

Time-Space Diagram Models for Single- and Double-track Railway System Capacities in Thailand

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Abstract: This manuscript presents time-space diagram analysis technique for creating models comparing single- and double-track railway system capacities. Actual operational data from State Railway of Thailand were also used as parameters for quantitative analysis. In each system with different scenarios, mathematical models were formulated with input variables, i.e., distances between stations, station idle times, train length. These equations could be used to calculate rail capacity for each scenario and to predict changes in capacity if some variables were altered, e.g., longer distances, longer train length, or changes in direction priority. The results from the analysis could be useful to recommending suitable rail operations technique for each scenario. In addition, this research could serve as a good example in solving complex transportation operations problems through time-space diagram analysis.

Keywords: Time-Space Diagram; Railway Capacity; Transportation Operations; Capacity Modeling.

1. INTRODUCTION

This research shows the analysis of railway capacity in different scenarios especially for single- and double-track systems based on graphical calculation from time-space diagram. The time-space diagram is considered to be a simple but powerful graphical thinking tool for transportation and traffic engineers to analyze vehicle motions and solve transportation operations problems. In this research herein, the time-space diagram is shown to solve the railway operations problems specifically for a case study in Thailand.

According to State Railway of Thailand (2010), the railway system in Thailand was first built in 1890 and operated until today. The last track was built in 2005 with the total track length is 4,070 km, all meter gauge. However, nearly all is single-track although some important sections around Bangkok Metropolitan Area or near large stations are double- or triple- tracked. Due to mostly single-track system, rail transportation in Thailand is considered to be an old-fashioned transportation mode with heavy delays and unreliable service. Its development is incomparable with other transportation modes such as road transport or air transport. Due to unrelenting delay complaints, Thai government is looking to expand single-track into double-track system on the rail network. However, the expansion of railway tracks is costly and might not be feasible throughout the whole line. Other possible way to increase railway capacity is to add a side-track, the short stretch of double-track system at some specific location as a buffer zone for two trains travelling in opposing direction or as a passing zone for two trains travelling in the same direction. Nevertheless, the increase in railway capacity due to side tracks would depend on the numbers and location of side tracks,

and other factors such as train speed, distance between stations, etc.

The remainder of the manuscript is organized as follows. Section 2 relates the present work to earlier work described in the literature. The parameters and variables used in the analysis as well as assumptions are described in Section 3. Section 4 presents the calculation and analysis in different scenarios. Results of model formulations and comparisons of capacities in different scenarios are shown in Section 5. The concluding remarks are discussed in the sixth and the final section.

2. LITERATURE REVIEW

Since the definition of railway capacity could be different, in this paper herein, railway capacity is defined as the maximum number of trains that can traverse the entire railway in a given period of time, subject to management constraints (such as junction capacity, track capacity, line capacity and interference between trains. This definition is correspondent with Abril *et al* (2008), Ambre (2005), Mussone and Calvo (2013), etc.

Generally, there are two approaches to determine the railway capacity. The first method is a rough estimation by using traditional Scott's formula (Johri, 2003) as follows:

$$Capacity = \frac{Total\ Time \times Scheduling\ factor}{Time\ required\ to\ cross\ critical\ block\ section + Block\ working\ time} \quad (1)$$

This formula's interpretation is that the maximum trains that can be scheduled depends on the total time required by the train to cross the critical block section plus block working time. A scheduling factor is a constant number ranged between 0.7 to 0.9, depending whether the section is busy or free. The second method of capacity estimation is to use the chart called Train Dispatch Simulator (TDS), which depicts the movement of trains on the distance-time plot, or the time-space diagram, the classical diagram for traffic and transportation engineers. Daganzo (1997) describes the time-space diagram as a powerful graphical thinking tool for transportation and traffic engineers to analyze vehicle motions and solve transportation operations problems. The uses of time-space diagram in railway operations were found since mid-nineteenth century, the era of railroad development in Europe. This TDS can be used together with stochastic models to give more realistic railway capacity results.

Recent research developments in railway capacity analysis are found in numerous literatures. For example, Harrod (2009) studies the optimization of 54 combinations of track network and speed differential by evaluating in a linear discrete time network model that maximizes an objective function of train volume, delays, and idle train time. This research mainly uses integer programming formulation for analysis. Burdett and Kozan (2006) did a similar study but focused on different proportional mix of train types. Also, D'Ariano *et al* (2008) focused on the Assessment of flexible timetables in real-time traffic management of a railway bottleneck. These three studies use time-space diagrams for graphical illustration.

