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Research Article

Simulating the Effects of Noncrossing Block Sections Setting Rules on Capacity Loss of Double-Track Railway Line due to the Operation of out-of-Gauge Trains

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Dispatchers often set noncrossing block sections (NCBSs) for railway out-of-gauge train (OGT) running on double-track railway line for safety reasons. In this paper, we will investigate the best location, length, and number of noncrossing block sections to reduce railway capacity loss due to the operation of OGTs. Firstly, yielding, overtaking, stopping, starting, and other operation rules for OGTs running on double-track railway line were designed, and a simulation model based on cellular automata was further put forward. Then, an assessment model for double-track railway line capacity loss due to the operation of OGTs was set up. Some simulation experiments and the comparisons of these results were further given to achieve the optimal setting of NCBS for OGTs running on double-track railway line. In the case of NCBSs number minus one, capacity loss caused by the operation of OGTs can be reduced up to 15.2% in the upstream direction and 6.3% in the downstream direction. Also, the NCBSs should lie at the nearest block sections (BSs) to depot stations and the NCBSs lengths should be as less as possible.

1. Introduction

In recent years, freight railways are expected to experience increasing capacity constraints and a great variety of goods and vehicle types. Generally, trains and structures were built to vehicle gauges and structure gauges, respectively, and there are safe clearances between trains and infrastructures as discussed in Takao and Uruga [1]. For common trains, there was a large safe gap between two crossing trains in double-track railway line. Railway out-of-gauge trains (OGTs) refer to the freight train vehicles that load goods with specific characteristics such as oversize, overweight, and being expensive. Usually, the OGT's loading gauge is beyond the vehicle or rolling stock gauge and even the structure gauge along its path as discussed in Edworthy [2], and railway administrations will perform a proving run on railway system to guarantee safety [3]. When one OGT is running on one BS and comes across or meets with an opposing common train running in the parallel BS in double-track railway line, the gap space between these two running trains may no longer meet the safety requirement and thus serious conflicts may occur. To solve this problem, railway dispatchers often limit the train speeds. Also, they set some NCBSs for OGTs running; namely, they let opposing common trains stop at the intermediate stations in the parallel line so that OGTs will not come across with any opposing common trains in the NCBSs. Once the OGTs run out the NCBSs, the NCBSs turn into common BSs where common trains which run in one line can come across opposing train in the parallel line. Of course, the setting of NCBSs for OGTs inevitably interferes in the operation of common trains in the parallel line and further leads to the total transport capacity loss of double-track railway line. However, these goods are generally expensive and important construction, chemical engineering, and military equipment, and thus the owners of these goods are willing to pay high costs. Besides, the OGTs usually have higher freight ton kilometer than common trains do, which offsets the capacity loss due to OGTs running in some extent. In such cases, the transport of OGTs is necessary for both economic and political reasons. Appropriate rules for NCBSs setting problem (NCSP) are vital to reduce the capacity loss due to OGT running. In this paper, we will analyze the impacts of NCBS location, length, number, and other different setting ways on capacity loss caused by introducing OGTs in double-track railway line and help planners find appropriate rules for NCSP.

Although there are many research works about railway capacity, research works on railway capacity loss caused by the operation of OGTs are rare. Mussone and Calvo [4] and Abril et al. [5] put forward an approach to calculate and assess railway system capacity, and Jelaska [6] constructed a railway line capacity planning support model. Also, Genovesi and Ronzino [7] and Lindfeldt [8] analyzed double-track railway line capacity, while Javadian et al. [9] and Corriere et al. [10] studied railway station capacity by using simulated annealing and logic fuzzy method.

There are many influencing factors on railway capacity, such as mixes of train types, lengths and speeds, length of BSs, and dwell times as shown in Kozan and Burdett [11], and many researchers have done some work in analyzing the impact of those factors on capacity. For example, Dingler et al. [12] studied the impact of train types on single-track railway capacity; Federica et al. [13] and Yaghini et al. [14] further analyzed the impacts of different speeds and different train types on railway line capacity. Besides, Harrod [15] analyzed the capacity factors of adding trains with speed differentials to railway line dominated by slower trains and analyzed how the selection of the best location to take siding and allow overtaking influences the carrying capacity. Moreover, Sogin et al. [16] used simulation software to analyze the delays caused by introducing passenger trains to a single-track freight network at different volume. Although OGTs fall into the category of slower trains, they have characteristics and operation safety requirements that are quite different from common slower trains. The OGTs running not only allow overtaking in the same line influencing the capacity but also allow setting NCBSs and letting common trains stop in intermediate station in the opposing line influencing the capacity. Therefore, we will consider the capacity loss caused by introducing OGTs in capacity computation of double-track railway line.

Capacity loss due to increased speed differentials can be compensated for by adding overtaking stations as pointed out in Lindfeldt [8], and OGTs can be overtaken by other higher speed trains in the same direction. Besides, Kohda and Fujihara [17] pointed out that capacity loss caused by railway accidents becomes more severe as the transportation capacity and speed increase, and OGTs with oversize and overweight characteristics are underlying factor for railway accidents. In this paper, based on existent work and common trains running processes on double-track railway line, we will further research NCSP for OGT running on double-track railway line and then put forward some appropriate NCBSs setting rules for OGT running on double-track railway line.

The remainder of this paper is organized as follows: Section 2 sets up a simulation model for various trains running on double-track railway line including OGT by cellular automata and also constructs a capacity loss assessment model for trains running on double-track railway line. In Section 3, simulation experiments and the comparisons of the different NCBSs setting rules are given. The paper is finished in Section 4 with some conclusions and discussions for our further research.

2. Models for Various Trains Running on Double-Track Railway Line

In this section, we will present a simulation model for train movements on dedicated freight double-track railway line based on cellular automata theory. Based on the simulation model, a capacity loss assessment model will also be formulated.

2.1. Simulation Model Based on Cellular Automata. Our research focuses on trains running at automatic blocking zone on two-direction and four-line double-track railway line. Based on cellular automata theory, we put forward the simulation model by including an actual line and virtual line for each direction. On the virtual line, a virtual intermediate station is set aside at the same location of the corresponding actual intermediate station, and both intermediate stations are used for temporary stop to realize overtaking or yielding between OGTs and common trains in the same direction and crossing between OGTs and opposing common trains in NCBSs. The virtual BSs without any train are further set aside at the same location of their actual BSs for consistency.

Generally, there are two depot stations (district stations), namely, origin station and destination station. A set of BSs and intermediate stations lie between the origin and destination stations. Also, there are three assumptions for our research:

(i) Each track or siding in railway stations can only host one train during certain time interval for security. Thus, all intermediate and depot stations are viewed as independent BSs, and each of these BSs is considered as a cellular station.

(ii) Each BS or cellular station can only host one train at each time, and both overtaking and yielding are realized at certain intermediate station, namely, cellular station.

(iii) All trains including OGTs run one by one and satisfy the minimum security distance constraint on double-track railway line.

Notations used in the simulation model are shown in Notations.

For train operation safety, the minimum security distance for two adjacent trains is decided by train speeds, BS lengths, and railway signaling indication system. Thus, minimum security cellular interval is also ensured by such minimum security time interval which is necessary to grant the space for completely blocking the train in case of emergency. Let $t_i^{(1)}$ and $t_i^{(2)}$ express running time in BS i for the preceding train and the following one, respectively. When the nearest preceding BS $i+1$ at the same direction is empty after the preceding train leaves section i, the minimum arriving time for the following train at section $i+1$ is calculated by $t_{\min}+t_i^{(2)}$.

The minimum security time interval $t_{\min}$ is further ensured by

$$t_{\min} \geq \max_{\forall i} \left\{ t_i^{(1)} - t_i^{(2)} + t_{i+1}^{(1)} \right\} \quad \forall i \in \{1, 2, \ldots, N-1\}. \quad (1)$$

Furthermore, the minimum security cellular interval is calculated by

$$d_{\min} = \begin{cases} \dfrac{\left(t_{\min} * \max_{\forall n}\{v_{\max}^n\}\right)}{l_0} & \left(t_{\min} * \max\limits_{\forall n}\{v_{\max}^n\}\right) \% l_0 = 0 \\ \left[\dfrac{\left(t_{\min} * \max_{\forall n}\{v_{\max}^n\}\right)}{l_0}\right] + 1 & \left(t_{\min} * \max\limits_{\forall n}\{v_{\max}^n\}\right) \% l_0 \neq 0. \end{cases} \quad (2)$$

As for train-following operations at automatic blocking zone on double-track railway line, the nth train may be overtaken by other trains if $v_{\max}^n < v_{\max}^{n-1}$ and $v_{\max}^n < v_{\max}^{n+1}$. When the preceding BS of a running OGT is a NCBS, if the minimum running time for OGT passing through the NCBS is shorter than that for the closest opposing train arriving at and passing through the parallel NCBS, the OGT goes on running without any stop; otherwise, the OGT should stop at its preceding intermediate station because of crossing operation. If the OGT is running in one direction in NCBS without stop, the opposing stopping trains in the intermediate stations in the parallel line should depart from the intermediate stations according to the relative positions between the OGTs and their stopped intermediate stations. Also, only if safety gap of crossing operations $\text{gap}(n, c_{tk}, t)$ is less than certain fixed value k may the corresponding train be considered to stop at its nearest preceding station for safety reasons.

Trains should stop at certain cellular station for overtaking or crossing operation which occurred in NCBS, and thus train's running cannot be treated as a simple shift of cellular space between the actual line and the virtual one at the same direction. These are the main differences between train overtaking (yielding) and lane-changing in traditional two-lane cellular automata problem. Besides, overtaking and crossing operation time, minimum security time interval, relative positions between OGT and intermediate stations at different direction, instantaneous speed for various trains, and other parameters should be considered in the cellular automation (CA) model of NCSP. Rules of the CA model can be concluded into the following eight points.

(1) Overtaking Trains Stopping Rule and Overtaking Rule for the following Train. If $\text{gap}(n, c_{tk}, t) \leq k$, $v_{\max}^n > v_{\max}^{n-1}$, and $|x_n(t) - x_{n-1}(t)| \geq d_{\min}/l_0$, the overtaking train n should stop at its preceding cellular station c_{tk} and the following train $n-1$ overtakes train n at a probability of $(v_{\max}^{n-1} d_{\min} p_{tk})/(v_{\max}^n \Delta v_{\max} \Delta x(t))$.

