

Research Article

Improving Synchronization in an Air and High-Speed Rail Integration Service via Adjusting a Rail Timetable: A Real-World Case Study in China

Yu Ke ¹, Lei Nie ¹, Christian Liebchen,² Wuyang Yuan ¹ and Xin Wu ^{1,3}

¹School of Traffic and Transportation, Beijing Jiaotong University, 100044 Beijing, China

²Technische Hochschule Wildau, Hochschulring 1, 15745 Wildau, Germany

³School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ 85281, USA

Correspondence should be addressed to Lei Nie; lnie8509@yahoo.com

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Air and high-speed rail (AH) integration services are gaining ground with the development of the high-speed railway and airline industries. A well-designed feeder train timetable with good synchronization is of great significance in an AH integration service, because it can improve the connectivity at transfer nodes and offer more opportunities for intermodal passengers to travel. In this study, we propose a multi-objective model of a feeder railway timetable problem in an AH integration service to improve synchronization. The aims of the optimization model are to maximize the number of synchronizations and the coverage of synchronized flights, as well as to minimize the transfer penalties of passengers. We focus on a scenario of a partial subnetwork in which one direction of a two-direction railroad line with one transfer station is considered. The model is applied to Shijiazhuang Zhengding International Airport, China. The results illustrate the effectiveness of the approach developed in the paper.

1. Introduction

With the rapid development of the airline and high-speed rail (HSR) industries, the two transport modes have moved beyond competition and into cooperation in some particular cases [1]. Many airports around the world are connected to railway systems, which facilitates the integration of transport modes. In this case, the rail trip usually serves as a leg of the journey as a substitute for short-haul feeder flights. Givoni and Banister [2] summarized the benefits of intermodal services for airlines, airports and railways, such as alleviating capacity constraints at major airports, expanding the catchment area, addressing environmental issues, etc.

Due to their advantages, air and high-speed rail (AH) integration services are provided all over the world. Historically, this type of service originated in Europe. In 1994, the Charles de Gaulle Airport TGV station was designed as a tool for expanding the airport capacity in France. Many cities, such as Brussels and London, can be reached within 3 hours by train from the TGV station in the airport [3]. In Germany, the AH integration service dubbed

“AIRail” was created in 2001 with the German train operator Deutsche Bahn, network carrier Lufthansa and airport operator Fraport as cooperation partners. This project successfully integrated ticketing and baggage and allowed the use of any train from any station in Germany to reach the airport and vice versa [4]. Until 1993, an earlier service had been dedicated exclusively to airplane ticket holders: from 1982 on, the Lufthansa Airport Express trains connected the intercontinental flight services of the Frankfurt airport with the city centres of Bonn, Cologne and Dusseldorf, as well as Stuttgart later on [4], at speeds of up to 200 km/h.

Presently, AH integration services are extending to Asian countries, especially China, where intermodal travel is well supported by the existing infrastructure. China has a vast territory and AH integration services can enhance the service accessibility of various locations. The rapid development of the HSR and airline industries over the past few years represents a valuable opportunity for AH integration services. By 2018, China had the world's largest HSR network, amounting to 29,000 km of HSR coverage, with speeds between 200 km and 350 km per hour. Meanwhile, air transport has also developed

rapidly. The number of civilian airports amounts to 235, and there are 37 airports with a yearly throughput of more than 10 million passengers. Moreover, there are currently 10 integrated hubs in which airports are linked to HSR stations. Some AH integration service products are offered in China. For example, China Eastern Airlines works with the Shanghai Railway Bureau to attract passengers from nearby cities to the Shanghai Hongqiao and Pudong airports by offering integrated air-HSR tickets [5].

Transfer is important in an AH integration service. Passengers who use AH integration services have to transfer between trains and flights to complete their travel, and they are more concerned with service connectivity and transfer coordination [6]. The connection times between two modes should be neither too short, such that there is not sufficient time for passengers to transfer from HSR trains to aircrafts, nor too long, making the total travel time unacceptable and discouraging transit use. Li and Sheng [7] found that an AH intermodal service becomes less attractive with increasing connection times. When the connection time exceeds a certain threshold, an AH integration service will lose its competitiveness.

The transfer quality improvement is especially important when the train frequencies on the lines under consideration are low. For transfers from trains to flights, a high frequency of trains means that passengers have enough opportunities to select the trains with appropriate transfer times. In Germany, the average frequency of daily trains exceeds 90 (here, the number of train services is summed across all directions, but for each passenger, the number of train services that are offered on her route, is the even more relevant criterion) at the airports which are equipped with long-distance railway stations, including Frankfurt, Düsseldorf, Cologne-Bonn, and Leipzig/Halle [4]. Among these stations, Frankfurt has the maximum frequency of 358. Dense synchronized timetables provide plenty of connections with appropriate transfer times. However, when train frequencies at some airport train stations are low, passengers may spend additional waiting time, or lack enough time during the process of transferring. This may discourage people from using AH integration services.

Designing a synchronized timetable for AH integration services is an effective way to improve the quality of transfers, and it requires cooperation between the rail and air operator. However, currently, there is no intermodal institution to offer a coordinated timetable for rail and air transport in China. Flight timetabling involves coordination between the Civil Aviation Administration of China (CAAC), airline companies, airports and other stakeholders (the CAAC is responsible for air transport safety and administers seven regional civil aviation administrations. Some airlines (Tier-1) which were split from the CAAC's airline operations are the largest state-owned airlines, and some airlines (Tier-2) are subsidized by local government. In addition, there are some fully privately owned airlines (Tier-3). Airports in China are owned and operated by the airport authorities of local governments [8]). Railway timetabling is scheduled uniformly by the China Railway Corporation (CRC) (the CRC is the national railway operator and is in charge of construction, operation, and management). From the perspective of management, it is easier to adjust a railway timetable because railway timetabling involves only one operator. Therefore, in this paper, synchronization is improved by adjusting a feeder HSR timetable in an AH integration service.

We propose a multi-objective optimization model of a feeder HSR timetable problem in an AH integration service to maximize the number of synchronizations and the coverage of synchronized flights, as well as to minimize the transfer penalties of passengers, aiming at improving synchronization.

1.1. Number of Synchronizations. The first objective is to maximize the number of synchronizations in the AH integration service by adjusting the current rail timetable. In this study, we redefine synchronization as follows: if the interval between the arrival of a train and the departure of a flight (or the arrival of a flight and the departure of a train) at a transfer node is within a separation time window, we say a synchronization is reached in the AH integration service. This definition is extended from those of Ceder et al. [9] and Eranki [10], who focused on bus networks. Maximizing synchronization to optimize the transfers is important for operators and passengers [11]. In an AH integration service, a synchronized timetable can improve the connectivity at transfer nodes and offer more opportunities for passengers to travel. Meanwhile, it might bring several concomitant benefits such as creating induced intermodal passengers.

