Hindawi Publishing Corporation
Mathematical Problems in Engineering
Volume 2013, Article ID 902562, 8 pages
http://dx.doi.org/10.1155/2013/902562

Research Article

Operational Impacts of Using Restricted Passenger Flow Assignment in High-Speed Train Stop Scheduling Problem

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Received 30 July 2013; Revised 1 October 2013; Accepted 29 October 2013

Academic Editor: Wuhong Wang

One key decision basis to the train stop scheduling process is the passenger flow assignment, that is, the estimated passengers' travel path choices from origins to destinations. Many existing assignment approaches are stochastic in nature, which causes unbalanced problems such as low efficiency in train capacity occupancy or an irrational distribution of transfer passengers among stations. The purpose of this paper is to propose a train stop scheduling approach. It combines a passenger flow assignment procedure that routes passenger travel paths freely within a train network and is particularly capable of incorporating additional restrictions on generating travel paths that better resemble the rail planner's purpose of utilizing capacity resources by introducing four criteria to define the feasibility of travel path used by a traveler. Our approach also aims at ensuring connectivity and rapidity, the two essential characteristics of train service increasingly required by modern high-speed rails. The effectiveness of our approach is tested using the Chinese high-speed rail network as a real-world example. It works well in finding a train stop schedule of good quality whose operational indicators dominate those of an existing stochastic approach. The paper concludes with a comprehensive operational impact analysis, further demonstrating the value of our proposed approach.

1. Introduction

As high-speed rail (HSR) networks are being constructed and expanded worldwide, rail operators face continuing problems of efficiently planning their high-speed train services. One such problem is the train stop scheduling problem (TSSP), which involves specifying a set or subset of stations within a HSR network where individual trains will stop. An efficient train stop schedule is crucial to improve train service connectivity, particularly for passengers whose origins and destinations (ODs) are not situated at limited terminals. On the other hand, the goal of scheduling many stops by a train on its route to ensure good connectivity conflicts with the goal of maintaining the rapidity of that train. From a practical perspective, a rail operator will always seek to maintain the most efficient schedule to provide the optimal balance between stop locations and frequencies.

Understanding passenger behavior requires a fundamental analysis to be conducted when designing services for any transportation modes [1]. For rail, a passenger flow assignment procedure is a key decision basis to develop a train stop schedule within a train network. Most of the work from the literature that deals with the TSSP concentrated on selectively allocating train stops at stations along a rail line or in a network, where train stop pattern combinations of the so-called non-stop (i.e., direct express), skip-stop, and all-stop are employed. Decisions regarding the number of stops made by a train and at which stations in the network those stops are to take place should be rationally built on a simulation of passengers' travel paths choice behavior. In principle, scheduling train stops (or any other train service plans) should be consistent with the specific passenger demand. Two optimization models with the objectives of covering more passenger demand with fewer train stops as well as saving more travel time for passengers were developed by Hamacher et al. A genetic algorithm was introduced and tested on a partial rail network in southern Germany [2]. In the context of The Netherlands' rail network, three types of stations and train lines are usually referred to as regional (R) or stop trains for type 1, interregional (IR) for type 2, and Intercity (IC) for type 3. Train lines of type 1 halt at all stations they pass. Lines of type 2 skip the small stations of type 1 and so forth. Goossens et al. established integer models combined with a multicommodity flow problem for multitype line planning problems to minimize operator's operating cost [3]. Using a 46 km long, six-station transit line in the northeastern US as the background, Ulusoy et al. optimized all-stop, short-turn, and express transit services by a cost-efficient operation model, and a logit-based model was used to estimate the ridership of all the seven pregiven train stop patterns [4]. In the setting of Taiwan's HSR line, Chang et al. formulated a multiobjective model with the TSSP embedded in that model to yield a train operation plan. The objectives included minimizing the operator's operating cost and the passengers' travel time loss. The model was solved by a fuzzy mathematical programming approach [5]. A bilevel programming model which was combined with a network equilibrium analysis of passenger flow assignment on trains in a lower-level problem was proposed by Lee and Hsieh. A numerical case study of the final train stop schedule included seven selectable train stop patterns among five stations along the line [6]. For the Beijing-Shanghai Chinese HSR line, Zhang et al. proposed a multiobjective 0-1 programming model to solve the TSSP. The objectives were minimizing train dwell time for travelers, improving the load of every train, and minimizing unsatisfied passenger demand for seven stations along the line [7]. Over a partial rail network mixed of both HSR and conventional rail lines, a bilevel programming model was applied by Deng et al. who exploited the user equilibrium theory to generate train stops together with a process of passenger flow assignment on trains [8].

