Train Rescheduling Incorporating Coupling Strategy in High-speed Railway under Complete Segment Blockage

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Abstract
This paper investigates the real-time train rescheduling problem in a high-speed railway line under a complete segment blockage by exploring the effectiveness of incorporating train coupling strategy on the train timetable rescheduling. The problem lies on determining the actual arrival and departure time as well as the platform track assignment of trains at stations after a complete segment blockage caused by disruptions, where trains satisfying strict coupling rules could be coupled with others to avoid being cancelled. A mixed integer linear programming model is formulated to minimize the total deviation of trains' arrival and departure time to that in the planned timetable, and to maintain the reasonability of the reordering and coupling decisions. In the model, both the acceleration and deceleration time of trains when departing from and arriving at stations are explicitly considered, while the platform track of trains at passed stations is jointly optimized. A rolling horizon algorithm is designed to effectively solve large-scale problem instances since the rescheduling of timetables is usually determined in stages in practice. Test instances constructed based on the Wuhan-Guangzhou High-Speed Railway in China are utilized to test the effectiveness and efficiency of the proposed approaches. Computational results demonstrate that the train coupling strategy is likely to reduce the total deviation and to relief the propagation of delays. Meanwhile, the rolling horizon algorithm can provide practically acceptable rescheduled timetables quickly. Thus, the train coupling strategy is promising in the field of train timetable rescheduling to cope with large-scale disruptions.

Keywords
Train timetable rescheduling, train coupling strategy, complete segment blockage, mixed integer linear programming, rolling horizon algorithm

1 Introduction

The high-speed railway system is operating based on the preplanned conflict-free timetables and resource utilization schedules if there is no perturbation including disturbance and disruption influencing the railway system. The term "disturbance" is usually utilized for relative small perturbation where only the timetables need to be slightly modified, and the term “disruption” for relatively large external incidents leading to modifications of not only the timetables but also the duties of rolling stocks or crews (Cacchiani et al., 2014). In real-time operations, however, unexpected perturbations are unavoidable and result in the subsequent infeasibility of preplanned timetables and resource utilization schedules. Passengers experience the negative influences caused by perturbations as train delays, broken connections and even train cancelations. Obviously, it is of great significance and necessity to reschedule train timetables and resources to recover from disturbed or disrupted situations as quickly as possible and to maintain the service level of railway system.

Research in the field of train rescheduling is promising from a practical point of view. However it is also a challenging work especially for the high-speed railway line with dense traffics and higher operating speed. Currently in practice, the rescheduling of train timetables and if necessary rolling stocks and crews, are mainly manually implemented by involved dispatchers based on their experiences and craftsmanship. The practical feasibility and quality of the resulting manually rescheduled plans are not certainly assured. Fortunately on the contrary, the real-time train rescheduling has attracted widely attentions in the academic community recently. Many researchers are devoting themselves to apply their advanced recovery approaches implemented in user-friendly intelligent decision support systems to improve the service and reliability of railway systems.

1.1 Related Works

Recently in high-speed railway system, the most common measures considered in practice and related academic researches to recover from a disturbed or disruption situation to a feasible one is the train timetable rescheduling, which is mainly further composed of retiming, reordering and rerouting, as well as cancelling trains if a large external incidence occurs. To reduce the negative influences caused by unpredicted perturbations, the rescheduling measures should be discreetly adopted to design high quality practically feasible rescheduled timetables. Up to now, a mass of mathematical models and algorithms have been developed to support dispatchers to make reasonable decisions. According to Cacchiani et al. (2014), existing approaches can be classified by the scale of the perturbations including disturbances and disruptions, and the level of detail considered in the railway system known as macroscopic and microscopic perspectives. In macroscopic approaches, the stations and the tracks between adjacent stations (i.e. segments) are treated as nodes and arcs, respectively, and the details of block sections and signals at stations and along segments are not taken into account. However, these aspects are all considered in detail in microscopic researches. In this paper, We focus on the real-time train timetable rescheduling under a complete segment blockage from a macroscopic aspect, where a complete blockage is denoted by Louwerse and Huisman (2014) as the situation in which all tracks of a segment are blocked and no trains can be operated on this segment. Thus, we mainly restrict ourselves to typical previous studies on real-time train timetable rescheduling under disrupted situations from a macroscopic perspective. Interested readers can refer to Cacchiani et al. (2014), Corman and Meng (2015) and Fang et al. (2015) for detailed reviews on traffic management/rescheduling of railway system, and to Törnquist and Persson (2007) and Krasemann (2012) for detailed methodologies dealing with disturbed situations.

Louwerse and Huisman (2014) focused on adjusting the timetable of a passenger railway operator in case of partial or complete blockages. An event-activity network was utilized to formulate their integer programming formulations, while the effectiveness of their models was tested based on periodic timetables collected from the Netherlands Railways. Zhan et al. (2015) and Zhan et al. (2016) studied similar problems of which the objective was minimizing the number of canceled trains and the total weighted delay (or deviations composed of earliness and tardiness). A two-stage algorithm and a rolling horizon approach were designed respectively to solve realistic instances constructed based on the non-periodic timetables in China. The capacity of infrastructures and rolling stocks as well as rerouting of trains were further considered by Veelenturf et al. (2016). As observed, cancelling trains is an important strategy adopted in existing studies to reschedule train timetables under disruptions. Besides, in these studies only the trains which have not already left their origin station when the disruption occurs are allowed to be cancelled. However, it is challenging to reschedule these trains not allowed to be cancelled, especially when the capacity of stations expressed by the number of platform tracks at stations is relative few, as trains need to dwell on a certain platform track at a reasonable station to wait for the recovery of the disruption.

Except for the common rescheduling measures (i.e. retiming, reordering, rerouting, and cancelling trains if necessary) adopted in practice, there are also other specific strategies in previous works which are designed to reduce the negative influences caused by the disruption or even the cancelation of trains, such as the stop-skipping strategy in Altazin et al. (2017) and short-turning strategy in Ghaemi et al. (2018). Altazin et al. (2017) investigated the train rescheduling problem through stop-skipping in dense railway systems and formulated their problem as an integer linear programming, where some stops of train services can be skipped such that the propagation of delays might be reduced. Ghaemi et al. (2018) formulated a macroscopic integer linear short-turning model in case of simultaneous complete blockages, such that the penalized cancellations and delay of planned trains services can be minimized. In addition to the operator-oriented works mentioned above, passenger-oriented timetable rescheduling is also attractive. Sato et al. (2013) formulated an MIP model to minimize the further inconveniences to passengers caused by the disruption so as to exactly consider the loss of time and satisfaction of passengers.

This paper tries to optimize the real-time train timetable rescheduling incorporating train coupling strategy in a high-speed railway line in case of a complete segment blockage. Under the train coupling strategy, two trains which strictly satisfy specific rules are allowed to be coupled on a platform track at a certain station once a large perturbation occurs, such that these two trains can form one train and run subsequent stations and segments along their planned route together. Obviously, the number of trains can be reduced while not cancelling any train by utilizing the train coupling strategy. Note that the coupling/combining of passenger trains has attracted attentions in early works focusing on the circulation of rolling stocks, such as Fioole et al. (2006) and Peeters and Kroon (2008). In these works, the rolling stocks can be added/combined or removed/splited from trains according to the predefined timetable and passenger demand for the efficient utilization of train units. These problems as tactical decisions arises in an early phase of the railway planning process. However, to the best of our knowledge, there is no previous work investigating the operational train rescheduling incorporating train coupling in the real-time setting.

1.2 Contributions

The contributions of this paper are mainly threefold. Firstly, as far as we know, our paper might be the first one trying to explore the practicability and effectiveness of train coupling strategy to avoid cancelling trains in train timetable rescheduling under a disruption of complete segment blockage, such that the negative influences caused by the cancellation of trains can be reduced as much as possible. Secondly, different with many existing macroscopic train rescheduling works (Cacchiani et al., 2014; Zhan et al., 2015, 2016), in this paper a station is represented by many platform tracks rather than a single node and the occupation of platform tracks at stations are determined, due to that the capacity of stations is represented more finely. Finally, several operational requirements are further considered in our approaches. The additional acceleration and deceleration time of trains when stopping at stations and the platform track assignment of trains at nonstop passed stations are all exactly incorporated to reflect better the actual situations of high-speed railway systems.

1.3 Outline of Paper

The rest of this paper is organised as follows. Firstly, a detailed problem description is presented in Section 2. In Section 3, a mixed integer linear programming model is established by taking into account many operational and safety requirements. Next, a rolling horizon algorithm is designed in Section 4 to effectively solve large-scale problems. Then, in Section 5 computational tests on instances constructed from Wuhan-Guangzhou High-Speed Railway in China are implemented to test the effectiveness and efficiency of the proposed approaches. Comparison of rescheduling strategies is also conducted in this section. Finally, we conclude our main research works in Section 6.

