Public transit planning and scheduling based on AVL data in China

Yindong Shen\textsuperscript{a,b}, Jia Xu\textsuperscript{a,b} and Zhongyi Zeng\textsuperscript{a,b}

\textsuperscript{a}School of Automation, Huazhong University of Science and Technology, Wuhan 430074, China
\textsuperscript{b}Key Laboratory of Image Processing and Intelligent Control (Huazhong University of Science and Technology), Ministry of Education, China

E-mail: yindong@hust.edu.cn [Shen]; smarts027@gmail.com [Xu]

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Abstract

The public transit operations planning process commonly includes the following activities: network route design, service planning (frequency setting and timetabling), and scheduling (vehicle scheduling, crew scheduling, and rostering). However, the network route design is generally the only one widely recognized, while service planning and scheduling are often ignored in China. This leads to the lack of elaborate timetables and schedules, hence, transit operation is often in disorder with high operating costs. To raise the service level and the utilization of resources, this paper presents an applied study for three cities in China, focusing on the enhancement of the recognition and execution of public transit planning and scheduling. A comprehensive framework of public transit planning is first proposed, which is composed of three traditional Chinese items (i.e. network route design, land use for depots, and deployment of vehicles) and the following newly added items: intelligent public transit system (IPTS) planning, service planning, and scheduling. This is pioneering work in China, in which an IPTS plan is conceived and a new vehicle scheduling approach based on AVL data is developed. Experiments during actual projects show that vehicle schedules with high on-time probability and low cost were compiled, while the essential input parameters such as headways and trip times were set automatically. It is anticipated that the fruits of this research and the practical experience obtained would be of great benefit in improving service and management levels and resource use in public transport in China and some other developing countries.

Keywords: public transit planning; vehicle scheduling; timetabling; AVL data; public transport

1. Introduction

In pace with rapid progress of urbanization and motorization, the problems of traffic jams, accidents, and environmental pollution are becoming increasingly serious, which bring severe challenges to urban transportation in China. It is gradually recognized that improving public transport is a fundamental way to tackle urban traffic problems. At present, many cities have been investing heavily...
in planning, construction, and improvement of urban transit systems. Unfortunately, there are widespread misunderstandings of public transport planning in China, which limit the improvement of public transit service and operation management.

The public transit operations planning process commonly includes the following basic activities, usually performed in sequence: network route design, frequency setting, timetabling, vehicle scheduling, and crew scheduling and rostering (Ceder and Wilson, 1986; Ceder, 2011), as shown in Fig. 1.

However, among the above-mentioned five activities, network route design is generally the only one widely recognized in China. It is usually carried out once every 10–20 years by planners under the support and supervision of local government. It is generally believed that network route design and dispatching, as well as the construction of infrastructure, are the most important factors in improving bus services. Unfortunately, the significance of service planning and scheduling is commonly disregarded and even ignored altogether. Consequently, without precise timetables and efficient schedules, bus services still remain unsatisfactory with high operating costs after a newly planned route network is implemented.

To raise public transit service levels and utilization of resources in China, this paper has three major objectives: (1) to increase understanding of public transit planning by transit authorities and operators; (2) to set up a comprehensive framework for public transit planning in China, which should be practical and could serve as a guideline for transit planning in the future; and (3) to develop a vehicle scheduling approach based on AVL data, which is to serve as a bridge when moving from the Chinese traditional transit planning to comprehensive transit planning.

The work is reported in this paper through three of our projects carried out in China for the cities of Haikou, Shiyan, and Jingmen. The organization of the paper is as follows. Section 2 gives an insight into the major practical problems encountered for public transit service in China; Section 3 proposes first a comprehensive framework of public transit planning in China, and then introduces the development status and bus service in each of the three cities, during which the pioneering

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work involved in the corresponding project is explained; Section 4 presents a new vehicle scheduling approach based on AVL data for high on-time probability, in which the methods of data handling, service reliability measurement, frequency setting, timetabling and scheduling are addressed; Section 5 reports implementation and computational results; and Section 6 gives the concluding remarks.

2. Insights into the major problems with public transport in China

The major problems encountered by public transit service in China can be classified into the following groups: (P1) incorrect cognition, (P2) inefficient operation mode and scheduling methods, and (P3) lack of data or scheduling parameters.

2.1. (P1) Incorrect cognition

The cognition problem that affects profoundly the other problems is summarized as follows.

Misunderstanding public transport planning as network route design

The core work in public transport consists of planning and operation. Since the Ministry of Construction of China issued “advice notice on the priority development of urban public transport (State Office Document No. 46)” in 2005, it has become obligatory for more and more city governments to compile a specialized public transport plan, instead of a small part in a comprehensive transportation plan as was usually previously done. This is obviously helpful in improving the public transit system.

Unfortunately, traditional public transport planning is only concerned with network route design, in addition to land use for depots and deployment of vehicles, which are together called traditional three items in planning by Shen et al. (2010). In other words, network route design is generally regarded as the whole content of public transport planning.

It is commonly expected by transport authorities and operators that the plan would be able to solve the problems encountered in operation. For example, when we carried out transit planning projects in several cities, we were often asked to solve problems such as the considerable difference of passenger demands between peak time and nonpeak time, especially for routes with schools and industrial parks or routes from suburb to downtown. This usually caused us great difficulty in balancing network route design with low or tidal passenger flow. Generally, transit operators believe that such routes would bring low fare revenue, and hence dislike or reject them. However, our plan should achieve a reasonable coverage area and access to public transport service.

Although traditional planning can lead to some improvement in the public transport system, unfortunately it is very common in many cities that the bus service still remains unsatisfactory with low service levels and high operating costs after newly planned bus routes are put into operation, since service planning and scheduling are missing or carried out roughly and arbitrarily.