If $\text{gap}(n, c_{tk}, t) \leq k$, $v_{\max}^n = v_{\max}^{n-1}$, and $|x_n(t) - x_{n-1}(t)| \geq (d_{\min} + l_0)/l_0$, the overtaking train n should stop at its preceding cellular station c_{tk} and the following train $n-1$ overtakes train n at a probability of $(d_{\min} p_{tk})/(2\Delta x(t))$.

If $\text{gap}(n, c_{tk}, t) \leq k$, $v_{\max}^n < v_{\max}^{n-1}$, and $|x_n(t) - x_{n-1}(t)| \geq d_{\min}/l_0$, the overtaking train n should stop at its preceding cellular station c_{tk} and the following train $n-1$ overtakes train n at a probability of $(\Delta v_{\max} d_{\min} p_{tk})/(v_{\max}^n \Delta x(t))$.

(2) OGT Stopping and Yielding Rule. If $\text{gap}(o, c_{tk}, t) \leq k$ and $[\text{gap}(o, c_{tk}, t) + c_{on} - \text{gap}(n, c_{tk}, t)] * v_{\max}^n < c_{on} v_{\max}^o$, OGT o should pass through the NCBS without any stop at its preceding cellular station c_{tk}, but its nearest preceding train at the opposing direction must stop at the cellular c_{tk} only if $\text{gap}(n, c_{tk}, t) \leq c_{on}$.

If $\text{gap}(o, c_{tk}, t) \leq k$ and $[\text{gap}(o, c_{tk}, t) + c_{on} - \text{gap}(n, c_{tk}, t)] * v_{\max}^n \geq c_{on} v_{\max}^o$, OGT o should stop at the cellular station c_{tk} at a probability of p_{tk}, but its nearest preceding train at the opposing direction must pass through the section without any stop at the cellular c_{tk}.

(3) Rule for Stopping Train Starting at the Same Direction. If $\text{gap}(n, c_{tk}, t)/v_{\max}^{n-1} \geq t_{\min}^s$, $v_{\max}^n \geq v_{\max}^{n-1}$, and $|x_n(t) - x_{n-1}(t)| \geq d_{\min}/l_0$, train n should start at a probability of $(p_{qd} \Delta x(t))/d_{\min}$ if $v_{\max}^n \geq 2v_{\max}^{n-1}$, while train n should start up at a probability of $(p_{qd} \Delta v_{\max} \Delta x(t))/(v_{\max}^{n-1} d_{\min})$ if $v_{\max}^n < 2v_{\max}^{n-1}$.

If $\text{gap}(n, c_{tk}, t)/v_{\max}^{n-1} \geq t_{\min}^s$, $v_{\max}^n = v_{\max}^{n-1}$, and $|x_n(t) - x_{n-1}(t)| \geq d_{\min}/l_0$, train n should start up at a probability of $(p_{qd} \Delta x(t))/(2d_{\min})$.

If $\text{gap}(n, c_{tk}, t)/v_{\max}^{n-1} \geq t_{\min}^s$, $v_{\max}^n < v_{\max}^{n-1}$, and $|x_n(t) - x_{n-1}(t)| \geq (d_{\min} + l_0)/l_0$, train n should start up at a probability of $(P_{qd} v_{\max}^n \Delta x(t))/(2v_{\max}^{n-1} \Delta v_{\max} d_{\min})$.

(4) Rule for Stopping Train Starting Up at the Opposing Direction. If $\text{gap}(n+1, c_{tk}, t)/v_{\max}^n \geq t_{\min}^s$ or $\text{gap}(o+1, c_{tk}, t)/v_{\max}^o \geq t_{\min}^s$, the stopping train n or o starts up at a probability of p_{qd}.

(5) Accelerating Rule. As for stopping train n after starting, if $\text{gap}(n, c_{tk}, t)/v_{\max}^n \geq t_{\min}^s$ and train n has been started, $v_n(t+1) = \min(v_n(t) + \Delta v_n(t), v_{\max}^n)$. And as for overtaking train $n-1$, if $v_{n-1}(t) < v_{\max}^{n-1}$ and $v_{\max}^{n-1} \leq v_{\max}^{n+1}$, $v_{n-1}(t+1) = \min(v_{n-1}(t) + \Delta v_{n-1}(t), v_{\max}^{n-1})$; if $v_{n-1}(t) < v_{\max}^{n-1}$ and $v_{\max}^{n-1} > v_{\max}^{n+1}$, $v_{n-1}(t+1) = \min(v_{n-1}(t) + \Delta v_{n-1}(t), v_{\max}^{n-1})$ when $d_n(t) > d_{\min} + l_0$, while $v_{n-1}(t+1) = \min(v_{n-1}(t) + \Delta v_{n-1}(t), v_{\max}^{n+1})$ when $d_{\min} + l_0 > d_n(t) > d_{\min}$.

(6) Decelerating Rule. If $v_n(t)t^n > d_{\min} l_0$, $v_n(t+1) = \min(v_n(t), (d_{\min} - l_0)/t^n)$.

(7) Random Slowing Down Rule. The value of $v_n(t+1)$ is calculated by $\max((d_n(t) - l_0)/t^n, v_n(t))$ at a probability of p due to incomplete driving accidental factors. However, if $v_n(t) = 0$, $v_n(t+1) = 0$.

(8) Position Renewing. New speed and positions for trains are calculated by (1) to (7) at $t+1$ moment. If $(x_n l_0 + v_{n+1} t_s) \% l_0 = 0$, $x_{n+1} = (x_n l_0 + v_{n+1} t_s)/l_0$; otherwise, $x_{n+1} = [(x_n l_0 + v_{n+1} t_s)/l_0] + 1$.

All the above rules are applicable to train running operations on double-track railway line from t moment to $t+1$ moment, which is also the basis for the simulation model based on cellular automation in the paper.

Table 1: Trains passing through given blocking zone within certain time interval.

Number	Train	Categories	$v^n_{\max}$ (m/s, km/h)	Running direction
I	82702	Luggage and parcel express train	33.33, 120	Up
II	26512	Through freight train	25.00, 90	Up
III	70210	OGT	13.90, 50	Up
IV	26561	Through freight train	25.00, 90	Down
V	36531	Depot freight train	22.20, 80	Down
VI	70641	OGT	11.10, 40	Down

Table 2: Results for different NCBSs setting locations.

Location	Average travel speed (m/s)						Zone occupation time	
	I	II	III	IV	V	VI	Up (s)	Down (s)
NCBS	30.365	23.690	12.699	23.223	21.096	10.688	8900	10460
Number 1	30.373	23.047	13.273	22.740	21.025	10.660	8580	10480
Number 2	30.051	23.466	12.640	17.221	16.779	10.551	8940	10580
Number 3	30.197	23.669	12.453	22.827	20.304	9.789	9080	11400
Number 4	30.034	23.685	12.636	22.985	20.209	9.718	8920	11480
Number 5	30.056	23.378	12.607	22.633	21.061	10.584	8960	10540

2.2. Capacity Loss Assessment Model. Let v_{st}, $v_{n'}$, ω_n, and m denote average speed among all common trains, average speed and capacity loss weighing for train n, and the total number of trains, respectively. The longer the distance between current train and its preceding train, the less the influence of its preceding train on the current train. Let ψ_n denote the weighing function about train distance $\Delta x_{n+j}(t)$, and the function is a decreasing one. Combined with the simulation model for various trains running on double-track railway line, a capacity loss assessment model aiming to minimize the running time loss rate per train and maximize the train flow is formulated as

$$\min \alpha = \frac{\lambda_1 \sum_{n=1}^{m} \omega_n \left(\left(v_{st}/N \right) \times \sum_{t_n=1}^{N} \left(1/v_n\left(t_n\right) \right) - 1 \right)}{m} - \frac{\lambda_2 \left(\sum_{n'=1}^{m} v_{n'} \right)}{L}, \quad (3)$$

$$\text{s.t.} \quad \frac{dv_j(t)}{dt} = V\left[\sum_{n=1}^{m-1} \psi_n \left(\Delta x_{n+j}(t) \right) \right] - v_j(t), \qquad \frac{\psi_j}{\psi_1} \le 1, \quad j = 2,3,4,\ldots,m, \quad (4)$$

$$x_n(t) - x_{n-1}(t) \ge d_{\min}, \quad (5)$$

$$x_n(t+1) = x_n(t) + v_n(t+1), \quad (6)$$

$$v_n(t+1), v_n(t) \in \left[0, v^n_{\max}\right], \quad (7)$$

where λ_1 and λ_2 denote train transfer coefficients including their important degrees of the running time loss rate per train and train flow. The measurement unit in (3) is one train. The speed transmission effect is presented in (4), which means the influence for the following train caused by its preceding train due to different speeds. Also, minimum security cellular interval is expressed by constraint (5), whereas (6) expresses train position renewing process. Constraint (7) ensures trains' velocities constraints.

3. Simulation Experiments and Comparisons

Taking the four-aspect automatic blocking zone on double-track railway line as simulation environment, we will analyze and compare the influence on railway capacity loss caused by OGT running with different setting locations, lengths, and numbers of NCBS so as to get better NCBSs setting rules for NCSP. There are four intermediate stations, two depot stations, and 100 BSs in the automatic blocking zone with a length of 100 000 meters. All intermediate and depot stations are viewed as independent BSs, and each of these BSs is considered as a cellular station. Thus, there are 106 cells and the length for each cell is 1 000 meters.

In the above simulation environment, we assume that update time interval is 20 seconds and trains depart from depot stations in decreasing order of the running speed. Moreover, all trains passing through the zone in certain period are shown in Table 1.

3.1. NCBSs Setting Location. With the same train departing order in origin station and other conditions, the whole zone occupation time and travel speed (calculated by the total length of the whole automatic blocking zone dividing the sum of total running time and stop time) for various trains will change in different extent due to different locations of the NCBS. Assume that there is only one NCBS for OGT running and the length for each section between different stations is 20 000 meters. With above models, results for different NCBSs setting locations are shown in Table 2.

Table 2 shows that when there are no NCBSs in the up running direction, their average travel speeds fluctuate within the scope of [−5%, 5%] due to the random slowing down rule.