From the aforementioned studies, we further examine three aspects of the TSSP, including two essential characteristics, connectivity and rapidity of a good train stop schedule, as well as the passenger flow assignment as follows. And we herein illustrate the motivation for this study.

(1) Typically, a binary decision variable defining a stop being added at a station on a train or not is adopted. In doing this, as the number of stations becomes larger, it turns out to be hard to ensure a complete connectivity, meaning that travelers cannot always reach their destinations using direct or transfer connections. To the best of our knowledge, the first approach in the direction of guaranteeing connectivity is the use of a mixed integer linear programming (MILP), in which a binary decision variable indicating whether stop(s) is (are) added on a train for a passenger OD is considered in the problem formulation, working well in finding satisfactory solutions (see [9]).

(2) Frequent train stops result in negative impacts including reducing train's rapidity, increasing passengers' total travel time as well as train operating cost. According to the literature, a common way to avoid the negative impacts of adding stops on trains is to define certain classes of trains and then restrict the total number of stops trains of each classification could make.

(3) In the planning phase, each rail line generally tends to be organized towards certain passenger ODs, and a few of the major stations in a network are designed with good transfer capabilities. Accordingly, an ideal train stop schedule would intentionally organize passenger traffic that better resembles planner's purpose (i.e., passengers may be appropriately guided towards corresponding train services through using tool, e.g., a seat reservation system). However, previous research has not incorporated this idea in their stochastic passenger flow assignment procedures in the TSSP.

The main goal of the present work is to investigate a train stop scheduling approach that retains good connectivity and rapidity while also being able to cope with intentionally organizing passenger traffic in the passenger flow assignment procedure. For the purpose of retaining connectivity and rapidity, we decided to build on the recent approach of Fu et al. [9], using the same way of defining the binary decision variable. As an improvement, a restricted passenger flow assignment will be used in this paper to replace their normal formulation.

The paper is organized as follows. In Section 2, we formally describe the nominal version of our TSSP and illustrate the associated MILP formulation. In Section 3, we modify the MILP formulation by introducing a new passenger flow assignment constraint to deal with rail planner's purpose as mentioned previously. Numerical examples on real-world instances from the Chinese HSR network are presented in Section 4. Conclusions and future research are discussed in Section 5.

2. The Nominal TSSP

In this section, we describe the nominal TSSP that we consider in this paper. We restrict ourselves to the HSR network case used by Fu et al. [9] to be able to compare with their method and briefly recall the assumptions prior to illustrating the MILP formulation. Generally, in a rail network, trains running within a single rail line are known as in-line trains, and trains running across at least two linked up rail lines are known as cross-line trains. Both in-line and cross-line train OD patterns and potential train operating frequencies are predetermined as inputs for the model. Also, the track capacity is sufficient to meet the passenger demand by operating trains with rational load factors.

2.1. Notation. In the nominal TSSP, the aim is to effectively utilize capacity resources and to minimize passengers' generalized cost using a combination of train stop patterns. Our underlying approach partly borrows from Fu et al. [9] the notations of parameters and variables which are outlined below:

$\mathscr{L}$: set of trains among the given train OD patterns, in which ℓ_k represent trains indexed by k (or v as shown in the underlying formulation).

$\varepsilon(\ell_k)$: the number of train stop patterns that could be generated for train ℓ_k in set $\mathscr{L}$.

$f(\ell_k)$: estimated operating frequency of train ℓ_k.

V: set of stations in network, in which v_i represent stations (that can also be indexed by j, p, or q).

$v_i(\ell_k)$: stations (may not be stops) on the route of train ℓ_k.

E: set of tracks in network, in which e_l represent tracks indexed by l.

D: set of passenger ODs, in which $d(v_i, v_j)$ represent passenger demand between station v_i and v_j.

$D'(\ell_k)$: the collection of possible passenger ODs for which stops can be added on train ℓ_k, and $D'(\ell_k) = \{(v_i, v_j) \in D \mid \ell_k \in (v_i, v_j)\}$.

$\mathscr{L}(v_i, v_j)$: the collection of possible trains on which stops can be added for a passenger OD (v_i, v_j), and $\mathscr{L}(v_i, v_j) = \{\ell_k \in L \mid (v_i, v_j) \in \ell_k\}$.

$\mathscr{L}(e_l)$: the collection of trains in set $\mathscr{L}$ with their routes covering track e_l.