Disregarding the significance of scheduling

In general, the significance of scheduling is widely disregarded in China. Research on bus transit scheduling using computers in China has just started in recent years. Much of it attempts to build a
mathematical or heuristic model to tackle the bus vehicle scheduling problem on a line-by-line basis (Shen and Xia, 2003, 2004; Chen et al., 2004; Liu and Shen, 2007; Xu et al., 2013). Unfortunately, it still requires much effort to meet the practical requirements of bus operators. In practice, buses and their drivers are usually scheduled manually on a line-by-line basis. Many of the schedules compiled manually, which only meet some service standards, such as minimum service span, headways, and the number of vehicles allocated to a given line, are not as elaborate as those compiled in the developed countries. Such a manual schedule is usually too simple to fit real service demands and operating environment, and hence it can seldom be executed and should not be regarded as a proper schedule. Some bus companies do not compile schedules at all (Shen and Xia, 2009).

Confusing scheduling with dispatching
Scheduling is often confused with dispatching while the latter is usually given more attention. Both the words “scheduling” and “dispatching” correspond to the same Chinese word “diaodu,” whose English translation is “scheduling.” Hence, when bus operators claim often that scheduling (i.e. diaodu) is the core work of bus operations, unfortunately they mainly refer to dispatching instead of scheduling. Each terminus is usually equipped with at least one dispatcher, who plays part of the roles of schedulers by deciding the departure time of each service trip according to experience. The efficiency of dispatching depends greatly on the experience, responsibility, and personal authority over drivers of an individual dispatcher.

2.2. (P2) Inefficient operation mode and scheduling methods

Due to the above-mentioned incorrect cognition and insufficient research on public transit scheduling, operators commonly schedule their vehicles and crews manually on a line-by-line basis. The operations mode and scheduling methods have not significantly improved since the establishment of P.R. China in 1949; however, the number of buses has increased more than 1500 times since then, from fewer than 200 to more than 300,000 buses. In contrast to the western countries, the operations mode and scheduling methods in China are very inefficient, and are difficult to adapt to the rapid increase in vehicle numbers and the changed service requirements. The backward mode of operations and the scheduling methods have caused many problems to public transit companies and the government. The major problems have been summarized by Shen and Xia (2009), which are as follows: (a) utilization of resources is restricted and inefficient, (b) the management and operational costs are high, (c) schedules are compiled manually and cannot be timely adjusted according to changes, (d) there are no practical schedules guiding dispatchers and drivers, and (e) bus services are often disordered.

2.3. (P3) Lack of data or scheduling parameters

Ceder (2007) indicates that a successful transit system contains three essential functions: the first is to gather and comprehend data, the second is to plan and decide intelligently, and the third is to operate astutely. Public transit operation planning is the core of the system, which is usually carried
out based on collected data. For example, vehicle scheduling (an essential component in transit operation planning as illustrated in Fig. 1) is based on the given service task, which is decided by headways and running times (e.g. trip times, TTs; or segment running time) presented in a timetable format. Therefore, the TT (i.e. the duration of a trip) and headway are the essential parameters (input data) of vehicle scheduling systems. The rationality of setting these parameters greatly affects the compilation and on-time probability of a vehicle schedule. However, in practice, they are usually set manually according to schedulers’ experiences. In China, the TT of a certain bus line is often set as a constant during the whole day, the variations of TT during different periods (e.g. at the peak or off-peak hours of a day) are seldom considered. Overall, the currently used TTs are unable to reflect the actual running time, hence, the resulting schedule is difficult to maintain (Xu and Shen, 2012). Consequently, lack of input parameters has acted as a disincentive to the widespread use of scheduling systems, and further restricts the progress of public transit service. In recent years, the above-mentioned problems have gradually been recognized.

First, the backward operation mode and scheduling methods (referring to the above-mentioned problem P2) have exerted more and more pressure on both public transit companies and the state and city governments, since most of the companies are fully or partially owned by the state. To enhance the operation mode and scheduling methods, with the aid of Ministry of Science and Technology and Beijing Bus Group (BJBUS, the largest bus company in China), Shen and Xia (2009) carried out a pioneering study of scheduling buses and drivers based on an interline mode of operation for BJBUS. The research aimed to assist BJBUS with the change from a line-by-line mode to an interline operation mode, during which an integrated transit scheduling system was devised accordingly. Furthermore, due to specific rules and constraints (e.g. scheduling buses with built-in meal periods and restricting drivers to one or two particular buses), the scheduling approaches successful in the developed countries cannot be directly applied in China. Therefore, we have been developing a series of scheduling approaches that can tackle some specific constraints in China (Chen et al., 2013; Chen and Shen, 2013; Shen and Chen, 2014).

Later, we found that it was still difficult to make computerized scheduling systems be extensively used in China, although some suitable approaches had been developed. The existence of incorrect recognition and lack of parameters (referring to the above-mentioned problems P1 and P3) have become two major barriers.

This paper aims to break through the barriers. The major means we employed can be summarized as follows: (a) to build a comprehensive framework for public transit planning in China; (b) to develop an adequate public transit scheduling approach, which should be practically applicable under the current situation of China.

To achieve the goal, first of all it is necessary to let the transit authority and operators have a comprehensive understanding of public transit operation planning. We believe that being involved in traditional transit planning projects would be a shortcut. During the projects, we would have more opportunities to demonstrate the new concepts and techniques to relevant officers and operators. Therefore, we have carried out several projects on public transit planning for cities such as Haikou, Huangshi, Shiyan, Jingmen, and Xiaogan in China since 2010. All of these projects are supported by city governments and transit authorities. During the project, a comprehensive framework of public transit planning in China has been built, which will be presented next.
3. Framework of public transit planning in China

Public transit planning in China is commonly concerned with the compilation of a 10–20 years development plan for the entire public transit system of a city. Such a specialized transit plan must be consistent with the city master plan, and has become obligatory in many cities of China. Public transit planning usually contains the following essential parts: network route design, land use for depots, and deployment of vehicles, which are together called traditional three items in planning by (Shen et al., 2010), as illustrated on the left-hand side of Fig. 2, where “L” or “M” on an arrow denotes that the corresponding item belongs to Long- or Medium-term planning, respectively.

Network route design is the process of deciding route paths and the corresponding termini with some major stops on routes. Land use for depots is the process of searching suitable locations for setting up various depots. Deployment of vehicles is the process of estimating the total number of vehicles to be deployed in the city according to the population size and economic development status over the planning period.

