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Optimization-based Train Timetables Generation for Taiwan High-Speed Rail System Considering Circulation and Disturbances

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Abstract

As more and more governments are planning or constructing their high-speed rail (HSR) systems, the central control mechanism of such systems, i.e., train timetables, should be investigated more in order to cope with various disturbances due to disasters. Several optimization-based approaches have been successfully utilized for generating stable and reliable train timetables; however, few researchers have considered train circulation issues, especially for HSR systems, even though it could be such a way to reschedule the timetable against disturbances. This research proposed a scheduling optimization model that has the capability to accommodate not only basic requirements but train circulation as well for Taiwan HSR system. The sensitivity analysis was applied in order to identify how disturbances propagate in the original timetable and which actions to be taken in order to mitigate the impact instead of cancelling trains. With proper enhancement, the proposed model could be a good simulation tool to help predict the effect of disruptions on the timetable without doing real experiments.

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Keywords: Timetable; Optimization model; Train circulation; Sensitivity analysis;

1. Introduction

Nowadays, railway transportation has become a good alternative in many countries as an efficient and economic public transportation mode. It plays an important role in the passenger and freight transportation market. The

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railway has grown by over 40% in both freight and passenger sectors over the past 10 years [1]. All railway companies try to provide good services in order to satisfy their customers. One way to realize this is by improving the quality of the train control process or scheduling so that railway companies could optimize the services as well. In fact, the train control process heavily relies on train timetables, which are the basis for performing all kinds of train operations. A timetable contains information regarding the topology of the railway, train numbers and classification, arrival and departure times of trains at each station, arrival and departure paths, etc. More formally, the train scheduling problem is to find an optimal timetable, subject to a number of operational and safety requirements. The scheduling problem in this research is emphasized to Taiwan high-speed rail (HSR) system, i.e., a type of passenger rail transport that operates significantly faster than the normal speed of rail traffic. Specific definitions of a HSR system by the European Union include 200 km/h (120 mph) for upgraded tracks and 250 km/h (160 mph) or faster for new tracks [2]. Commonly, a HSR system has dedicated rights of way due to safety issues. It uses lines without branches and minimizes the amount of stoppage times to keep the speed constant. As the name high-speed suggests, predicting disturbances propagation and minimizing the consequences is a challenging problem for HSR operators because of the speed itself. In addition, managing circulation of HSR trains during disturbances, including regular and special inspections, car maintenance and cleaning activities and the turning back operation, has become crucial due to the mitigation efforts. Taiwan HSR system already has cyclic patterns of daily train circulation, but these patterns have not been modeled yet especially during disturbances. Moreover, based on a review of the literature, only few researchers have considered the train circulation model, especially in HSR systems, even though it is an important requirement and the arrangement of the circulation time in a given timetable could be such a way that the timetable becomes maximally robust against stochastic disturbances [3,4,5].

The objectives of this research are listed as follows: (1) designing train timetables using an optimization-based approach which can accommodate basic requirements such as railway topology, traffic rules, user requirements and train circulation requirements as well; (2) checking the model using real data from Taiwan HSR system; and (3) analyzing the responses of the model results to the disturbances using the sensitivity analysis. Compared to air transport, a HSR system can provide passengers with more frequent and punctual services. As more and more governments are considering the construction of a new HSR system to facilitate their intercity travel, it can be expected that such the system will require highest safety standards while employing a simple infrastructure layout to connect cities. Just like the same strategies used in Taiwan HSR system, a more comprehensive and easy-to-use mechanism to help the control center manage disturbances is highly needed. Hence, this research aimed at developing a formal model to represent the case study system. With proper modification of the model and customization of the application developed, the same approach could be applied to other HSR systems in order to assess and mitigate disturbances.

2. Related work

HSR systems are currently favorable for sustainable development of a country. The central control mechanism of such systems, i.e., train timetables, should be investigated more in order to cope with various disturbances due to disasters. Several optimization-based approaches have been successfully utilized for generating stable and reliable train timetables; however, no such optimization-based models exist in Taiwan HSR system. The real problem in Taiwan HSR system is its use of a contingency timetable to solve the timetabling problem under disturbances. It considers two conditions of disruption effects: (1) low-speed running operations at a certain location, and (2) line tracks or stations blocked. To solve the first condition, the system creates a timetable with speed restrictions and applies it to the train running time and headway calculations. Each speed would create different timetable results. Moreover, to solve the second problem (line tracks blocked), the system uses five types of blocked track possibilities and one type of bi-directional solution. This system generates the timetable according to a specified train running route. Each condition also has different timetable results. Nevertheless, as many contingency timetables can be prepared as planners can make in Taiwan HSR system. In fact, it still has a big problem, in that it is especially time consuming to maintain and select the appropriate contingency timetable for one disruption and create an optimal timetable during the disturbances. There are more than five thousand types of contingency timetables in the system, and the train operator should select the most appropriate timetable within a limited time [6].