$A(v_i, v_j)$: set of feasible travel sections for travelers of passenger OD (v_i, v_j) within the given train OD patterns.

$a_n(\ell_k)$: passenger travel sections in set $A(v_i, v_j)$ indexed by n (or m); each travel section is uniquely on one train ℓ_k.

$\kappa(\ell_k)$: seating capacity of train ℓ_k.

$h(v_i, v_j)$: route length between stations v_i and v_j.

$N(\ell_k)$: the maximum number of stops that can be added on train ℓ_k.

$\eta(v_i, \ell_k)$: count parameter of whether a stop being added at station v_i on train ℓ_k.

$Y((v_i, v_{i+1}), \ell_k)$: accumulative passenger flow assigned on train ℓ_k between two adjacent stations v_i and v_{i+1} on the train route.

$T(a_n(\ell_k))$: passengers' generalized cost on travel sections $a_n(\ell_k)$.

$\tau^{it}(a_n(\ell_k))$: in-vehicle time on travel sections $a_n(\ell_k)$.

$\tau^{vt}(a_n(\ell_k))$: time converted from the ticket fares by time value on travel sections $a_n(\ell_k)$.

$\tau^{rt}(a_n(\ell_k))$: wait time on travel sections $a_n(\ell_k)$.

$\delta^{it}, \delta^{vt}, \delta^{rt}$: weights of generalized cost components.

$x((v_i, v_j), a_n(\ell_k))$: binary variable, it is 1 only if for passenger OD (v_i, v_j), stops are added on train ℓ_k; else it equals 0.

$y((v_i, v_j), a_n(\ell_k))$: variable of the passenger flow of OD (v_i, v_j) assigned on train ℓ_k with stops added on it.

2.2. Problem Formulation. The nominal MILP formulation for the TSSP is as follows:

$$\min \sum_{\ell_k \in \mathscr{L}} \sum_{v_i(\ell_k) \in V} \left(\kappa(\ell_k) \cdot f(\ell_k) - Y((v_i, v_{i+1}), \ell_k)\right) \cdot h(v_i, v_{i+1}), \tag{1}$$

$$\min \sum_{(v_i, v_j) \in D} \sum_{a_n(\ell_k) \in A(v_i, v_j)} T(a_n(\ell_k)) \cdot y\left((v_i, v_j), a_n(\ell_k)\right) \tag{2}$$

$$\text{s.t.} \quad \sum_{\ell_k \in \mathscr{L}(v_i, v_j)} y\left((v_i, v_j), a_n(\ell_k)\right) = d(v_i, v_j), \quad \forall (v_i, v_j) \in D, \tag{3}$$

$$\sum_{\ell_k \in \mathscr{L}(v_i, v_j)} x\left((v_i, v_j), a_n(\ell_k)\right) \cdot \kappa(\ell_k) \cdot f(\ell_k) \geq d(v_i, v_j), \quad \forall (v_i, v_j) \in D, \tag{4}$$

$$\sum_{(v_i, v_j) \in D'(\ell_k) : a_n(\ell_k) \supseteq e_l} y\left((v_i, v_j) \cdot a_n(\ell_k)\right) \leq \kappa(\ell_k) \cdot f(\ell_k), \quad \forall e_l \in E, \ell_k \in \mathscr{L}(e_l) \tag{5}$$

$$\sum_{v_i \in V} \eta(v_i, \ell_k) \cdot x\left((v_i, v_j), a_n(\ell_k)\right) \leq N(\ell_k), \quad \forall \ell_k \in \mathscr{L}, \tag{6}$$

$$y\left((v_i, v_j), a_n(\ell_k)\right) \leq M \cdot x\left((v_i, v_j), a_n(\ell_k)\right), \quad \forall \ell_k \in \mathscr{L}, \quad (v_i, v_j) \in D, \tag{7}$$

$$x\left((v_i, v_j), a_n(\ell_k)\right) \in \{0, 1\}, \quad \forall \ell_k \in \mathscr{L}, (v_i, v_j) \in D, \tag{8}$$

$$y\left((v_i, v_j), a_n(\ell_k)\right) \in \mathbb{R}_+, \quad \forall \ell_k \in \mathscr{L}, (v_i, v_j) \in D. \tag{9}$$

Objective function (1) minimizes total trains' deadhead kilometers, where

$$Y((v_i, v_{i+1}), \ell_k) = \sum_{v_j \in V} \sum_{a_n(\ell_k) \in A(v_i, v_j)} y\left((v_i, v_j), a_n(\ell_k)\right), \quad \forall v_i(\ell_k) \in V. \tag{10}$$