There have been several studies that determine railway capacity by mathematical models without using time-space diagrams. For example, Abril *et al* (2008) reviews the main concepts and methods to perform capacity analyses, and presents an automated tool that is able to perform several capacity analyses. It separated analytical tools for railway capacity analysis based on approaches such as traffic patterns, single-track analytical models, or algebraic approaches and reviews several railway operations programs, i.e., DEMIURGE, CMS, RAILCAP, VIRIATO, CAPRES, and FASTTRACK II. More recently, Mussone and Calvo (2013)'s method is based on defining and solving an optimization is based on defining

and solving an optimization problem to find out the capacity value of a railway system, which is not based on timetables. The formulas derived in this research although are more realistic and could take into accounts several account priorities between trains and possible delays. They are using complex mathematics, which is difficult to understand and implement in the real work.

In fact, the problems in Thailand are much simpler and require merely rough solutions since there are only two types of trains, passenger trains and freight trains, and only single- or double-track system. This kind of problems can be geometrically solved by analyzing time.

3. MODEL ASSUMPTIONS AND EMPIRICAL VALUES

The most congested rail traffic in Thailand is a 47-km single-track bottleneck section east of Bangkok Metropolitan Area between Huatakae and Sriracha rail stations as shown in Fig. 1. This section is now the main route for both passenger and freight trains. The passenger train route is between Bangkok and Pattaya/Sattahip and the freight one is between ICD near Ladkrabang and Laemchabang Port, Thailand’s biggest deep-water seaport. From Fig. 1, both routes pass through the single-track section between Huatakae and Sriracha stations, causing major capacity constraint problem. We also assume that there is no capacity problem on the route between Bangkok to Huatakae stations, which is currently in a double-tracked system. Also, the demand of passenger trains beyond Pattaya station is quite low.