Furthermore, based on past experiences, Taiwan HSR system prefers to cancel many trains and operates only two trains per hour in many cases of disturbances. Creating an optimal timetable, which means the optimal journey time, is important since the system still needs to transport passengers efficiently and effectively during disturbances. Additionally, in order to mitigate the impact of disturbances instead of cancelling many trains, Taiwan HSR system needs a method for analyzing how disturbances propagate within the original timetable and which actions to be taken to minimize the consequences. In the end, the train operator could predict the effects of disruptions on the timetable without doing real experiments.

Train scheduling problems have been studied by researchers over the years. They have been formulated using operation research-based techniques including mixed integer programming [7] and network optimization models [8]. Among the solution techniques developed to solve the problems were branch and bound [9], heuristics [10], and Lagrangian relaxation [11]. In addition, researchers have proposed some methods to solve scheduling problems as the Job-Shop problem [12], program evaluation and review technique or PERT [13], and satisfaction constraint [14]. The strengths and weaknesses of each method depend on research assumptions. For example, there is no guarantee that the heuristic will generate an optimal solution in every test case [14].

The scheduling and rescheduling problem in this research is formulated as mixed-integer-programming (MIP), in which some of the variables are real-valued and some are integer-valued. There are two ways to solve MIP: exact solution, including branch and bound, and dynamic programming and approximation, including heuristic and Lagrangian relaxation techniques [15]. Since the train scheduling problem is being used to find an optimal train timetable, it has many rules to consider. Early work has considered six types of scheduling rules in railway systems: speed constraints, station occupancy, station entry and exit constraints, stopover, and line time constraints [14,16]. Further, railway topology, traffic rules, and user requirements have been considered in mathematical formulations modeled [7,16]. There are two types of disturbances that may affect HSR train operations. The first type of disturbances, namely planned disturbances, would be scheduled track or other equipment maintenance which would have a temporary blockage, likely followed by a slow order for a few days. Since this type of disturbances may be known several months before the actual occurrence, the consequent train timetable can be generated with plenty of preparation time. The second type of disturbances, namely unexpected disturbances, results from natural disasters or man-made accidents and requires a modified train timetable as early as possible for the HSR system to recover. For example, earthquake, landslide, cloudburst, flood, gale pertain to natural disasters and may affect the HSR corridors and disturb train operations. Generally a HSR system consists of numerous sensors installed such as landside sensors, earthquake sensors, rock fall sensors, intrusion sensors, wind velocity sensors, flood level sensors, and rain fall sensors [6]. These sensors can record detailed events information and transmit to the HSR control center. Once the HSR control center completes the assessment of the current situations due to the disturbance, the train timetables generation process should be performed so that the HSR system can be recovered quickly and effectively following the disruption.

In this paper, we use an optimization method to solve the train timetabling problem and discuss the problem occurred during the sensitivity analysis. This research also used sensitivity to investigate the maximum relative travel times with respect to dwell times. The results concluded that only some trains modify the optimal solution locally if the dwell times of those trains are modified. Otherwise, no such local affect, that is, a small change in the corresponding dwell times does not modify the optimal relative travel time. In short, the sensitivity analysis provides important information about critical resources and trains, which used to improve the line and, indirectly, the timetable design. For example, in many important decisions, such as the number of stations, speed restrictions, departure times and dwell times modifies, could be derived from the sensitivity analysis results.

3. Model development

3.1. Scheduling and Rescheduling

Train scheduling is how to assign trains to tracks in order to get the effective time thus a passenger convenient for ordering the ticket and estimating the journey time. The train diagram, or graphical timetable, is a representation of the timetable in a more perceptive way. It is a time distance graph where all the train routes are represented. The advantage of this diagram is that it makes it much simpler and intuitive to read the timetable and to detect conflicts. In the design of a train timetable, many factors need to be considered. In a HSR system, the interdependency among components such as trains, infrastructure (tracks, stations), security regulations, and speed restrictions are very high. Since, in a railway system all trains are sharing tracks, thus schedules for different lines might depend on each other. A timetable should be designed to be feasible, in the sense that no disturbances occur thus there will be no delays. On the other hand, if it is impossible to run all trains at the assumed speed, then delays will occur.