1.2. Coverage of Synchronized Flights. We should also consider the coverage of synchronized flights while improving the synchronization number between trains and flights. Assuming that the major leg of an AH-itinerary is the flight, then this perspective aims to make the largest number of flights accessible by train. Notice that the highest number of synchronizations and the highest number (maximum coverage) of synchronized flights are not necessarily equivalent. A small case is used to illustrate this problem as shown in Figure 1. We assume that the appropriate transfer time range from the HSR station to the airport is 1-2 hours. Figure 1(a) shows the flight plan and the initial train schedule before adjusting the rail timetable. Only two synchronization events are valid and the number of synchronized flights is two. The timetabling model, aiming only to maximize the number of synchronizations, has many solutions, and Figure 1(b) illustrates one of them. When the second train arrives 15 minutes early, the number of synchronizations increases to three and the coverage of synchronized flights remains unchanged. Another solution, shown in Figure 1(c), optimizes the synchronization and the coverage. The former number is 3, but the coverage number increases to 3, which means that any of the flights has corresponding feeder trains. As the seat capacity of a train is much larger than that of an aircraft, this is further motivation to preferably cover a flight that was not covered before, instead of covering a flight that was already covered by one train with a second train. The improvement of coverage will improve the accessibility and attract flight passengers to arrive at the airport by HSR. Hence, the optimization of the coverage of synchronized flights is regarded as a further objective.

1.3. Transfer Penalties of Passengers. Moreover, given a valid synchronization event, intermodal passengers perceive transfer times differently. We still take transfers from trains to flights as an example. In a transfer node, some passengers prefer short transfer times for quick trips, while some passengers would like to spend some additional waiting time to guarantee that they can get to their flights, even with the

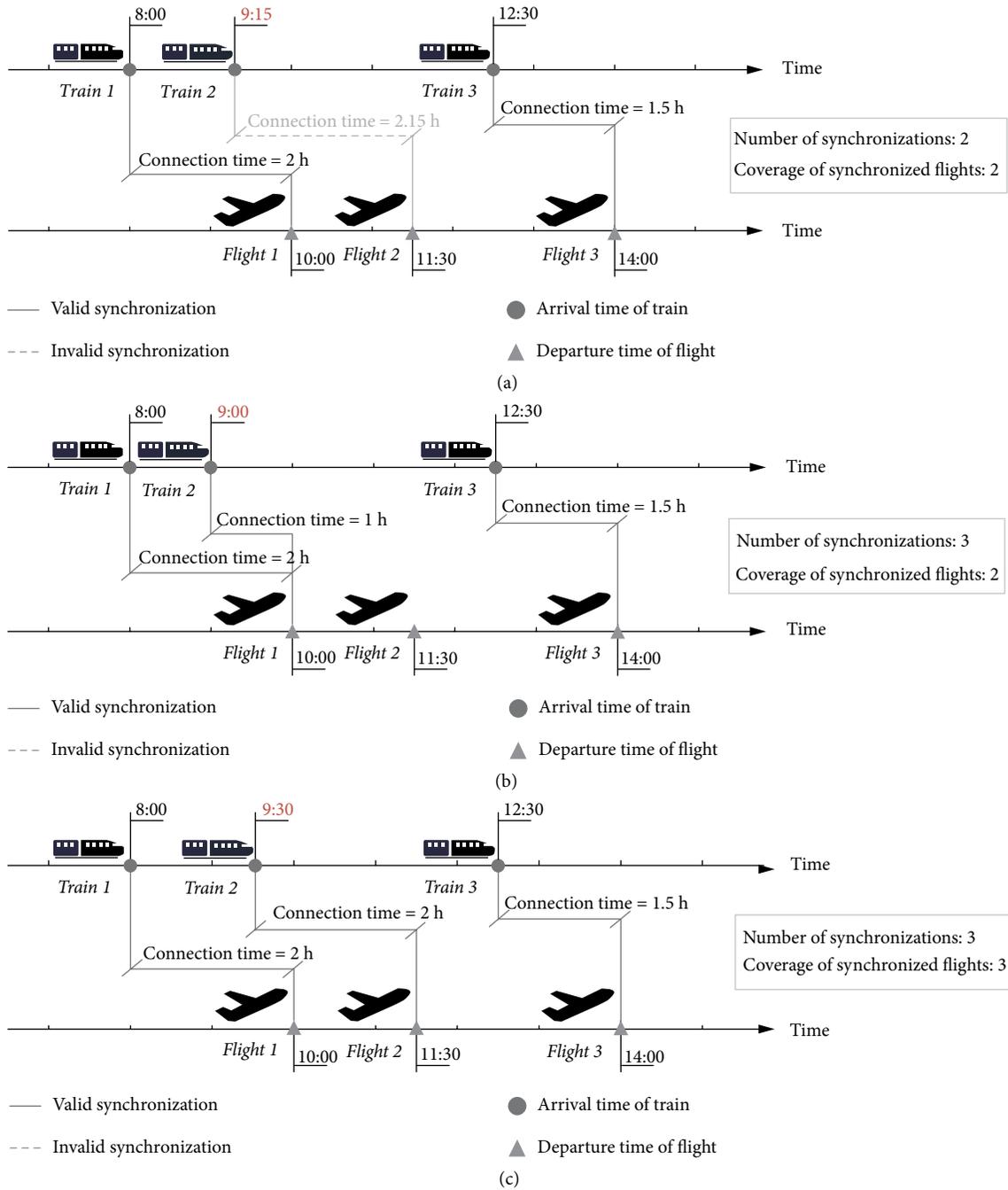


FIGURE 1: Number of synchronizations and coverage of synchronized flights.

long queues at baggage drop-off and security check. For this reason, we will introduce transfer penalization functions representing the different preferences of passengers. This leads to a minimization of penalties which is the third objective.

The remainder of this paper is organized as follows. First, in Section 2, we present a literature review. In Section 3, an extended HSR timetable model of improving synchronization in AH integration services is developed. In Section 4, the Shijiazhuang Zhengding International Airport serves as a model illustration, and comparison analyses are conducted. Finally, Section 5 provides concluding remarks and potential avenues for future research.

2. Literature Review

In recent years, AH integration services have received worldwide attention. Many studies have adopted a qualitative or descriptive approach to discuss experiences [4, 12], as well as the advantages and disadvantages [2, 13]. In response to the quantitative literature, Socorro and Vicens [14] developed a theoretical model to analyze the circumstances under which integration between HSR trains and flights may be beneficial. They found that such integration can alleviate the capacity of a hub airport, but its environmental and social effects are ambiguous. Okumura and Tsukai [15] discussed air-rail

intermodal network formation from the viewpoint of passengers, with Haneda Airport as a research object. The results showed that the operational capacity shortage of Haneda Airport may be solved by providing additional HSR service. Chiambaretto et al. [16] estimated passenger preferences for intermodal travel regarding some basic attributes, such as ticket integration, ground-handling integration, price, transfer, and travel time. The results showed that in-vehicle, connecting, and access times are more valued than baggage integration. In addition, the study found that baggage integration is only valued for leisure travel. Li and Sheng [7] investigated the mode choice behaviour of the AH integration service for the Beijing-Guangzhou corridor using the logit model. The market shares of four city pairs were estimated, and sensitivity analyses were performed. However, few studies have focused on timetable coordination in AH integration services.