It should be noticed that neither detailed frequency by time of day nor timetable is considered among the traditional three items. Therefore, service planning is missing, which further leads to the lack of some essential data for scheduling. Without timetables and schedules, transit operation is hard pressed to meet passenger demands and is often in disorder, while utilization of resources is usually inefficient.

To increase the transit service quality, we have tried our best to promote the entire public transit planning process illustrated in Fig. 1. Moreover, we have tried to persuade transit authorities to allow us to add the following new items to the planning: the development plan of intelligent transit systems (ITS), service plan (frequency setting and timetabling), and scheduling (vehicle scheduling, crew scheduling and rostering), as shown on the right-hand side of Fig. 2. In Fig. 2, the traditional three items and the newly added items compose a comprehensive framework of public transit planning in China, which encompasses all the contents of the public transit planning process shown in Fig. 1.

Although these newly added items are widely applied in the developed countries (Jütte and Thonemann, 2012; Mesquita et al., 2013; Shen et al., 2013) they are quite new in China. It is very hard to persuade the transit authority to accept all of them at once, since these new items are difficult to understand without proper demonstration and adequate solution methods. We have to introduce them into actual city transit planning projects gradually. Three of our typical practices in Haikou, Shiyan, and Jingmen are represented next, in each of which we only focus on some of the new items. For clarity, the items included in each of the public transit planning projects are listed in

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Table 1

<table>
<thead>
<tr>
<th>City</th>
<th>Project period</th>
<th>Traditional three items</th>
<th>IPTS planning</th>
<th>Demonstration on scheduling</th>
<th>Automatically set parameters</th>
<th>Demonstration on timetable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haikou</td>
<td>2010–2011</td>
<td>✓</td>
<td>✓/*</td>
<td>✓/*</td>
<td>✓/*</td>
<td>✓/*</td>
</tr>
<tr>
<td>Shiyan</td>
<td>2011–2012</td>
<td>✓</td>
<td>✓/*</td>
<td>✓/*</td>
<td>✓/*</td>
<td>✓/*</td>
</tr>
<tr>
<td>Jingmen</td>
<td>2013–2014</td>
<td>✓</td>
<td>✓/*</td>
<td>✓/*</td>
<td>✓/*</td>
<td>✓/*</td>
</tr>
</tbody>
</table>

✓ denotes the work included in the projects. * denotes the pioneering work involved in the traditional public transit planning of China.

Table 1, where the rightmost three items (corresponding to service planning and scheduling) belong to medium-term planning. The demonstration is only provided on a few routes in the projects. One purpose is to attract attention and deepen the understanding of the entire public transit planning process, while another is to lay the theoretical and technical foundation of widespread use in China in the future.

The project for Haikou, the capital of Hainan Province, is the first transit planning project in which we were involved (Shen et al., 2010). As can be seen in Table 1, in addition to the traditional three items in planning (i.e. network route design, land use for depots, and deployment of vehicles), a plan for the development of intelligent public transit systems (IPTS) was introduced while a demonstration of scheduling buses and their crews for a selected line was carried out.

Subsequently, the projects on public transit planning for the cities of Huangshi and Shiyan have been carried out. As shown in Table 1, we have expanded the research on public transit scheduling in the project for the city of Shiyan. During the project, an automatic parameter setting method is devised, based on which a vehicle scheduling approach based on AVL data is proposed.

In our most recent on-going research for the city of Jingmen, we focus on encouraging bus companies to provide a service based on timetables. Such a practice has little difference from providing service based on schedules as usually done in the developed countries. Its implementation is easier, since some conventional behaviors of drivers and dispatchers, such as overtaking, can remain. Therefore, it would serve as a good alternative during the transition period of China reformation.

3.1. Public transit planning for Haikou

This project was sponsored by Haikou Municipal Bureau of Transportation in 2010. Haikou, as the capital of Hainan province, is a beautiful booming city located on the northern coast of Hainan, by the mouth of the Nandu River. Haikou is comprised of four districts, having an area of 2304.84 km² with a population of 2.05 million. Haikou is also a model of an international tourism island in China; hence, an advanced public transit system should be an important infrastructure for the city. Therefore, the city government and transit authority ran a project on public transit planning in 2010, in which we were involved (Shen et al., 2010). The project attempted to set up a comprehensive development plan of an advanced Haikou public transit system for the years from 2010 to 2020.
In response to the requirement for an advanced transit system, a development plan of IPTS was proposed besides the traditional three items in planning. A general framework of Haikou’s IPTS was devised as shown in Fig. 3.

Among the planned application systems in the general framework, only the GPS-based automatic vehicle location (AVL) system (some with a dispatching interface) and the the integrated circuit (IC) card system, a kind of automatic fare collection (AFC) system, were installed before the planning project started. An amount of AVL data had been accumulated in a database but never been used for any service reliability measurement.

The bus service in Haikou was provided on 60 lines by nine bus companies (together called HKBUS), among which Haikou City Bus Company and Haikou Bus Corporation, Ltd were the largest two companies. The former owned 25 lines while the latter owned 15 lines. There were 1135 buses carrying 0.8 million passengers per day by the end of October 2010.

HKBUS schedules its buses and crew manually on a line-by-line basis. The schedule compiled is normally too simple to serve the real demand and operating environment effectively, and too crude to guide dispatchers or drivers. The dispatchers stationed at each terminus play an important role of schedulers by deciding the departure time of each service trip based on their experience.

Since computerized vehicle and crew scheduling was a new concept to transit service operators, we selected one route (i.e. Route 4) to demonstrate the compilation of comprehensive and efficient vehicle and crew schedules using our previously developed integrated scheduling system named iPTS system (Shen and Ni, 2006; Shen and Xia, 2009). The underlying principle of the vehicle and crew scheduling approach embedded in the iPTS system is similar to that of the scheduling approach.
approaches widely applied in the developed countries. None of these scheduling approaches can be executed until service frequencies and TTs in a timetable are given as input parameters.