Researchers have described the differences between scheduling and rescheduling in two aspects [3,14,16,17]. First, while scheduling creates a timetable from scratch, rescheduling assumes a feasible timetable and user modifications, which may introduce inconsistencies to the timetable, as input. Second, optimality criteria used in scheduling, such as minimum operating journey time, are usually defined in the absolute sense. In rescheduling, however, the quality of the output is measured with respect to the original timetable.

3.2. Problem description

Taiwan HSR system is about a 335 km intercity service line without branches along the western corridor of Taiwan. Railway topology of the system is linear with the southbound and northbound directions. It connects two major cities in Taiwan, i.e., Taipei and Kaohsiung, with eight stations along the line. Each station has multi-tracks (at least two tracks) which are used as platforms, waiting time terminals, and free passes. In one day, the system provides 120 services with 29 trains running. The goal of the optimization model in this research is to minimize the operation times of services, subject to basic requirements (railway topology, traffic control, user requirements) and train circulation requirements. Since the operation time of each train as well as required headway between consecutive trains depend on the track assignment, railway topology and train circulation issues have to be considered simultaneously to obtain a feasible result in order for the control center to dispatch train movements.

3.3. Model formulation

Suppose a railway system with r stations, n trains going down and m trains going up. Minimizing the operation times for all trains means minimizing the journey times (arrival and departure times) for all trains going-down, initialized as i (1 to n), plus the journey times of trains going-up as j (1 to m) in every station (1 to r). Thus, the objective function to minimize the total operation time is shown below:

$$Z = \sum_{i=1}^{i=n}\left(T_i A_r - T_i D_1\right) + \sum_{j=1}^{j=m}\left(T_j A_1 - T_j D_r\right) \quad \forall i = 1-n \quad and \quad \forall j = 1-m \tag{1}$$

The variables of this model are the journey times and the arrival and departure times of all trains. The constraints to this model are explained in the following paragraphs.

Constraints of travel time between two consecutive stations restrict the minimum time to travel between two consecutive stations (k to k+1) for all trains going up initialized as i (1 to n) and trains going down initialized as j (1 to m). As represented by Equation (2), the arrival time for the train i in the station k+1 minus the departure time in the station k (origin station) should be greater or equal to the needed time for the train i to travel between two consecutive stations (k to k+1). The arrival time for the train j in the station k minus the departure time in the station k+1 should be greater or equal to the needed time for the train j to travel between two consecutive stations (k+1 to k). This research uses the minimum travel time between two consecutive stations, because different types of trains have different speed limits and the travel time would automatically differ. Additionally, since the geographic characteristics of each segment are different, real data were acquired from Taiwan HSR system in order to define speed limits accordingly.

$$T_i A_{k+1} - T_i D_k \geq time\ i_{k\rightarrow(k+1)} \qquad \forall i = 1-n \ and \ \forall k = 1-r \tag{2}$$
$$T_j A_k - T_j D_{k+1} \geq time\ j_{(k+1)\rightarrow k} \qquad \forall j = 1-m \ and \ \forall k = 1-r \tag{3}$$

A dwell time constraint for each train i or j at the station k means the departure time minus the arrival time, as shown in Equations (4) and (5). This dwell time should be greater than or equal to the technical stop time (TS), which means a minimum time for passengers getting on and off. Additionally, the dwell time should be also less than or equal to the sum of the technical stop time and the commercial stop time (CS). This condition represents that the model uses the maximum station time at each station, because not all trains will stop at every station.

$$TS_{i_k} \le T_i D_k - T_i A_k \le TS_{i_k} + CS_{i_k} \quad \forall i = 1-n \text{ and } \forall k = 1-r \tag{4}$$
$$TS_{j_k} \le T_j D_k - T_j A_k \le TS_{j_k} + CS_{j_k} \quad \forall j = 1-m \text{ and } \forall k = 1-r \tag{5}$$

The headway constraint restricts to the departure times differences between two consecutive trains in the same station. The headway time in this research is fixed to one constant value because we want to keep the minimum time spacing between two trains identical.

$$T_{i+1} D_k - T_i D_k \ge headway \quad \forall i = 1-n \text{ and } \forall k = 1-r \tag{6}$$
$$T_{j+1} D_k - T_j D_k \ge headway \quad \forall i = 1-m \text{ and } \forall k = 1-r \tag{7}$$