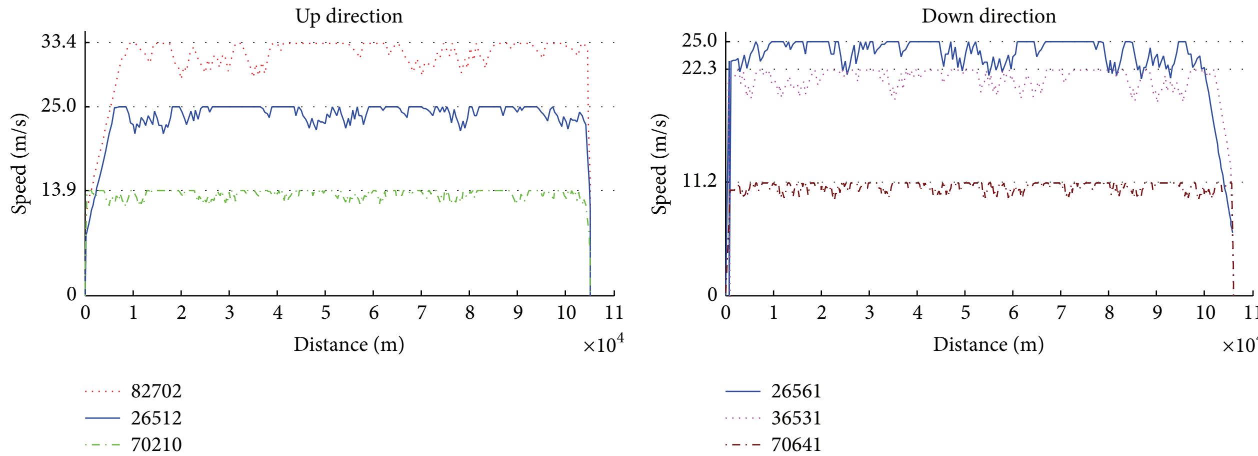

Figure 1: Train speed-distance curve (NCBS: blocking section 1 in the left).

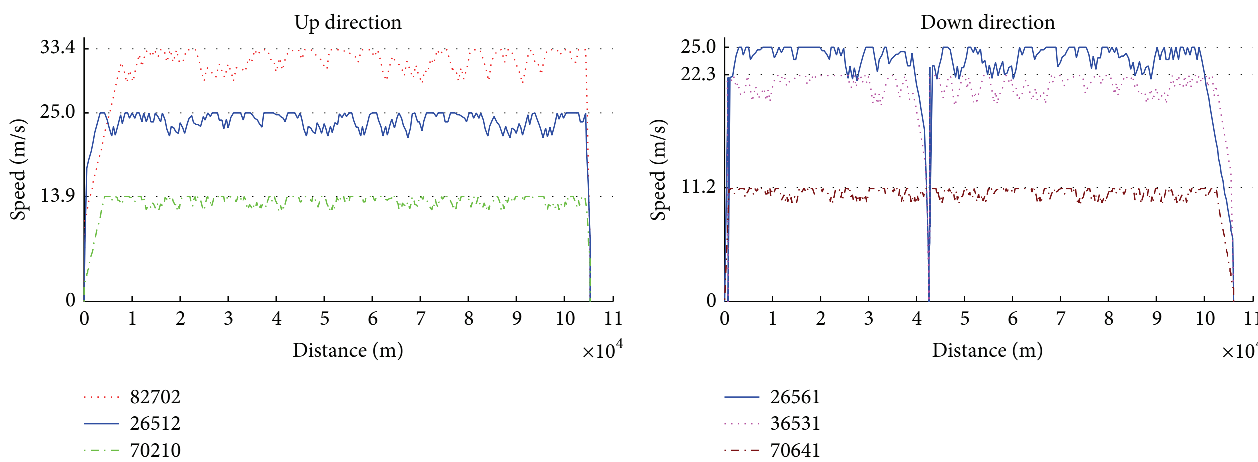

Figure 2: Train speed-distance curve (NCBS: blocking section 2 in the left).

Comparing blocking sections with NCBS and those without NCBS, we can find that the difference of zone occupation time is within the scope of [−5%, 5%], and the capacity loss is almost zero in the up running direction. But, for the down direction, when the NCBS is blocking section 1 or 5 (as for train speed-distance curve, please see Figures 1 and 5), the total zone occupation times and running speeds of the trains are the same as those without NCBS. Thus, the NCBS that is the nearest to a depot station has the minimum impact on double-track railway line capacity. When the NCBS is blocking section 2 in the left (see Figure 2), trains 26561 and 36531 in the down direction should stop and yield to OGT 70210 in the up direction, which increases their blocking zone occupation times. Due to the short stop and yielding time of trains 26561 and 36531, the trains' impact on running speed of OGT 70641 in the down direction is tiny and the OGT's total zone occupation time is almost the same as that without NCBS. Therefore, when the blocking section 2 in the left is the NCBS, double-track railway line capacity is less affected. When blocking section 3 or 4 in the left is NCBS (as for train speed-distance curve, please see Figures 3 and 4), the travel time of OGT 70641 and its blocking zone occupation time increase due to stop at intermediate stations for yielding to trains 82702 and 26512 in the up direction. The time interval for adjacent trains is 8 minutes. The capacity loss is 1.96 if NCBSs are considered (cf. Figure 3) and 2.12 trains if NCBSs are not considered (cf. Figure 4).

If only a single NCBS is considered and the NCBS is blocking section 3 or 4 in the left, then the NCBS has the biggest impact on capacity loss which is almost 2 trains; if the NCBS is blocking section 2 in the left, then the NCBS's impact on capacity comes second. Because of NCBS, the travel times of faster trains are increased and the total zone occupation times are slightly further increased. If the NCBS is adjacent to a depot station such as blocking section 1 or 5 in the left, then NCBS has the smallest impact on capacity loss of double-track railway line. Different train speeds have different influence on capacity as discussed in [8, 9, 16]. Based on the above analysis, we can conclude that the smaller the distance between the NCBS and the depot station, the smaller the impact for a NCBS on capacity loss caused by OGT; the closer the distance between the NCBSs with the middle of the blocking zone, the greater the impact for a NCBS on capacity loss caused by OGT. Thus, the NCBS setting location rule for

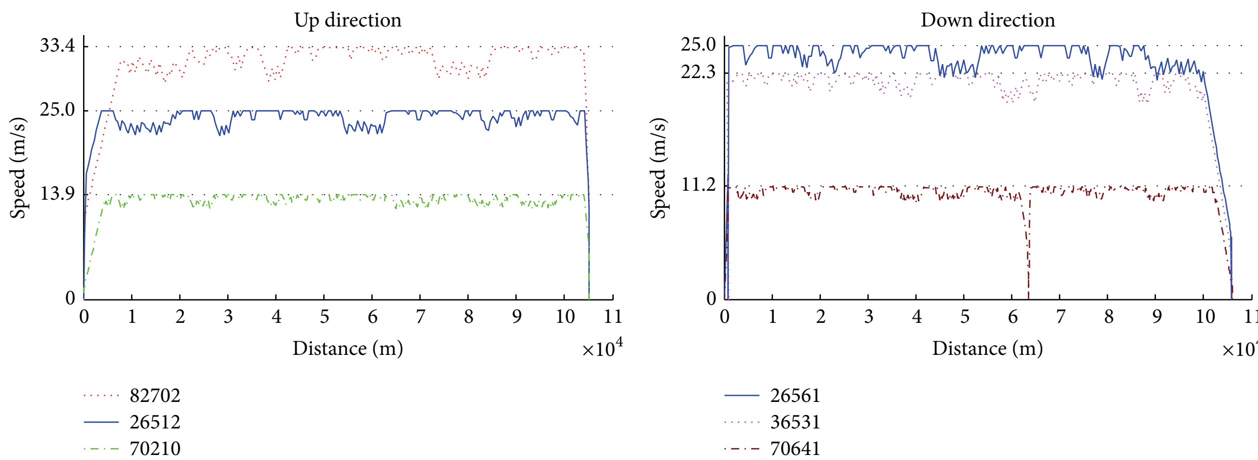

FIGURE 3: Train speed-distance curve (NCBSs setting: blocking section 3 in the left).

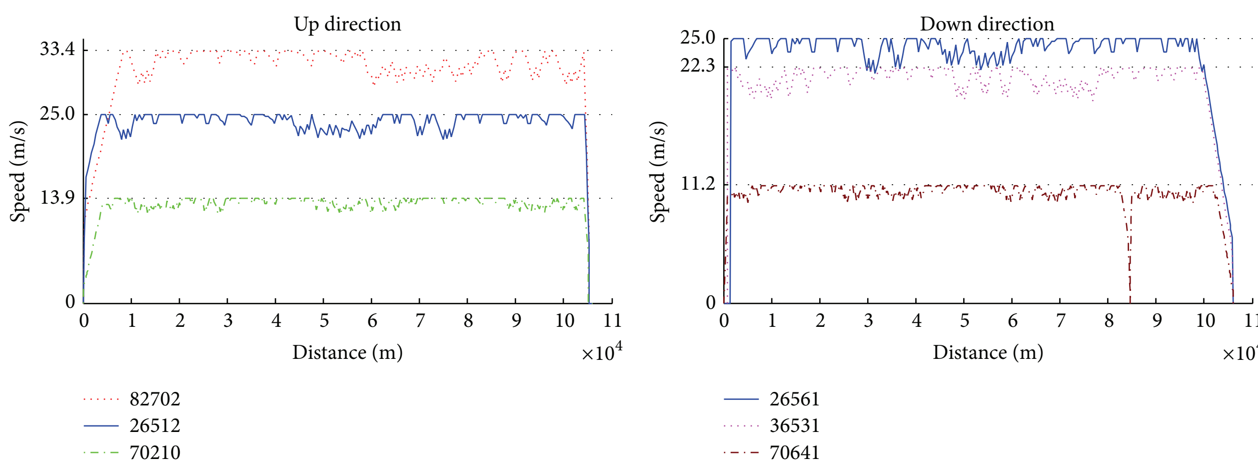

FIGURE 4: Train speed-distance curve (NCBS: blocking section 4 in the left).

