserted into the same route but at a different position. A move is considered feasible if the corresponding operation does not violate any requirement (for instance, time constraints). Hence, the neighborhood of the current solution is defined as all the feasible moves. In each iteration of the steepest decent approach, the feasible move that gives the best improvement (or least deterioration) of the cost is selected.

To avoid the search from revisiting the same solution in the near future, the Tabu search mechanism was introduced. A Tabu list records the previous moves performed. A potential move is considered Tabu if it is in the Tabu list. Moreover, a move is “aspired” if the resultant cost is lower than the cost of the best solution encountered. If the best move selected by the steepest decent approach is Tabu and not aspired, then the next best move in the neighborhood of the current solution would be considered; otherwise, the selected move is made. The improvement process in this phase continues until a pre-set maximum number of iterations ($maxIter$) or a pre-set maximum computation time ($maxTime$) has been reached. The key steps of the improvement phase are as follows:

1. Let the current solution X be the feasible solution generated in the construction phase, and set the solution of “best so far” $z^* = \infty$.
2. Choose the best move $bestMove$ from the neighborhood of the current solution.
3. If $bestMove$ is Tabu and not aspired, repeat from Step 2; otherwise, accept $bestMove$ and update the solution x and cost $z(x)$.

4. If $z(x) < z^*$, then $x^* = x$ and $z^* = z(x)$.
5. Repeat steps 2–4 until the number of iterations equals *maxIter* or until *maxTime* computation time has been performed.
6. Output x^* and z^* .

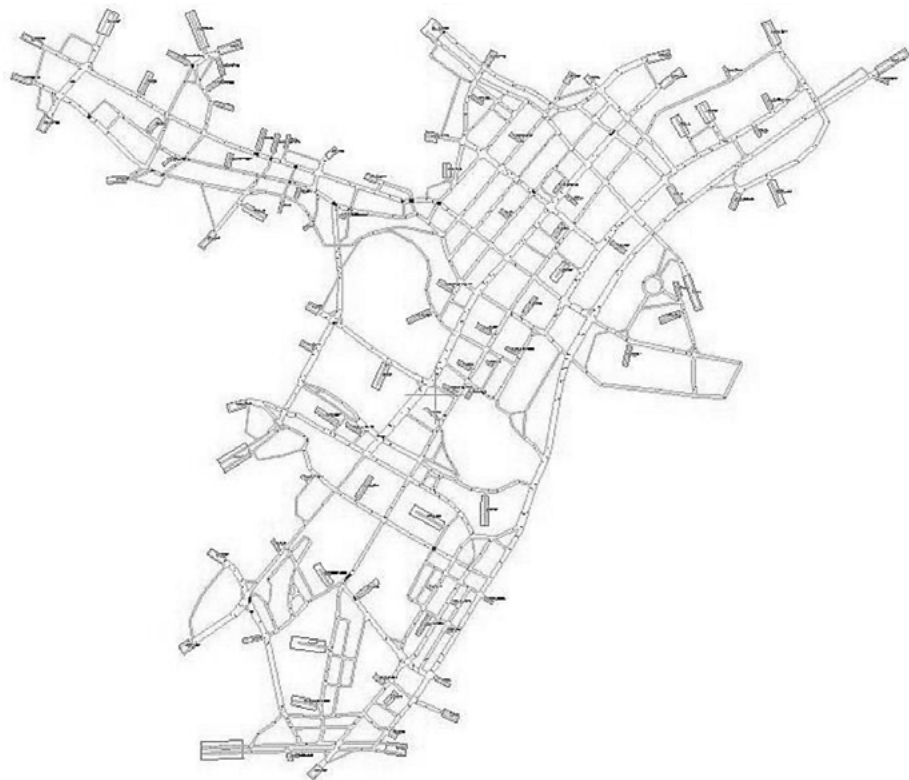
Simulation Experiment

This section describes the experiment conducted to test the proposed two-phase solution approach for the STAR problem. A customized microscopic simulation model, PARAMICS (Quadstone 2009), was adopted to generate time-dependent link travel times for the experiment. A portion of the Central Business District (CBD) area in Singapore, which is bounded by the Electronic Road Pricing (ERP) gantries and covers an area of approximately 3.0 km by 2.5 km, was used for the simulation.