The travel time in one line constraint determines the total travel time for one train to travel through either one direction, plus the allowed time margin. The maximum travel time has been applied in the model; thus, the difference between arrival and departure times for one train in the same station should be less or equal to this travel time, as formulated in Equations (8) and (9). In Taiwan HSR system, the allowed time margin was set to different numbers for different types of trains. Therefore, this parameter would be a good input in sensitivity analysis to reveal the effects of changes in this parameter on the objective value.

$$T_i A_r - T_i D_1 \le \left(1 + \partial/100\right) \times time\ i_{1\to r} \quad for \quad \forall i = 1-n \quad and \quad \forall j = 1-m \tag{8}$$
$$T_j A_1 - T_j D_r \le \left(1 + \partial/100\right) \times time\ j_{r\to 1} \quad for \quad \forall i = 1-n \quad and \quad \forall j = 1-m \tag{9}$$

Crossing time constraints assume that the crossing time would be performed by two trains headed in different directions (southbound and northbound trains). Although Taiwan HSR system has multiple tracks at stations, sometimes crossing operations become necessary for one train to allow another train to pass through the station. Thus, the difference between arrival time for train *i* and departure time for train *j* at the same station *k*+1 (because the second train had already departed from its original station) should be less or equal to the upper bound time minus buffer time in the available segment. $Y_{i\text{-}j;\,k \to (k+1)}$ is the decision variable for the availability of track in one segment. The value is 1 if there is a track available between station *k* to *k*+1 and 0 otherwise, as formulated in Equation (10) below:

$$T_i A_{k+1} - T_j D_{k+1} \le UB \times (1 - Y_{i-j;k\to(k+1)}) \quad \forall i = 1-n \quad and \quad \forall j = 1-m \tag{10}$$

Train circulation constraints deal with the time needed for work performed at the terminal stations. Like many railway companies, Taiwan HSR system has a cyclic timetable in order to manage the resources comprising its infrastructure. Based on the real timetable, the cycle time is 120 minutes. Thus, if the headway time is set to 12 minutes, it means there are ten trains in the first cycle, and the next train (11th train) would be the same train as the train number one. It means the timetable at every two hours will have the same pattern; the daily timetable is obtained by carrying out this pattern repeatedly. A train circulation model is needed to deal with these requirements. In Taiwan HSR system, the train circulation operation takes at least 30 minutes time, including regular and special car inspections, car maintenance and cleaning activities, and the turning back operation. If there were an event that required long travel times and headway between two consecutive trains, then the train circulation pattern would change as well. Consequently, the departure time for another train which will use the same track as those operations should be greater or equal to the arrival time plus the train circulation time as formulated in Equations (11) and (12) below:

$$T_{i=\left(j+\frac{traveltime}{headway}\right)} D_r \ge T_j A_1 + (InsT_{i,j,k=1} + ClT_{i,j,k=1} + TB_{i,j,k=1}) \quad for \quad \forall i = 1-n \quad and \quad \forall j = 1-m \tag{11}$$

$$T_{j=\left(i+\frac{traveltime}{headway}\right)}D_r \geq T_i A_r + (InsT_{i,j,k=r} + ClT_{i,j,k=r} + TB_{i,j,k=r}) \quad for \quad \forall i = 1-n \quad and \quad \forall j = 1-m \tag{12}$$

4. Sensitivity analysis

4.1. Data collection and model checking

After the mathematical model for the scheduling problem was formulated, a collection of data regarding scheduling requirements from Taiwan HSR system began. Data requirements include number of stations, number of trains in the southbound and northbound directions, headway time, allowed margin time, upper bound in one line, station time, distance between stations, and the operation times regarding train circulation, etc.

Primary data were collected from interviews with senior engineers in Taiwan HSR system, and secondary data were gathered from the company documents including the Equipment and Facilities Operations Manual, and existing timetables. The CPLEX solver was utilized for this research. The algorithm derived good results and obtained the minimum total travel time (6780 minutes). The results of this research involve the value of the departure and arrival times and the timetable diagrams. The value of the minimum travel times, departure times, and arrival times for all trains at every station would be described first. Furthermore, to illustrate the result simply, the departure and arrival times could be figured as train timetable diagrams. Every variable as the departure and arrival times for all trains in each station could be performed by the algorithm. The results could obtain the operation time for each train in the southbound or northbound direction. The granularity (minimum time unit) in making the timetable in this research is assumed to be one minute (see Fig. 1).