Although studies on timetable coordination in AH integration services are limited, there is a wealth of literature on timetable coordination for urban public transportation systems. Considerable research has attempted to minimize the transfer time, passenger travel time and waiting time at railway stations, as reviewed in Wong et al. [17], Liebchen [18], Zhou et al. [19], Guo et al. [6], Shafahi and Khani [20], and Kang et al. [21]. For example, Wong et al. [17] presented an MIP optimization model for planning a synchronized nonperiodic timetable that minimizes the total transfer waiting time for all passengers. Zhou et al. [19] presented a coordination optimization model for the first train departure times. The objective of the model is to minimize the total passenger waiting time at the origins and the transfer waiting time for the first connecting trains. Guo et al. [6] constructed a first train timetabling optimization model with explicit consideration of the importance of lines and transfer stations. Kang et al. [21] proposed an extended problem of last train timetabling by introducing bus bridging services and a defuzzification approach for the last train dwell times. The models and approaches were applied to the Vienna subway.

The synchronization issue has often been studied in the literature. Domschke [22] minimized the waiting times of passengers at transfer stations. The author proposed a formulation that was similar to the quadratic assignment problem. This study was extended in [23] and [24] to improve the quality of transfers. Ceder et al. [9] described the problem of maximal synchronization in creating a bus timetable at transfer nodes. Eranki [10] and Guo et al. [25] extended the definition of synchronization presented in Ceder et al. [9]. In Guo et al. [25], synchronization is defined as the separation time between two trains (belonging to different lines or different periods), which can be satisfactory within a specific time window at a station instead of both trains arriving at the same time. Wu et al. [26] presented a timetable synchronization optimization model that aimed to reduce the worst weighted transfer waiting time as well as the probability and propagation of delay. Cao et al. [27] proposed a model for the synchronized and coordinated railway scheduling optimization problem. They maximized the number of synchronized meetings considering the importance of transfer stations and rail lines.

Although a number of studies have been developed for train timetabling, to the best of our knowledge, no research has focused on synchronized rail timetables for AH

integration services. Therefore, this paper first proposed a feeder HSR timetable problem in an AH integration service by adjusting the original rail timetable to improve the transfer synchronization based on the given flight schedules. A multi-objective optimization model is formulated, aiming to maximize the number of synchronizations and the coverage of synchronized flights, as well as to minimize the transfer penalties of passengers. Finally, the model is applied to the case of Shijiazhuang Zhengding International Airport in China.

3. Model Construction

In contrast to traditional railway timetables (for example, [28–31]), this paper focuses on adjusting the original HSR timetable, aiming to improve the transfer synchronization in AH integration services. We consider this timetabling problem along one direction of a two-direction railroad line on which a transfer station is located. The railroad line can be a part of a large network, whereas we keep the rest of the network out of the scope of this study. The adjustments of the rail timetable include the departure times, arrival times, running times, dwell times and headways within a small deviation from the original timetable, while the set of trains that are to be scheduled remains unchanged.

3.1. Model Assumptions. To facilitate model formulation, the following assumptions are made throughout the paper:

- (i) We assume that a joint ticket may be offered with any airline and any railway operator in a transfer hub. In other words, any one flight may connect to any one train.
- (ii) There are two types of connections: train-flight connections and flight-train connections. This paper focuses on train-flight connections. Since the punctuality of airlines is worse than that of railways [32], the probability of a passenger missing the corresponding HSR train in the case of a flight delay is larger. This makes it even more difficult to come up with reliable travel plans for the passengers, and thus in this first study we concentrate on train-flight connections.
- (iii) The flight timetable is given and remains unchanged.
- (iv) The HSR line plan is given, too. While the line plan including the set of trains, stop patterns and traveling routes remains unchanged, the optimization model may make use of the types of adjustments that we sketched, at the beginning of this section.
- (v) The number of passengers who may use transfers is neglected in our model. It is difficult for transit planners to obtain transfer data with sufficient accuracy [24]. However, in our model, if the data on passenger demand are available for all transfers, they could be used as a multiplicative factor in the objective function.
- (vi) We assume that the minimum transfer time is known and fixed for all transfer passengers. For train-flight connections, the transfer time from a

- train to a flight is the time difference between the departure time of the flight and the arrival time of the train. The minimum transfer time is the cumulative time required for passengers getting off the train, leaving the train station, walking/taking bus to the airport, checking in, passing the security check, and getting on the flight.
- (vii) Nevertheless, we consider two different groups of passengers who might pursue different time preferences: While businessmen (e.g., with only hand baggage) might prefer the shortest transfer times that we are considering, leisure passengers (e.g., with drop-off baggage) might feel significantly more comfortable for their holiday when transfer times are not too short. We propose to model different penalty objective functions for their transfer waiting times.
- (viii) Only one air-rail transfer node is considered in our model. The model can be expanded for application to a line with more than one transfer node.

3.2. Symbols

3.2.1. Parameters

- i, j : Train index,
 k : Outgoing flight index,
 s : Station index,
 I : Set of trains, where $I = I^T \cup I^N$,
 I^T : Set of trains that serve the transfer station,
 I^N : Set of trains that do not serve the transfer station,
 K : Set of outgoing flights at the transfer node,
 S : Set of stations,
 S_i : The ordered set of stations visited by train i , $S_i \in S$,
 st : The transfer station,
 \underline{b}, \bar{b} : The minimum transfer time and the maximum transfer time between a train and a flight for a valid synchronization event,
 l_k : Lower time bound of the connection time window of flight k at the transfer station, where $k \in K$,
 u_k : Upper time bound of the connection time window of flight k at the transfer station, where $k \in K$,
 ori_i : Starting station for train i , where $i \in I$,
 des_i : Terminus station for train i , where $i \in I$,
 $xs_{i,j}$: The first station that both train i and train j visit, where $i, j \in I$,
 $xe_{i,j}$: The last station that both train i and train j visit, where $i, j \in I$,
 $r_{i,s}$: Pure running time for train i on the segment $(s, s + 1)$, where $s \in S_i \setminus \{des_i\}$,
 $\beta_{i,s}$: Acceleration time for train i at station s , where $i \in I, s \in S_i \setminus \{des_i\}$,

- $\gamma_{i,s}$: Deceleration time for train i at station s , where $i \in I, s \in S_i \setminus \{ori_i\}$,
 $y_{i,s}$: Time supplement for train i on segment $(s, s + 1)$, where $i \in I, s \in S_i \setminus \{des_i\}$,
 $x_{i,s}$: = 1 if train i stops at station s , 0 otherwise, where $i \in I, s \in S_p$,
 $\underline{d}_{i,s}, \bar{d}_{i,s}$: The minimum dwell time and the maximum dwell time for train i at station s , where $i \in I, s \in S_i \setminus \{ori_i, des_i\}$,
 HA_s : The minimum headway between the arrival times of two consecutive trains at station s , where $s \in S_i \setminus \{ori_i\}$,
 HD_s : The minimum headway between the departure times of two consecutive trains at station s , where $s \in S_i \setminus \{des_i\}$,
 $\underline{dw}_p, \bar{dw}_i$: Lower bound and upper bound of the departure time window for train i at its starting station, where $i \in I$,
 $\underline{aw}_p, \bar{aw}_i$: Lower bound and upper bound of the arrival time window for train i at its terminus station, where $i \in I$,
 wt_i : Width of the time window for train i at its starting station and terminus station, where $i \in I$,
 $a_{i,s}^o$: Arrival time of train i at station s in the input timetable, where $i \in I, s \in S_i \setminus \{ori_i\}$,
 $d_{i,s}^o$: Departure time of train i at station s in the input timetable, where $i \in I, s \in S_i \setminus \{des_i\}$,
 D_k : Departure time of outgoing flight k at the transfer station, where $k \in K$,
 v_1 : The sensitivity that models the penalty of business passengers during transfer,
 w_1 : The proportion of business passengers among the total passengers,
 v_2 : The sensitivity that models the penalty of leisure passengers during transfer,
 w_2 : The proportion of leisure passengers among the total passengers, where $w_1 + w_2 = 1$,
 H : The upper bound of the planning horizon.