2 Problem Description and Assumptions

2.1 Problem Description

This paper investigates the real-time train timetable rescheduling incorporating train coupling strategy in a high-speed railway line under a complete segment blockage from the macroscopic prospective, where a station is treated as several platform tracks instead of a single node to model the capacity of stations, as illustrated by Figure 1. We mainly focus on the Chinese situation where trains are running on separated double parallel tracks in a high-speed railway line. When a complete segment blockage caused by disruptions occurs, trains bounding for the disrupted segment in both the downstream and the upstream directions have to wait on the platform tracks at reasonable stations until the disrupted situation is recovered. The consequent negative influences to the operators and passengers should be controlled which is usually achieved by the strategies of retiming, reordering, rerouting and canceling trains to minimize the total deviation of trains' arrival and departure time to that in the planned timetable. Large negative influences are usually inevitable when trains have to be cancelled due to the limited capacity of stations and segments.

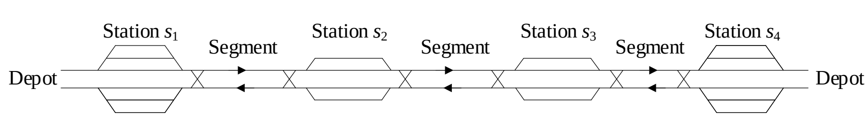


Figure 1: Illustration of a high-speed railway line

The purpose of this paper lies on exploring the effects of train coupling strategy on the train timetable rescheduling such that the cancellation of trains and its subsequent negative influences might be reduced. Under the train coupling strategy, two trains strictly satisfying specific coupling rules can be coupled together at a certain station to form one train so as to reduce the number of trains needed to be arranged at subsequent segments and stations along the line. We consider the coupling rules in the high-speed railway in China. To be specific, only the trains served by the same type of rolling stock with 8-carriage are able to be coupled with each other. Meanwhile, if two trains are about to couple at a station, they should pass through the same subsequent stations and terminate at the same destination station. Besides, there are mainly two coupling modes of trains based on practical situations. The first one is the shunting mode in which the former train firstly arrives and stops on a platform track at a station. When the latter train arrives at the same station, it firstly stops on another platform track and then couples with the former train through shunting operations. The second one is the receiving mode. There, at the coupling station, the former train arrives and stops on a platform track. Next when the latter train arrives, it firstly bounds for the same platform track and stops behind the former train, and then it couples with the former train with a lower speed. Obviously, the second mode can increase the utilization efficiency of platform tracks. Thus we formulate our train rescheduling approaches based on the second train coupling mode. Moreover, to ensure the practicability of the rescheduled timetables, the detailed occupation of platform tracks of trains at each passed station should also be exactly determined, as the safety requirements at stations and on segments expressed by different headway between trains have to be strictly fulfilled.

The railway line shown in Figure 1 is used to describe our problem. This line has 4 stations denoted as s_1–s_4 along the downstream direction. As trains run independently in the two directions of the line, w.l.o.g. we only consider the train rescheduling in the downstream direction, and trains are not allowed to utilize the tracks that normally are used in the opposite direction. Along the downstream direction, at stations s_1 and s_4 there are 3 platform tracks denoted as k_1–k_3 based on their distance to the main track (i.e. k_1), while only 2 platform tracks are set in intermediate stations s_2 and s_3. There are in total 5 trains numbered as i_1–i_5 running and terminating at station s_4 in the line. The planned timetable of these trains is displayed by the blue lines in Figure 2(a). Suppose that a disruption occurs in segment (s_3, s_4) at time t_1 leading to a complete blockage to this segment, which is predicted to be recovered at time t_2 and expressed by the light gray rectangle, these planned trains will be affected by the disruption and should be rescheduled. Feasible rescheduled timetables without and with the train coupling strategy are illustrated by Figures 2(b) and 2(c), respectively, where red lines indicate that the related trains are affected by the disruption at associated stations and segments, and magenta lines represent that the related trains couple with others at a certain station and pass through the subsequent segments together. Meanwhile, the rescheduled platform track assignment at parts of stations under coupling strategy is shown in Figure 2(d), where dark gray rectangles illustrate the platform track occupations of corresponding trains at associated stations.

As observed from Figure 2, when the disruption occurs, trains i_1–i_3 are directly affected by the disruption and each of them should dwell on a platform track at a certain station to wait for the recovery of the disruption. In the given rescheduled timetable using coupling, these trains are arranged to stop at station s_3 such that the planned timetable of these trains before station s_3 can be strictly fulfilled. Meanwhile, due to the lack of platform tracks, trains i_1 and i_2 couple with each other at station s_3 on platform track k_1 and pass through the subsequent segment (s_3, s_4) together. At this point, train i_3 can arrive at station s_3 and stop at platform track k_2 until the disruption is finished. Even though train i_4 is not

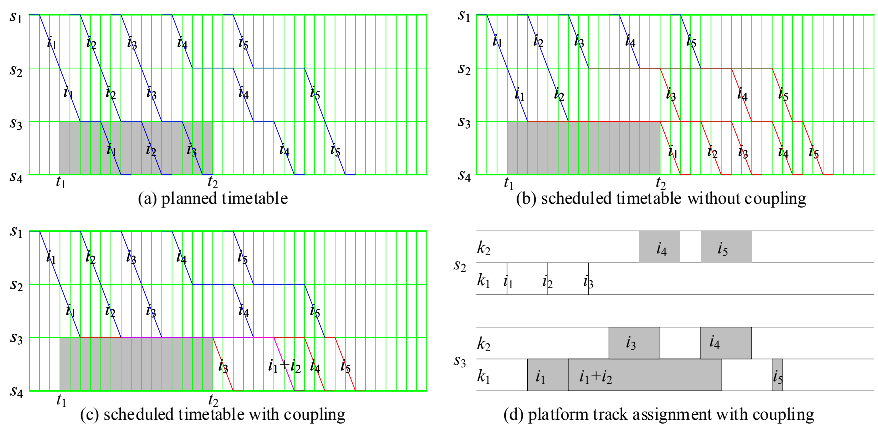


Figure 2: Representation of rescheduled timetable and platform track assignment

directly affected by the disruption, to maintain the enough headway between the departures of coupled train $i_1 + i_2$ and train i_4 at station s_3, train i_4 is postponed to depart from the station. Similarly, train i_5 is delayed at station s_3 to maintain the departure headway between train i_4. Note that trains should occupy the associated main track at each nonstop passed station (e.g. trains i_1-i_3 at station s_2) according to the practical requirement in China. By comparing Figures 2(b) and 2(c), the influence of the disruption to the planned timetable can be obviously reduced at a certain degree.

From the perspective of railway operators, the purpose of train rescheduling after disruptions is to maintain the stability of planned train timetables and to reduce the inconveniences to passengers as much as possible. The total deviation of timetables is widely used as the objective function for train rescheduling (e.g. Zhan et al. (2015)) in China. As a result, there are likely different rescheduled timetables with the same objective function value caused by the reordering and coupling of trains. For example, in Figure 2(b) trains i_1 and i_2 cross segment (s_3, s_4) sequentially based on their planned order. However, it is also feasible by swapping the order of these trains while not increasing the total deviation. At the same time, in Figure 2(c) trains i_1 and i_2 are coupled at station s_3, while coupling train i_1 and i_3 could also obtain the best objective function if the dwell time is enough for the associated coupling of trains i_1 and i_3. Obviously, swapping trains i_1 and i_2 in Figure 2(b) and coupling trains i_1 and i_3 instead of trains i_1 and i_2 might be strange and not be attractive for practical application, they should be prevented as much as possible while not deteriorating the total arrival and departure deviation.

Thus, the real-time train rescheduling problem considered in this paper is defined as follows. Given the layout of the studied high-speed railway line, the capacity of stations and segments, the planned timetable, and the location, start time and predicted duration of the segment blockage, our problem lies on determining the actual arrival time, departure time and platform track of trains at passed stations along their predetermined route, as well as the coupling decisions of trains, such that the weighted sum of the total deviation of trains' arrival and departure time to that in the planned timetable and the strange reordering and coupling decisions is minimized, and specific operational and safety requirements are respected.

2.2 Assumptions

We focus on incorporating the coupling strategy to improve the quality of train rescheduling in a high-speed railway line under a complete segment blockage from the macroscopic perspective. To facilitate the formulation of our model, the following assumptions are made.