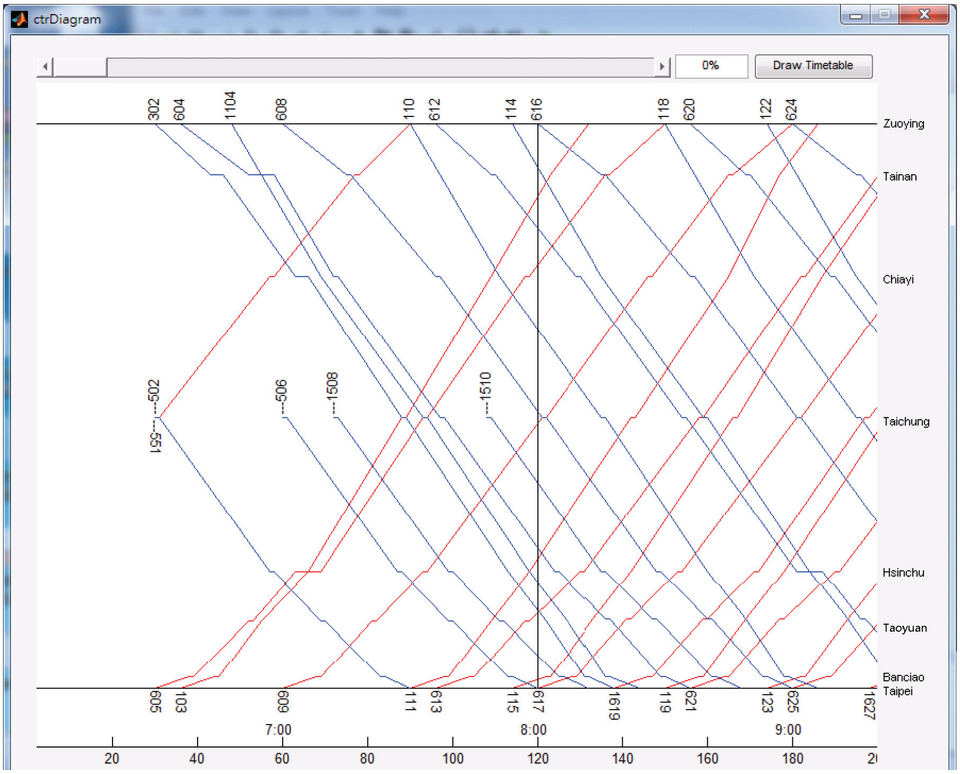

Fig. 1. Timetable diagram generated for Taiwan HSR system.

Model checking is a task of demonstrating that the model is reasonable to represent the real world. Usually, assumptions, input parameters, output values and conclusions should be considered in the model checking process. There are many methods to check the model, such as expert intuition, real system measurements, and theoretical result/analysis [17]. The real system measurements method has been selected to check the model for this research, because the comparison technique with real data is the most reliable and preferred way to validate the proposed model. Due to page limitation, the comparison between the original timetable and the proposed model output can be found in [18].

Compared to the real timetable, it has 6420 minutes of the total travel time in Taiwan HSR system, thus the gap between these two timetables is 360 minutes or a 2.72% gap. It may be caused by the difference in assumptions between the model and the real problem. For example, the proposed model does not accommodate the requirement of the acceleration or deceleration times needed for a train to reach the designate speed. Hence, the speed limits between segments have to be lower in the proposed model, causing the total travel time of the model larger.

The train circulation pattern depends on maximal travel times divided by headway times. In the assumption that Taiwan HSR system has 120 minutes of the maximum travel time with the average headway of 12 minutes, the train circulation is every tenth train in each direction. Therefore, this circulation pattern operates 20 trains instead of 29 trains in the real problem of Taiwan HSR system, and saves nine trains per day. If an event requires a longer headway time between two consecutive trains, then the train circulation pattern would change as well.

4.2. Sensitivity analysis

In this research, the change of the parameter values can be categorized as a disturbance, and the sensitivity analysis can determine how sensitive the model to the disruptions that may occur in the operation time. Previous research has identified some events that may occur during the train operation time such as disasters, engine breakdowns, signal problems, human errors, etc. [19]. Those events probably disrupt the timetable and cause delayed times, stoppage and running times that exceed a certain threshold, long headway times, broken rails, trains changing order, etc. The delayed time is the disruption that is often discussed and investigated by researchers. Such the times happen at stations can be seen as dwell time extensions and at segments as travel time extensions.