3.2.2. Decision Variables

- $a_{i,s}$: Arrival time of train i at station s , where $i \in I, s \in S_i \setminus \{ori_i\}$,
 $d_{i,s}$: Departure time of train i at station s , where $i \in I, s \in S_i \setminus \{des_i\}$,
 $O_{i,j}^s$: = 1 if train i departs from station s before train j , 0 otherwise, where $i, j \in I, s \in S$,
 $P_{i,k}$: = 1 if train i can synchronize with flight k at the transfer station, 0 otherwise, where $i \in I^T, k \in K$,
 C_k : = 1 if flight k can be synchronized with some train, 0 otherwise,
 $P_{i,k}$: Penalty variable reflecting the preferences of the passengers from the train i to the flight k for the transfer time.

3.3. Mathematical Formulations. We present a multi-objective mixed integer programming model of the timetabling problem for all trains I that make use of the target railroad line. There are two kinds of trains running on the line. The first kind of train I^T serves the transfer station. In other words, these trains stop at the transfer station. The second kind of trains I^N does not serve the transfer station. The transfer synchronization between trains and flights can be improved by adjusting the timetable of the first kind of trains. Meanwhile, due to the interaction between trains, the timetables of other trains might have to be adjusted, too, to guarantee safety constraints. The timetable is adjusted within a planning horizon, and we let H be the upper bound of the time horizon.

3.3.1. Objective Functions.

(1) *Maximizing the Number of Synchronizations.* For train-flight connections, a synchronization in an AH integration service is valid if the difference between the arrival of a train i and the departure of a flight k is within a separation time window $[b, \bar{b}]$ at the transfer station. Let b denote the minimum transfer time, and \bar{b} is the acceptable maximum transfer time of passengers. As we assume the flight timetable to be given, the departure time of any flight is fixed. Thus, a synchronization between a train i and a flight k is valid if the arrival time of the train is within the connection time window of the flight k at the transfer node. The departure time D_k of the outgoing flight k minus the maximum transfer time \bar{b} is the lower bound of the connection time window l_k , and the departure time D_k minus the minimum transfer time b is the upper bound of the connection time window u_k :

$$l_k = D_k - \bar{b}, \quad (1)$$

$$u_k = D_k - b. \quad (2)$$

The auxiliary binary, $P_{i,k}$, which indicates whether the train i synchronizes with the flight k at the transfer station, is introduced, see Equation (21). If the synchronization is valid, $P_{i,k} = 1$; otherwise, it is 0. Therefore, the first objective function – denoted by Z_1 – is put forward to maximize the number of synchronizations:

$$\text{Max } Z_1 = \sum_{i \in I^T} \sum_{k \in K} P_{i,k}. \quad (3)$$

(2) *Maximizing the Coverage of Synchronized Flights.* The number of synchronized flights should be increased while improving the synchronization number between trains and flights. Here, additional binary variable C_k , which indicates whether the flight k is synchronized with some trains, is introduced, see Equation (24). C_k is equal to 1 if the flight k is synchronized; otherwise, it is 0. The second objective Z_2 , aiming to maximize the coverage of the flights by the trains, is proposed:

$$\text{Max } Z_2 = \sum_{k \in K} C_k. \quad (4)$$

(3) *Minimizing the Transfer Penalties of Passengers.* The different preferences of passengers should also be considered. Even though a train i synchronizes with a flight k , passengers on the train i perceive transfer times differently. Here, we introduce

a continuous non-negative penalty variable $p_{i,k}$ reflecting the specific preferences of business and leisure passengers from the train i to the flight k for the transfer time. This is demonstrated by constraints (25)–(27), described later. The third objective Z_3 (with much lower priority than the above two objectives) is to minimize these transfer penalties:

$$\text{Min } Z_3 = \sum_{i \in I^T} \sum_{k \in K} p_{i,k}. \quad (5)$$

3.3.2. Train Operation Constraints. Constraints (6) and (7) ensure that the travel time $a_{i,s+1} - d_{i,s}$ of a train i on a segment $[s, s+1]$ considers the pure running time $r_{i,s}$, acceleration time $\beta_{i,s}$, deceleration time $\gamma_{i,s}$, and time supplement $y_{i,s}$. The running time of a train on a segment will be longer when the train stops at a station.

$$a_{i,s+1} - d_{i,s} \geq r_{i,s} + \beta_{i,s} x_{i,s} + \gamma_{i,s+1} x_{i,s+1} \quad \forall i \in I, s \in S_i \setminus \{\text{des}_i\}, \quad (6)$$

$$a_{i,s+1} - d_{i,s} \leq r_{i,s} + \beta_{i,s} x_{i,s} + \gamma_{i,s+1} x_{i,s+1} + y_{i,s} \quad \forall i \in I, s \in S_i \setminus \{\text{des}_i\}. \quad (7)$$

The requirements for the dwell time should be satisfied to ensure operating efficiency and safety, as shown in constraints (8) and (9), respectively. The actual dwell time $d_{i,s} - a_{i,s}$ of train i at station s should be greater than or equal to the minimum planned dwell time $\underline{d}_{i,s}$ to provide passengers with sufficient times to board and alight. It should also be less than or equal to the maximum planned dwell time $\overline{d}_{i,s}$ in the case of a long travel time. When a train passes a station, the dwell time equals 0.

$$d_{i,s} - a_{i,s} \geq \underline{d}_{i,s} x_{i,s} \quad \forall i \in I, s \in S_i \setminus \{\text{des}_i, \text{ori}_i\}, \quad (8)$$

$$d_{i,s} - a_{i,s} \leq \overline{d}_{i,s} x_{i,s} \quad \forall i \in I, s \in S_i \setminus \{\text{des}_i, \text{ori}_i\}. \quad (9)$$

Constraints (10) and (11) ensure that every train i has a departure time window at its start station ori_i and an arrival time window at its terminus station des_i . An overly large deviation from the original timetable will directly influence the cost or performance of the railway system. On the one hand, timetable adjustments may change the turnaround times of trains at terminus stations. If the difference between the adjusted timetable and the original timetable becomes too large, it will have a strong influence on the vehicle schedule, resulting in extra trains with high additional costs. On the other hand, as this study focuses on only a part of the network, timetable adjustments of the target railroad line will affect the timetables of the converging and diverging lines. Thus, time windows are imposed to restrict the timetable shift. Constraints (12)–(15) state that the departure and arrival time windows are relatively close to the input timetable.

$$\underline{dw}_i \leq \underline{d}_{i,\text{ori}_i} \leq \overline{dw}_i \quad \forall i \in I, \quad (10)$$

$$\underline{aw}_i \leq \underline{a}_{i,\text{des}_i} \leq \overline{aw}_i \quad \forall i \in I, \quad (11)$$

$$\underline{dw}_i = \underline{d}_{i,s}^0 - \frac{wt_i}{2} \quad \forall i \in I, s \in \text{ori}_i, \quad (12)$$

$$\overline{dw}_i = \underline{d}_{i,s}^0 + \frac{wt_i}{2} \quad \forall i \in I, s \in \text{ori}_i, \quad (13)$$

$$aw_i = a_{i,s}^o - \frac{wt_i}{2} \quad \forall i \in I, s \in des_i, \quad (14)$$

$$\overline{aw}_i = a_{i,s}^o + \frac{wt_i}{2} \quad \forall i \in I, s \in des_i. \quad (15)$$