- We only consider one side of the stations along the railway line. In other words, trains are not allowed to utilize tracks that normally are used in the opposite direction.
- When disruption occurs, the trains that locate at the blocked segment cannot pass through the segment and they should return to the behind station incident to the segment to wait until the disruption is recovered.
- The earliness and tardiness of arrival time are both allowed, while the earliness of departure time will never occur for the consideration of the boarding of passengers.
- The cancelling of trains is not considered as the train coupling strategy is adopted.
- At most two trains which strictly satisfy the coupling rules can be coupled together at a certain station due to the length of platform tracks at stations. The coupled trains will not be decoupled until their destination station is reached.

3 Model Formulation

3.1 Notation

We formulate our problem as a mixed integer linear programming model. The sets, indices and parameters to be used in the formulation of the model are explained in Table 1, and Table 2 expresses the decision variables.

3.2 Objective

As introduced, from the perspective of railway operators, it is necessary to minimize the total deviation of trains' arrival and departure time to that in the planned timetable so as to maintain the stability of timetable as far as possible after disruptions. At the same time, the unattractive reordering and coupling should be eliminated as much as possible. This objective function is expressed as follows.

$$
\begin{aligned}
&\min \quad U = U_1 + U_2 + U_3 \\
&U_1 = \sum_{i \in T} \sum_{m \in A_i} y_{im} + \sum_{i \in T} \sum_{m \in A_i} (f_{im} - d_{im}) \\
&U_2 = \sum_{i \in T} \sum_{m \in A_i} \sum_{j \in C_{im}} \gamma_{ijm} \cdot x_{ijm} \\
&U_3 = \sum_{i \in T} \sum_{j \in T} \sum_{(m,n) \in B_i \cap B_j} \pi_{ijmn} \cdot \lambda_{ijmn} \cdot u_{ijmn}
\end{aligned}
\tag{1}
$$

The first part of U_1 is the total deviation of arrival time including the tardiness and earliness of arrival time simultaneously, and the second part is that of departure time which only

Table 1: Definition of sets, indices and parameters

Notation	Description
T	Set of trains, $T = \{1, 2, \cdots, \|T\|\}$, $\|T\|$ is the number of trains running in the studied line.
i, j	Index of trains, $i = 1, 2, \cdots, \|T\|$, $j = 1, 2, \cdots, \|T\|$.
S	Set of stations which are indexed along the downstream direction, $S = \{1, 2, \cdots, \|S\|\}$ where $\|S\|$ is the number of stations in the studied line.
m, n, s	Index of stations, $m = 1, 2, \cdots, \|S\|$, $n = 1, 2, \cdots, \|S\|$, $s = 1, 2, \cdots, \|S\|$.
E	Set of segments, $E = \{(m, n) \| m, n \in S\}$.
(m, n)	Index of segments which represents the segment between adjacent stations m and n.
A_i, B_i	Set of stations and segments contained in the predetermined route of train i, respectively.
K_m	Set of platform tracks at station m indexed incrementally by their distance to the main track.
k	Index of platform tracks, where the index of the main track at each station equals to 1.
θ_{im}	Order of train $i \in T$ to leave station $m \in A_i$ based on the planned timetable. Note that θ_{im} is not always equal to i as the overtaking of trains usually exists.
β	Integer constant introduced to assure the attraction of the coupling decision. It requires that a train can only couple with its previous and latter β trains satisfying the coupling rules at a passed station.
C_{im}	Set of trains which can be coupled with train i at station $m \in A_i$. It is generated in advance based on the predefined route of trains and coupling rules as well as β to ensure the reasonability of the rescheduled timetable.
N_{ij}	Set of segments where train i and train j can be coupled together to pass through, $N_{ij} \subseteq B_i \cap B_j$. If these two trains do not satisfy the coupling rules, $N_{ij} = \emptyset$.
t_1, t_2	Start time and predicted end time of the disruption, respectively.
(e_1, e_2)	Disrupted segment, where e_1 and e_2 are its behind and front incident station, respectively.
a_{im}, d_{im}	Scheduled arrival and departure time of train i at station $m \in A_i$, respectively.
r^1_{imn}, r^2_{imn}	Minimum and maximum running time of train i on segment $(m, n) \in B_i$, respectively.
q_1, q_2	Additional acceleration and deceleration time of trains once stopping at stations, respectively.
π_{ijmn}	0-1 constant, 0 if train $i \in T$ enters segment $(m, n) \in B_i \cap B_j$ before train j enters the segment based on the planned timetable, 1 otherwise.
b_{im}	Minimum dwell time of train i at station $m \in A_i$ for the boarding and alighting of passengers.
g_m	Duration time to couple two trains which strictly satisfy the coupling rules at station m.
δ_{ij}	The first station at which trains i and j can be coupled together. If these two trains do not satisfy the coupling rules, $\delta_{ij} = \emptyset$.
h_1	Departure headway of two consecutive trains to depart from the same station.
h_2	Arrival headway of two consecutive trains to arrive at the same station.
h_3	Departure-arrival headway of two consecutive trains not being coupled together.
h_4	Arrival-departure headway of two consecutive trains not being coupled together.

Table 2: Definition of decision variables

Notation	Description
x_{ijm}	Binary variable, 1 if train i is coupled with train $j \in C_{im}$ at station $m \in A_i$, 0 otherwise.
y_{im}	Nonnegative integer variable, represents the arrival time deviation of train i at station $m \in A_i$ compared to that in planned timetable.
c_{im}	Nonnegative integer variable, represents the actual arrival time of train i at station $m \in A_i$.
f_{im}	Nonnegative integer variable, represents the actual departure time of train i at station $m \in A_i$.
w_{im}	Binary variable, 1 if train i stops at station m in the rescheduled timetable, 0 otherwise.
u_{ijmn}	Binary variable, 1 if the actual time of train i to enter segment $(m, n) \in B_i \cap B_j$ is earlier than that of train j, 0 otherwise.
p_{ijm}	Binary variable, 1 if the actual departure time of train i from station $m \in A_i \cap A_j$ is earlier than the actual arrival time of train j at the station, 0 otherwise.
v_{imk}	Binary variable, 1 if train i occupies platform track $k \in K_m$ at station m, 0 otherwise.
z_{ijmn}	Binary variable, 1 if trains i and j couple together to cross segment $(m, n) \in N_{ij}$, 0 otherwise.

contains tardiness. U_2 is introduced to penalize the unattractive train coupling decisions, where γ_{ijm} is a small constant. As coupling consecutive trains seems to be much more attractive for practical application, we set γ_{ijm} to $|\theta_{im} - \theta_{jm}|$. Similarly, U_3 is utilized to penalize the unattractive reordering of trains, where λ_{ijmn} is a small constant which is also set to $|\theta_{im} - \theta_{jm}|, \forall(m,n) \in B_i \cap B_j$.

3.3 Constraints

Train running constraints
Specific train running requirements should be strictly satisfied to maintain the feasibility of rescheduled timetables and the safety of trains. Constraints (2) mean that the actual running time of trains on a segment should be no less than the minimal time and be no greater than the maximum time to maintain the practical feasibility, where the additional acceleration and deceleration time are exactly considered. Note that the range of running time of a train whether being coupled with others or not on a segment makes no difference as each train has the tractive force. Indeed the actual running time of each train on a segment is also flexible within the range in this paper. Constraints (3) and (4) calculate the deviation of arrival time to that in planned timetable, where the former is dedicated for the tardiness and the latter for the earliness. Constraints (5) require that trains cannot depart from any passed station ahead of planned time. Trains are prevented from entering the disrupted segment during the disruption by constraints (6) to ensure the safety of trains. Besides, these constraints can also maintain that the trains locating at the disrupted segment once the disruption occurs should return to the behind station incident to the disrupted segment.

$$r^1_{imn} + q_1 \cdot w_{im} + q_2 \cdot w_{in} \leq c_{in} - f_{im} \leq r^2_{imn} \quad \forall i \in T, \forall(m,n) \in B_i \tag{2}$$

$$y_{im} \geq c_{im} - a_{im} \quad \forall i \in T, \forall m \in A_i \tag{3}$$

$$y_{im} \geq a_{im} - c_{im} \quad \forall i \in T, \forall m \in A_i \tag{4}$$

$$f_{im} - d_{im} \geq 0 \quad \forall i \in T, \forall m \in A_i \tag{5}$$

$$f_{ie_1} \geq t_2 \quad \text{if } (d_{ie_1}, a_{ie_2}) \cap [t_1, t_2] \neq \emptyset \quad \forall i \in T | (e_1, e_2) \in B_i \tag{6}$$