The purpose in doing the sensitivity analysis for the dwell time parameter is investigating how sensitive this parameter in the timetable and determining the critical stations which can affect the overall system performance significantly. That is, due to the increased dwell time in one station, the total operation time of the system will become longest, compared to the same increase in the other stations.

As shown in Fig. 2(a), as the value of the delayed time at stations increased, the total operation times increased. Although the increased dwell times in the same level (e.g., 3 minutes at all stations), only the Banciao and Taichung stations increase the optimal solution significantly if the dwell times of those stations are modified. Compared to the real problem in Taiwan HSR system, Banciao and Taichung are the intermediate stations between the main terminal stations, Taipei and Zuoying, which have the largest dwell times than the other stations and all trains should stop in these two stations. Thus, changing the corresponding dwell times in these two stations would not only affect the system performance but increase the total operation times of the system.

a b

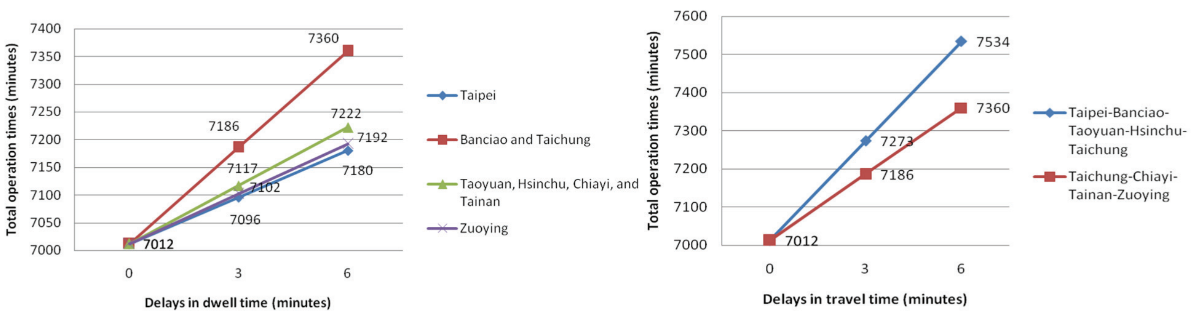

Fig. 2. Sensitivity of the total operation times respect to (a) the dwell times; (b) the travel times at segments.

The sensitivity analysis on the total operation times with respect to the delayed travel times at segments needs to be investigated in order to determine the critical segments which can significantly affect the entire timetable. Such the delay in one segment can contribute most to the extension of the total operation time, compared to the same delay occurred in the other segments. As shown in Fig. 2(b), as the value of the delayed times at segments increased, the total operation times increased. Although there is a same increase in the delayed times at all segments, only the Taipei to Taichung segments influence the total operation time significantly. The corridor of Taiwan HSR system between Taipei and Taichung has many tunnels, viaducts, hillsides, and landslide areas that impose more speed restrictions. The Taipei to Taichung segments pertain to the north area of Taiwan, thus if any events such a landslide disaster at these segments occur, the total operation time should be affected significantly, meaning that these speed restrictions might be the factor to cause the prolongation of the system's total operation time. Moreover, this result allows us to conclude that segments in the south area of Taiwan have more flexibility to recover disturbances than the segments in the north area. To mitigate and solve this problem, Taiwan HSR system is thinking of developing a new infrastructure plan along the north segments, such as adding new lines, or providing more signal warning systems through these segments. The sensitivity analysis on the total operation times with respect to the allowed time margin is used to determine which types of the trains that can contribute more to the total operation times, if their allowed time margins increase. There are four types of trains in Taiwan HSR system. Type I means the trains for the southbound direction. Type II means the express trains that will stop only at three main stations, i.e., Taipei, Taichung, and Kaohsiung. Type III means the trains for the northbound direction. Type IV means the trains that run between the Taichung and Kaohsiung segments.

As shown in Fig. 3(a), as the percentage margin of the allowed travel time increased, the total operation times also increased. Continuous increases of the allowed travel margins would cause the diagram of the total operation times becomes flat and provide no further impact to the timetable. This picture allows us to conclude that due to the express characteristics, increasing the allowed time margins of the Type II trains has little impact on the timetable. However, because all the other types of trains will stop at each station, increasing the allowed time margins will inevitably cause the extension of the total operation times of the system. Below the sensitivity analysis was conducted for different numbers of trains and stations of the system, to see their impacts on the total operation times. Fig. 3(b) shows a comparison of the total operation times associated with different numbers of trains for different combinations of the number of the stations. This figure also shows that the total number of trains and stations are the essential inputs to the model and decision making. As the number of trains and stations increased the total operations times also increased linearly. With respect to the number of stations, two cases should be considered: (1) the case of the actual number of stations in Taiwan HSR system (that is eight stations), and (2) the case of reducing three or five stations. Note that when a station is closed because of disruptions, the trains would increase their mean speeds and the capacity of the line decreases. On the contrary, when an intermediate station is introduced, the trains would decrease the speeds, but the capacity of the line increases so that the system becomes more complex to solve during disturbances. Previous research found that increasing the number of trains per day leads to more than proportional increases in the risks of collisions [8]. On the other hand, this modifies the robustness of the line and the way real time disturbances propagate the original timetable. Therefore, the optimal number of trains and stations need to be addressed.