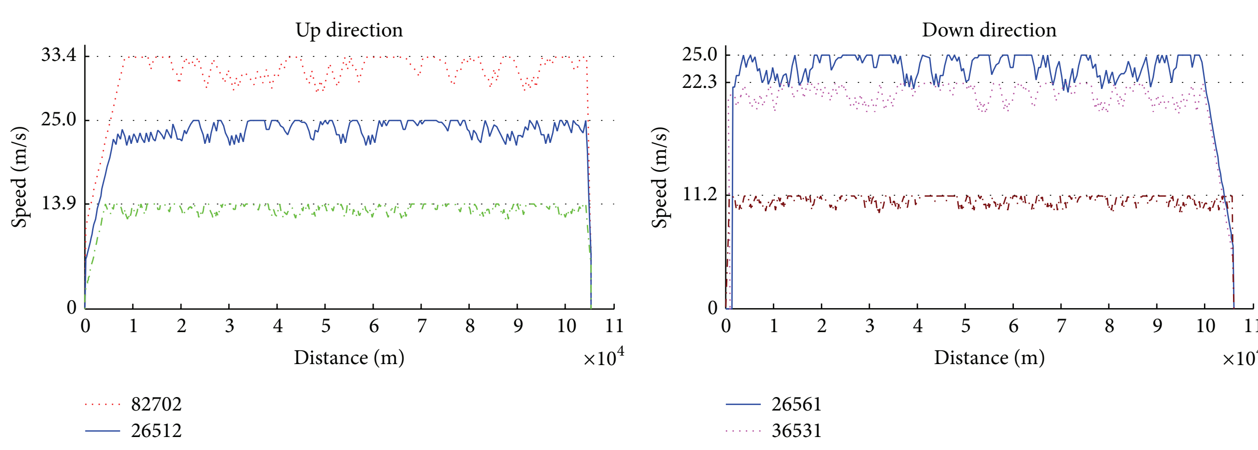

FIGURE 5: Train speed-distance curve (NCBS: blocking section 5 in the left).

Table 3: Results for different NCBSs setting length.

Length (km)		Average travel speed in the up direction (m/s)			Average travel speed in the down direction (m/s)			Zone occupation time (s)	
		I	II	III	IV	V	VI	Up	Down
Noncrossing	10	30.122	22.745	12.581	22.798	21.122	10.186	8180	9960
	15	30.365	23.713	12.602	22.760	20.122	10.133	8740	10500
	20	30.376	23.775	12.699	22.863	20.436	10.222	8940	10940
	25	30.256	22.666	12.624	22.943	21.089	10.195	9300	11380
	30	30.456	23.595	12.704	22.876	20.301	10.257	9760	11920
With nonintersection	10	30.294	23.652	12.578	22.668	20.147	10.182	8180	9980
	15	29.619	22.258	12.609	22.354	20.732	9.745	8660	10900
	20	30.195	23.582	12.629	22.837	20.146	9.714	8980	11480
	25	30.438	23.634	12.713	22.850	20.391	9.502	9220	12140
	30	30.461	22.742	12.678	22.736	20.194	8.865	9820	13520

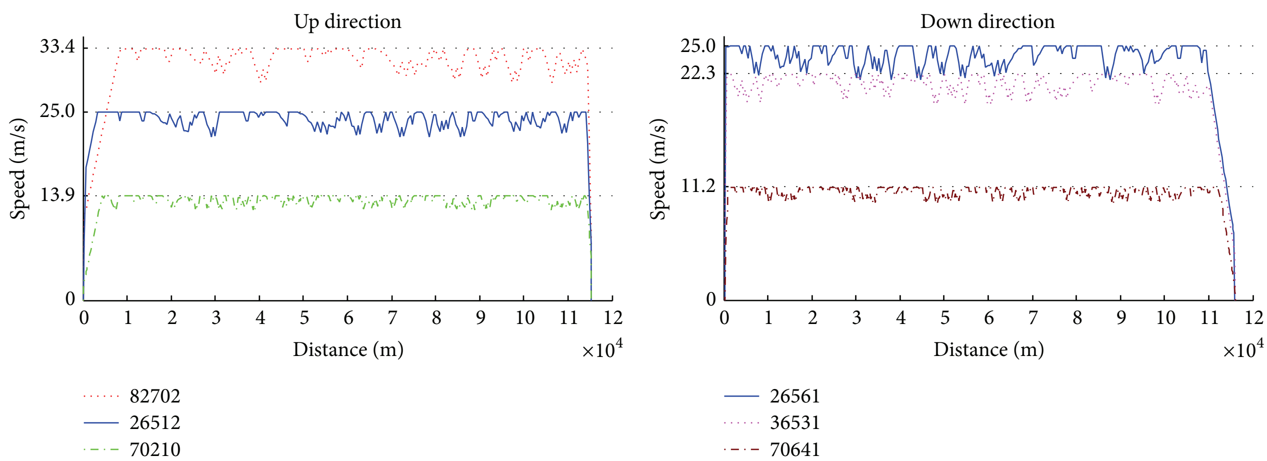

Figure 6: Train speed-distance curve (section 3 is 30000 m, without NCBS).

NCSP is that the NCBS setting location should be as near as possible to depot stations and OGT's synthetic outline should also be considered.

3.2. NCBSs Setting Length. According to above conclusion in Section 3.1, we only choose blocking section 3 as the NCBS in the next experiment. Assume that the lengths of other BSs are fixed; we progressively increased the length of blocking section 3 in the left and then compare results from such experiment with or without NCBS. The results for different NCBSs setting length are shown in Table 3.

Table 3 shows that there is no NCBS situation occurring in the up direction, and thus the zone occupation time has no obvious change. But, for the down direction, the blocking section 3 as the NCBS has no impact on railway capacity, when the NCBS length is 10000 m. The zone occupation time increases by 3.8%, 4.9%, and 6.7% and capacity losses are 0.83, 1.13, and 1.58 trains, respectively, when the blocking section 3 is NCBS with the length of 15000 m, 20000 m, and 25000 m, respectively. If the length of blocking section 3 is 30000 m without NCBS, the train speed-distance curve is shown in Figure 6. If the length of blocking section 3 is 30000 m without NCBS, the train speed-distance curve is shown in Figure 7. When the length of blocking section 3 increased from 15000 to 30000, the stop time of OGT 70641 at the intermediate station increases significantly (see Figures 8 and 9), which makes its zone occupation time increase by 15.1% and capacity loss is 3.75 trains caused by such case. In Figures 6 and 7, the distances reach 120 km, because the length of blocking section 3 in the left is changed from original 10 km to 30 km.

The above results show that a proper reduction of NCBSs setting length can raise the double-track railway line's capacity with NCBSs substantially, especially the sections with busy OGT running. Capacity loss due to speed differences can be compensated for by additional stations [13], and railway capacity on double-track railway line with OGT running can be released by increasing the intermediate station number and further shortening the NCBS length. Also, we can conclude that the capacity loss caused by OGT running is the biggest when the NCBSs setting location is in the middle of such double-track railway BSs. Moreover, the longer the

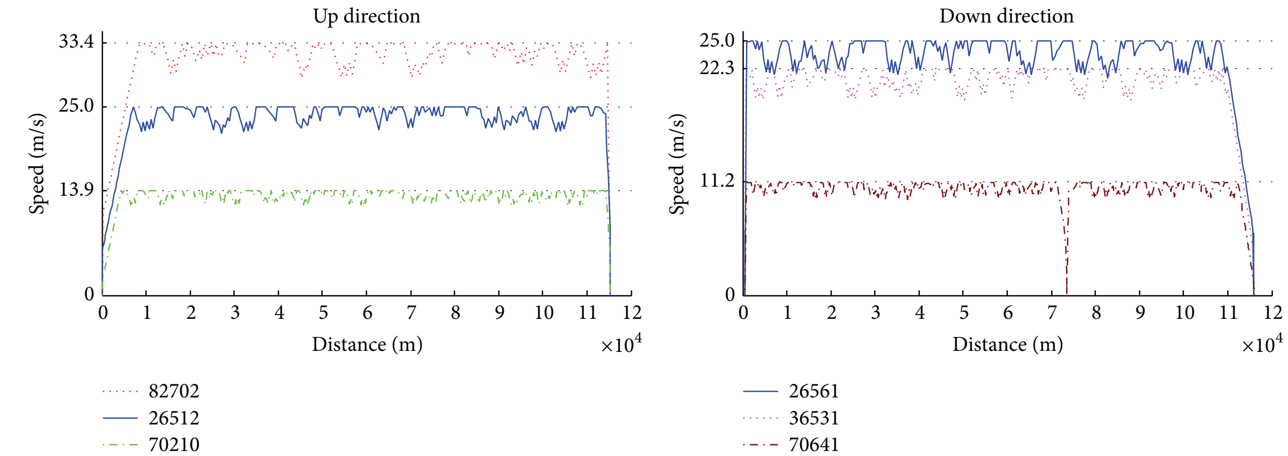

FIGURE 7: Train speed-distance curve (section 3 is 30000 m, with NCBS).

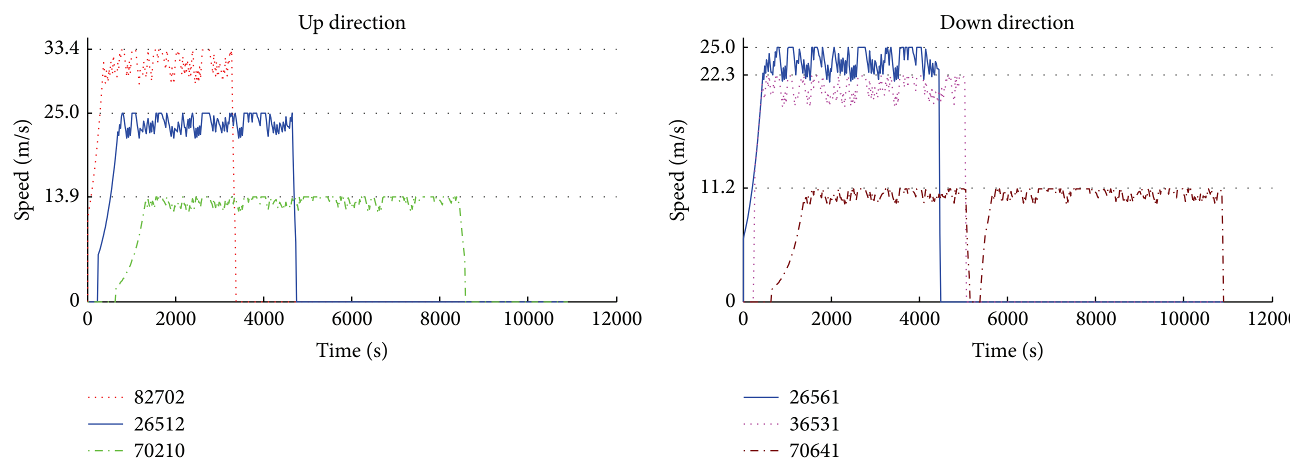

FIGURE 8: Train speed-time curve (the NCBS length is 15000 m).