Train dwelling constraints
Specific train dwelling requirements should be fulfilled to enable the normal boarding and alighting of passengers and the coupling of trains. Constraints (7) ensure that the dwell time of trains at stations should be valued enough for the boarding and alighting of passengers and the coupling of trains if necessary. Constraints (8) are designed to determine whether a train needs to stop at a station after the disruption, where M_1 is a large positive constant and its value could be the length of the studied timetable. Together with constraints (7), no station at which a train is about to stop in the planned timetable will be skipped.

$$b_{im} + g_m \cdot \sum_{j \in C_{im}} x_{ijm} \leq f_{im} - c_{im} \quad \forall i \in T, \forall m \in A_i \tag{7}$$

$$w_{im} \leq f_{im} - c_{im} \leq M_1 \cdot w_{im} \quad \forall i \in T, \forall m \in A_i \tag{8}$$

Train coupling constraints
Any two trains if being coupled together should satisfy not only the strict coupling rules but also specific operational requirements. Constraints (9) mean that each train can be coupled with at most one another train at only a certain station for the consideration of

operations. Constraints (10) represent that if trains i and j are coupled together on segment $(m, n) \in N_{ij}$, then they should also be coupled to pass through the immediate subsequent segment $(n, s) \in N_{ij}$ since coupled trains are not allowed to be decoupled until they reach their destination station. Constraints (11) and (12) are introduced to express the relationship between variables z_{ijmn} and x_{ijm} based on their definition, which imply that trains only might be coupled at a station and coupled train cannot decoupled until arrives at destination station. Constraints (13) and (14) assure that the actual departure and arrival time of two trains coupled at a certain station should be equal at subsequent stations.

$$\sum_{m\in A_i}\sum_{j\in C_{im}} x_{ijm} \leq 1 \qquad \forall i \in T \tag{9}$$

$$z_{ijns} \geq z_{ijmn} \qquad \forall i,j \in T, \forall (m,n),(n,s) \in N_{ij} \tag{10}$$

$$x_{ijn} = z_{ijns} - z_{ijmn} \qquad \forall i,j \in T, \forall (m,n),(n,s) \in N_{ij} \tag{11}$$

$$x_{ij\delta_{ij}} = z_{ij\delta_{ij}n} \qquad \forall i,j \in T, (\delta_{ij}, n) \in N_{ij} \tag{12}$$

$$M_1 \cdot (z_{ijmn} - 1) \leq f_{im} - f_{jm} \leq M_1 \cdot (1 - z_{ijmn}) \quad \forall i,j \in T, \forall (m,n) \in N_{ij} \tag{13}$$

$$M_1 \cdot (z_{ijmn} - 1) \leq c_{in} - c_{jn} \leq M_1 \cdot (1 - z_{ijmn}) \quad \forall i,j \in T, \forall (m,n) \in N_{ij} \tag{14}$$

Train headway constraints

There are series of headway requirements that should be strictly met to avoid the potential route conflicts of trains at stations, including the departure headway h_1, arrival headway h_2, departure-arrival headway h_3 and arrival-departure headway h_4. The headway between two consecutive trains which are not coupled together is illustrated by Figure 3.

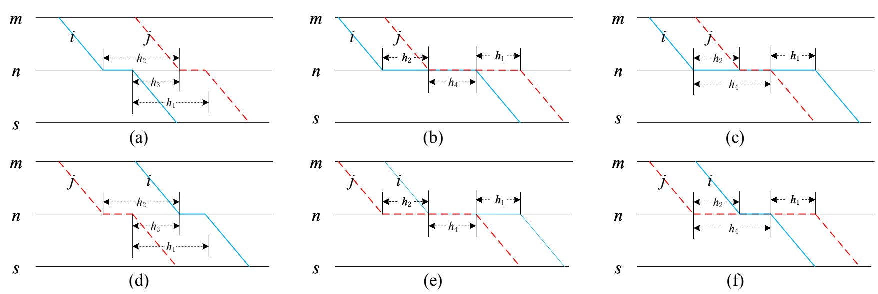


Figure 3: Headway between two consecutive trains

As observed from Figure 3, the arrival and departure headway between two consecutive trains should always be respected, while either the departure-arrival headway (Figures 3(a) and 3(d)) or the arrival-departure headway (Figures 3(b), 3(c), 3(e) and 3(f)) should be strictly satisfied. For example, if the departure-arrival headway between the departure of train i and the arrival of train j at station n is fulfilled shown in Figure 3(a), then the arrival-departure headway between the arrival of train i and the departure of train j at the station can be naturally respected. As a consequence, the train headway constraints are formulated as follows.

$$u_{ijmn} + u_{jimn} = 1 - z_{ijmn} \qquad \forall i,j \in T, \forall (m,n) \in B_i \cap B_j \tag{15}$$

$$f_{im} + h_1 \leq f_{jm} + M_1 \cdot (1 - u_{ijmn}) \qquad \forall i, j \in T, \forall (m,n) \in B_i \cap B_j \tag{16}$$

$$c_{in} + h_2 \leq c_{jn} + M_1 \cdot (1 - u_{ijmn}) \qquad \forall i, j \in T, \forall (m,n) \in B_i \cap B_j \tag{17}$$

$$f_{im} + h_3 \leq c_{jm} + M_1 \cdot (1 - p_{ijm}) \qquad \forall i, j \in T, \forall m \in A_i \cap A_j \tag{18}$$

$$c_{jm} + h_4 \cdot (1 - z_{ijmn}) \leq f_{im} + M_1 \cdot p_{ijm} \quad \forall i, j \in T, \forall m \in A_i \cap A_j \tag{19}$$

Constraints (15) reflect the relationship between variables u_{ijmn} and z_{ijmn}, which mean that if trains i and j are not coupled together to pass through section $(m,n) \in B_i \cap B_j$, i.e. $z_{ijmn} = 0$, then the time of train i to enter the segment should be earlier than that of train j, or on the contrary. Otherwise, these two trains should enter the segment at the same time and they need not to satisfy the departure headway at station m. Note that these constraints transform to $u_{ijmn} + u_{jimn} = 1$ if $(m,n) \in B_i \cap B_j$ and $(m,n) \notin N_{ij}$. Constraints (16) and (17) maintain the headway between two consecutive trains to depart from a station (i.e. departure headway) and to arrive at a station (i.e. arrival headway), respectively. Obviously, these constraints do not apply for coupled trains on segment (m,n). At the same time, these two constraints can also prevent the overtaking of trains along the segment. The departure-arrival headway of two consecutive trains is guaranteed by constraints (18) which only take effect under the situation that $p_{ijm} = 1$ or $p_{jim} = 1$ illustrated by Figures 3(a) and 3(d), respectively. Constraints (19) are for the arrival-departure headway which should be respected if the actual departure time of train $i(j)$ is not earlier than the arrival time of train $j(i)$ at station m, i.e. $p_{ijm}(p_{jim}) = 0$. Note that $p_{ijm} = 0$ holds if $z_{ijmn} = 1$ according to constraints (13) and (18). Then constraints (19) are transformed to $c_{jm} \leq f_{im}$ which are obviously valid since $c_{jm} \leq f_{im} = f_{jm}$ if $z_{ijmn} = 1$ according to constraints (13).

Station capacity constraints

The capacity of stations is expressed by the headway between two trains to occupy the same platform track since each track can be occupied by only one train or two coupled trains at a time. Meanwhile, a track should have been cleared for a specific time when another train starts to occupy the track. As observed from Figure 3, only under the situations in Figure 3(a) and 3(d), the two consecutive trains which are not coupled together or are about to be coupled at station m can occupy the same platform track at the station. Note that the necessary headway for these trains to occupy the same platform track has ensured by constraints (18). Thus, the station capacity requirements are expressed as follows.

$$\sum\nolimits_{k \in K_m} v_{imk} = 1 \qquad \forall i \in T, \forall m \in A_i \tag{20}$$

$$\sum\nolimits_{k \in K_m | k \neq 1} v_{imk} \leq w_{im} \qquad \forall i \in T, \forall m \in A_i \tag{21}$$

$$v_{imk} + v_{jmk} \leq 1 + p_{ijm} + p_{jim} + z_{ijmn} \quad \forall i, j \in T, \forall m \in A_i \cap A_j, \forall k \in K_m \tag{22}$$

$$M_2(z_{ijmn} - 1) \leq \sum\nolimits_{k \in K_m} k \cdot v_{imk} - \sum\nolimits_{k \in K_m} k \cdot v_{jmk} \leq M_2(1 - z_{ijmn}) \quad \forall i, j \in T, \forall (m,n) \in N_{ij} \tag{23}$$

Constraints (20) declare that each train should occupy exact one platform track at each of its passed station. Along with constraints (20), constraints (21) require that the trains not about to stop at a passed station should occupy the associated main track (i.e. $k = 1$) at the station. Constraints (22) and (23) together with the train headway constraints are designed to reflect the station capacity requirements. Constraints (22) mean that if trains i and j

occupy the same platform track k at station $m \in A_i \cap B_j$ (i.e. $v_{imk} = v_{jmk} = 1$), then these two trains should be coupled to pass through the subsequent segment $(m,n) \in N_{ij}$ (i.e. $z_{ijmn} = 1$), or these trains should satisfy the departure-arrival headway illustrated in 3(a) and 3(d) (in other words, $p_{ijm} + p_{jim} = 1$ should hold). Note that constraints (22) will be transformed to $v_{imk} + v_{jmk} \leq 1 + p_{ijm} + p_{jim}$ if $m \in A_i \cap A_j$ and $(m,n) \notin N_{ij}$. Constraints (23) ask that if trains i and j are about to be coupled together to pass through segment $(m,n) \in N_{ij}$ (i.e. $z_{ijmn} = 1$), then they should occupy the same platform track at station m (i.e. $\sum_{k \in K_m} k \cdot v_{imk} = \sum_{k \in K_m} k \cdot v_{jmk}$). where M_2 is a large positive constant and it can be set to the number of platform tracks at station m.