Passengers' generalized cost in objective function (2) consists of three parts: in-vehicle time, consuming time converted from the ticket fares by time value, and wait time. Thus, $T(a_n(\ell_k))$ extends as

$$T(a_n(\ell_k)) = \delta^{it} \cdot \tau^{it}(a_n(\ell_k)) + \delta^{vt} \cdot \tau^{vt}(a_n(\ell_k)) + \delta^{rt} \cdot \tau^{rt}(a_n(\ell_k)). \tag{11}$$

Because train sets running on the same section do not necessarily operate at a uniform speed, different passengers for a given OD may have different in-vehicle time. Similarly, the ticket fares pricing would adopt a differentiation strategy in terms of either train speed classifications or being based on in-line trains and cross-line trains. Wait time depends on train operating frequencies.

Constraint (3) imposes passenger flow conservation in the assignment process. Demand-supply constraints are illustrated in (4) and (5). Constraint (4) ensures the total train stop frequencies at a given station are adequate to meet the passenger demand requirements. Constraint (5) denotes that the flow of different passenger ODs assigned on a given train ℓ_k should not exceed that train's seating capacity. The condition of "$a_n(\ell_k) \supseteq e_l$" means that only passenger OD(s) using travel sections $a_n(\ell_k)$ which pass through track e_l is (are) taken into account. Constraint (6) limits the maximum number of stops on train ℓ_k. The count parameter $\eta(v_i, \ell_k)$ equals 0 if a stop will not be added at station v_i; and equals 1 if station v_i is to be added as a stop for more than one passenger OD. Constraint (7) ensures that if stop(s) is (are) not added on train ℓ_k for passenger OD (v_i, v_j), its flow assigned on train ℓ_k equals 0; M is a very large positive number. Finally, the two types of decision variables are restricted in constraints (8) and (9).

3. Our TSSP with Restricted Passenger Flow Assignment

Passengers may have a large set of travel paths from which they choose without any restrictions. A main drawback of the nominal TSSP illustrated in the previous section is that it assigns passengers onto trains in a stochastic way, not taking into account guiding passengers towards certain train services on planner's capacity resources allocation strategy. Stochastic assignment can strongly affect the quality of train capacity occupancy, causing unbalanced problems; for example, short-distance travelers may preempt seats of long-distance travelers and be served by a long-distance train, while long-distance travelers are expelled out of that service. Additionally, the formulation ignores and is not easy to describe transfer behavior of travelers. Therefore, train service connectivity for travelers that mostly obtained from scheduling additional train stops would instead depend on the quality of the given train OD patterns.

To overcome these problems, and stimulated by applications of routing passenger travel paths freely in a public transit network discussed by, for example, Goossens et al. [3] and Borndörfer et al. [10], we convert the nominal TSSP into a TSSP embedded with a multicommodity flow problem (MCFP) by modifying constraint (3). Subsequently, we are able to assign passengers onto trains in a restricted way, via incorporating additional restrictions on generating passenger travel paths. Our modified version of the MILP model (1)–(9) includes objective functions (1) and (2), constraints (4)–(9) but uses the following new constraint:

$$\sum_{v_q \in V, a_m(\ell_k) := (v_p, v_q)} y\left(\left(v_i, v_j\right), a_m\left(\ell_k\right)\right) - \sum_{v_q \in V, a_n(\ell_k) := (v_q, v_p)} y\left(\left(v_i, v_j\right), a_n\left(\ell_k\right)\right) = \begin{cases} d\left(v_i, v_j\right) & \text{if } v_p = v_i \\ 0 & \text{if } v_i \neq v_p \neq v_j \\ -d\left(v_i, v_j\right) & \text{if } v_p = v_j, \end{cases} \quad \forall \left(v_i, v_j\right) \in D, \; v_p \in V. \tag{12}$$