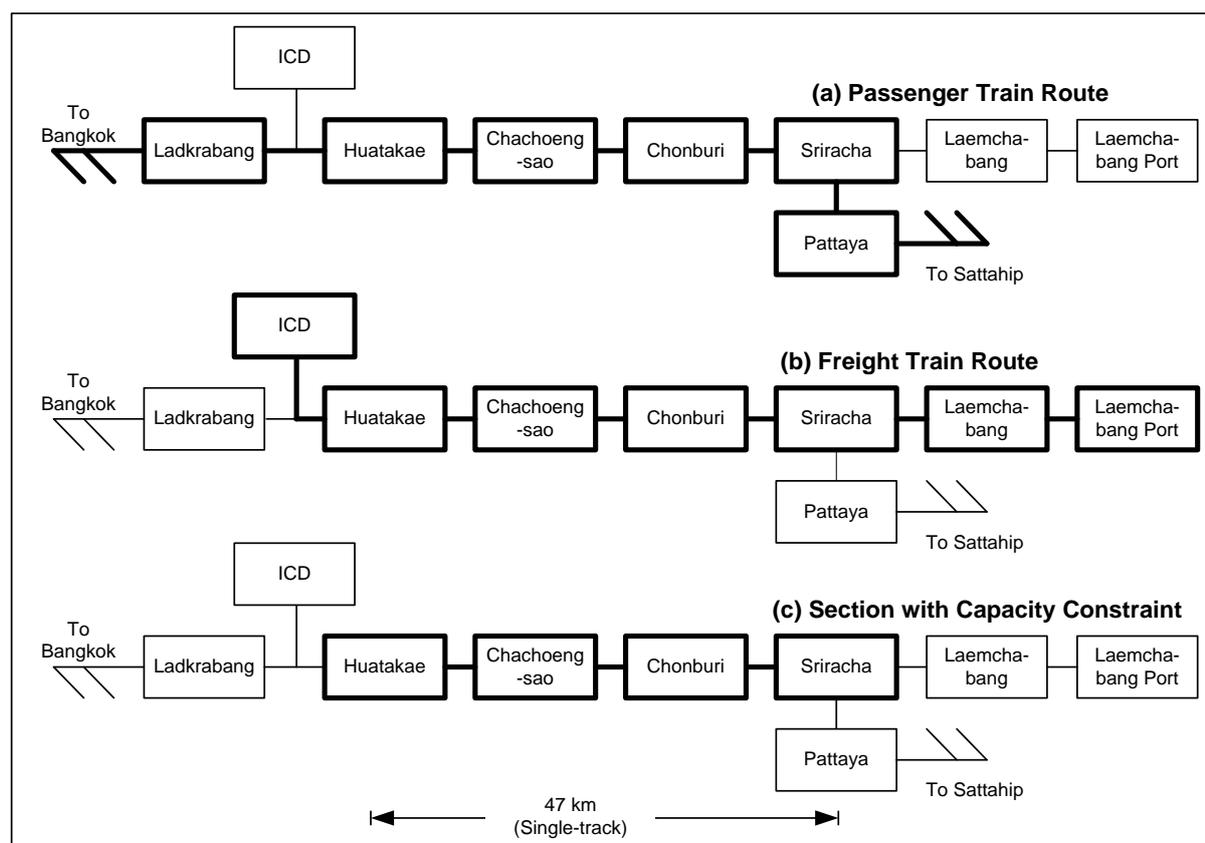


Figure 1. Railway section with a capacity constraint

To determine values of variables in the analysis, we collected railway operations data

from the State Railway of Thailand’s operations manual and also interview train operators. We assume that total waiting time at a train station (w) is the sum of a train’s actual stopping time plus the delays due to train acceleration and deceleration. From the train schedule and time measurement, we found that actual stopping time is approximately 5 minutes, while the sum of delays due to acceleration and deceleration per stop is averaged at 7 minutes. Therefore the total waiting time per station is 12 minutes. (Note that this waiting time is a simple approximation and could be different between passenger and freight trains in reality.) The block distance between trains (B) is approximately 1 kilometer. The operating speeds of passenger and freight trains are 90 and 55 km/hr, respectively. The passenger and freight train lengths are 498 and 528 meters, respectively. Therefore, the default values and variables in this study are summarized in Table 1 below.

Table 1. Model estimation results

Variable	Definition	Value	
		Passenger Train (PT)	Freight Train (FT)
w	Waiting time at a train station	12 minutes	12 minutes
L	Distance between train stations	47 kilometers	47 kilometers
B	Block distance	1 kilometer	1 kilometer
V	Train speed	90 km/hr	55 km/hr
l	Train length	0.498 km	0.528 km
H	Headway between trains	Dependent variable in analysis	

4. ANALYTICAL RESULTS

This section will show the analytical results from time-space diagram analysis in different scenarios. We now define the term “homogeneous system” if all trains in the same direction travel at one speed, or are in the same type, i.e., all passenger trains or all freight trains. This includes the case if all passenger trains travel from A to B and all freight trains travel from B to A. The system is called “non-homogeneous system” if there are more than one type of train traveling in the same direction. The description of analysis will start from the homogeneous system for easy understanding

4.1 Analysis of Homogeneous System

Double-track scenario

The analysis of homogenous double-track scenario is considered to be the easiest case and found in any basic textbook, e.g., Daganzo (1997), etc. Trains on both sides can travel independently as shown in Fig. 2. The intersecting points outside the stations A and B mean that opposing trains can travel without any conflict.

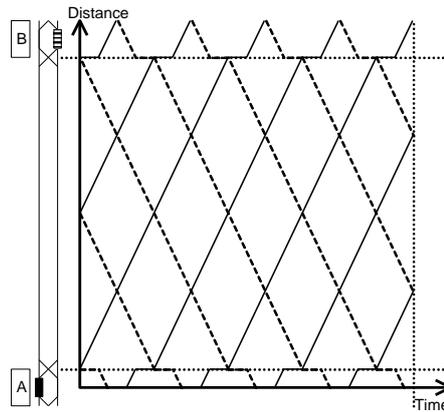
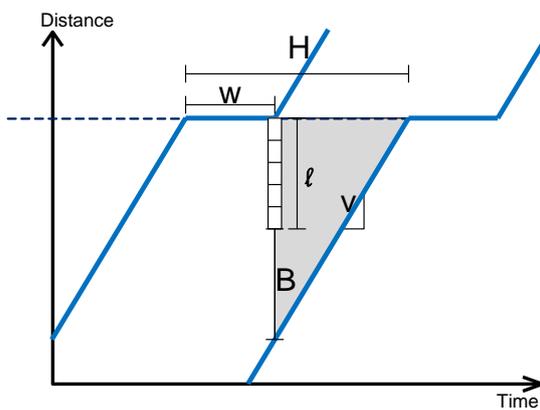