Due to lack of a predetermined timetable, we had to set the parameters manually according to our investigation results and the experiences of the managers, dispatchers, and drivers in HKBUS. Although a set of vehicle and crew schedules was successfully compiled for the selected bus line, we found that setting parameters was very time-consuming, and frustrated the system users. This has motivated our further research on vehicle scheduling based on AVL data, in which the scheduling parameters are to be set automatically based on accumulated AVL data.

3.2. Public transit planning for Shiyan

This project was sponsored by Shiyan Municipal Bureau of Transportation in 2011. Shiyan is a city located in the northwest of Hubei province, famous for its Wudang Mountain, well-protected ecology, and automobile industry. The city has an area of 24,000 km² with a population of 3.5 million.

Bus services on 42 bus lines are provided by Shiyan Bus Group (SYBUS), which is a public owned company. There were 859 buses carrying 726 thousand passengers per day by the end of 2011. The total length of the bus lines was 677 km. The buses and crews were scheduled manually on a line-by-line basis. The schedule compiled was also too simple to serve the real demand and operating environment effectively. It might even be said that SYBUS did not compile schedules at all. The so-called schedule was in fact a part of service delivery policy for a route, which simply specified the span and rough frequency of service.

As one of the pilot cities for developing a low-carbon transport system in China, the city government and SYBUS were vitally concerned about the quality of the public transit service. Similar to Haikou, the GPS-based AVL system and the IC card system were installed before the planning project started. An amount of AVL data had been accumulated in a database but never been used for any service reliability measurement.

In the specified plan for the public transit system of Shiyan, the traditional three items in planning have been carefully proposed. Meanwhile, the development plan of Shiyan’s IPTS has also been made, the general framework of which is similar to that of Haikou as shown in Fig. 3.

As shown in Table 1 and described in Section 2.1, vehicle and crew scheduling has been demonstrated in the Haikou’s project. However, the lack of suitable parameters has hindered the application of scheduling systems by frustrating human schedulers (system users). Moreover, inaccurate parameters may decrease dramatically the on-time probability of the resulting schedules.

During this project, we proposed a brand new idea, in which an AVL-based vehicle scheduling approach is developed, in which major scheduling parameters such as headways (frequencies) and TTs are set automatically based on AVL data. The details are given in Section 3.

3.3. Public transit planning for Jingmen

This project is sponsored by Jingmen Municipal Bureau of Transportation in 2013. Jingmen, located in central Hubei province, is one of the cities with the most vigorous economy in Hubei Province. It has a long history and is rich in cultural heritage and natural resources. Monuments and unearthed cultural relics dot the landscape. The city has an area of 12,404 km² with a population of...
about 3 million by the end of 2012. Bus services on 21 bus lines are provided by two subsidiaries of Jingmen Bus Company (JMBUS). There are 347 buses carrying more than 210 thousands passengers per day. The total length of bus routes is 364 km. Regarding development of information systems, as in many other cities in China, a GPS-based AVL system and an IC card system have been set up. Although a lot of AVL data and IC card data have been stored in databases, the value of the data is unfortunately not realized.

Gratifyingly, after several years of efforts on publicity and promotion, the development plan of IPTS has been widely accepted as an essential part of the specified public transit plan of a city in China. Therefore, besides the traditional three items, an IPTS plan has been compiled for Jingmen, its general framework is similar to that shown in Fig. 3.

Although the demonstration of vehicle and crew scheduling with automatic setting of parameters has been carried out in our previous public transit planning projects, the significance of schedules has still not been taken much into account. One important reason is that people do not believe that the schedules could be executed under terrible traffic conditions. Moreover, once an abnormal running (e.g. delay, vehicle trouble) occurs, how to adjust the pre-compiled schedule is also a new problem for dispatchers and drivers. In fact, due to lack of schedules, drivers used to drive freely in their own way, therefore, overtaking each other is a widespread phenomenon. It takes time to train drivers and dispatchers to adhere to schedules. Patience and alternative strategies are needed.

Compiling an elaborate timetable instead of a schedule might be treated as an alternative means at this transition period. Such a timetable can serve as guidance for the drivers and dispatchers while some freedom remains. A dispatcher in a terminal can dispatch any vehicle on-site according to the timetable, in which a service trip is not pre-assigned to a vehicle. Moreover, when the previous vehicle is delayed or encounters trouble, the vehicle behind can overtake it without the constraint of a precompiled schedule. In practice, it is generally easier for operators to follow an elaborate timetable than an elaborate schedule.

In this project, we would like to focus on the publicity and promotion of timetabling. The major work is to measure the service reliability based on the stored AVL data and then to compile an elaborate timetable. The goal is to propel public transit operators to provide service according to designated timetables. The demonstration on timetabling has been carried out on a number of bus routes in Jingmen. The resulting timetables are given in Section 4.

4. Vehicle scheduling based on AVL data for high on-time probability

As already mentioned, service planning (frequency setting and timetabling) and scheduling (vehicle scheduling, crew scheduling, and rostering) are ignored or disregarded in China. However, they are the bridge between network route design and actual operation, and hence play a crucial role on increasing public transit service quality. This bridge should be built urgently in China.

Since each subproblem in service planning and scheduling is individually hard and various problem definitions and solution methods have been proposed over the years (Ernst et al., 2004; Guihaire and Hao, 2008; Mesquita et al., 2013), it is infeasible to develop a global solution approach or complete an intensive research on each of subproblems within several project periods. By contrast, a simple but applicable bridge is more acceptable in China. Vehicle scheduling is the most suitable for the role.
From the point of view of the public transit planning process, the vehicle scheduling problem is the successor to the timetabling problem and the precursor to the crew scheduling and rostering problem. Service reliability such as on-time probability is mainly determined by timetabled vehicle schedules, which will further govern the compilation of crew schedules and rosters. Therefore, vehicle scheduling can be selected as the bridge linking the Chinese traditional route design and on-site operation. To play this role well, traditional vehicle scheduling approaches are not adequate. A more powerful vehicle scheduling approach is needed, which should embody the essential functions of frequency setting and timetabling. This paper proposes such a vehicle scheduling approach, which is expected to be able to compile a vehicle schedule with high on-time probability and low operating cost, while the major input parameters can be set automatically based on AVL data.