3.3.3. Safety Headway Constraints. Limits on the headways for all trains $i \in I$ should be satisfied to ensure operational safety. Constraints (16) and (17) ensure that the difference between the departures of any two trains at station s (visited by the both trains) satisfies a lower bound HD_s . Analogously, constraints (18) and (19) ensure that the difference between the arrivals of any two trains at station s satisfies a lower bound HA_s . M is a large number that is no smaller than $H + \max(HD_s, HA_s)$.

$$d_{j,s} - d_{i,s} + M(1 - O_{i,j}^s) \geq HD_s, \quad (16)$$

$$d_{i,s} - d_{j,s} + MO_{i,j}^s \geq HD_s, \quad \forall i, j \in I, s = xs_{i,j} \cdots xe_{i,j} - 1, \quad (17)$$

$$a_{j,s+1} - a_{i,s+1} + M(1 - O_{i,j}^s) \geq HA_{s+1}, \quad (18)$$

$$a_{i,s+1} - a_{j,s+1} + MO_{i,j}^s \geq HA_{s+1}, \quad \forall i, j \in I, s = xs_{i,j} + 1 \cdots xe_{i,j}. \quad (19)$$

3.3.4. Logic Constraints. Constraint (20) states the logical relationship (ordering) in each section between any two trains.

$$O_{i,j}^s + O_{j,i}^s = 1 \quad \forall i, j \in I, s \in S. \quad (20)$$

3.3.5. Synchronization Number Constraints. Constraint (21) is the synchronization number constraint between trains and flights at the transfer station. The constraint states that if the arrival time of a train i is within the connection time window $[l_k, u_k]$ generated by a flight k , which means that the train can synchronize with the outgoing flight k , then the value of variable $P_{i,k}^s$ equals 1; otherwise, $P_{i,k}^s$ equals 0.

$$P_{i,k} = \begin{cases} 1 & l_k \leq a_{i,s} \leq u_k \\ 0 & \text{otherwise} \end{cases} \quad \forall i \in I^T, k \in K, \quad s = st. \quad (21)$$

Constraint (21) can be linearized into constraints (22) and (23) using a large positive value M' . As can be observed in constraints (22) and (23), if $a_{i,s} < l_k$ or $a_{i,s} > u_k$, then $P_{i,k} = 0$. If $l_k \leq a_{i,s} \leq u_k$, then in principle $P_{i,k}$ could equal either 0 or 1, but the maximization objective function will force it to have a value of one. M' is a large number and its value is greater than or equal to H .

$$a_{i,s} \geq l_k - M'(1 - P_{i,k}) \quad \forall i \in I^T, k \in K, \quad s = st, \quad (22)$$

$$a_{i,s} \leq u_k + M'(1 - P_{i,k}) \quad \forall i \in I^T, k \in K, \quad s = st. \quad (23)$$

3.3.6. Coverage Constraints. The coverage variable C_k represents whether the flight k is synchronized with at least one feeder train. Because of the maximization objective function Z_2 , the variable C_k must only be set to one, if some of the corresponding variables $P_{i,k}$ have already been set to one. Therefore, constraint (24) must be satisfied for any flight.

$$C_k \leq \sum_{i \in I^T} P_{i,k} \quad k \in K. \quad (24)$$

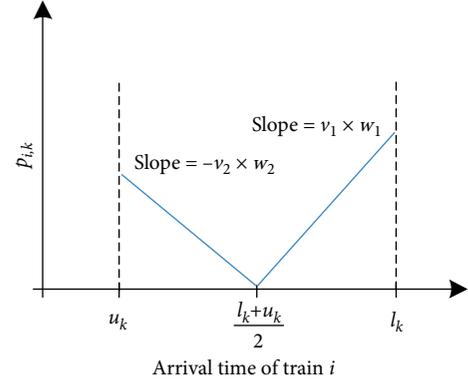


FIGURE 2: A V-shaped piecewise linear function.

3.3.7. Passenger Preference Constraints. As mentioned above, intermodal passengers have different preferences for transfer times. We divide passengers into two types based on the purpose of trips: business and leisure passengers. Business passengers prefer shorter transfer times while leisure passengers prefer longer transit times to reduce the risk of missing the plane [33]. For a valid synchronization $P_{i,k}$ between a train i and a flight k , business passengers from the train i to the flight k are less sensitive to the short transfer time and could thus prefer arriving at the transfer station during $[l_k, (l_k + u_k)/2]$; when the transfer time exceeds $(l_k + u_k)/2$, they become sensitive and the penalty should increase, e.g., from $(l_k + u_k)/2$ to u_k . In contrast, leisure passengers prefer slightly longer transfer times and they would like to arrive at the transfer station during $[l_k, (l_k + u_k)/2]$. They are more sensitive to short transfer times, and thus the penalty should increase there, e.g., from $(l_k + u_k)/2$ to u_k . Therefore, we introduce a continuous non-negative penalty variable $p_{i,k}$ representing the preferences of the passengers from the train i to the flight k for the transfer time, as shown in constraints (25)–(27). Due to the objective function Z_3 (5), the optimization model will push $p_{i,k}$ to the smallest possible value.

$$p_{i,k} \geq v_1 \times w_1 \times \left(a_{i,s} - \frac{l_k + u_k}{2} \right) \quad (25)$$

$$- (1 - P_{i,k}) \times M'' \quad \forall i \in I^T, k \in K, \quad s = st,$$

$$p_{i,k} \geq v_2 \times w_2 \times \left(\frac{l_k + u_k}{2} - a_{i,s} \right) \quad (26)$$

$$- (1 - P_{i,k}) \times M'' \quad \forall i \in I^T, k \in K, \quad s = st,$$

$$p_{i,k} \geq 0 \quad \forall i \in I^T, k \in K. \quad (27)$$

The slope coefficient v_1 represents the sensitivity that models the penalty that the business passengers associate with a waiting time that exceeds $(l_k + u_k)/2$, and w_1 is the proportion of business passengers among the total passengers. Analogously, v_2 is the corresponding coefficient for the leisure passengers associating with a waiting time of less than $(l_k + u_k)/2$, and w_2 is the proportion of leisure passengers. The values of v_1, v_2, w_1 , and w_2 can be estimated by stated preference surveys. It should be noted that the timetable adjustments will be sufficiently affected by the proportion of $(v_1 \times w_1)/(v_2 \times w_2)$. Therefore, the values of both v_1 and v_2 are set to be between 0 and 1 in this paper. When a train i can synchronize with a flight k ($P_{i,k} = 1$), the penalty $p_{i,k}$ is a