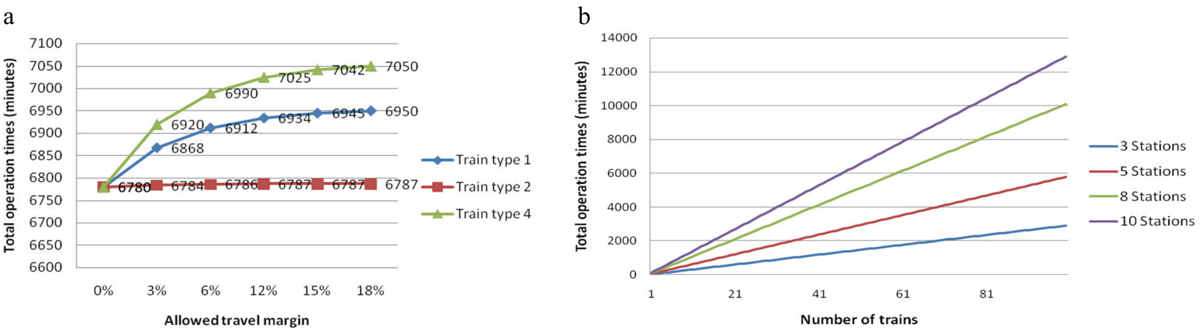

Fig. 3. Sensitivity of total operation time respect to (a) the allowed travel margin; (b) the number of trains/stations involved.

A disturbance in a railway transportation network, e.g. a train being delayed, causes deviations from the original timetable. Often, such a deviation disrupts the timetable for other trains in the network especially the departure and arrival times, making the consequences of long delayed times difficult to be predicted. By knowing the response or sensitivity of the arrival times of each train to the delayed times, we could determine the value of the delayed times that is critical. As shown in Fig. 4, as the value of the delayed times increased, the number of the trains disordered increased. Given the delayed times (0 to 19 minutes) would produce no disruption to the timetable. Increasing the delayed time to 20 minutes, it will disrupt the timetable in a way that the sequence of six trains in the northbound direction is different to the original one, and the sequence of four trains in the southbound direction is different to the original one.

By predicting the response of the timetable to the delayed times, the train operator could decide the next step to solve this problem instead of cancelling trains. Managing uses of tracks at stations could be the solution to solve trains disorder and overtaking problems. Taiwan HSR system has multi-tracks at stations to separate trains that would arrive at stations in the same time. In addition, to avoid train disorders, the system also has radio communication systems, which used to ask the train drivers to decrease or increase the train speed manually during the disturbances.

5. Conclusions

This research developed an optimization model for designing timetables in HSR systems that consider basic requirements as well as special requirements regarding train circulation, including car cleaning, regular inspections, and the train turning back operation. The model could generate a good timetable result as good as a real timetable. Furthermore, the model could generate train circulation patterns as illustrated in the timetable diagram results. Sensitivity analysis could determine the essential parameters, critical infrastructure, and predict the propagation of disruptions on the original timetable. Thus, sensitivity could be a good simulation analysis for predicting the effects of disruptions on the timetable without conducting real experiments.

Optimization approach in designing a timetable could create an optimal timetable as good as original timetable. Thus, in the future timetable planning, Taiwan HSR system could use the optimization model-based approach to create their optimal timetables and preserve the full profit during the disturbances. Hopefully, when the timetable disrupted by unforeseen events, the system operator could be able to create a new optimal timetable, instead of cancelling trains. Sensitivity analysis results concluded that segments in the north area of Taiwan were more sensitive and more complicated to recover from disturbances, than segments in the south area. Thus, local governments are recommended for collecting more data and developing feasibility research to study and investigate the need for infrastructure development (adding new lines, tracks, warning signals) in the north area to recover and mitigate the trains during disturbances.