For network coding, the details of the geometry and physical layout of the roads were collected via field surveys. The coded network features included the number of lanes (mid-block and at intersections), turn restrictions, posted speed limit, etc. Signal timing plans, O-D matrices of background traffic, and boundaries of traffic analysis zones in the CBD area were collected from the Land Transport Authority of Singapore.

The coded CBD network in PARAMICS consisted 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 hourly O-D data. Figure 1 is a screen shot of the CBD network coded in PARAMICS.

FIGURE 1.
Simulated CBD network
of Singapore



A customized program developed through PARAMICS' Application Programming Interface (API) was developed to collect the time-dependent travel time of each link in the CBD network as the simulation progressed. These travel times were used to construct the link-to-link travel time between each pickup and drop off locations.

As there are ERP gantries to separate the CBD area from other parts of Singapore, a fleet of taxis may always do their business within the CBD to avoid the ERP toll. Based on the data provided by taxi companies in Singapore, approximately 3,000 advance bookings are made during the day time (from 8:00 AM to 6:00 PM) across the whole island of Singapore. We assume that one-third of the above demands (pick-up and drop-off locations) are within the CBD area.

In this study, 1,000 pairs of taxi pick-up and drop-off locations were randomly generated from among 100 major trip generators (e.g., major office buildings, shopping malls, hospitals, hotels, and convention centers) to form a demand set. The pick-up times were from 8:00 AM to 6:00 PM (see Table 2). For each demand set, the average pickup time deviation is defined as $\sum_{i=1}^n |T_i - \bar{T}| / n$, where T_i is the desired pickup time and \bar{T} is the average pickup time for all the $n=1000$ requests within a demand set. Ten sets of taxi demands were generated. The average deviation of pick-up times for each set varied from half an hour to more than two hours (see Table 3). To study the performance of the proposed heuristics, the pick-up time deviation could not be too small during the experiment. This is because an extremely small deviation means that all the pick-ups will happen at almost the same time and, thus, there is very limited opportunity to chain these trips.

Experimental Results

All the computation works were carried out in a personal computer with an Intel Core i3 CPU and 4 GB of RAM. To solve the STAR problem, numerical comparisons between the proposed insertion earliest time window insertion and other construction heuristics. The results are listed in Table 4. The computation times of these construction heuristics always took less than 30 seconds to arrive at the initial solution with a problem size of 1,000 trips in this study. Then, each of these initial solutions was improved by using the move operations and Tabu search procedure. The Tabu search had a pre-set maximum computation time of 30 seconds. The results at the end of the improvement phase are shown in Table 5. In the objective function, $f(R)$ was set to the total travel time of all the routes. Intuitively, C could be set to 6 hrs \times 60 minutes/hr = 360 minutes so that the term $C \times m$ is equivalent to the total taxi-hours available to serve customers during the 6-hour planning horizon. This will also convert $C \times m$ to the unit of travel time in minutes used in $f(R)$. However, in our experiment, C was set to a very high value so that the objective function forced the solution to converge to the minimum number of taxi used. This was done deliberately so that the different heuristics could be evaluated by comparing the number of routes or taxis.