In both versions of the MILP models, the passenger flow is assigned on a section (i.e., arc) basis (the reader interested in the MCFP applied for passenger flow assignment on a path basis is referred to, e.g., [11]). A travel section in the nominal version equates to a travel path. Comparatively, since transfer can be considered in constraint (12), a travel path now becomes splittable. That is to say, a travel path consists of at least one travel section, two travel sections compose a travel path if one transfer occurs during one single trip, and so forth. Accordingly in the modified version, we attach transfer time on travel sections $a_n(\ell_k)$ in (11) denoted by $\tau^{tt}(a_n(\ell_k))$ and assign a weight δ^{tt} to them; (11) thus reads

$$T\left(a_n\left(\ell_k\right)\right) = \delta^{it} \cdot \tau^{it}\left(a_n\left(\ell_k\right)\right) + \delta^{vt} \cdot \tau^{vt}\left(a_n\left(\ell_k\right)\right) + \delta^{rt} \cdot \tau^{rt}\left(a_n\left(\ell_k\right)\right) + \delta^{tt} \cdot \tau^{tt}\left(a_n\left(\ell_k\right)\right). \tag{13}$$

Apparently, $\tau^{tt}(a_n(\ell_k))$ is not equal to zero only if the section is a part of one travel path with transfer(s).

As the foundation of producing restrictions on generating passenger travel paths, we first recall the rail planner's purpose as already mentioned in the introduction section and make some further interpretations. A passenger rail line as part of a rail network is built, generally, tending to be organized towards certain passenger ODs along the corridor of priority. For the sake of efficient train capacity occupancy, in-line travelers should be organized onto in-line trains as much as possible, which is a practical representation of the important principle of that passenger travel distance should match train trip distance. Second, to adapt to passenger distributing capacity, stations with eligible facilities are recommended as main transfer hubs spread all over the entire rail network. From a functional perspective, transfer hubs have good performance if one transfer occurs within the same platform, and trains have convenient as well as fast connections with other high-speed or conventional trains or urban public transport.

We next illustrate our adopted restrictions in consideration of rail planner's objectives when generating passenger travel paths in the MCFP. A general rule is to limit a feasible travel paths set for passengers of each OD, using two primary criteria as follows.

(1) A travel path, or a travel section being part of a path with transfer(s) possible for passengers of a certain OD is feasible, only if the ratio between the length itself and the trip distance of a train onto which passengers are probably assigned is greater than a given baseline value (notated as μ).

(2) A travel path with transfer(s) is feasible if the transfer hub(s) is (are) selected from recommended stations.

From the viewpoint of providing better quality train services, alternative restrictions include the following:

(3) a controlled percentage of nonstop trains for travelers are provided;

(4) a single passenger is not required to transfer more than once during a single trip.

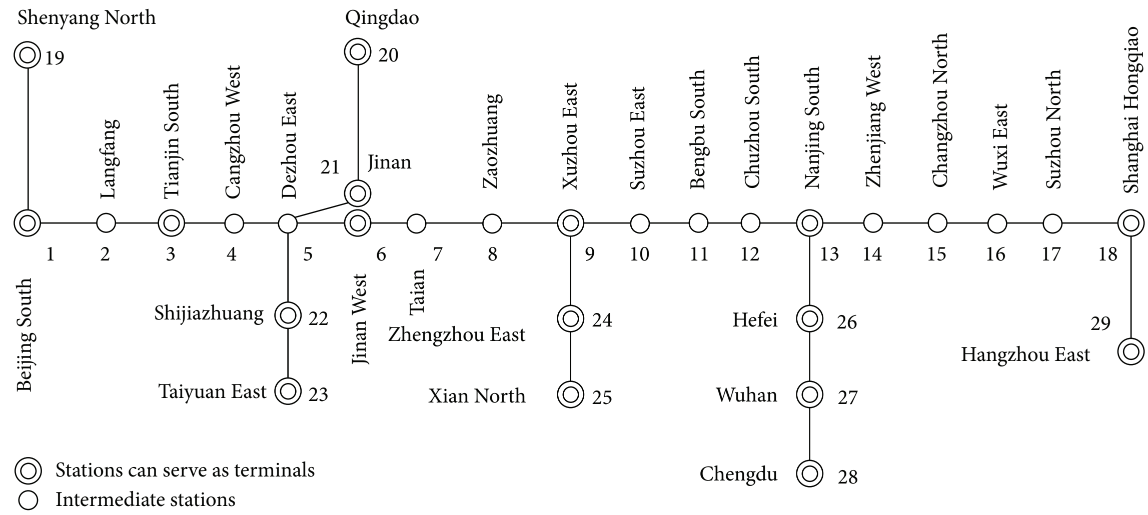

Figure 1: Topology of study HSR network.

Of course, many other restrictions on paths generation are allowed in practice; a rail operator could adopt many other criteria to define the feasibility of a path and choose a desirable set of paths, depending on the specific requirements. For example, even if criterion (1) is met, a rail operator could additionally delete travel paths on a train if that train precedes other trains not serving passengers among smaller stations. Certain travel paths could be likewise specified to passengers, for whom, in extreme case, no travel paths can be found by following the given criteria.