Figure 2. Time-space diagram for double-track homogeneous system

Readers can easily identify the one-way railway capacity from the time-space diagram shown in Fig. 3 and total railway capacity is shown in Eq. 2.



$$Capacity = \frac{1}{H}$$

$$= \frac{1}{w + \frac{B+l}{v}}$$

Figure 3. Calculation of one-way railroad capacity by time-space diagram

$$Railway\ Capacity = \frac{1}{H_1} + \frac{1}{H_2} = \frac{1}{w + \frac{B+l_1}{v_1}} + \frac{1}{w + \frac{B+l_2}{v_2}} \quad (2)$$

where,

- l_1, l_2 = Train length in directions 1 and 2, respectively
- v_1, v_2 = Speeds of trains in directions 1 and 2, respectively

Single-track scenario

When both directions of train have to travel on a single track, they can traverse each other at a station (with separated track) or at side tracks only. The analysis in the case without a side track is shown in Fig. 4. In this scenario, only one train can be between two stations at a time. The other trains must wait until the track is available. If the trains on both directions use the track alternately in 1:1 ratio, the railway capacity is significantly reduced. Therefore, it might be preferable to group trains in each direction as a platoon and let each group go

alternately instead of an individual one, i.e., let N_1 trains in A to B direction go first and alternate with N_2 trains in B to A direction go ($N_1:N_2$ ratio) as shown in Fig. 5. Equation 3 shows the result of railway capacity based on this strategy.

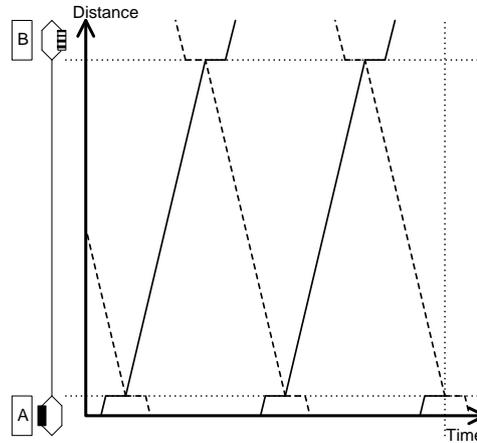


Figure 4. Time-space diagram for single-track system without a side track (1:1 ratio)

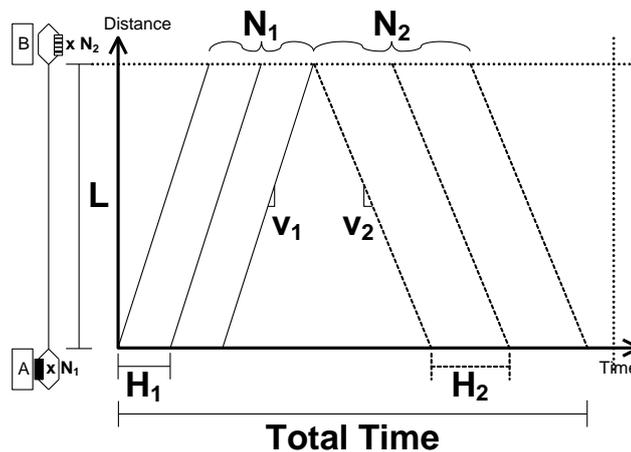


Figure 5. Time-space diagram for single-track system without a side track ($N_1:N_2$ ratio)

$$\text{Railway Capacity} = \frac{N_1 + N_2}{(N_1 - 1) \left(w + \frac{B + l_1}{v_1} \right) + (N_2 - 1) \left(w + \frac{B + l_2}{v_2} \right) + \frac{L}{v_1} + \frac{L}{v_2}} \quad (3)$$

From Equation 3, it should be noted that if $N_1 \gg N_2$, the capacity of single-track system will approach the double-track system since no opposing train can travel on this track. In addition, the storage for waiting trains at each station is limited. In practice, the “total time”, the maximum allowable time to change the train direction, must be given.

Side track system is a way to reduce the headway between trains and increase railway capacity. Fig. 6 shows that a side track in the middle between two train stations could double railway capacity, and could increase the capacity up to the double-track capacity. However, this case is not always true if the positions of side tracks are not equally located in strategic manners.