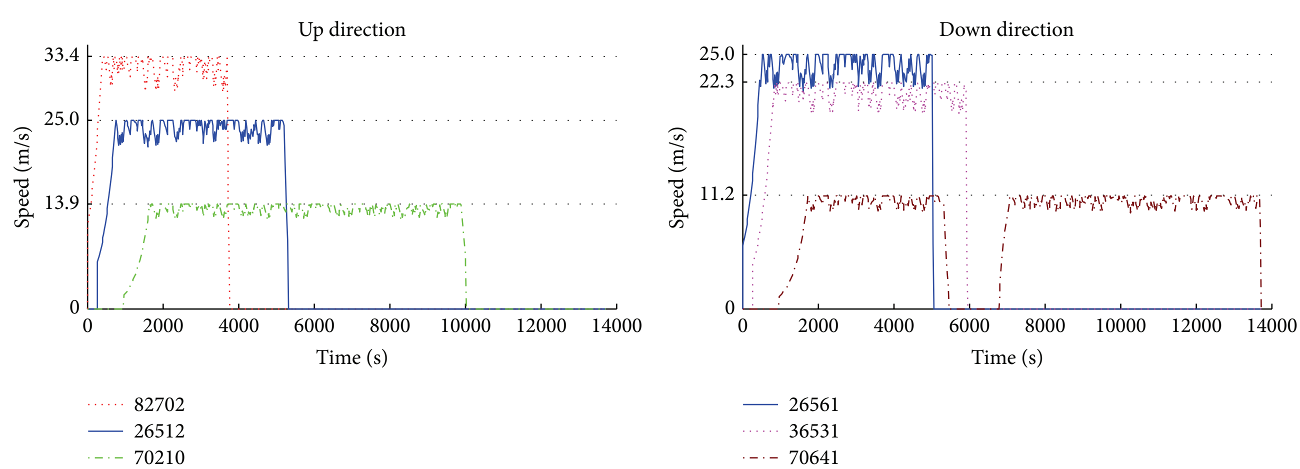

FIGURE 9: Train speed-time curve (the NCBS length is 30000 m).

NCBSs setting length, the bigger the capacity loss caused by OGT running on double-track railway line. Thus, the NCBSs setting length rule for NCSP is that the NCBS length should be as short as possible, and we can choose shorter sections as NCBSs.

3.3. NCBSs Setting Number. With certain trains and departing orders, we can see that the capacity impact is great once there is a NCBS for OGT running. If the NCBS number is increased in continuous way, then what would be the impact of different NCBS number for OGT running on capacity?

Table 4: Results for different NCBSs setting number.

NCBSs number	Average travel speed in the up direction (m/s)			Average travel speed in the down direction (m/s)			Zone occupation time (s)	
	I	II	III	IV	V	VI	Up	Down
0	30.365	23.690	12.699	23.223	21.096	10.688	8900	10460
1 (1)	30.373	23.047	12.773	22.740	21.025	10.660	8880	10480
2 (12)	30.385	23.674	12.699	18.539	18.061	10.307	8900	10860
3 (123)	30.215	22.857	12.636	17.372	17.298	9.502	9000	11740
4 (1234)	30.206	22.752	12.190	17.437	17.312	9.385	9280	11940
5 (12345)	26.817	22.857	12.161	17.179	17.337	9.316	9400	12040

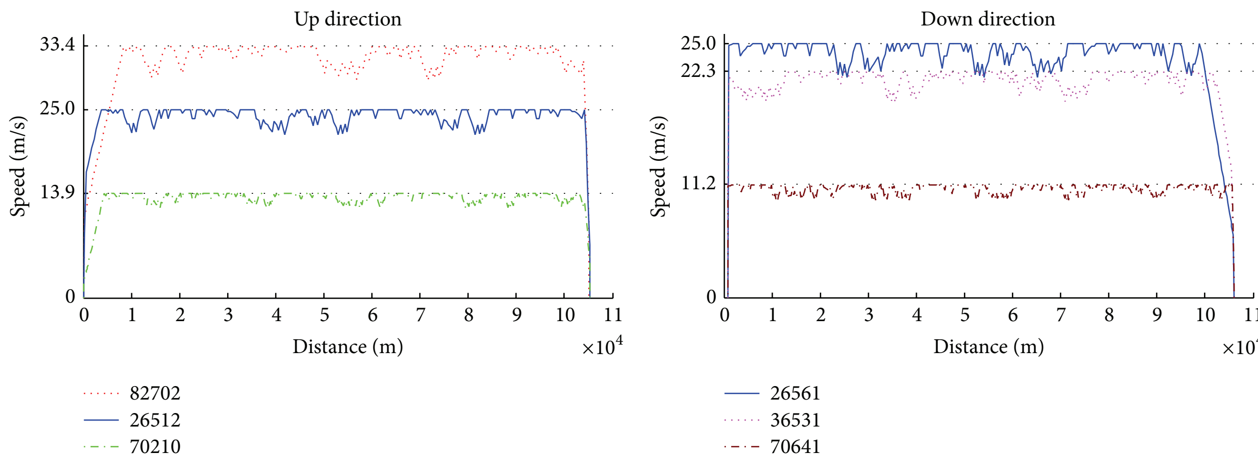

Figure 10: Train speed-distance curve (NCBS number: 0).

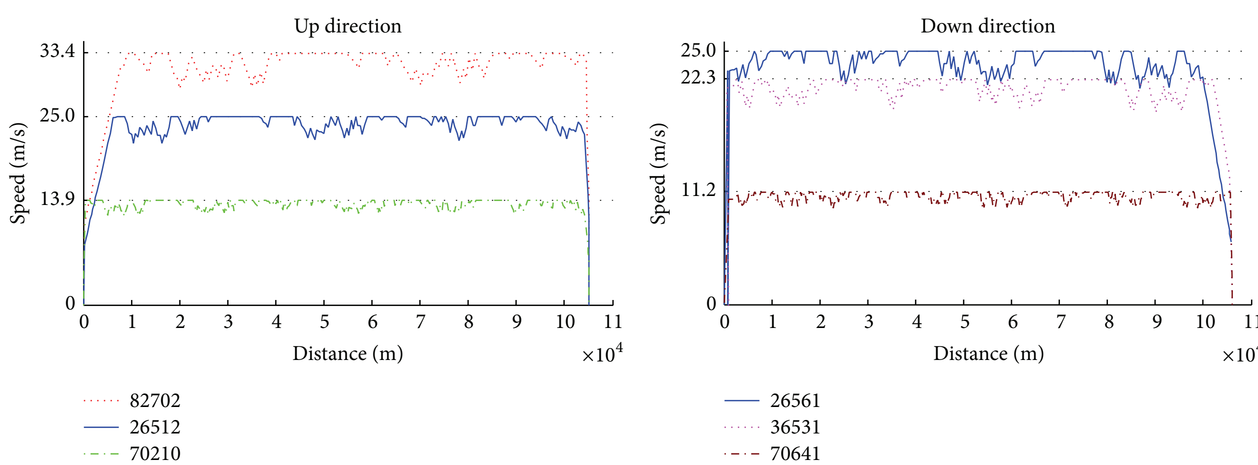

Figure 11: Train speed-distance curve (NCBS number: 1).

Based on the simulation experiment of only one NCBS (blocking section 1 in the left), we successively add a blocking section as NCBS, and the results for different NCBSs setting numbers are shown in Table 4.

(1) Figure 10 shows train speed-distance curve without NCBS, while Figures 11–13 show train speed-distance curves with different NCBSs setting number. Specifically, the NCBS is blocking section 1 in the left in Figure 11; the NCBSs are blocking sections 1 and 2 in the left in Figure 12, and the NCBSs are blocking sections 1, 2, and 3 in the left in Figure 13. Compared with above three situations, all trains in the up direction have no stop or yielding behaviors; thus their zone occupation times are nearly the same as those without NCBSs (see Table 3), and capacity loss is not obvious. For the down direction, it is completely different. There is no OGT stop or yielding behavior in Figure 11 and capacity loss is almost zero. But, for two NCBSs, trains 26561 and 36531 stop and yield to OGT 70210 running in opposite direction at the second

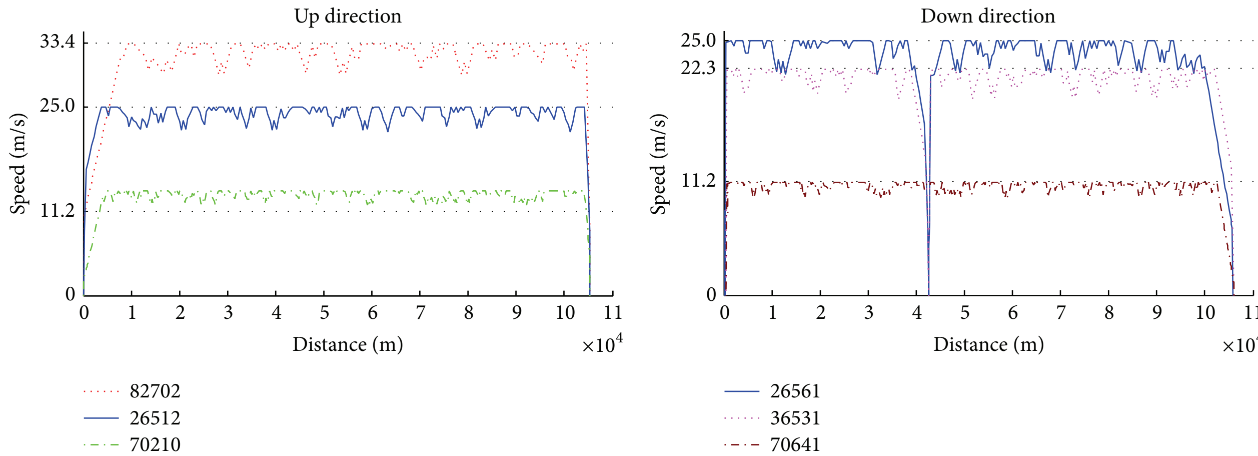

FIGURE 12: Train speed-distance curve (NCBS number: 2).