TABLE 2.
Example of Randomly-Generated Demand Set with 1,000 Trips

Reservation Request	Pick-up Location	Destination Location	Pick-up Time
1	The Paragon Tower	Parco Bugis Junction	9:30 AM
2	Cairnhill Place	Bank of China	9:55 AM
3	Sunshine Plaza	People's Park Complex	11:40 AM
4	Sin Tai Hin Building	Centennial Tower	8:35 AM
5	Parco Bugis Junction	Maxwell Road Food Center	8:25 AM
6	Bugis Village	UIC Building	1:25 PM
7	Golden Mile Complex	Air View Building	4:35 PM
8	Keypoint Building	People's Park Complex	10:30 AM
9	Ngee Ann City	OUB Center	8:25 AM
10	Singapore Power Building	Centennial Tower	5:10 PM
11	Suntec City Tower	Sunshine Plaza	8:50 AM
12	Centennial Tower	Air View Building	4:45 PM
13	People's Park Complex	Ngee Ann City	8:05 AM
14	Ministry of Manpower	Golden Mile Complex	10:00 AM
15	OUB Center	The Paragon Tower	9:45 AM
16	Bank of China	Golden Mile Complex	8:10 PM
17	Maxwell Road Food Center	CPF Building	8:05 PM
18	Air View Building	Sin Tai Hin Building	3:30 PM
19	CPF Building	Ngee Ann City	2:10 PM
20	UIC Building	Bugis Village	4:50 PM
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999	The Paragon Tower	Centennial Tower	11:15 AM
1000	Suntec City Tower	Golden Mile Complex	3:45 PM
Average deviation of pick-up time:		$\sum_{i=1}^n T_i - \bar{T} / n$	62.7 minutes

TABLE 3.
Average Pick-up Time Deviation within Each Demand Set

Demand Set	1	2	3	4	5	6	7	8	9	10
Average deviation of pick-up time (min)	36.7	45.8	54.5	62.7	71.9	82.0	91.2	101.5	112.1	122.5

TABLE 4.

Initial Solutions after Construction Phase

(a) Initial solutions by nearest neighbor insertion heuristic

Demand Set	1	2	3	4	5	6	7	8	9	10	Average
Taxis used	160	149	146	136	128	121	123	119	119	117	131.8
Total travel time (min)	5450.1	5430.7	5420.7	5533.4	5527.5	5532.0	5562.2	5538.7	5548.0	5558.2	5510.2

(b) Initial solutions by sweep insertion heuristic

Demand Set	1	2	3	4	5	6	7	8	9	10	Average
Taxis used	136	116	112	96	91	90	93	87	91	90	100.2
Total travel time (min)	8383.1	8609.9	8597.9	8665.2	8819.2	8769.5	8780.6	8837.1	8858.3	8828.3	8714.9

(c) Initial solutions by earliest time window insertion heuristic

Demand Set	1	2	3	4	5	6	7	8	9	10	Average
Taxi used	73	56	54	53	42	40	34	32	32	28	44.4
Total travel time (min)	6951.7	6977.6	7015.4	7191.3	7164.9	7252.1	7325.3	7416.0	7349.4	7388.3	7203.2

From Table 4, it can be observed that the initial solution from the proposed earliest time window insertion heuristic was significantly better than the other two heuristics (nearest neighbor insertion and sweep insertion) in terms of the number of taxis required. However, a smaller number of routes (or taxis) could increase the total travel time (for example, see the total travel times for demand set 1 in Tables 4(a), 4(b) and 4(c)). This is because the calculation of travel time of each route involved in this study began with the origin of the first booking demand and ended with the destination of the last trip and included all the travel times between these connected trips (between drop-offs and pick-ups). Therefore, using fewer routes may force taxis to travel a longer distance or time between last drop-offs and next pick-ups, i.e., vacant or empty cruising between jobs.

In the improvement phase, the Tabu search has proven to be so efficient that even fairly poor initial solutions (in Table 4[a],4[b]) can be improved into solutions (in Table 5[a],5[b]) which are comparable to those of good initial solutions.

TABLE 5.

Solutions after Improvement Phase

(a) Improved solutions by nearest neighbor insertion heuristic

Demand Set	1	2	3	4	5	6	7	8	9	10	Average
Taxis used	73	58	59	55	50	40	36	34	33	33	47.1
Total travel time (min)	7233.8	7286.8	7402.2	7062.4	6891.3	7420.7	7651.0	7769.8	7696.0	7587.5	7400.2

(b) Improved solutions by sweep insertion heuristic

Demand Set	1	2	3	4	5	6	7	8	9	10	Average
Taxis used	59	62	55	46	40	36	32	33	32	46.9	47.1
Total travel time (min)	7525.7	7518.2	7641.2	7808.5	7664.6	7695.3	7744.4	7738.5	7654.4	7613.1	7660.4