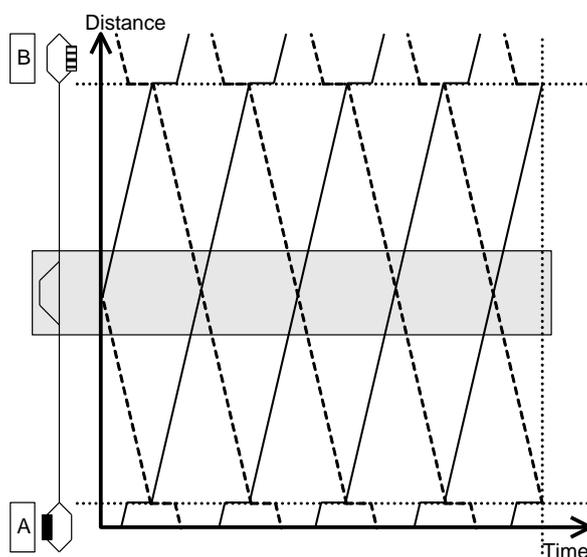


Figure 6. Effect of a side track to railway capacity

From Fig. 6, we could imply that if trains on both directions travel at the same speed, side tracks must be located at equal distance along the single track. If the number of side tracks are not fitted or not evenly located, the effect of capacity increase will be reduced. Equation 4 shows the number of side tracks (n) that would fit for the operations as follows.

$$n = \frac{L}{H_2} \left(\frac{1}{v_1} + \frac{1}{v_2} \right) \quad (4)$$

where,

$$H_2 = \text{Train headway for the less-priority direction (higher headway)}$$

Since the distance between side tracks should be even for maximum effect, the ratio between the headway for the higher-priority direction and the one for the less-priority must be an integer, i.e., $H_2 = mH_1$, where m is a positive integer. However, since $H_1 = \frac{1}{w + \frac{B+l_1}{v_1}}$,

therefore we can determine H_2 from the Equation 5 below.

$$H_2 = \min \left\{ \frac{1}{w + \frac{B+l_2}{v_2}}, m \left(\frac{1}{w + \frac{B+l_1}{v_1}} \right) \right\} \quad (5)$$

After that, the railway capacity for homogeneous single-track system with side tracks

can be determined by substituted H_1 and H_2 in Equation 2.

4.2 Analysis of Non-Homogeneous System

The non-homogeneous system is a border and more complex case when trains on the same direction travel in different speeds and need to overtake one another to increase higher capacity. To simplify this system, we assume that there are only two types of trains, i.e., freight or “slow” trains and passenger or “fast” trains. Each track scenario is shown below.

Double-track scenario

When a fast train is followed by a slow one, it can overtake a slow one through three strategies as follows.

- (1) Use an opposing track for overtaking This strategy is to use the opposing track when no train is coming. It is similar to traffic operations on a two-lane highway. Fig. 7 shows this strategy on a time-space diagram. The benefit of this strategy is the increase in railway capacity without building more tracks. However, it requires high automated precision in track alteration; otherwise, it could lead to a major train accident. This is not feasible for an existing Thailand’s train system since most operations are manually done and regularly experience substantial delays.

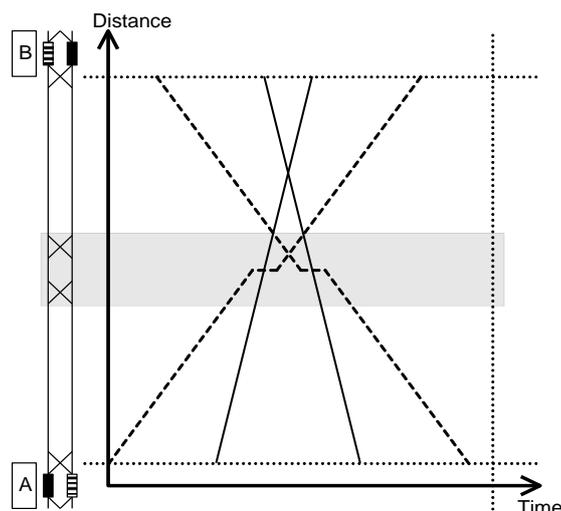


Figure 7. Time-space diagram for using an opposing track for overtaking

- (2) Overtake at stations only In this strategy, fast trains are allowed to overtake slow ones at stations only. The calculation of one-way capacity with fast and slow trains is analogous to the one of two-way capacity in homogeneous single track without a side track scenario. The strategy to maximize capacity is to group the same train types, i.e., a group of fast trains and a group of slow trains, together and alternate them, according to the illustration in Fig. 8. The railway capacity in this case can be calculated by Equation 6 below.