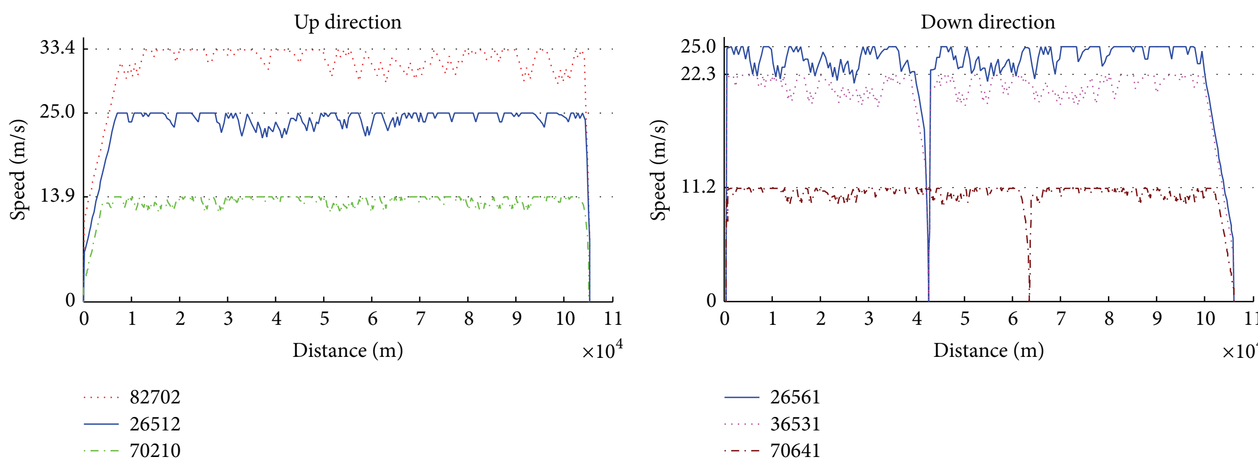

FIGURE 13: Train speed-distance curve (NCBS number: 3).

intermediate station in the left; thus the zone occupation time in the down direction increased by 3.8% and capacity loss is 0.83 trains. As for three NCBSs, trains 26561, 36531, and OGT 70641 stop and then yield to OGT 70210 running in opposite direction at the second and third intermediate stations in the left, respectively; thus the zone occupation time in the down direction increased by 12.2% and capacity loss is further 2.67 trains.

(2) Figure 14 shows train speed-distance curve with four NCBSs, such as blocking sections 1, 2, 3, and 4 in the left. For the up direction, there is only OGT 70210 stopping and then yielding to OGT 70641 running in the opposite direction at the third intermediate station in the left, and its zone occupation time increased by 4.3% and capacity loss is 0.79 trains. For the down direction, both trains 26561 and 36531 stop and yield to OGT 70210 running in the opposite direction at the second intermediate station in the left, and OGT 70641 stops and then yields to trains 82702 and 26512 in opposite direction at the fourth intermediate station in the left. Moreover, the zone occupation time in the down direction rises up 14.2% and capacity loss is up to 3.08 trains.

(3) Figure 15 shows train-distance curve with five NCBSs when the NCBSs are blocking sections 1, 2, 3, 4, and 5 in the left. As for the up direction, train 82702 and OGT 70210 stop and yield to train 70641 running in the opposite direction at the fourth and third intermediate stations in the left, respectively. Also, the zone occupation time in the up direction increases by 5.6% and capacity loss is 1.04 trains. Meanwhile, for the down direction, both trains 26561 and 36531 stop and yield to OGT 70210 running in the up direction at the second intermediate station in the left, while OGT 70641 stops and yields to train 26512 running in the up direction at the fourth intermediate station in the left. Therefore, the zone occupation time in the down direction reaches up to 12040 s (see Table 4), it increases by 15.1%, and capacity loss is 3.29 trains.

From Figures 12–15, the total stop/yielding numbers are 2, 3, 4, and 5, respectively, while the NCBS numbers are 2, 3, 4, and 5 accordingly. Thus, there is an interesting relationship between the stop/yielding numbers and the numbers of NCBSs. On the above basis, we can conclude that the more the number of NCBSs, the bigger the capacity loss caused by

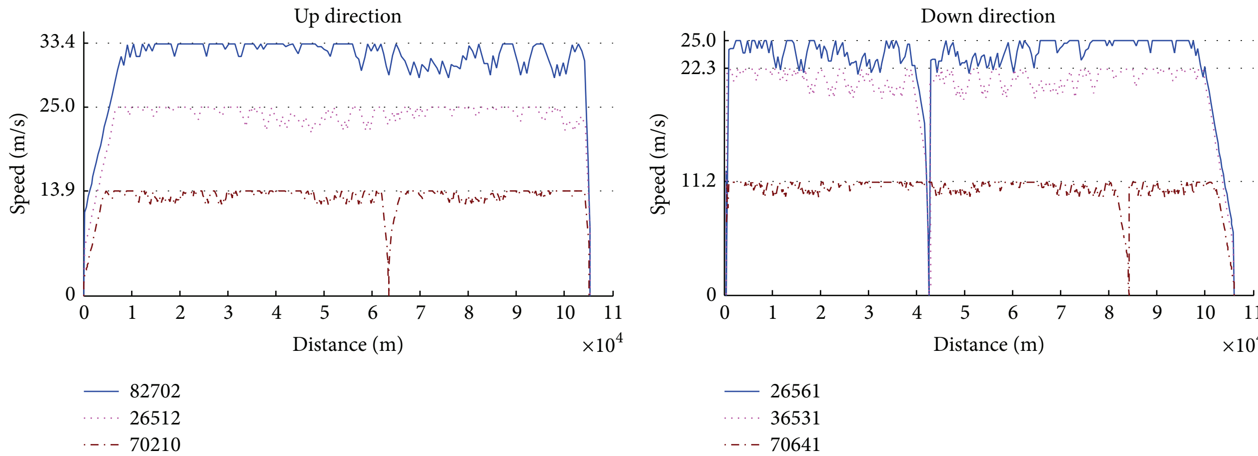

FIGURE 14: Train speed-distance curve (NCBS number: 4).

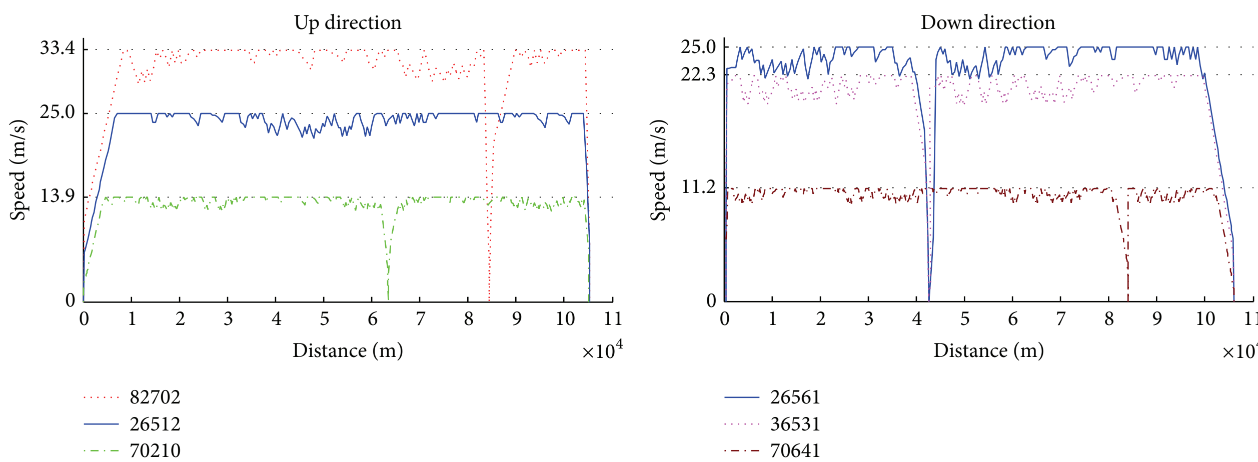

FIGURE 15: Train speed-distance curve (NCBS number: 5).

OGT running; and the number of stop/yielding operations increases with the number of NCBSs in a linear way. Thus, the NCBSs setting rule for NCSP is that the number of NCBSs should be the least, and we cannot set other unnecessary NCBSs except for safety reasons.

3.4. NCBSs Setting with Continuous Way. OGT often has to stop and yield to other trains in the opposite direction when the gap space between two trains on double-track line no longer meets the safety requirement, which has great influence on the capacity of those sections, especially when there are continuous NCBSs within the blocking zone. In order to quantize the impact of the NCBSs with continuous way on railway capacity, we simulate all possible situations for such case and then analyze their results in a horizontal comparison way. Also, results are shown in detail in Table 5.

From Table 5, we will analyze the impact of the continuous way of NCBSs setting on double-track railway line capacity in the following ten setting ways.

(S1) First is continuous NCBSs including blocking sections 1 and 2 in the left. There are four types, Cases 1, 5, 8, and 10, whose train speed-distance curves are shown in Figures 12–15. The average zone occupation times for all these cases are 9145 s and 11645 s in the up and down directions, respectively. Compared with the OGT running without NCBS, the zone occupation time increases by 2.8% and capacity loss is 0.51 trains in the up direction, while the zone occupation time increases by 11.3% and capacity loss is 2.47 trains in the down direction.

(S2) Second is continuous NCBSs including blocking sections 2 and 3 in the left. There are six types, Cases 2, 5, 6, 8, 9, and 10, whose train speed-distance curves are shown in Figures 16, 13, 17, 14, 18, and 15. The average zone occupation times for such six cases are 9204 s and 11834 s in the up and down directions, respectively. Compared with OGT running without NCBS, the zone occupation time increases by 3.4% and capacity loss is 0.63 trains in the up direction, while the zone occupation time increases by 13.1% and capacity loss is 2.86 trains in the down direction.