4 Solution Approach

Overall, the real-time train timetable rescheduling incorporating coupling strategy (TRCS) in a high-speed railway line under a complete segment blockage can be formulated as a mixed integer linear programming model to minimize objective (1) under constraints (2)–(23). Obviously, the original problem is NP-hard as it can be easily reduced to the NP-hard problem investigated in Zhan et al. (2015) if trains are not allowed to couple (i.e. to set all x_{ijm} to 0 in advance). Fortunately, our model is a linear programming due to that optimal or high quality feasible solutions for small-scale problems can be obtained quickly by state-of-the-art commercial solvers. Observe that train dispatchers usually reschedule timetables in stages in practice as the duration of the disruption is updated gradually. Thus, a rolling horizon algorithm is customized to effectively solve large-scale problems under the real-time decision requirement of train rescheduling. The effectiveness of rolling horizon algorithm in the field of railway rescheduling has been testified by several previous works such as Zhan et al. (2016) for the train timetable rescheduling and Nielsen et al. (2012) for the rolling stock rescheduling.

In our algorithm, the original problem (TRCS) is decomposed into several small-scale subproblems according to the given horizon length σ and update step size τ. Specifically, the long time span of the original problem is divided into several overlapped shorter stages in each of which a similar subproblem is directly solved by commercial solvers. The procedures of the algorithm are as follows.

Step 1: Initialization. We firstly initialize the stage $l = 0$, the considered train set $T_l = \emptyset$ in stage l, the passed station set $A_i^l = \emptyset$ of train i in the stage. Then, we set the start time of the algorithm denoted as t_{start} to be the earliest planned arrival time of all affected trains at their origin station. Meanwhile, suppose that D_l (which includes the trains of which all the arrival and departure time at all passed stations have been fixed) is composed of the trains certainly not affected by the disruption, i.e. the trains which have crossed the disrupted segment before the occurrence of the blockage and the trains will not pass the disrupted segment according to their predetermined route from the planned timetable. Finally, introduce the best rescheduled timetable $X^* = \{c_{im}^*, f_{im}^*, v_{imk}^*\}$ of the algorithm by setting all of its elements to be 0. Set $l = l + 1$ and go to the next step.

Step 2: Pick out the considered train in stage l. Firstly we calculate the start time t_{start}^l and the end time t_{end}^l of stage l by $t_{\text{start}}^l = t_{\text{start}} + (l-1) \times \tau$ and $t_{\text{end}}^l = t_{\text{start}}^l + \sigma$. Then, we pick out the considered train set T_l in the stage based on the range of $[t_{\text{start}}^l, t_{\text{end}}^l]$. To be specific, $T_l = \{T_{l-1} \cup I_l\} \backslash D_{l-1}$, where I_l includes the trains that are newly about to run at a certain station or segment in stage l (i.e. the trains at least one of their planned arrival and departure time locates within the range).

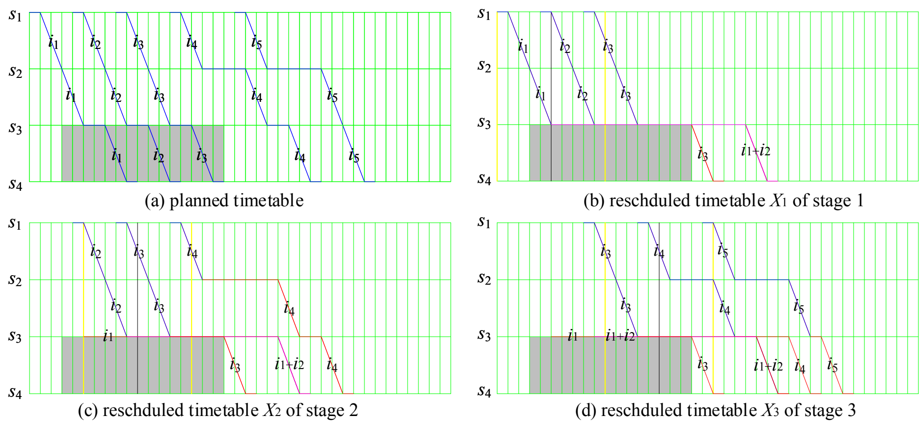
Step 3: Update the passed station set A_i^l for each train $i \in T_l$. The origin station of train i in stage l is set to either the last station at which its actual arrival time is fixed in stage $l-1$ or its origin station determined by the planned timetable if $i \notin T_{l-1}$. Meanwhile, the destination station of each train in this stage is set to its final destination predefined in the planned timetable to maintain the feasibility of subsequent stages.

Step 4: Solve the subproblem arising from stage l. We firstly fix the actual arrival time and platform track assignment of each train $i \in T_l \backslash I_l$ at its origin station in stage l to those fixed in stage $l-1$. Then, the simpler subproblem (TRCS) in stage l is solved to optimality or until prescribed termination conditions are met. The resulting solution is denoted as X_l. Note that the boundary conditions between consecutive stages including the earliest arrival and departure time of trains, the occupation of platform tracks and the train coupling states should be strictly respected.

Step 5: Fix the rescheduled timetable in stage l. In X_l, if $c_{im} \leq t^l_{\text{start}} + \tau$, then the related c^*_{im} and v^*_{imk} in X^* are fixed to c_{im} and v_{imk} in X_l, respectively. Meanwhile, f^*_{im} is also fixed if $f_{im} \leq t^l_{\text{start}} + \tau$ holds. Stage l is completed. Note that if all trains have already be considered, then fix all associated decision variables based on X_l.

Step 6: Termination condition. Check out whether all of the arrival and departure time as well the track assignment of train i $(\forall i \in T_l)$ at all passed station have be fixed in X^*. If so, add this train to D_l. After update the D_l, if $D_l = T$ (i.e. all operations of trains at all passed stations have been fixed), then a rescheduled timetable is obtained and the rolling horizon algorithm is terminated. Otherwise, we set $l = l + 1$, return to Step 2 and the algorithm continues.

We take the planned timetable in Figure 2 as an example to describe the procedures of our algorithm. For simplicity, Figure 4 only gives the obtained rescheduled timetables arising from 3 stages. Besides, we suppose that the value of σ and τ are 10 and 5, respectively. Thus, in stage 1 shown in Figure 4(b), trains $i_1 \sim i_3$ are firstly picked out as they are about to run at one station or segment within the stage (the start and end time of the stage are expressed by the yellow lines). Then, the origin and destination of all these trains are set to s_1 and s_4 respectively since no arrival time is fixed. Next, the underlying simper subproblem (TRCS) is solved and a rescheduled timetable X_1 for trains $i_1 \sim i_3$ is obtained. Finally, the value of parts of variables is fixed if they do not exceed $t^1_{\text{start}} + \tau$ expressed by the black line. To be specific, we fix specified actual arrival time (including $c^*_{i_1 s_1}$, $c^*_{i_1 s_2}$, $c^*_{i_1 s_3}$ and $c^*_{i_2 s_1}$) and actual departure time (including $f_{i_1 s_1}$, $f_{i_1 s_2}$ and $f_{i_2 s_1}$) to that in X_1. Besides, parts of the track assignment decision should also be determined according to X_1, i.e. the occupation of train i_1 at stations $s_1 \sim s_3$ and train i_2 at station s_1. At this point, we check whether the arrival and departure time as well as the platform track of all trains at all passed stations are fixed. If so, the algorithm is terminated. Obviously, the termination condition is not met and we come to stage 2. In this stage, train i_4 is newly picked out and no train can be added to D_2, i.e. $I_2 = \{i_4\}$, $D_2 = \emptyset$, $T_2 = \{s_1, s_2, s_3, s_4\}$. Note that the route of train i_1 becomes to (s_3, s_4) as $c^*_{i_1 s_3}$ is fixed in stage 1, while the route of other trains is still (s_1, s_2, s_3, s_4). The associated subproblem (TRCS) is then solved to obtain a new rescheduled timetable X_2 in Figure 4(c) and parts of variables are fixed based on the time instant expressed by the black line in X_2. These procedures are executed repeatedly until the termination condition is satisfied. Actually, all trains have been considered after stage 3, thus all the unfixed variables in X^* can be fixed based on X_3 and the algorithm terminates.