4.1. The vehicle scheduling problem

The vehicle scheduling problem in public transport (e.g. bus, tram and train) involves finding the most efficient way of assigning vehicles to the predetermined trips with consideration of practical requirements, such as multiple depots, vehicle types, and depot capacities. The objectives are to minimize fleet size and operating cost including costs for nonrevenue trips (deadheads) and idle time (layovers). The number of feasible solutions to this problem is extremely high, especially when the vehicles are based in multiple depots. The problem has attracted much research interest (Huisman et al., 2004; Ceder, 2011).

Early research focused on the vehicle scheduling problem with a single depot (SDVSP) (Gavish and Shlifer, 1979; Bodin et al., 1983). Since the 1990s, most research has focused on the problem with multiple depots (MDVSP; Kliewer et al., 2006), which is proven to be NP hard by Bertossi et al. (1987). Meanwhile, more realistic characteristics are included, such as fuel consumption (Haghani and Banihashemi, 2002), time windows (Desaulniers et al., 1998; Kliewer et al., 2011), and multiple vehicle types (Kliewer et al., 2006; Ceder, 2011). Moreover, considering disturbances that can affect TTs, dynamic vehicle scheduling approaches are proposed (Huisman et al., 2004), and delay penalties are introduced into the operating cost of vehicles (Naumann et al., 2011).

In general, the vehicle scheduling problem is based on a given timetable, which consists of a set of timetabled trips. Efficient schedules (i.e. solutions of this problem) can produce monetary savings for operators, but cannot improve the quality and reliability of service to users, which is mainly governed by the given in-service trips.

The in-service trips represent the scheduled public transport services. The reliability or punctuality of the scheduled services is important in planning, management, dispatching, and marketing of these services (Carey, 1999). It becomes a standard in many developed countries where transit operators regularly publish statistics on reliability (Börjesson et al., 2012).

Carey (1999) indicated that various methods could be used to measure reliability with the most widely used measures being either ad hoc or heuristic. For an overview of reliability measurement the reader can refer to Cham (2006) and Furth et al. (2003). With the increasingly widespread use of automated systems that collect data, such as AVL, automatic passenger counting (APC), and automatic fare collection (AFC) systems, new opportunities for automatic and quantitative measurement of service reliability have arisen. Furth (2006) reviewed studies on travel time and headway measurement using AVL and APC data. Aguiléra et al. (2012) proposed a reliability measurement...
approach based on cellular network data, and compared the results with analysis based on AFC data. In recent years, application of automatically collected data to service measurement has become more common (Barabino et al., 2012; Orth et al., 2012; Yetiskul and Senbil, 2012). Meanwhile, using the data, some research has focused on operation and dispatching strategies, such as holding, to improve reliability (Uniman, 2009; van Oort et al., 2012); other research has focused on predicting travelling time (Börjesson et al., 2012) and improving timetables (Cevallos et al., 2011; Salicrú et al., 2011).

In general, scheduling and service reliability measurement are seen as distinct research areas, and research in each area is normally carried out independently. Scheduling parameters (input data) are usually set by schedulers instead of by directly using the service reliability measurement outputs of the operation. Setting numerous scheduling parameters is not trivial and often frustrates human schedulers. Moreover, the precision of parameters are not guaranteed to be good, so the resulting schedule may have poor reliability.

This paper proposes a new vehicle scheduling approach based on using AVL data for high reliability service. The basic idea is to integrate service reliability measurement and service planning with vehicle scheduling. It is not a simple method but can be regarded as a comprehensive framework focusing on the compilation of an efficient and reliable schedule by all the means.

4.2. Vehicle scheduling based on AVL data

As already mentioned, gathering and comprehending data is one of three essential functions of a successful transit system Ceder (2007). It forms the foundation of the other two functions: planning and operation. In public transit system, the use of automated data collection (ADC) systems, such as AVL, APC, and AFC systems, is widespread in the developed countries. However, in many developing countries such as China, there are no APC systems while AFC data are often incomplete. AVL systems are deployed relatively more widely, and record vehicle movements throughout the day.

In recent years, more and more bus companies in China (e.g. above-mentioned HKBUS, SYBUS and JMBUS) have increasingly deployed AVL systems. A large amount of AVL records has been stored in databases although their value has not been recognized. One of the important tasks in this paper is to study how to utilize the AVL data to support bus transit planning and scheduling, especially to set scheduling parameters automatically.

Unlike traditional vehicle scheduling approaches that are based on given timetables, the vehicle scheduling approach presented in this paper is based on using the AVL data. The approach is composed of the following steps: handle AVL data, identify homogeneous running time (HRT) bands, measure service reliability, set scheduling parameters, and compile a schedule.

Handle AVL data

AVL systems in China are normally GPS-based, locating and recording vehicle movements. They usually do not provide well-arranged TTs. A TT is the actual running time of a trip, which is an essential input parameter of vehicle scheduling systems (Xu and Shen, 2012). Due to the complex conditions and circumstances of public transit operation, TTs vary throughout a day.
Therefore, a set of sample TTs needs to be extracted from the original AVL data, before utilizing AVL data to enhance transit service planning and scheduling. Xu and Shen (2012) indicated that AVL data handling is a nontrivial work. The process can be described as shown in Fig. 4.

As shown in Fig. 4, a matching method is devised to match the longitude and latitude data in the GPS with its corresponding locales in the GIS in order to identify the stations or stops, to determine the arrival and departure times at each stop, and to judge the directions of vehicle movements (inbound or outbound). Since equipment failure or system failure occurs sometimes, a vehicle movement may fail to be recorded. Moreover, some wrong records may exist due to the errors in the recording or matching procedure. Among these incorrect records, some can be corrected while some cannot be and have to be filtered out. After the original records have been processed, all the trips should be extracted, and then the running time of each trip should be calculated. In this way, a set of sample TTs is formed, which constitute a database of the following steps.

**Identify HRT bands**

TTs may vary dramatically within the service span during a day. To have accurate measure of TTs, it is necessary to analyze the TTs lying in different HRT bands individually. Therefore, HRT bands must be identified first.