(c) Improved solutions by earliest time window insertion heuristic

Demand Set	1	2	3	4	5	6	7	8	9	10	Average
Taxis used	71	54	53	52	42	37	33	31	32	27	43.2
Total travel time (min)	6327.6	6370.0	6357.6	6486.1	6444.6	6496.6	6538.0	6709.0	6538.8	6692.8	6496.1

Overall, the larger the booking time deviation, the fewer the taxis required. However, the deviation defined as $\sum_{i=1}^n |T_i - \bar{T}|/n$ indicates only the average deviation from the average pick-up time. A large value of deviation does not necessarily mean that the pick-up times are evenly distributed that could lead to a solution in which fewer taxis are necessary.

Through the customized two-phase approach, a practical routing plan for a batch of 1,000 advance reservations could be generated quickly to provide real-time dispatch decisions. Under the existing taxi dispatch system, these 1,000 advanced reservations may be taken up by up to 1,000 different taxis. However, through our proposed trip-chaining strategy, these 1,000 trips may be grouped into fewer than 80 routes and assigned to a fleet with fewer than 80 taxis (see Table 5). The reduction of fleet size involved in reservation service is significant.

The authors caution that the above reduction in fleet size is computed for taxis that respond to advance reservations. This is because, although only a small fleet of taxis is necessary to cater to the advance reservations, the other taxis are free to pick up customers who make current reservations or are on the streets at any time. Having two different groups of taxis, each specializing in different types of customers or trips, will most likely lead to better utilization of taxis and increased revenue for the drivers. However, this scenario is much more complex to analyze and will be the direction of future research.

Conclusion

This research has identified the STAR taxi dispatch problem and proposed a two-phase solution approach. The two-phase approach consists of an earliest time window insertion heuristic to construct an initial solution followed by move operations cum Tabu search to improve the solution. Experimental results have showed that the two-phase approach is efficient in providing an instantaneous solution. The numerical results also show that by chaining advance-reservation trips, the taxi fleet could be reduced significantly.

The main contribution of this study is that a revolutionary system has been proposed for a real-life problem of advance taxi reservation in Singapore that would reduce operating costs and empty cruising time and could be deployed by taxi companies without any extra devices or facilities. Under the proposed system, the benefits for taxi drivers, taxi companies, and customers are summarized as follows:

- For taxi drivers, there will be an increase in productivity since they can serve more customers with less empty cruising, thus reducing operating cost. The system might also increase taxi driver income by (1) accepting a planned route with multiple advance-reservation trips and (2) having an increase in taxi occupancy time.
- For taxi companies, the most attractive part is that an increase in resource utilization would be expected. With the same vehicle resource, a taxi company will be able to handle a higher number of advance reservations. In other words, with the same demand level, a taxi company could reduce the number of vehicles in use, which translates into a reduction in inventory cost.

With a reduced fee for advance reservations, customers may be more willing to make reservations in advance, thus reducing their transportation expenses and improving travel time reliability.

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About the Authors

HAO WANG (wanghao@nit.zju.edu.cn) is an Associate Professor at the Ningbo Institute of Technology, Zhejiang University in China. His research interests include commercial vehicle operations, hub location problems in supply chain systems, and large-scale microscopic traffic simulation.

RUEY LONG CHEU (rchou@utep.edu) is an Associate Professor at the University of Texas at El Paso. He serves as an editorial board member of two international journals, *Transportation Research Part C: Emerging Technologies* and *Journal of Intelligent Transportation Systems*. His research program at UTEP focuses on border transportation, with emphasis on transportation planning, public transportation, and transportation security.

DER-HORNG LEE (dhl@nus.edu.sg) is an Associate Professor at the National University of Singapore. He is an editor for *EURO Journal of Transportation and Logistics* (Springer) and associate editor for two international referred journals, *IEEE Transactions on Intelligent Transportation Systems* and *IEEE Transactions on Automation Science and Engineering*. His specialties include intelligent transportation systems, container port operations, transportation planning and policy, high fidelity traffic and travel simulation, and transportation network modeling and analysis.