(a) planned timetable

(b) reschduled timetable X_1 of stage 1

(c) reschduled timetable X_2 of stage 2

(d) reschduled timetable X_3 of stage 3

Figure 4: Illustration of the rolling horizon algorithm

5 Computational Tests

We construct realistic instances based on the Wuhan-Guangzhou High-Speed Railway in China to test the effectiveness of the train coupling strategy and the efficiency of our approaches. The train rescheduling model and the rolling horizon algorithm are both coded in MATLAB R2016a, and CPLEX 12.8 is invoked to solve the model, where the parameters of CPLEX are set to their default value.

The computations are executed on a PC with Inter Core i7-7700 3.6 GHz CPU, 16 GB RAM and Windows 10-64 bits operating system. For comparison, the maximum running time of CPLEX is limited to 4 hours. Meanwhile, to satisfy the real-time decision requirement of train rescheduling, the horizon length σ and update step size τ in the algorithm are set as 1 hour and 30 minutes respectively based on our preliminary computational results. The maximum computation time in each stage of the algorithm is limited to 60 seconds to control the total computation time of the algorithm.

5.1 Test Instances and Parameter Setting

The Wuhan-Guangzhou High-Speed Railway line is 1068 km long and it is one of the longest and busiest high-speed railway lines in China. There are 16 stations and 15 segments in total along the downstream direction from Wuhan to Guangzhou of this line at the end of 2016. The location and sketch map of this line are illustrated in Figure 5, where the number in cycles stands for the index of stations, and that in parentheses represents the number of platform tracks at associated stations and the minimum and maximum running time of trains on related segments. For example, the (8,19,24) near station 1 means that there are in total 8 platform tracks in the downstream direction at station 1, while the minimum and maximum running time of trains on segment (1, 2) are 19 and 24 minutes, respectively. Besides, "–" shows that the current station is the end point of the railway line.

The planned timetable utilized in our computational tests is extracted from the actual timetable used from 2015 to 2016 in practice, where only the trains in the downstream direction are adopted. We consider 63 long distance trains that run through the complete

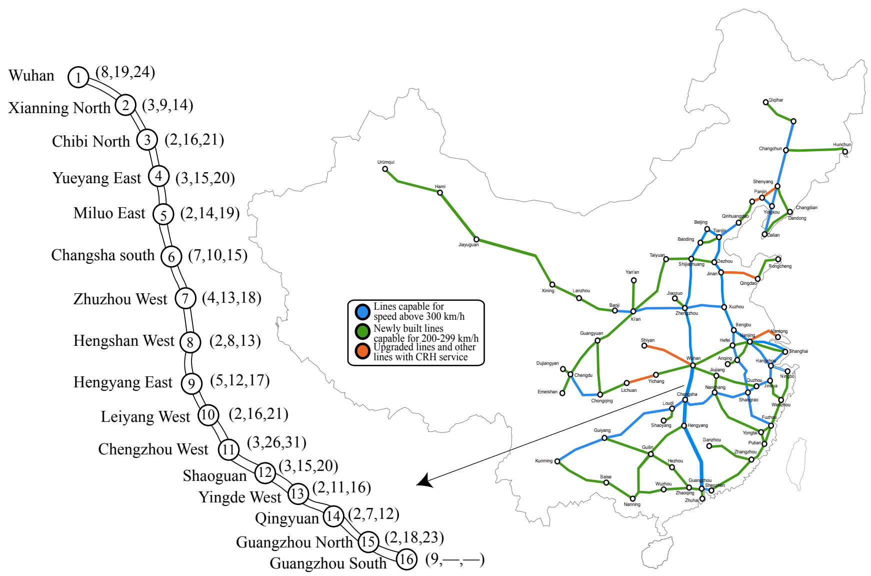


Figure 5: Chinese high-speed railway network and Wuhan-Guangzhou railway line

route from Wuhan Station to Guangzhou South Station, such that the train destination requirement in the coupling rules can be easily satisfied. Besides, the rolling stock type and the formation of some trains are reasonably modified to increase the diversify and applicability of the train coupling in case of complete segment blockages. Specifically, we assume that all trains are served by the same type of 8-carriage rolling stock, such that each two of them can be coupled together at any station passed through by both of the two trains. The considered time span is 6:00-24:00 and the integer time values represent minutes. The associated planned timetable is displayed in Figure 6, where trains are indexed by the sequential order of their planned departure time at their origin station. The planned platform track assignment of trains at stations are not given due to the limitation of space.

To generate representative instances, we firstly construct 3 disruption scenarios according to the location and start time of the disruption: (i) Scenario 1: the disruption occurs at 9:00 and segment (5, 6) is blocked, (ii) Scenario 2: the disruption occurs at 14:00 and segment (9, 10) is blocked, (iii) Scenario 3: the disruption occurs at 19:00 and segment (13, 14) is blocked. We further suppose that the duration of each disruption scenario ranges from 30 minutes to 90 minutes with a fixed increment of 15 minutes. As a result, in total 15 different instances are constructed to test our approaches.

The parameters of the test instances are set as follows. The minimum running time of trains on passed segments and the minimum dwell time of trains at passed stations equal to their predetermined value in the planned timetable. The additional acceleration and deceleration time equal to 2 and 3 minutes, respectively. The maximum running time of each train on each passed segment is set as the minimum value plus 5 minutes. The duration for each station to couple two trains is set as 10 minutes. The arrival, departure, departure-arrival and arrival-departure headway between two consecutive trains not coupled together are set as 3, 3, 2 and 2 minutes, respectively. Finally, we set β to 2 to prevent unreasonable coupling.

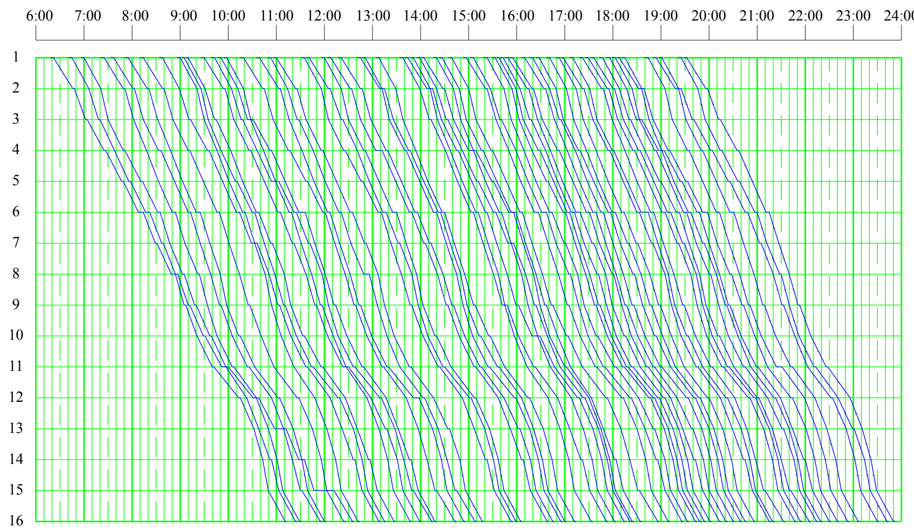


Figure 6: Planned timetable of the test line

5.2 Computational Results

The main results of computational tests are summarized in Table 3, and the meaning of the headers is explained below the Table. Note that the number of variables and constraints in our problem (TRCS) are related to the number of trains, passed stations/segments and platform tracks at stations rather than the disruption instances. Thus, the number of variables and constraints are the same for all test instances. According to CPLEX, in total our model has 354318 constraints and 96940 variables when solving the full problem.