4. Numerical Examples

4.1. Data Set. This section presents a numerical test of the proposed approach for the TSSP using data from a real-world example on the Chinese railways. We focus our attention on the example adopted by [9] to allow for comparisons. For the sake of clarity, we stretch their real-world HSR network to be a topology with each station numbered as shown in Figure 1. Additional information reflecting each line or section's operating condition is shown in Table 1. For the 2015 forecast year, our numerical example includes a total of 303 passenger ODs and total 453,205 passenger traffic per day associated with the Jinghu HSR (the center of the network, we abbreviate it as JHSR in the following). Due to data sizes, passenger flow OD matrix is not shown but is available from the authors. Table 2 shows the train OD patterns as given from the operational plan, which includes 7 in-line trains and 29 cross-line trains for the JHSR network. Other input parameters of our models are specified in Table 3.

4.2. Discussion of Results. Progressing to our appropriate code based on the original one (used in [9]), both models in two versions were applied to the network and solved on an Intel i5 2.4 GHz with 2 GB RAM in the environment of Microsoft Windows XP using the Lingo 10.0 optimizer. Note that in the modified version, we incorporated all the four restrictions into predetermined feasible travel paths set. In addition to the already mentioned criteria, we provided that the terminal stations in Figure 1 served as transfer hubs, and 70 percent of travelers of one OD were organized towards nonstop trains with load factor not less than 0.85. During the solving process, a layered sequence method was employed to convert the multiobjective problem to a single-objective one. The models were first solved under single-objective (1); its optimization results were put into constraints as

$$\sum_{\ell_k \in \mathscr{L}} \sum_{v_i(\ell_k) \in V} \left(\kappa\left(\ell_k\right) \cdot f\left(\ell_k\right) - Y\left(\left(v_i, v_{i+1}\right), \ell_k\right)\right) \cdot h\left(v_i, v_{i+1}\right) = M^* \tag{14}$$

with M^* being the optimum solution; afterwards the problems were optimized under single-objective (2).

Using a branch-and-bound algorithm, our restricted TSSP took 57 minutes of computing time to find an optimum solution compared to 36 minutes for the nominal TSSP. The final train stop schedule obtained for the restricted TSSP is displayed in Table 4 and a comparison of our method with the method for the nominal TSSP is shown in Table 5. Due to the increase in complexity, as expected, the efficiency gotten for our solution is lower than that of the nominal one, but the gain in most operational indicators (to be discussed later) is quite significant and confirms the effectiveness of the proposed approach. Because the TSSP has to be solved in the planning phase, the computing time is acceptable.

According to Table 5, although it is a straightforward modification of an existing approach for the nominal case, our approach turns out to be effective in scheduling train stops of good quality, as indicated by operational metrics which clearly dominate those of the nominal TSSP. In spite of the differences, the two schedules have some similarities. First, both methods result in a flexible combination of train stop patterns, that is, nonstop, skip-stop, and all-stop. However, an "all-stop" train stop pattern is only recommended for short- or medium-distance trains (e.g., the train from station 13 to 18). Another similarity between the two methods is

Table 1: Line or section information of study HSR network.

HSR line or section	The year in operation	Approximate length (km)	Speed classification (km/h)
Jinghu (1-18)	2011	1,318	350
Jingshen (1-19)	—	676	350
Jiaoji (21-20)	2008	362	200~250
Shijiazhuang-Dezhou	—	180	250
Shitai (22-23)	2009	190	250
Zhengxu (24-9)	—	360	350
Zhengxi (24-25)	2010	458	350
Hening (26-13)	2008	166	200
Hewu (26-27)	2008	356	200
Wuhan-Chengdu	—	1,260	200
Huhang (18-29)	2010	158	350

"—" indicates that the rail line or section is planned or not completely in operation.

Table 2: The given train OD patterns.

In-line train ODs	Cross-line train ODs	Train ODs for transfer connections only
(1, 13) (1, 18) (3, 18) (6, 13) (6, 18) (9, 18) (13, 18)	(1, 20) (1, 26) (1, 29) (3, 20) (3, 27) (3, 29) (6, 19) (6, 27) (6, 29) (9, 20) (9, 26) (9, 29) (13, 20) (13, 23) (13, 25) (13, 29) (18, 19) (18, 20) (18, 23) (18, 25) (18, 24) (18, 28) (18, 27) (18, 26) (20, 19) (20, 27) (20, 25) (29, 25) (29, 24)	(19, 1) (20, 21) (23, 6) (25, 9) (24, 9) (28, 13) (27, 13) (26, 13) (28, 27) (28, 26)

Table 3: Input parameters of the models.