The service span during a day can be usually divided into a set of HRT bands according to running time variation (Furth et al., 2003). The INTERVAL algorithm used by Haifa Bus provides four options, say 1, 2, 3 hours, and all day long, to form an initial set of time bands, which are then merged into HRT bands (Ceder, 2007). To increase the precision of time period specification, shorter initial time bands are employed in the TriTAPT system, which are then merged into HRT bands by a differential interval judgment method and a sequence merging strategy (Furth et al., 2003). Salicrú et al. (2011) present a maximum interclass variance method and a greedy strategy in the merging process, in which the evaluation of a new HRT band is based on the classical formula:

\[
B(\mu_1, \sigma_1) \land B(\mu_2, \sigma_2) \approx B(\mu_3, \sqrt{\sigma_1^2 + \sigma_2^2})
\]  

(1)

where \(B(\mu_1, \sigma_1)\) represents a time band, \(\mu_1\) is the average of the TTs in the sample set, \(\sigma_1\) denotes the standard deviation, and \(\land\) represents the merging operation. This is an approximate method but
is less time-consuming. Later, Xu and Shen (2012) extend the method by considering the weight of sample size in an HRT as displayed in Equation (2).

\[
B(\mu_1, \sigma_1, n_1) \land B(\mu_2, \sigma_2, n_2) = B(\mu_3, \sigma_3, n_1 + n_2)
\]

\[
w_1 = \frac{n_1}{n_1 + n_2}; w_2 = \frac{n_2}{n_1 + n_2}
\]

\[
\mu_3 = \mu_1 \cdot w_1 + \mu_2 \cdot w_2
\]

\[
\sigma_3 = \sqrt{\sigma_1^2 \cdot w_1 + \sigma_2^2 \cdot w_2 + (\mu_1 - \mu_3)^2 \cdot w_1 + (\mu_2 - \mu_3)^2 \cdot w_2},
\]

where \(n_1\) and \(n_2\) represent the sample sizes, \(w_1\) and \(w_2\) are the corresponding weights.

At present, we propose a basic K-means algorithm to cluster HRTs, and further improve it by devising the following methods: an enhanced cluster initialization method, a cluster center updating method based on triangle inequality, and fuzzy clustering method (Shen et al., 2014). Note that the outputs of the above-mentioned approaches can be manually adjusted and should be confirmed by operators.

Measure service reliability

After the HRT bands are identified, each HRT band contains a cluster of TTs, corresponding to a subset of sample TTs. Given the samples, the service reliability (mainly referring to on-time probability in this paper) at each HRT band can be measured. During the service reliability measurement, the probability density and cumulative distribution of TTs at each HRT band are calculated, which constitute the knowledge base for the next step of parameter setting.

Interested readers may refer to (Furth et al., 2003) and (Uniman, 2009), an illustration of travel time distributions for the London Underground using the data collected by the Oyster system has been provided in where Uniman (2009).

Set scheduling parameters

Headways and TTs (by which a timetable is constituted) are the most essential parameters for the compilation of a vehicle schedule. These parameters are also called scheduled headways and scheduled TTs in order to be distinguished from the actual headways and TTs.

Determining frequency of service (equivalent to headway setting) is a hard problem in public transport. The following elements usually need to be considered: accumulated hourly passenger counts, average travel time, given vehicle capacity, desired occupancy (load standard), and the minimum frequency permitted by time of day (Ceder, 2007). However, this paper focuses on finding a simple and easy way to set scheduled headways for each time period (e.g. peak- or nonpeak) during a day. A K-means algorithm is proposed to cluster homogeneous headways, which are extracted from given sample trips. Since there is too much bunching and also big gaps in the sample data (representing the actual situation in operation), the resulting scheduled headways are very unsatisfactory, and have to be significantly adjusted according to schedulers’ experiences before serving as input parameters. In China, headway setting is also closely related to the fleet size. The headways are usually designated by operators. So far, the analysis results obtained by experienced schedulers based on actual AVL data are more consistent with the real demand and operation conditions.

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Setting scheduled TTs is the core work of parameter setting, which greatly affects the on-time probability of a vehicle schedule. There are various ways to set TTs for each HRT band. The empirical methods are to use two minutes less than the 85% observed running time (Furth, 2006) or mean running time minus 2 (Salicrú et al., 2011). Zhao et al. (2006) propose a waiting time optimization model for TT setting. The objective is to minimize the passenger expected waiting time

\[ E\{w\} = \frac{1}{2} \cdot SH \cdot \left(1 + \frac{Var\{l\}}{SH^2}\right), \]

where \( H \) denotes headway, \( SH \) denotes scheduled headway, \( l \) denotes lateness, \( var\{l\} \) can be calculated through the proximate lower or upper bounds or the proximate distribution of delay for instance (Rao and Feldman, 2001; Zhao et al., 2006). In the light of our numerous experiments, this paper adopts the empirical method in which the scheduled TT is set as two minutes less than the TT with a given percentile (say 85th denoting 85% of scheduled trips are expected to be able to completed on time) based on the TT distributions calculated in the previous step.

**Compile a schedule**

In public transport, traditional vehicle scheduling is concerned with the allocation of vehicles to predetermined service trips in such a way that the total number of vehicles and operating cost are minimized. Given scheduled headways and TTs, a vehicle schedule theoretically can be compiled through various existing vehicle scheduling approaches (Huisman et al., 2004; Shen and Ni, 2006; Ceder, 2011; Kliwer et al., 2011; Naumann et al., 2011). However, some special constraints, such as a built-in meal period when a driver has a mealbreak and his/her vehicle stops and waits in termini, are commonly imposed in China. Suitable vehicle scheduling approaches are therefore needed.