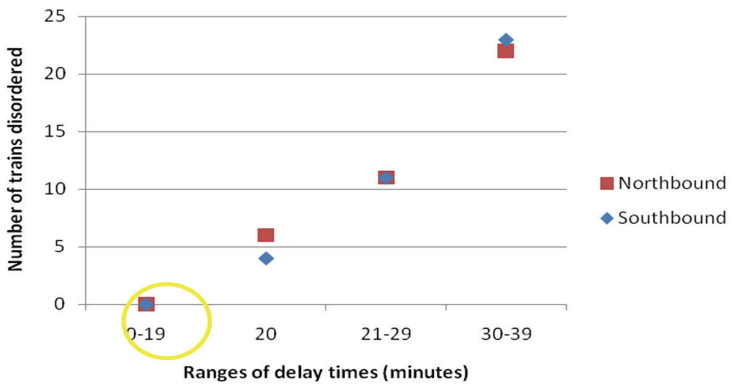

Fig. 4. Timetable disruptions respect to the delay times.

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References

[1] Railway Safety and Standard Board (RSSB), The Rail Industry - A Way Forward on Sustainable Development, RSBB, London, 2006. (http://www.rssb.co.uk, viewed on December 26, 2012).
[2] European Union Law (EUL), The Interoperability of the Trans-European High-Speed Rail System, EUL, Brussels, 1996. (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31996L0048:EN:HTML, viewed on December 26, 2012).
[3] L. Kroon, G. Maroti, M.R. Helmrich, M. Vromans, R. Dekker, Stochastic improvement of cyclic railway timetables, Transportation Research B 42 (2008) 553-570.
[4] P. Serafini, W. Ukovich, A mathematical model for periodic scheduling problems, SIAM J. Disc. Math. 2 (1989) 550-581.
[5] J. Tornquist, J.A. Persson, N-tracked railway traffic re-scheduling during disturbances, Transportation Research B 41 (2007) 342-362.
[6] Taiwan High-Speed Rail Corporation (THSRC), Equipment and Facilities Operations Manual, THSRC, Taipei, 2007.
[7] M. Salido, F. Barber, Mathematical solutions for solving periodic railway transportation, Mathematical Problems in Engineering 2009 (2009) 1-19.
[8] C.D. Martland, Y. Zhu, Y. Lahrech, J.M. Sussman, Risk and train control: a framework for analysis, Transportation Research Record: Journal of Transportation Research Board 1742 (2001) 25-33.
[9] A. Higgins, E. Kozan, L. Ferreira, Optimal scheduling of trains on a single line track, Transportation Research B 30 (1996) 147-161.
[10] Y. Lee, C.Y. Chen, A heuristic for the train pathing and timetabling problem, Transportation Research B 43 (2009) 837-861.
[11] U. Brännlund, P.O. Lindberg, A. Nõu, J.E. Nilsson, Railway timetabling using Lagrangian relaxation, Transportation Science 32 (1998) 358-369.
[12] S. Mladenovic, M. Cangalovic, Heuristic approach to train rescheduling, Yugoslav Journal of Operations Research 1 (2007) 9-29.
[13] T. Norio, T. Yoshiaki, T. Noriyuki, H. Chikara, M. Kunimitsu, Train rescheduling algorithm which minimizes passengers' dissatisfaction, Lecture Notes in Computer Science 3533 (2005) 829-838.
[14] C.K. Chiu, C.M. Chou, J.H.M. Lee, H.F. Leung, Y.W. Leung, A constraint-based interactive train rescheduling tool, Constraints 7 (2002) 167-198.
[15] L.G. Kroon, L.W.P. Peeters, A variable trip time model for cyclic railway timetabling, Transportation Science 37 (2003) 198-212.
[16] A. Caprara, M. Fischetti, P. Guida, M. Monaci, G. Sacco, P. Toth, Solution of real-world train timetabling problems, Proceedings of the 34th Hawaii International Conference on System Sciences 3 (2001).
[17] M. Carey, I. Crawford, Scheduling trains on a network of busy complex stations, Transportation Research B 4 (2007) 159-178.
[18] N. Firdausiyah, C.C. Chou, Decision Support Tool Using Integration of Optimization and Data Mining Techniques for High-Speed Train Timetables Generation, National Central University, Jhongli, 2012.
[19] B. Diaz, M. Adenso, O. Gonzalez, P. Gonzalez-Torre, On-line timetable re-scheduling in regional train services, Transportation Research B 33 (1998) 387-398.