Parameter	Value or descriptive calculation
Split coefficient $\varepsilon(\ell_k)$	11 for in-line trains and 3 for cross-line trains
Seating capacity $\kappa(\ell_k)$	1,060 seats/train-set
Number of train stops $N(\ell_k)$	Maximum of 7 times for in-line trains, and 8 for cross-line trains
In-vehicle time $\tau^{it}(a_n(\ell_k))$	Train route length $h(v_i, v_j)$ /train travel speed (accommodates to the rail line's speed classification)
Consuming time $\tau^{vt}(a_n(\ell_k))$	Ticket fares (0.55 RMB/km for 350 km/h train, 0.45 RMB/km for other trains) $\times$ $h(v_i, v_j)$ /time value of passenger (45 RMB/h on average)
Wait time $\tau^{rt}(a_n(\ell_k))$	$0.50/f(\ell_k)$: a fraction (taken as 0.50 here) of headway which is the inverse of a train's operating frequency
Transfer time $\tau^{tt}(a_n(\ell_k))$	30 minutes
Weights δ^{it}, δ^{vt}, δ^{rt}, and δ^{tt}	0.39, 0.28, 0.12, 0.21
Baseline value μ	0.80 for in-line travelers and 0.50 for cross-line (transfer) travelers

that, in the interaction with objective functions, the obtained train stop schedules perform even better. For instance, under the schedule for the restricted TSSP, 73 percent of trains are assigned to a number of stops less than restricted as compared with 65 percent by the nominal TSSP. This difference is due to a hard rule applied in the restricted TSSP that more nonstop trains are allowed operations, and the consequence arising from this influences the average train travel speeds in the same way. In both methods, the entirely assured connectivity for travelers is not surprising because travelers are always tracked on which train(s) they are assigned and stops are accordingly determined by defining such type of a decision variable. For example, the train "9-11-13-14-17-18" stops at four intermediate stations for estimated travelers of 10 passenger ODs assigned on it, even though in practice, travelers of all 15 combinatorial passenger ODs can be absolutely served by that train. Therefore, from a practical perspective, the number of possible passenger OD combinations served by each train is necessarily higher than the measures from the computing results of passenger flow assignment.

The indicator of realized passenger traffic represents a notable difference between the two methods. The realized passenger traffic of our restricted TSSP is significantly larger. As already mentioned in Section 3, this is achieved by allowing transfers in travel paths. However, the gain in reducing passengers' generalized cost is not that much higher when compared to the nominal TSSP. To make a more accurate comparison, we calculate generalized cost on the scale of

Table 4: Train stop schedule estimated from the method of our restricted TSSP.

Train OD	Train route no.	Train stop pattern with station sequence
In-line trains		
1, 13	1	1-9-13
	2	1-2-4-8-9-10-11-12-13
1, 18	1	1-18
	2	1-3-18
	3	1-3-6-13-18
	4	1-3-5-6-7-13-18
	5	1-3-6-11-13-16-17-18
	6	1-2-3-5-7-8-9-16-18
	7	1-2-3-4-5-9-15-17-18
	8	1-2-3-6-9-10-11-13-18
	9	1-2-3-4-9-10-12-14-18
	10	1-3-6-9-11-13-15-17-18
3, 18	1	3-18
	2	3-6-18
	3	3-6-9-18
	4	3-5-6-7-8-15-17-18
	5	3-4-5-6-7-8-12-17-18
6, 13	1	6-13
	2	6-7-9-10-11-12-13
6, 18	1	6-9-18
	2	6-13-18
	3	6-7-8-9-14-16-17-18
	4	6-10-11-12-13-16-17-18
9, 18	1	9-13-18
	2	9-11-13-14-17-18
13, 18	1	13-18
	2	13-14-15-16-17-18
Cross-line trains		
1, 20	1	1-3-20
	2	1-2-3-4-5-20
1, 26	1	1-3-6-9-26
	2	1-3-5-6-8-11-26
	3	1-3-4-5-6-7-9-10-11-26
1, 29	1	1-3-6-9-13-29
3, 20	1	3-5-20
3, 27	1	3-9-13-26-27
	2	3-4-7-10-12-27
3, 29	1	3-5-6-10-11-13-18-29
19, 6	1	19-1-5-6
6, 27	1	6-8-26-27

Table 4: Continued.