As observed from Table 3, our model (TRCS) can obtain feasible solutions for all instances and in total 4 instances are solved to optimality within the limited time. Note that in the model the convergency rate of the lower bound is much slower than that of the upper bound. Thus the feasible solutions found by CPLEX within 4 hours are likely to be close to the optimal ones. However, the computation time is extremely large especially when the duration of the disruption is long. The average computation time of CPLEX reaches 10885 seconds which obviously does not satisfy the real-time decision requirement. Thus, solving our model directly using commercial solvers is not applicable for large-scale problems due to the real-time requirement of train timetable rescheduling. It is necessary to develop efficient algorithms. Compared to CPLEX, our rolling horizon algorithm can obtain feasible solutions for all instances very quickly. The maximum and average computation time are only 495 and 224 seconds, respectively. The computation time is reasonable for the test instances with such a long time span. Even though the maximum and average relative gaps between the objective value obtained by the algorithm and the best lower bound obtained by CPLEX reach 21.68% and 12.52% respectively, the quality of the solutions found by the algorithm can be improved by 2.13% in average when compared to the solutions obtained by CPLEX within 4 hours. Therefore, our algorithm is capable of solving practical-sized train rescheduling problems incorporating coupling strategy in high-speed railway lines in

Table 3: Summary results of computational tests

Instance[1]	CPLEX									Rolling horizon algorithm									
	OBJ[2]	LB[3]	U_1 /min	U_2	U_3	GAP[4] %	TIME[5] /s	NA[6] /train	NC[7] /train	OBJ	U_1 /min	U_2	U_3	GAP /%	IR[8] /%	TIME /s	NA /train	NC /train
(5,9:00,30)	1776	1776	1726	0	50	0.00	408	3	0	1861	1811	0	50	4.57	-4.92	12	4	0
(5,9:00,45)	3030	3030	2949	0	81	0.00	1802	5	0	3099	3028	2	69	2.23	-2.68	68	5	1
(5,9:00,60)	5049	4287	4929	2	118	15.10	14400	7	1	5122	5069	1	52	16.31	-2.84	249	7	1
(5,9:00,75)	7571	6199	7388	2	181	18.12	14400	8	1	7675	7641	3	31	19.23	-3.42	258	8	2
(5,9:00,90)	10622	8524	10470	3	149	19.75	14400	11	2	10533	10382	5	146	19.07	0.84	495	11	3
(9,14:00,30)	1953	1953	1945	1	7	0.00	1418	5	1	1953	1945	1	7	0.00	0.00	63	5	1
(9,14:00,45)	3392	2965	3362	1	29	12.58	14400	8	1	3395	3364	2	29	12.66	-0.06	278	8	1
(9,14:00,60)	5250	4209	5190	2	58	19.83	14400	8	1	5374	5301	2	71	21.68	-2.14	354	9	1
(9,14:00,75)	6870	6024	6749	4	117	12.32	14400	9	3	6870	6749	4	117	12.32	0.00	302	9	3
(9,14:00,90)	11748	7797	11394	1	353	33.63	14400	22	1	9707	9649	2	56	19.68	15.32	431	12	2
(13,19:00,30)	1080	1080	1074	2	4	0.00	1251	7	2	1088	1086	2	0	0.74	-1.12	64	8	2
(13,19:00,45)	2017	1965	1991	4	22	2.56	14400	10	3	2092	2079	5	8	6.05	-4.42	136	10	3
(13,19:00,60)	3230	2728	3220	6	4	15.53	14400	11	4	3236	3225	6	5	15.69	-0.16	186	11	4
(13,19:00,75)	6137	3817	6053	6	78	37.80	14400	23	4	4727	4687	8	32	19.25	22.57	198	13	5
(13,19:00,90)	7770	5143	7316	8	446	33.81	14400	16	5	6294	6220	8	66	18.29	14.98	262	14	6
Average	5166	4100	5050	3	113	14.74	10885	10.2	1.9	4868	4816	3	49	12.52	2.13	224	8.9	2.3

[1] Instance: the location, start time and duration of the disruption in instances, for example (5, 9:00, 30) means that a disruption occurs at 9:00 and makes segment (5,6) being blocked from 9:00 to 9:30.
[2] OBJ: the objective function value of the best feasible solutions obtained by the CPLEX/algorithm.
[3] LB: the best lower bound obtained by CPLEX within the maximum allowable computation time.
[4] GAP: the relative gap between the objective function value obtained by the CPLEX/algorithm and the related best lower bound.
[5] TIME: the total computation time of the CPLEX/algorithm.
[6] NOA: the total number of trains affected by the disruption.
[7] NOC: the total number of coupled trains.
[8] IR: the relative improvement rate of the objective value obtained by the algorithm to that of CPLEX.

the real-time setting.

It can also be known from Table 3 that the location, start time and duration of disruptions have different influences to the resulting rescheduled timetables. Firstly, the total deviation of arrival and departure time, the total number of affected trains and the associated computation time increase monotonically with the increment of the duration time. Meanwhile, the instances in which the disruption occurs in the segment near to the beginning of the railway line (e.g. Instances 1–5) seem to be easier to solve compared to the instances where the segment in the middle of the line is blocked (e.g. Instances 6–10), since the average computation time are 216 and 285 seconds. The reasons might be explained as follows. Under the former disruptions, many trains are able to be delayed at their actual origin station where much more platform tracks are usually available. Due to that, trains do not need to occupy the somewhat more limited platform tracks at intermediate stations. On the contrary, under the latter disruptions, many trains have already departed from their actual origin station when the disruption occurs. These train have to dwell and wait on a certain platform track at a reasonable intermediate station, making the instances more difficult to solve especially when there are relative few platform tracks at the front station of the disrupted segment. Note that the total deviation under the former disruptions may be worse than that under the latter ones, as trains are likely to be affected at more passed stations in the former cases. Moreover, when the blocked segment is close to the end of the line, the total deviation is likely to be small. However, if the disruption further occurs during the peak hour, much more trains will be affected and more trains could be coupled together to reduce the total deviation due to the restriction of limited station capacity.

5.3 Rescheduled Timetables

We now analyse the detailed rescheduled timetables by adopting the train coupling strategy under a complete segment blockage. For simplicity, we only give the rescheduled timetable of Instance (13, 19:00, 90) as the number of trains affected by the disruption and the number of coupled trains in the instance are both the largest. The rescheduled timetable of the instance is illustrated in Figure 7, where only the trains affected by the disruption are shown. In this Figure, the blue lines mean that the trains run following strictly the planned timetable. The magenta lines represent that the trains couple together at certain stations and pass through associated segments. The red lines indicate that the trains affected by the disruption pass through the associated segments alone. Note that the coupled trains are also affected by the disruption. From this Figure we observe that most affected trains need to dwell at stations 12 and 13 to wait for the recovery of the disruption. Thus, we only provide the rescheduled platform track assignment for the affected trains at these two stations. The rescheduled platform track assignment is depicted in Figure 8, where the left and right margins of the gray rectangles represent the start and end time of the associated trains to occupy the platform tracks, respectively.

Compared with Figure 6, we find in Figure 7 that there are in total 14 trains (i.e. trains 38–51) affected by the disruption, and the total deviation of arrival and departure time reaches 6220 minutes. Other trains are not impacted by the disruption as the buffer time in the planned timetable can relief the propagation of delays. Among the affected trains, train 40 is most heavily influenced and the associated total deviation reaches 763 minutes. Meanwhile, there are in total 6 trains of which the total deviation exceeds 500 minutes, i.e. trains 38–43. Besides, the maximum deviation of a train at a station reaches 196 minutes,

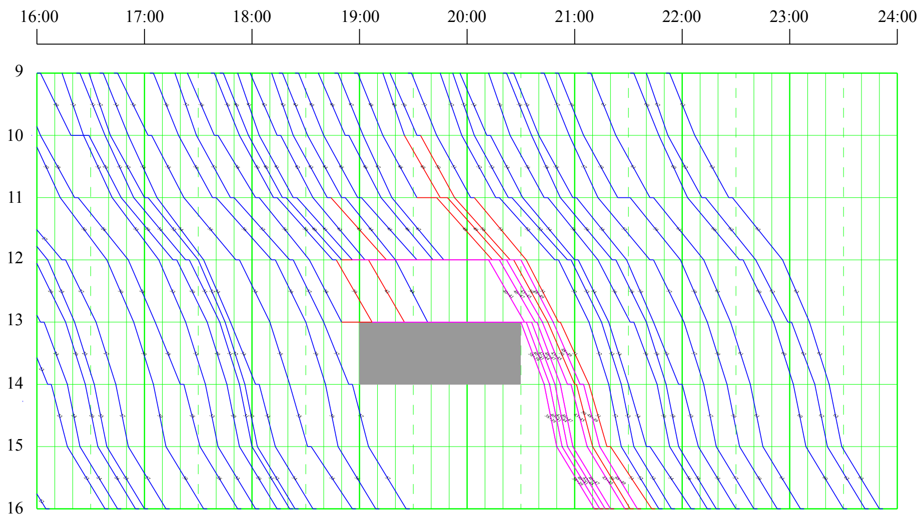


Figure 7: Rescheduled timetable of Instance (13, 19:00, 90)