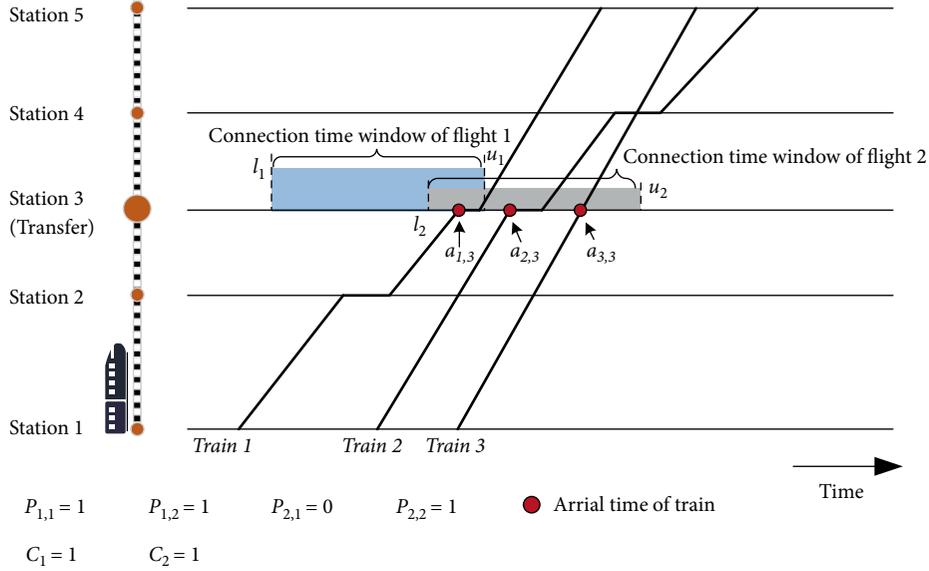


FIGURE 3: Illustration of a train timetable based on an AH integration service.

V-shaped piecewise linear function of the arrival time $a_{i,s}$ of the train i , as shown in Figure 2. M'' is a large positive number with a value no less than $H \times \max(v_1 \times w_1, v_2 \times w_2)$.

Figure 3 illustrates a train schedule that covers 5 stations and 3 trains. Station 3 is the transfer station. At the transfer point, there are two outgoing flights. The arrival time of train 1 is within the connection time windows of both outgoing flights. The arrivals of trains 2 and 3 are within the connection time windows of the second outgoing flight. However, train 3 does not serve station 3. Therefore, there are 3 train-flight synchronizations. The coverage of synchronized flights is two.

3.4. Priori Method. We choose to apply the a priori method [34] to our multi-objective model. In our formulation, the first and second objectives have much higher priority than does the third objective. The first two objectives aim to determine the synchronization events. Subsequently, the third-level optimization is to further narrow the solutions by minimizing the transfer penalties of different passengers. We aim to provide more smooth transfers, and thus, the first objective has a higher priority than does maximizing the coverage of synchronized flights. The multi-objective model is converted into three single-objective problems that can be solved exactly by any optimization solver such as CPLEX.

First, we propose a single objective model for maximizing Z_p , denoted by **M1**.

Model M1:

Objective function (3).

Subject to constraints (6)–(20) and (22)–(23).

Output: P (the maximum number of synchronizations).

The maximum number of synchronizations is fixed and we impose an addition constraint (28).

$$\sum_{i \in I'} \sum_{k \in K} P_{i,k} = P. \quad (28)$$

Then, the second single objective model for maximizing Z_2 , denoted by **M2**, is proposed.

Model M2:

Objective function (4).

Subject to constraints (6)–(20), (22)–(24) and (28).

Output: C (the maximum number of synchronized flights while maximizing the number of synchronizations).

The maximum coverage of synchronized flights is fixed, and we impose another constraint (29).

$$\sum_{k \in K} C_k = C. \quad (29)$$

The last single-objective model **M3** is then reformulated as follows to minimize the transfer penalties of passengers. We can obtain the adjusted timetable.

Model M3:

Objective function (5).

Subject to constraints (6)–(20) and (22)–(29).

Output: T (the adjusted timetable).

4. Real-World Case

In this section, we apply the proposed model to Shijiazhuang Zhengding International Airport Station on the Beijing-Guangzhou corridor. In Section 4.1, the characteristics of the target airport and station are presented. Section 4.2 provides the data and parameter information. In Section 4.3, we investigate the adjusted results, and some analyses are presented.

4.1. Characteristics of the Target Airport and Station. Shijiazhuang Zhengding International Airport is selected as the case study. Zhengding airport is adjacent to the Zhengding airport HSR station, and the station and the airport offer the infrastructure for AH integration services. The characteristics of Zhengding airport and the Zhengding airport station are listed below.

- (i) The Zhengding airport HSR station is located on the Beijing-Guangzhou HSR corridor in mainland China, as shown in Figure 4 (only the section between



FIGURE 4: Track layout of the HSR line section between Beijing and Zhengzhou.

Beijing South and Zhengzhou East is presented). An HSR trip between Beijing and the Zhengding airport HSR station takes only 70 minutes.

- (ii) Only 32 high-speed trains (including inbound and outbound trains) serve the Zhengding airport HSR station per day. The train frequency in each direction of the two-direction railroad line is 16.
- (iii) To alleviate the current traffic congestion issues at Beijing Capital airport, some domestic air flights are diverted to Shijiazhuang Zhengding airport according to “Opinions on Further Deepening the Reform of Civil Aviation Industry”, facilitated by the CAAC.
- (iv) The distance from the Zhengding airport HSR station to the airport terminal is 3 kilometres. This journey takes passengers approximately 5 minutes by shuttle bus. The short transfer time provides considerable convenience to passengers regarding their luggage when arriving or departing from the station to the airport.
- (v) Several low-budget airlines are based at the Zhengding airport, and these airlines typically offer lower ticket fares. Therefore, the AH integration service in Shijiazhuang has price advantages, and it strengthens the competitiveness of the Zhengding airport compared to adjacent airports, such as the Tianjin Binhai Airport.

TABLE 1: Input parameters for the real-world rail example.

\bar{b} (min)	\bar{b} (min)	w_i (min)	v_1	w_1	v_2	w_2
60	120	30	0.6	0.5	0.4	0.5

TABLE 2: The computational performances of the three models.

Model	Computational time (seconds)	Number of variables	Number of constraints	Gap
M1	2154	191072	242338	<1%
M2	2326	191182	242448	<1%
M3	2443	203502	267088	<1%

- (vi) The demand for the AH integration service in Shijiazhuang has increased rapidly. In 2016, over 412,000 passengers finished their travel using the intermodal service of the Zhengding airport. In 2017, the passenger volume increased to 737,700, and the number exceeded 1132,000 in 2018.

4.2. Parameters Settings. In this section, we concentrate on the rail section from Beijing to Zhengzhou in the Beijing-Guangzhou HSR corridor, including 14 stations. We consider the timetable for trains that depart from the starting stations between 6:30 and 20:00. During this planning horizon, there are 112 trains and 16 trains serving the Zhengding airport HSR station. The number of outgoing flights in Zhengding airport is 110. We make assumptions about other parameters due to a lack of validated data provided by any of the operators, as shown in Table 1.

The model was coded and solved using MATLAB R2015b and ILOG CPLEX 12.5 running on a PC with an Intel i5 3.0-GHz processor and 8 GB of RAM.

4.3. Model Applications. The computational performances of three models are shown in Table 2. It requires 6923 seconds (115 minutes) to yield the optimal feeder rail timetable solution using CPLEX solver.