Train OD	Train route no.	Train stop pattern with station sequence
6, 29	1	6-7-9-29
	2	6-8-13-18-29
20, 9	1	20-6-9
9, 26	1	9-11-26
9, 29	1	9-11-13-17-29
20, 13	1	20-6-13
23, 13	1	23-22-6-7-8-10-11-13
25, 13	1	25-9-13
13, 29	1	13-18-29
	2	13-14-15-16-17-18-29
19, 18	1	19-1-3-6-9-13-18
	2	19-2-7-8-9-10-11-13-17-18
	3	19-2-4-5-9-13-14-15-16-18
20, 18	1	20-6-14-15-16-17-18
23, 18	1	23-22-9-14-15-16-17-18
25, 18	1	25-9-12-13-18
	2	25-9-10-11-13-14-15-16-17-18
24, 18	1	24-9-13-18
	2	24-9-10-11-12-14-15-16-17-18
28, 18	1	28-13-17-18
27, 18	1	27-13-15-16-17-18
26, 18	1	26-13-18
	2	26-13-15-16-17-18
19, 20	1	19-3-4-5-20
20, 27	1	20-9-10-11-27
20, 25	1	20-6-8-25
25, 29	1	25-9-12-13-18-29
24, 29	1	24-9-13-18-29

an individual traveler. For the case of the restricted TSSP, the total passengers' generalized cost is 3.59392×10^6 (h) while the cost is 3.12417×10^6 (h) for the nominal TSSP. This represents a saving of approximately 0.27 hours per traveler. This small but meaningful amount of time saving is attributed to that, in the restricted TSSP, the decrease of travel time via operating nonstop trains is greatly offset by the increase of transfer time.

The effectiveness of the approach of our restricted TSSP is also supported by another operational indicator. It is apparent from Table 5 that the matching degree measured by μ for the nominal TSSP is much lower, since no limitation is imposed on μ when assigning each passenger to his optimal itinerary. An operational outcome of this result is that the average train deadhead kilometers is nearly 4 percent higher in the nominal TSSP compared to our restricted TSSP.

Table 5: Comparison of operational indicators between methods for our restricted TSSP and the nominal TSSP.

Operational indicator	Restricted TSSP	Nominal TSSP
Using combinatorial train stop patterns or not	Yes	Yes
Percentage of trains with number of stops less than restricted (%)	73	65
Average train travel speed (km/h)	301	294
Realized passenger traffic by train services (people)	453,205	380,772
Connectivity degree for realized passenger traffic (%)	100	100
Percentage of travelers organized onto nonstop trains (%)	33	21
Matching degree measured by μ (%)	100	51
Percentage of transfer passengers (%)	9	0

Transfer hubs in travel paths are distributed at stations mostly on the JHSR as restricted by the model. Stations 1, 3, 6, 9, and 13 assemble approximately 92 percent of transfer passengers. Due to being covered by travel paths of a larger amount of cross-line passenger ODs in this instance, stations 9 and 13 together are estimated to have a higher probability of being transfer hubs selected by approximately 65 percent of transfer passengers. Obviously, there are clear benefits in assisting rail operator to plan passenger transfer organization work as part of the TSSP and, as an added benefit, the inconvenience of making a transfer connection is reduced relative to the convenience of direct connection.

5. Conclusions

Rail operators develop train stop schedules with the goals of retaining good connectivity and rapidity to travelers while also in the face of requirements for capacity resources utilization. In this paper, we have shown how to incorporate restricted passenger flow assignment into a TSSP formulation to achieve this purpose. To this end, two procedures need to be implemented: (1) introducing the MCFP constraint intended to route passenger travel paths freely and (2) during passenger travel paths generation, establishing four criteria to produce restrictions so that the operator can collect a desirable set of travel paths. Our approach has been applied to a real-world HSR network case from the Chinese railways along with a comparison with a nominal train stop scheduling method that uses stochastic passenger flow assignment. The results showed that our approach is very competitive and obtains a train stop schedule solution of good quality in acceptable computing time. Future direction of research into efficient formulation of the TSSP can be devoted to collaboratively optimize train operating frequency which is treated as constant value in the present paper.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This work was supported by the Fundamental Research Funds for the Central Universities (Beijing Jiaotong University) under Grant no. 2013JBM042. The authors are grateful to the referees for their valuable comments and suggestions.

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