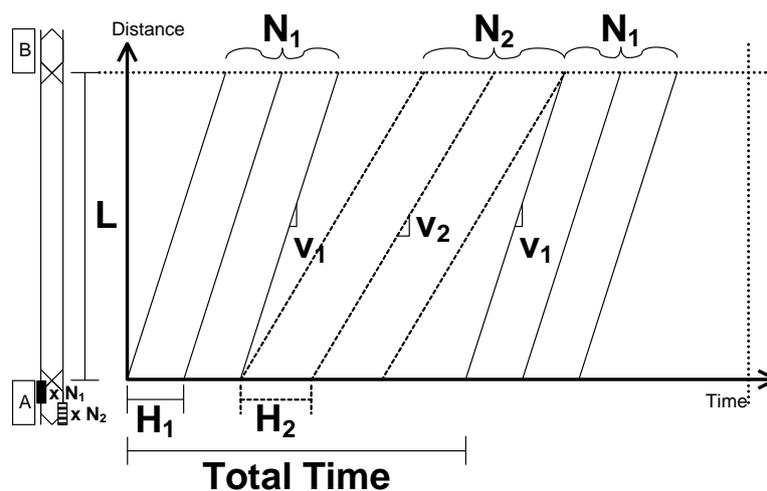


Figure 8. Time-space diagram for double-track system without a side track

$$\text{Railway Capacity} = \frac{N_1 + N_2}{(N_1) \left(w + \frac{B + l_1}{v_1} \right) + (N_2) \left(w + \frac{B + l_2}{v_2} \right) + \frac{L}{v_1} - \frac{L}{v_2}} \quad (6)$$

- (3) Use side tracks This strategy applies side tracks for passing opportunities in the same direction as shown in Fig. 9. The concept is similar to the adding of a passing lane on a two-lane highway. It reduces headways between trains and increase capacity. Similarly, side tracks must be purposefully located evenly in appropriate numbers to maximize the capacity. The number of side tracks (n) that would fit for the operations are shown in Equation 7:

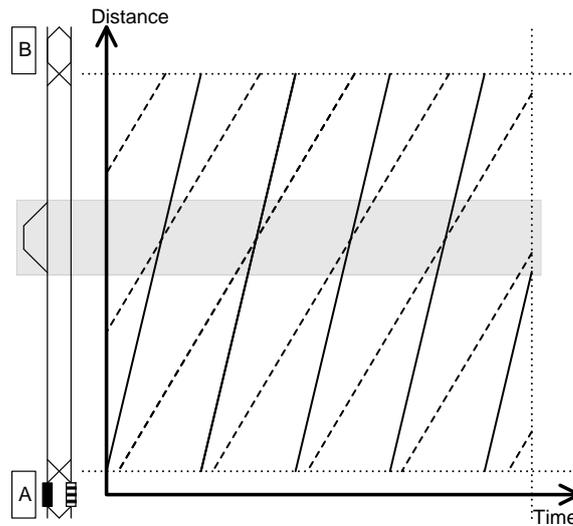


Figure 9. Time-space diagram for one-way double-track system with a side track

$$n = \frac{L}{H_2} \left(\frac{1}{v_2} - \frac{1}{v_1} \right) \quad (7)$$

where,

H_2 = Train headway for the less-priority direction (higher headway)

In this case, the ratio between the headway for the higher-priority direction and the one for the less-priority must be an integer, i.e., $H_2 = mH_1$, where m is a positive

integer. Since $H_1 = \frac{1}{w + \frac{B+l_1}{v_1}}$, therefore we can determine H_2 from the Equation

8 below.

$$H_2 = \min \left\{ \frac{1}{w + \frac{B+l_2}{v_2}}, m \left(\frac{1}{w + \frac{B+l_1}{v_1}} \right) \right\} \quad (8)$$

After that, the railway capacity for non-homogeneous double-track system with side tracks can be determined by substituted H_1 and H_2 in Equation 2.