4.3.1. Optimal Rail Timetable Solution. The number of synchronizations increases from 104 in the original rail timetable to 129 after the adjustments, representing a rise of 24%. Figure 5 shows the number of synchronizations for each train that serves the transfer station before and after the adjustments. It can be seen that more than half of the trains show improvements in the number of synchronizations. The coverage of synchronized flights increases from 83 to 86, which means that three more flights are served. Therefore, the transfer synchronization can be improved by the proposed model. The adjusted timetable is presented in the Appendix.

4.3.2. Effects of Departure and Arrival Time Windows on Synchronization. As constraints (10)–(15) show, the train departure times at the starting stations and arrival times at the terminus stations should not exceed the upper and lower bounds. Here, we test the effects of the train time windows on

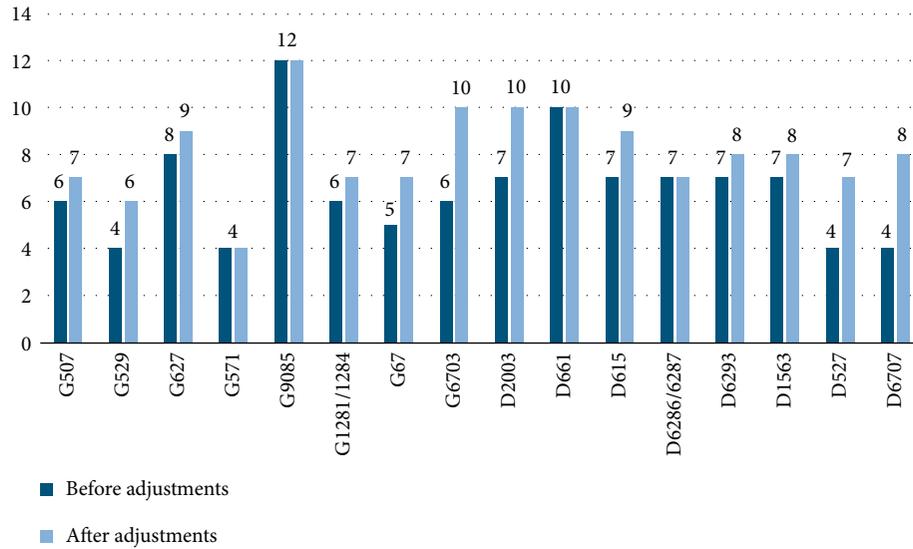


FIGURE 5: Number of synchronizations for each train.

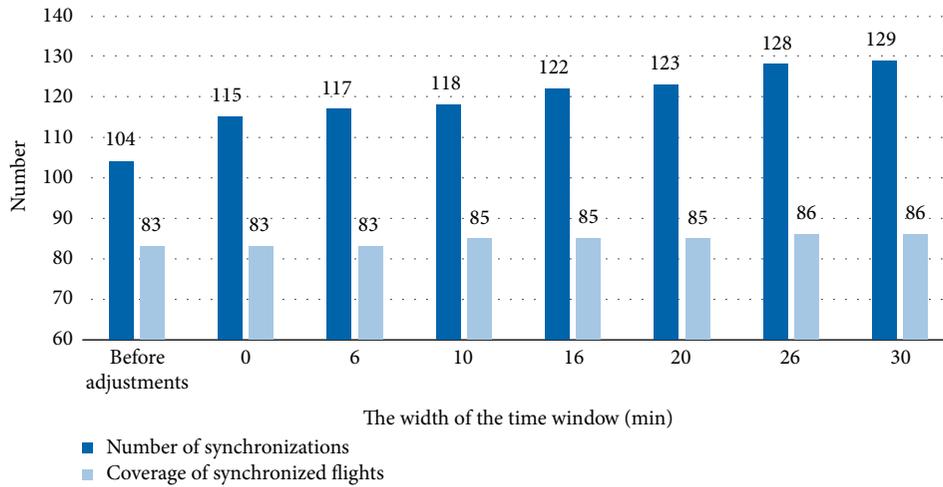


FIGURE 6: Effects of departure and arrival timetable windows on synchronization.

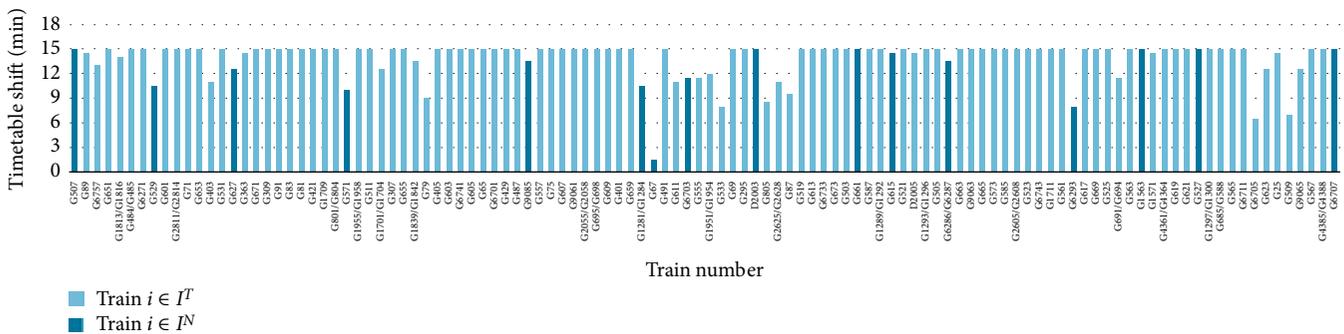


FIGURE 7: Time shift of each train.

the problem. As can be observed in Figure 6, when each train maintains the departure time at its origin and the arrival time at its destination, the number of synchronizations increases by 11, simply by changing dwell times at some intermediate

stations and time supplements in some sections. Compared to the other cases, these results demonstrate that larger bounds can improve the number of synchronizations and coverage of synchronized flights.

TABLE 3: Penalties for different v_1 and v_2 values.

v_1	v_2	Total penalties	Average penalty of each synchronization event
0.1	0.9	1007.4	7.81
0.2	0.8	1031.8	8.00
0.3	0.7	1050.2	8.14
0.4	0.6	1049.6	8.14
0.5	0.5	1037.5	8.04
0.6	0.4	1009.4	7.82
0.7	0.3	969.9	7.52
0.8	0.2	925.6	7.18
0.9	0.1	879.7	6.82

TABLE 4: Accessible cities for 5 origins before and after adjusting timetable.

Origin	Before adjustments	After adjustments	Change
Beijing	35	40	+5
Zhuozhou	8	14	+7
Gaobeidian	12	14	+2
Baoding	33	36	+3
Dingzhou	7	7	+0

4.3.3. *Train Timetable Shift.* The timetable shift is the difference between the adjusted timetable and the original timetable. The shift of each train is measured by Equation (30):

$$TS_i = \frac{|d_{i,s}^o - d_{i,s}| + |a_{i,s'}^o - a_{i,s'}|}{2} \quad \forall i \in I, s = \text{ori}_i, s' = \text{des}_i. \quad (30)$$

Figure 7 shows the timetable shift TS_i for all trains. As mentioned above, the width of the departure and arrival time windows is 30 minutes. In other words, every train can depart/arrive 15 minutes early or late compared to the original timetable. We find that most trains make full use of the time windows, which means that many trains have a 15-minute timetable shift. The average time shift is 13.9 minutes. A 13.9-minute shift can be accepted by passengers because it is short compared to the average travel time of passengers served by the trains operating in the Beijing-Guangzhou corridor.