(S3) Third is continuous NCBSs including blocking sections 3 and 4 in the left. There are six types, Case 3 and Cases 6~10, whose train speed-distance curves are shown in Figures 19, 17, 20, 14, 18, and 15. The average zone occupation times for such six cases are 9290 s and 11910 s in the up and

Table 5: Results of NCBSs setting with different continuous way.

Setting way	Average travel speed in the up direction (m/s)			Average travel speed in the down direction (m/s)			Zone occupation time (s)	
	I	II	III	IV	V	VI	Up	Down
NCBS	30.365	23.690	12.699	23.223	21.096	10.688	8900	10460
Case 1: 12	30.385	23.674	12.699	18.539	18.061	10.307	8900	10860
Case 2: 23	30.543	23.880	12.726	18.367	18.491	9.775	8940	11420
Case 3: 34	30.387	22.764	12.186	22.836	20.292	9.308	9300	11980
Case 4: 45	27.636	23.583	12.696	22.748	20.202	9.636	8960	11560
Case 5: 123	30.215	22.857	12.636	17.372	17.298	9.502	9000	11740
Case 6: 234	30.384	22.771	12.137	17.502	17.263	9.283	9340	11960
Case 7: 345	27.226	23.781	12.386	22.931	20.367	9.588	9160	11640
Case 8: 1234	30.206	22.752	12.190	17.437	17.312	9.305	9280	11940
Case 9: 2345	27.492	22.670	12.244	17.373	17.139	9.342	9260	11900
Case 10: 12345	26.817	22.857	12.161	17.179	17.337	9.316	9400	12040

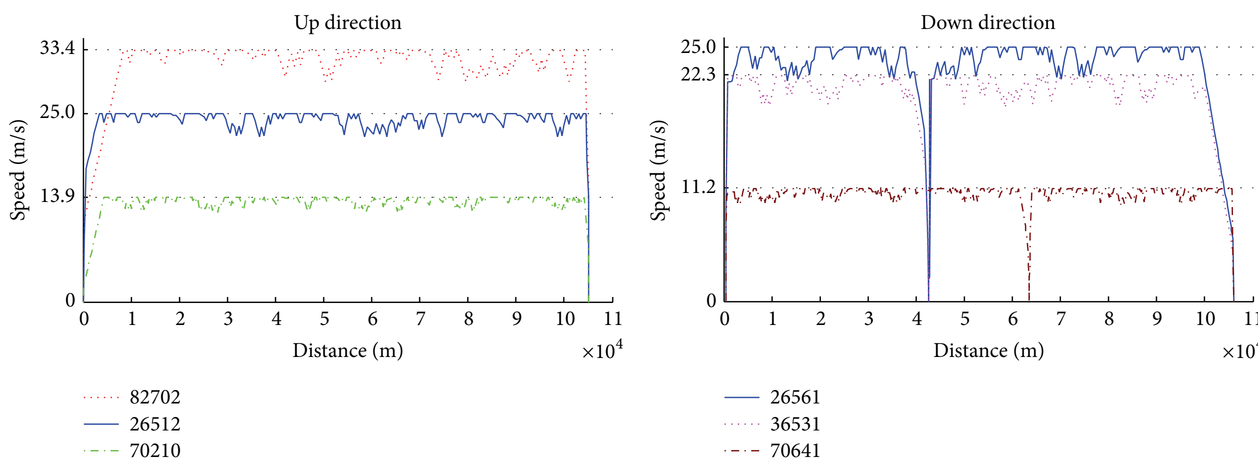

Figure 16: Train speed-distance curve (NCBS: blocking sections 2 and 3 in the left).

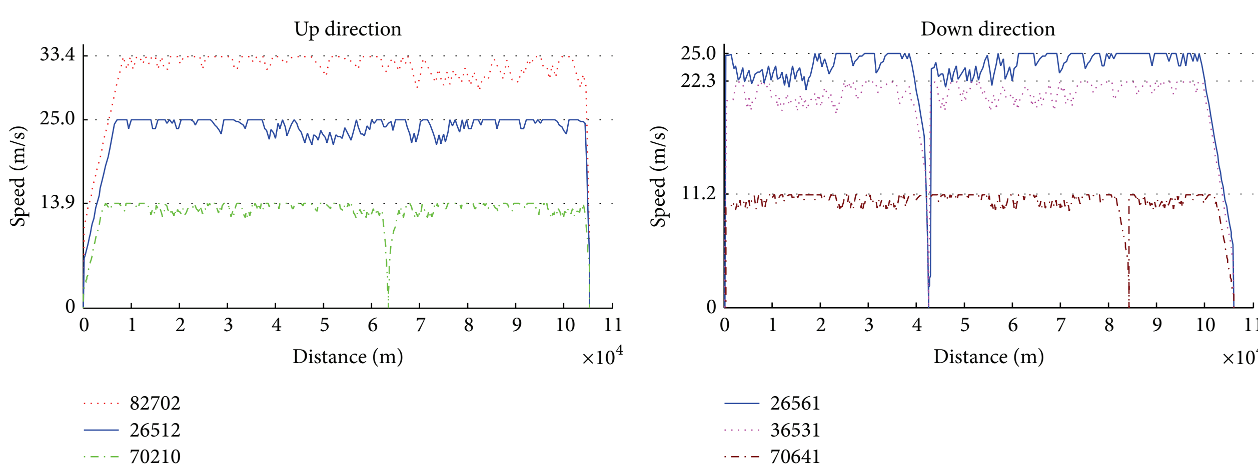

Figure 17: Train speed-distance curve (NCBS: blocking sections 2~4 in the left).

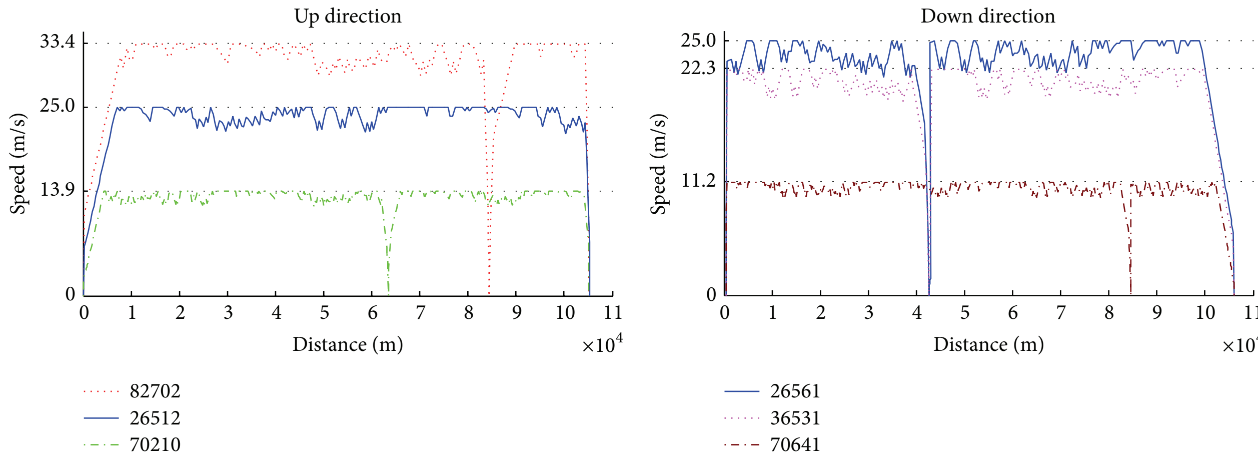

FIGURE 18: Train speed-distance curve (NCBS: blocking sections 2~5 in the left).

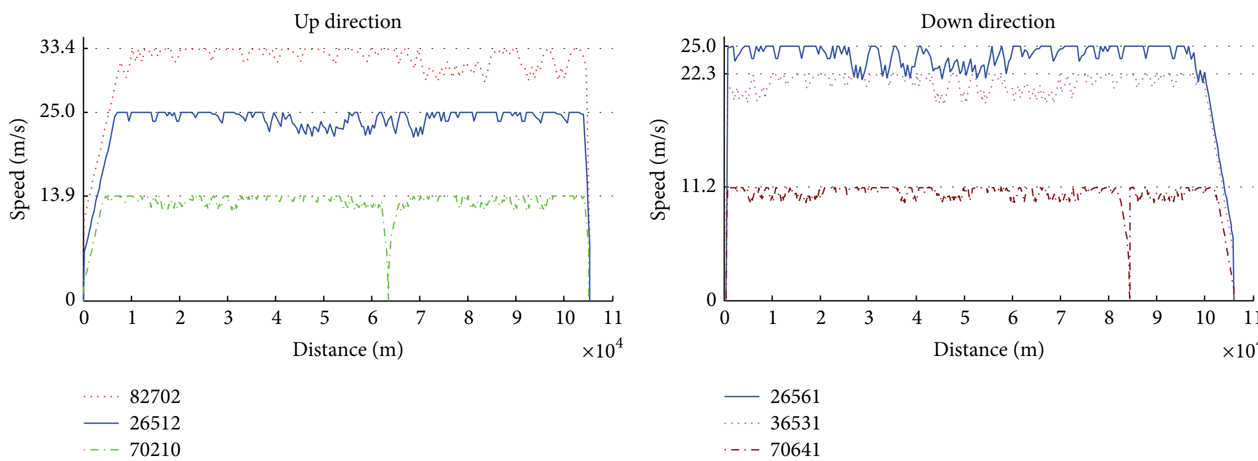

FIGURE 19: Train speed-distance curve (NCBS: blocking sections 3 and 4 in the left).