Single-track scenario

This scenario is the general case on Thai single-track railway system. Without a side track, the operation is similar to the homogenous single-track without a side track in Fig. 9 since all fast trains must follow a slow one until they reach a station. However, if side tracks are built as shown in Fig. 10, the problem is much more complex since passenger trains can overtake a freight train at a side track or a station only and other trains could not use the track until it is available. This strategy is quite difficult to manage since one side track must be used for both train directions and required automated control to avoid train accidents, which would not occur in Thailand presently.

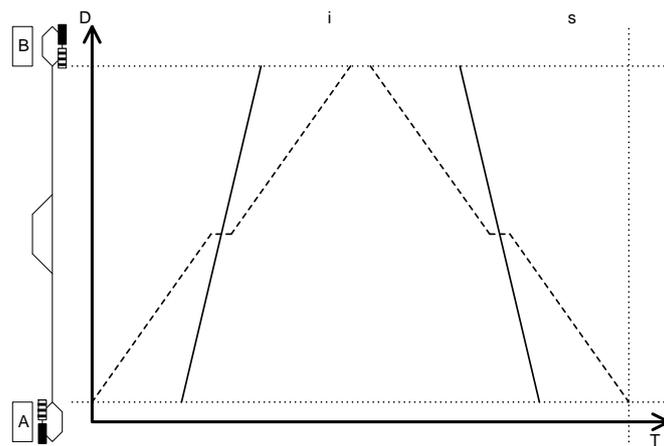


Figure 10. Time-space diagram for non-homogeneous single-track system with a side track

5. EMPIRICAL RESULTS

Table 2 shows empirical capacity results based on the substitution the values of variables from Table 1 or actual operating data in Equations 2-8. This table assumes 2 hours of the maximum allowable time to change the train direction, or “total time” in Figs. 5 and 8, and that the positions and numbers of side tracks are ideal and yield maximum possible rail capacity.

Table 2. Empirical results of railway capacity (train/day) from actual operating data

System	High Priority	Low Priority	Total	High Priority	Low Priority	Total	High Priority	Low Priority	Total
Homogeneous System	PT vs PT			FT vs FT			PT vs FT		
Double-track (Eq. 2)	111	111	222	105	105	210	111	105	216
Single-track without side tracks* (Eq. 3)	63	12	75	25	12	37	39	13	52
Single-track with side tracks** (Eqs. 2, 4, 5)	111	111	222	105	105	210	111	105	216
Non-homogeneous System	PT vs PT			FT vs FT			PT vs FT		
Double-track without side tracks*	Not applicable			Not applicable			90	90	180
Double-track with side tracks on both sides (Eqs. 2, 7,8)	Not applicable			Not applicable			216	216	432

Note:

PT = Passenger train;

FT = Freight train

*Assume that the maximum allowable time to change the train direction, or “total time”, is 2 hours

** Assume that side tracks are located strategically and evenly to yield maximum possible rail capacity.

The empirical results show that double-track system yield almost three times as much as the one for single-track without side tracks. With side tracks, it is possible that the capacity of single-track system could be increased as much as the double-track one. Nevertheless, these simple calculations do not take the delay due to deceleration or waiting time at the side tracks into consideration. Also, it might not be feasible to build side tracks at all strategic locations due to geographic, land-use, or financial constraints. Therefore, for real situations, the capacity of single-track system with side tracks could be 30-50% much less than the ideal condition.

6. CONCLUDING REMARKS

In summary, this research shows the time-space diagram analysis technique for creating models comparing single- and double-track railway system capacities, with the empirical data from State Railway of Thailand. It uses graphical illustration to determine the relationships among operating variables into a set of simple equations. These equations could be used to roughly determine railway capacities in different scenarios. We found that the capacity of single-track system with side tracks could be 30-50% much less than the ideal condition and the capacity of double-track system is approximately three times as much as one of single-track system. Although the results are somewhat rough, they are quite useful for rail operators and planners in Thailand.

This research has some limitation. First, some variables that affect operations such as slow-down when moving to side tracks were excluded. Second, the number of side tracks in Equations 4 or 8 might not be a whole number or side tracks are not located in equidistance manner, this would significantly reduce capacities. In addition, this research did not take the stochastic effects of train speeds, waiting times at stations, etc, into the calculations.

For future research direction, more related operating variables should be added for more realistic scenarios. Computer simulation might be used to investigate the stochastic effect of independent variables as well as do sensitivity analysis. In practice, side tracks could be expensive and could not be built at all strategic locations. The benefit-cost analysis of adding more side tracks and finding the most economically suitable locations could be useful for rail transportation planners and designers.

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