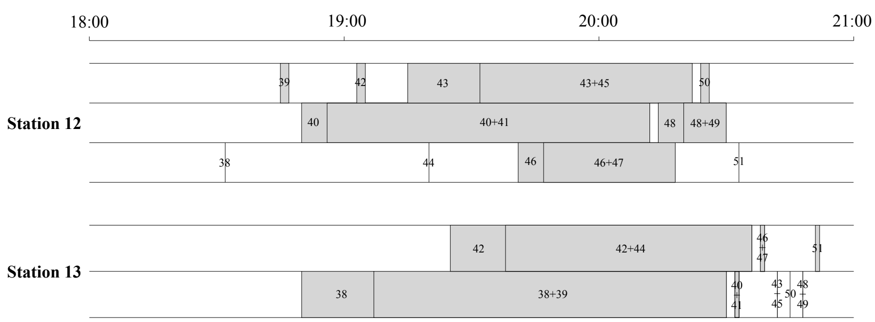
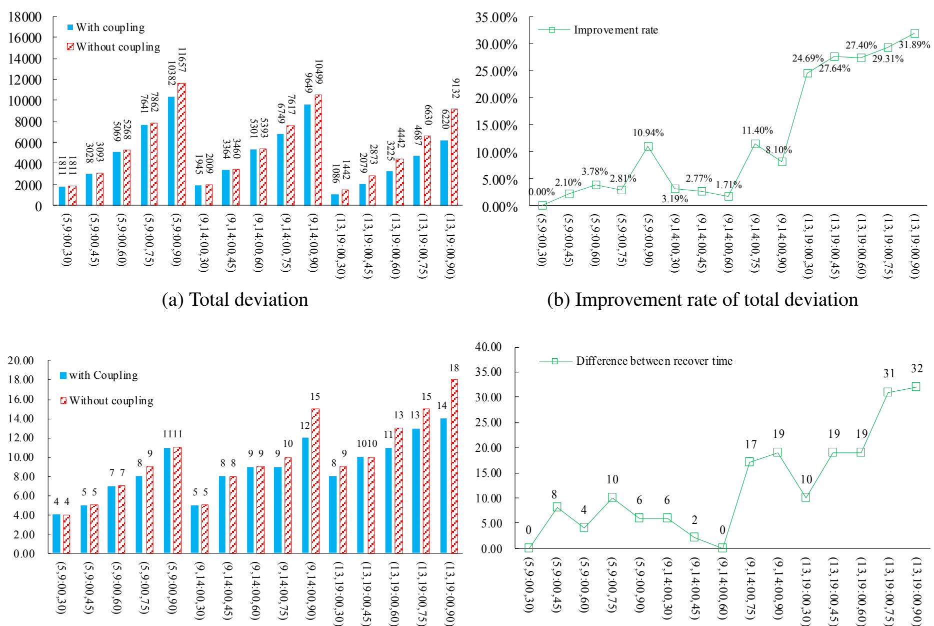


Figure 8: Platform track assignment of Instance (13, 19:00, 90)

leading to a maximum delay of 98 minutes for train 38 at stations 14–16. Regarding to the coupling decision, after the disruption is recovered, trains 40 and 41, trains 43 and 45, trains 46 and 47, and trains 48 and 49 are coupled respectively at station 12, while trains 38 and 39, and trains 42 and 44 are coupled respectively at station 13, such that the limited capacity at stations 12 and 13 and that on segments (12, 13) and (13, 14) are utilized sufficiently to reduce the total deviation. Obviously, most of the coupled trains are composed of consecutive trains except for trains 42+44 and 43+45. The reason might be that train 43 needs to dwell at station 14 based on the planned timetable, thus trains 42 and 43 will be overtaken by trains 44–47 and incur strange train reordering if they are coupled together. Besides, coupled trains 46+47 and 43+45 are swapped after station 12, due to that trains 46 and 47 need not to dwell at stations 14–15 so as to reduce the total arrival and departure deviation. Finally, as shown in Figure 8, every two coupled trains are accommodated on the same platform track at a station, while the departure-arrival headway between two (coupled) trains occupying the same track is respected strictly. Thus, our algorithm can be used to obtain practically feasible rescheduled timetables and platform track assignments for high-speed railway lines under complete segment blockages.

5.4 Comparison of Rescheduling Strategies

In this section, the rescheduling strategies with coupling and without coupling are tested on all instances to further evaluate the effectiveness of the train coupling strategy. The rescheduling strategy without coupling can be easily realised by fixing all variables x_{ijm} to 0 in advance in the model (TRCS). The two rescheduling strategies are both implemented by our rolling horizon algorithm. The comparison results are illustrated in Figure 9. Figure 9(a) gives the total deviation of all trains at all passed stations under different strategies, while the improvement rate of total deviation by the coupling strategy is shown in Figure 9(b) in which a positive value means that the total deviation with coupling is smaller than that without coupling. The total number of trains affected by the disruption is shown in Figure 9(c). We define that the recover time of timetables equals to the latest departure time of the affected trains at all affected passed stations. The difference between the recover time of timetables without coupling and that with coupling is provided in Figure 9(d) where a positive value means that the recover time with coupling can get earlier than that when coupling is not allowed.



(a) Total deviation (b) Improvement rate of total deviation

(c) Number of affected trains (d) Difference between recover time

Figure 9: Comparison results of rescheduling strategies

As seen from Figure 9, compared to the rescheduled timetables where trains are not allowed to couple, the total deviation and the number of affected trains under the coupling strategy are both reduced. The maximum improvement rate of the total deviation and the maximum decrement of the number of affected trains is 31.89% and 4, respectively. Meanwhile, the recover time of timetables is also likely to be earlier. Besides, the improvement rates are more notable if the disruption lasts for a longer time and occurs at the peak hour with denser traffic volume. Thus, we indicate that the train coupling strategy is promising to reduce the negative influences of large scale disruptions and to relief the propagation of train delays. It could be used as one alternative strategy to reschedule trains in high-speed railway lines in case of complete segment blockages.

6 Conclusions

Real-time train timetable rescheduling under complete segment blockage is of great significance to maintain the operating efficiency and service quality of high-speed railway. Currently, cancelling parts of trains is one of the main strategies to cope with complete segment blockages caused by large-scale disruptions both in academic and in practice, leading to large inevitable negative influences to passengers. Observe that the train coupling strategy gradually begins to be adopted in the daily operations of high-speed railways, this paper aims to explore the effects of this strategy on the real-time train rescheduling, such that the strategy of cancelling trains might be replaced by the better train coupling strategy and the negative influences to passengers can be reduced.

A novel mixed integer linear programming model is firstly formulated to minimize the total deviation of trains' arrival and departure time to that in planned timetable so as to maintain the stability of the timetable as much as possible once a disruption occurs. Meanwhile, strange reordering and coupling decisions are further considered and penalized in the objective function, such that the resulting rescheduled timetables will be more attractive for practical application. Series of operational and safety requirements including the train running and dwelling, train coupling and indispensable headway and station capacity are all considered. The model can be directly solved to find optimal or high quality feasible solutions in short time for small-scale problem instances by state-of-the-art commercial solvers due to its linear feature. To effectively solve large-scale problem instances in real-time setting, a rolling horizon algorithm is developed by utilizing that rescheduled timetables are usually determined in stages in practice. The effects of the proposed approaches are tested on instances generated from the Wuhan-Guangzhou High-Speed Railway in China. Computational results demonstrate that the train coupling strategy is likely to reduce the total deviations and the total number of affected trains. The rolling horizon algorithm can provide high quality rescheduled timetables satisfying the requirement of real-time decisions. Thus, the train coupling strategy is promising in the field of train rescheduling to cope with large-scale segment blockages.

To the best of our knowledge, this paper might be the first one to study the train timetable rescheduling incorporating train coupling strategy in case of a complete segment blockage. We focus on the coupling decisions of trains at stations under practical and safety restrictions, and the decoupling of trains are not taken into account. Thus, the subsequent train coupling rules are strict, making this strategy seeming to be more applicable for dense timetables with a large portion of trains having the same type and route. Therefore, it is valuable to consider the coupling and decoupling of trains simultaneously to extend the application scope of this strategy. Besides, the platform track assignment of trains at stations is adjusted to assure the practical feasibility of the rescheduled timetables, which may be great different to the planned assignments and increase the operating difficulty of organizing passengers at stations. Thus, it is also significant to consider the stability of the planned platform track assignments in the further study. Finally, we suppose that the end time of the disruption can be predicted in advance and whether the rescheduling of trains should be carried out can be determined in advance. However, it is probably not the case and the uncertainty of the disruption needs to be further considered in the future.

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