4.3.4. *Passenger Preferences.* In the original timetable, the transfer penalties of business and leisure passengers for all valid synchronizations are 769.60, and the average penalty of each synchronization is 7.26. After adjustments with a 30-minute train departure time window, the total penalties are 1009.40 and the average value is 7.82. This result indicates that a higher average penalty is the price for improving the number of synchronizations and the coverage of serviced flights based on the original timetable.

We assume that the number of business passengers and the number of leisure passengers are the same, and then change the sensitivity of business and leisure passengers to the transfer time. Given the maximum synchronization

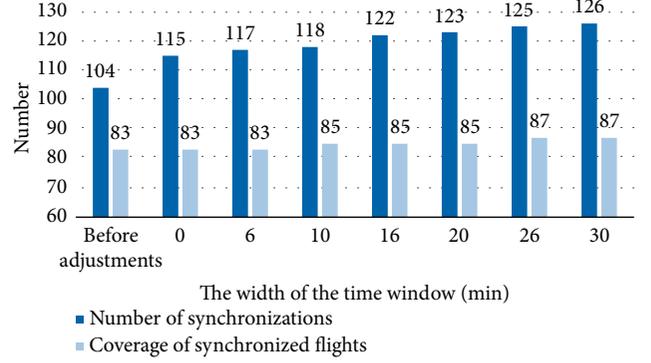


FIGURE 8: Effects of departure and arrival timetable windows on synchronization when maximizing the coverage of synchronized flights has priority over maximizing the number of synchronizations.

number and coverage of served flights, the results with different v_1 and v_2 values are shown in Table 3. We can find that the proportion of v_1-v_2 of 3:7 corresponds to the highest total penalties. When leisure passengers are less sensitive to the waiting time, the penalties are lower. Therefore, reducing the sensitivity of leisure passengers during transfer has a good effect on reducing the total penalties based on the current adjustments.

4.3.5. *Accessibility.* Accessibility is an important concept that is broadly used in the field of transportation planning. We introduce an indicator, called “accessible cities”, counting the number of cities that can be reached from one origin using the timetable information. Notice that we only focus on the valid synchronizations, which means that the origin is served by train $i \in I^T$ and the destination is served by the synchronized flight k . A higher value of this indicator for a city implies that the AH integration service can provide more appropriate trips for passengers from the city and that the accessibility is greater.

We measure the cities that are accessible from Beijing, Zhuozhou, Gaobeidian, Baoding, and Dingzhou before and after adjusting the HSR timetable (see Table 4). The number of accessible cities increases for most origins after the adjustments. This indicator has the largest increase for Zhuozhou, adding 7 cities. In other words, passengers living in Zhuozhou can reach additional 7 cities through the optimized AH integration service. The indicator does not change for Dingzhou. The results show that the adjustments are effective in improving the accessibility of AH integration services.

4.3.6. *Priority of Objectives.* We analyze the influence of the priority of the objectives on synchronization (we only focus on the first two objectives). When maximizing the coverage of synchronized flights has a higher priority than does maximizing the number of synchronizations, the results with different train time windows are shown in Figure 8. Obviously, the number of synchronizations and the coverage of synchronized flights increase with the enlargement of the time window. Comparing the results of this section with those of Section 4.3.2, when the width of the train time window is less than or equal to 20 minutes, the solutions

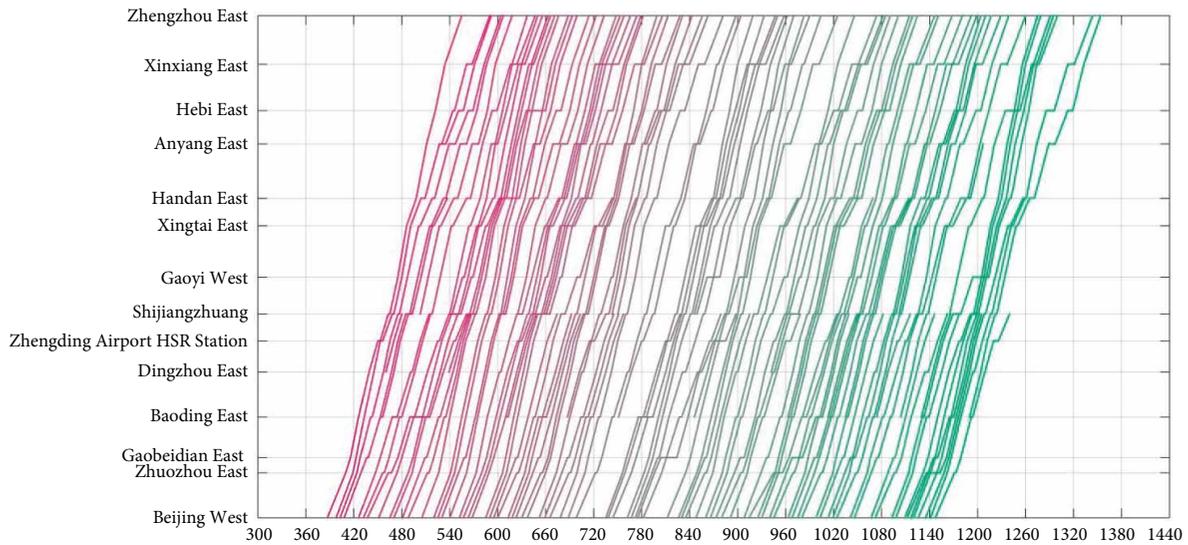


FIGURE 9: The adjusted timetable.

are the same, regardless of priority. However, the coverage of flights in this section is larger in the cases of windows of 26 or 30 minutes, while the number of synchronizations is less. Yet, it is interesting to notice that this yields just only one single additional flight that is served in addition. We conclude that in this particular data set, the first objective function “maximizing the number of synchronizations” essentially already tends to maximize the coverage of synchronized flights. In particular, the first objective function does not concentrate several trains too often just around the very same outgoing flights.

5. Conclusions

AH integration services are becoming an important transportation mode with the development of HSR and air travel. During the travel process, passengers must transfer between the two modes to complete their journey. To provide inter-modal passengers with more opportunities to travel, we focus on improvement of the synchronization in an AH integration service. A multi-objective model of a feeder railway timetable model is developed with the aim of maximizing the number of synchronizations and the coverage of synchronized flights, as well as minimizing the penalty of passengers. The model is solved using the CPLEX solver.

We apply the model to Shijiazhuang Zhengding International Airport. The number of synchronizations increases by 24% compared to that in the original timetable, and the coverage of synchronized flights increases by 3. The average shift of each train is 13.9 minutes. The accessibility improves for most cities. The results show that the proposed model is effective for improving synchronization at this airport. However, passengers’ average penalty in each valid synchronization event is higher after the adjustments.

The delay characteristics of flights are not considered in this study. However, they influence connections between trains

and flights. Hence, future research should attempt to study timetable coordination based on the robustness of flights and trains to make the model more realistic.

Appendix

See Figure 9.

Data Availability

The railway and air timetable data are from July 2018 from <https://www.12306.cn/index/> (the railways ministry’s official ticketing website) and <http://www.ctrip.com/> (an online travel site).

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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