During our planning project for Haikou, a heuristic vehicle scheduling approach previously developed was adopted (Wren, 1972; Smith and Wren, 1981; Shen and Ni, 2006; Shen and Xia, 2009). The approach contains two stages. The first one is to generate a crude initial schedule using a target number of vehicles. The target number is estimated by an automatic process but can be increased or decreased by operators. The second stage is to refine the initial schedule iteratively by breaking and re-linking pairs of links using 2-opt heuristics aided by 3-opt heuristics. This approach belongs to a family of Neighborhood Search, in which a large number of solutions have to be evaluated during the scheduling process. The definition of costing methods is essential. The usual costing method is link-based, which is insufficient to form a schedule with built-in meal-breaks as often requested by the operators in China. According to this requirement enforced on driver duties, each vehicle whose duration is longer than the stipulated maximum continuous driving time, should have at least a built-in period at conventional lunch or dinner time. Therefore, when any link in a vehicle is changed, the validation of built-in periods has to be evaluated again. In this case, it is hard to assess precisely how much a link is contributing to optimality, and hence the operating cost of a vehicle. Therefore a chain-based costing method is developed. It simply treats all the links in the same vehicle as having the same cost as the entire vehicle (i.e. a chain of links). When any link in a vehicle is changed, the vehicle is transformed, and the cost must be recalculated according to its constituent links, the consistency of vehicle types, and the validation of built-in periods. This costing method is generally more complicated and time-consuming than the link-based costing method. Moreover, since the initial schedule and some intermediate schedules generated during the scheduling process may be infeasible (i.e. infeasible links exist in the schedules), a penalty costing...
method is also essential. Similarly, a chain-based penalty costing method is defined instead of a link-based method.

5. Implementation

The three projects presented in this paper have been carried out in China. Some results of the research are reported in this section.

5.1. Implementation of the comprehensive framework of public transit planning

During the projects that we have carried out since 2010 in China, a comprehensive framework of public transit planning (see Fig. 2) has been established and implemented. Fortunately, after several years of effort, it has been gradually accepted that a development plan of IPTS (e.g. in Fig. 3), as the traditional three items, should be an integral part of the public transit plan of a city in China. These four items (i.e. the traditional three items and the IPTS planning) belong to city government’s long-term planning, whereas the others (service planning and scheduling) in the framework belongs to a medium- or short-term planning.

In general, long- and short-term planning should not be in the same project. It can be anticipated that service planning and scheduling would become the major work in public transit planning while radical network route planning within the scope of the city would be replaced by adjusting some service routes and adding new routes when necessary in the future.

However, in the early stage of public transit reformation of China, demonstration of the new concepts has to be carried out within a well-known traditional project in order to attract more attention and correct misunderstanding. The research results, that is, the public transit plans, in our projects for Haikou and Shiyan have been approved by City Planning Committees, while the on-going project for Jingmen is close to being completed.

5.2. Implementation of the vehicle scheduling approach based on AVL data

The proposed approach for vehicle scheduling based on AVL data has been implemented and tested on a number of real-world problem instances in China. A case study on the Route 4 in Shiyan is described next.

Route 4 is a key route of SYBUS, which provides service between Shiyan Railway Station and Dongfeng Tyre Factory via the busiest street, Dongfeng Road. The outbound line contains 25 stops and the inbound line contains 27 stops. The bus service has to meet high levels of demand and heavy traffic congestion. The span of service is 5:30 a.m. to 23:00 p.m. and the headways in the peak are between two and three minutes. All of the vehicles on Route 4 are equipped with GPS-based AVL devices.

To prepare a sample of TTs, AVL data for October 2011 are first selected, from which 18,756 trips on Route 4 are extracted into the sample set. Then, the HRT bands for inbound and outbound directions are determined, respectively. In the outbound direction, for instance, the service span
Table 2
HRT bands for weekdays on Route 4 of SYBUS (outbound)

<table>
<thead>
<tr>
<th>Name</th>
<th>Early AM</th>
<th>AM peak</th>
<th>AM base</th>
<th>PM base</th>
<th>PM peak</th>
<th>Evening peak</th>
<th>Late evening</th>
</tr>
</thead>
</table>

![Probability Density](image1.png)  ![Cumulative Probability](image2.png)

Fig. 5. Probability density and cumulative probability of trip times (outbound).

Table 3
Scheduled trip times by HRT band (outbound, in minutes:seconds)

<table>
<thead>
<tr>
<th>HRT band</th>
<th>Early AM</th>
<th>AM peak</th>
<th>AM base</th>
<th>PM base</th>
<th>PM peak</th>
<th>Evening peak</th>
<th>Late evening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trip times</td>
<td>31:50</td>
<td>37:30</td>
<td>39:15</td>
<td>38:45</td>
<td>46:05</td>
<td>34:25</td>
<td>31:25</td>
</tr>
</tbody>
</table>

is automatically divided into 10 HRT bands, among which several are very small and can be further merged. Seven HRT bands are finally decided as listed in Table 2. Subsequently, the TT distribution at each HRT band is calculated. Examples are given in Fig. 5, where the probability density function and cumulative density function of the TTs during AM peak and PM peak are displayed. Furthermore, based on the distributions, a scheduled TT is proposed for each HRT band as shown in Table 3.

It should be noticed from Table 3 that the TT in the AM peak is shorter than that in the AM Base and PM Base, which is unusual. The reason is that Route 4 provides service via Dongfeng Road, which has very heavy traffic throughout the day, especially between 10:00 a.m. and 9:00 p.m. Meanwhile, the scheduled headways are decided based on the AVL records, as approved by the operators and mainly lie between two and three minutes as shown in Fig. 6.

Based on the scheduled headways and scheduled TTs, a vehicle schedule $S_i$ is compiled using the 2-opt heuristic approach presented in the previous section. The detailed information related to the costs of $S_i$ is listed in Table 4 in comparison with the manual schedule $S_0$. The schedule $S_0$ is reconstructed from the actual running records on October 11, 2011 and dispatchers’ knowledge,
Fig. 6. Scheduled frequency per hour on weekday of Route 4 (outbound).

Table 4
Summary of improved and initial schedules

<table>
<thead>
<tr>
<th>Cost</th>
<th>Manual schedule $S_0$</th>
<th>Improved schedule $S_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of vehicles</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>No. of service trips</td>
<td>740</td>
<td>740</td>
</tr>
<tr>
<td>Trip time</td>
<td>436:27</td>
<td>439:13</td>
</tr>
<tr>
<td>Deadhead time</td>
<td>00:00</td>
<td>0:00</td>
</tr>
<tr>
<td>Idle time at terminals</td>
<td>130:38</td>
<td>82:42</td>
</tr>
<tr>
<td>No. of temporary depot returns</td>
<td>7</td>
<td>22</td>
</tr>
<tr>
<td>Time temporarily spent at depot</td>
<td>35:32</td>
<td>78:17</td>
</tr>
<tr>
<td>Total operating cost</td>
<td>567:05</td>
<td>521:55</td>
</tr>
</tbody>
</table>

Table 5
Percentiles of the schedules in term of scheduled trip times

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Early AM</th>
<th>AM peak</th>
<th>AM base</th>
<th>PM base</th>
<th>PM peak</th>
<th>Evening peak</th>
<th>Late evening</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_0$</td>
<td>100th(39)</td>
<td>97th(69)</td>
<td>76th(58)</td>
<td>89th(123)</td>
<td>52th(27)</td>
<td>89th(44)</td>
<td>100th(10)</td>
<td>87th(370)</td>
</tr>
<tr>
<td>$S_i$</td>
<td>100th(34)</td>
<td>88th(65)</td>
<td>75th(64)</td>
<td>90th(115)</td>
<td>91th(36)</td>
<td>100th(41)</td>
<td>100th(15)</td>
<td>89th(370)</td>
</tr>
</tbody>
</table>

due to there being no compiled schedules in SYBUS, so $S_0$ could be viewed as a schedule compiled manually. The capital cost of a bus in China is typically 60–120 thousand dollars. The total operating cost is the sum of \( TT \), deadhead time and idle time at terminals. The deadhead time is a time when a vehicle runs without carrying passengers (including a pull-out from and a pull-in to a depot). The idle time at terminals is a time when a vehicle waits at a terminal between two consecutive running activities. A temporary depot return is allowed only when there is a long gap between consecutive service trips, and the gap plus the necessary deadhead is larger than some threshold length (e.g. at least two or three hours), during which the vehicle can be left without a driver.

Based on the cumulative density function calculated above, on-time percentile of a schedule can be calculated by counting the percentage of trips that can be completed on time. Table 5 shows the percentiles of the schedules $S_0$ and $S_i$ in terms of TTs for each HRT bands, where the digits in brackets denote the numbers of service trips lying in the corresponding HRT bands. It can be seen
that the schedule $S_i$ surpasses the schedule $S_0$ with same fleet size, lower operating cost and higher on-time probability.

5.3. Compilation of timetables for Jingmen

Seven of the 21 bus routes of JMBUS are selected to demonstrate the compilation of timetables, which are Routes 1, 3, 8, 11, 13, 22, and 36. Among these routes, some are high-frequency lines via downtown (e.g. 1, 3, 8), some are low-frequency lines bound for suburbs (e.g. 11, 22, 36), and some are across urban fringe areas (e.g. 13). The major purpose is to set up a demonstration of “running based on timetables” in China.

A case study on Route 3 is presented below. It is a key route of JMBUS, which provides service between Eco Zoo (or Duodao High School) and Longquan Villa via the busiest street, Xiangshan Avenue as illustrated in Fig. 7, where the bigger circles denote time points (usually main stops) while the smaller circles are ordinary bus stops. The Chinese characters beside bus stops are the stop names. For the convenience of reference, only the termini are translated into English with Chinese Pinyin. The length of the route is 14 km and there are 34 points in both the directions. The span of service is 5:35 a.m. to 21:50 p.m. The bus service has to meet high levels of demand and heavy traffic congestion. All of the vehicles are equipped with GPS-based AVL devices.

During the process of compiling timetables for Jingmen, the first four steps in Section 3.2 are employed as done in Shiyan. The difference from Shiyan is that a set of segment running times is considered instead of an entire TT. A segment is defined as the piece between two consecutive time points. In this project, the service reliability measurement (including analyzing frequency, the segment running time, and the dwell time at any time point) is carried out for each HRT band in a given segment individually. Based on such an exhaustive measurement, the frequencies and running times obtained (see Fig. 8) would be more precise, and then elaborate timetables are generated in a publishable format as shown in Fig. 9, where a map of the bus route is on the right, while the timetables for weekday and weekend are on the left.
Fig. 8. Frequencies and trip times of Route 3 (outbound).

Fig. 9. Elaborate timetables in a publishable format for Route 3.
The public transit planning project for Jingmen is still on-going. The compiled timetables have not been published, but have attracted the attention of the relevant officers in the city government of Jingmen and in the provincial government of Hubei.

6. Conclusions

The paper has presented the research on solving the practical public transit planning and scheduling problem in China, during which a comprehensive framework for public transit planning has been established, a new approach of scheduling vehicles based on AVL data is developed, and an idea of running based on timetables is embodied and visualized.

It is a case study relevant to developing countries. In contrast to the applications in the developed countries or to the theoretical research on algorithms, this research has its important features: it focuses on the enhancement of the cognition and means of public transit planning and scheduling; it forms comprehensive plans for the public transit of Haikou, Shiyan, and Jingmen and makes the IPTS plan widely accepted as an integral part; it mines the significant value of the AVL data to timetabling and vehicle scheduling; it implements in SYBUS the vehicle scheduling based on AVL data; and it embodies in JMBUS the idea of running based on timetables.

During the research, various ideas, methods, and techniques applied successfully in the developed countries have been adopted. However, China, as a developing country, is in a different development stage, especially the reform of public transit is still at an early stage. It becomes inevitable that transit authority and operators will encounter difficulties in accepting new concepts and adapting existing techniques to the particular problems of China. The innovative work presented in this paper, such as developing a vehicle scheduling approach based on AVL data, has enriched the research on public transit scheduling, but the most significant achievements are as follows: the public transit development plans for Haikou and Shiyan have been approved by City Planning Committees, of which the IPTS development plan has become an integral part. Meanwhile, developing adequate systems for service planning and scheduling is embedded in the IPTS plan. Furthermore, it is written into the text of the plan that the compilation of timetables and schedules should be carried out on all the routes gradually at regular intervals, which would benefit passengers, transit companies, and city government in terms of service level, management level, and operational cost. Although this research has been conducted for the three cities, the fruits of the research and practical experiences would be of great benefit to other cities in China and some other developing countries.

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