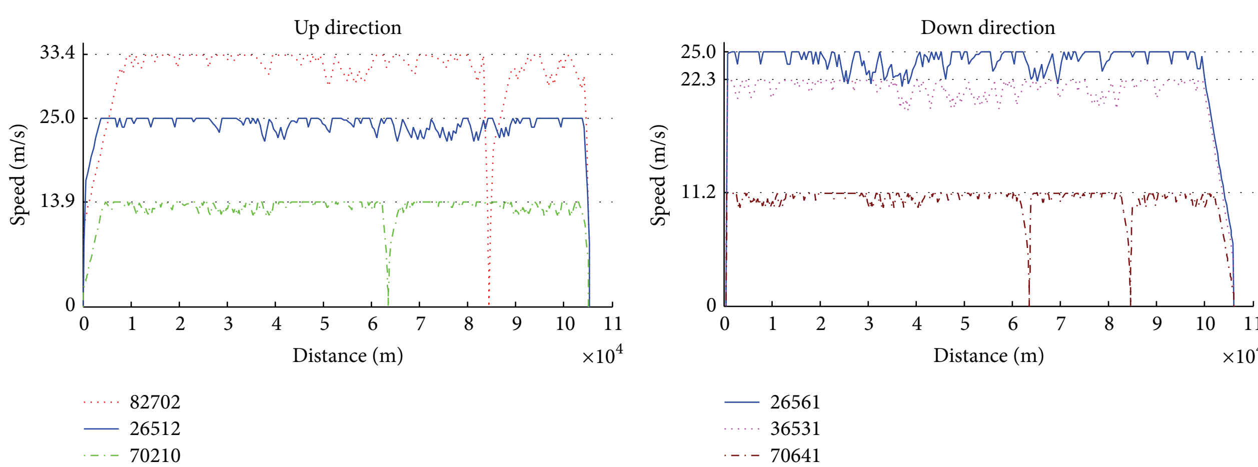

FIGURE 20: Train speed-distance curve (NCBS: blocking sections 3~5 in the left).

down directions, respectively. Compared with OGT running without NCBS, the zone occupation time increases by 4.4% and capacity loss is 0.81 trains in the up direction, while the zone occupation time increases by 13.9% and capacity loss is 3.02 trains in the down direction.

(S4) Fourth is continuous NCBSs including blocking sections 4 and 5 in the left. There are four types, Cases 4, 7, 9, and 10, whose train speed-distance curves are shown in Figures 21, 20, 18, and 15. The average zone occupation times for all these cases are 9195 s and 11785 s in the up and

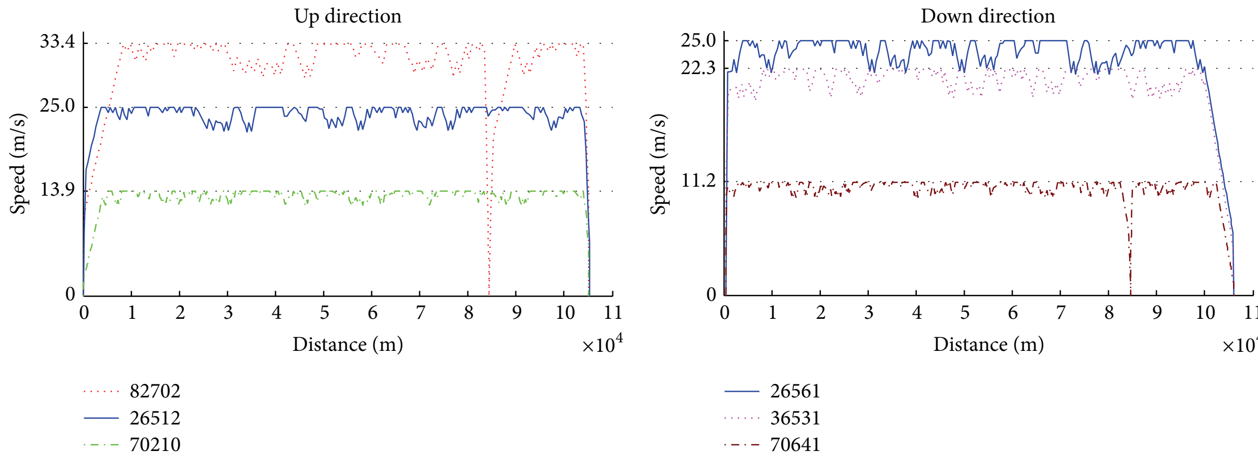

FIGURE 21: Train speed-distance curve (NCBS: blocking sections 4 and 5 in the left).

down directions, respectively. Compared with OGT running without NCBS, the zone occupation time increases by 3.3% and capacity loss is 0.61 trains in the up direction, while the zone occupation time increases by 12.7% and capacity loss is 2.76 trains in the down direction.

(S5) Fifth is continuous NCBSs including blocking sections 1, 2, and 3 in the left. There are three types, Cases 5, 8, and 10, whose train speed-distance curves are shown in Figures 13, 14, and 15. The average zone occupation times for all these cases are 9227 s and 11907 s in the up and down directions, respectively. Compared with OGT running without NCBS, the zone occupation time increases by 3.7% and capacity loss is 0.68 trains in the up direction, while the zone occupation time increases by 13.8% and capacity loss is 3.01 trains in the down direction.

(S6) Sixth is continuous NCBSs including blocking sections 2, 3, and 4 in the left. There are four types, Cases 6, 8, 9, and 10, whose train speed-distance curves are shown in Figures 17, 14, 18, and 15. The average zone occupation times for all these cases are 9320 s and 11960 s in the up and down directions, respectively. Compared with OGT running without NCBS, the zone occupation time increases by 4.7% and capacity loss is 0.88 trains in the up direction, while the zone occupation time increases by 14.3% and capacity loss is 3.13 trains in the down direction.

(S7) Seventh is continuous NCBSs including blocking sections 3, 4, and 5 in the left. There are three types, Cases 7, 9, and 10, whose train speed-distance curves are shown in Figures 20, 18, and 15. The average zone occupation times for all these cases are 9274 s and 11860 s in the up and down directions, respectively. Compared with OGT running without NCBS, the zone occupation time increases by 4.2% and capacity loss is 0.78 trains in the up direction, while the zone occupation time increases by 13.4% and capacity loss is 2.92 trains in the down direction.

(S8) Eighth is continuous NCBSs including blocking sections 1, 2, 3, and 4 in the left. There are only two types, Case 8 and Case 10, whose train speed-distance curves are shown in Figures 14 and 15. The average zone occupation times for such two cases are 9340 s and 11990 s in the up and down directions, respectively. Compared with OGT running without NCBS, the zone occupation time increases by 4.9% and capacity loss is 0.92 trains in the up direction, while the zone occupation time increases by 14.6% and capacity loss is 3.19 trains in the down direction.

(S9) Ninth is continuous NCBSs including blocking sections 2, 3, 4, and 5 in the left. There are only two types, Case 8 and Case 10, whose train speed-distance curves are shown in Figures 18 and 15. The average zone occupation times for such two cases are 9330 s and 11970 s in the up and down directions, respectively. Compared with OGT running without NCBS, the zone occupation time increases by 4.8% and capacity loss is 0.90 trains in the up direction, while the zone occupation time increases by 14.4% and capacity loss is 3.15 trains in the down direction.

(S10) Tenth is continuous NCBSs including all BSs. The train speed-distance curves are shown in Figure 15. The zone occupation times for such case are 9400 s and 12040 s in the up and down directions, respectively. Compared with OGT running without NCBS, the zone occupation time increases by 5.6% and capacity loss is 1.04 trains in the up direction, while the zone occupation time increases by 15.1% and capacity loss is 3.29 trains in the down direction.

From above analysis, we can conclude that different continuous NCBSs setting ways have different impacts on railway capacity caused by OGT running, as shown in Figure 22.

In Figure 22, the horizontal axis presents above 10 NCBSs setting ways from Case 1 to Case 10, and the vertical one expresses the capacity loss (unit: one train). From Figure 22, we can know that the capacity loss may be at peak among all these ten ways with the continuous NCBSs setting ways including Case 3, Case 6, Case 8, and Case 10. Moreover, for Case 3, Case 6, Case 8, and Case 10, their NCBSs all include sections 3 and 4 in the left. Meanwhile, compared with other positions settings of NCBSs, section 3 in the left has the biggest impact on railway capacity from Section 3.1. Therefore, if there appears continuous NCBSs setting way, the elimination of section 3 in the left as a NCBS has the greatest impact on capacity. Besides, capacity loss in the up direction is less than that in the down direction. The reason is

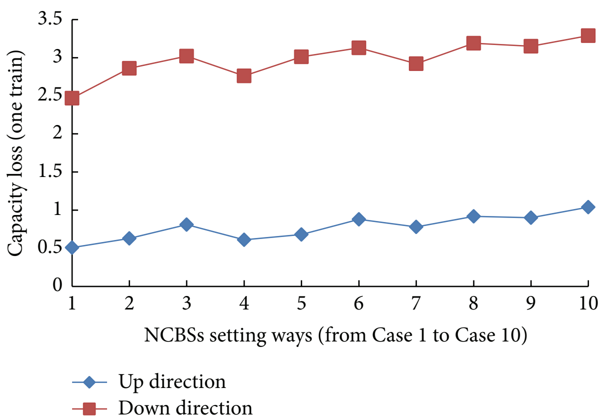

Figure 22: Capacity loss caused by different NCBSs setting ways.

that trains in the down direction are slower than those in the up direction, such as OGT and through freight train, and the highest speed train is 82702 (luggage and parcel express train) in the up direction, which means that these slower trains can occupy much longer occupation time once stop/yielding occurs. In such case, it certainly leads to much more railway capacity loss.

Above experiment results also show that in the case of NCBSs number minus one, capacity loss caused by the operation of OGTs can be reduced up to 15.2% in the upstream direction and 6.3% in the downstream direction. Also, different train categories and their speeds variation caused by yielding and transfer effects have different impacts on capacity. Besides, we should set NCBSs as less as possible. If the NCBSs are set continuously, the continuous NCBS containing the middlemost blocking section will have the greatest impact on capacity loss caused by OGT running; and the capacity loss caused by OGT running on double-track railway line tends to increase with the continuous number of NCBSs settings.

4. Conclusions

In this paper, firstly, the NCSP due to OGT running on double-track railway line based on capacity loss was analyzed and the NCBSs setting rules including the NCBSs setting location, length, number, and continuous setting ways aiming at reducing capacity loss on double-track railway line were put forward. Secondly, the NCBSs for OGT running on double-track railway line should lie at the nearest sections to depot stations with shorter BSs lengths; the total number of NCBSs should also be the least expected for transport safety reasons; and the number of stop/yielding operations increases with the number of NCBSs in a linear way. Thirdly, different incremental or continuous ways of NCBSs settings have different impacts on capacity loss caused by OGT running, and in the case of NCBSs number minus one, capacity loss caused by the operation of OGTs can be reduced up to 15.2% in the upstream direction and 6.3% in the downstream direction. Thus, the proposed NCBSs setting rules can effectively ease the double-track railway line capacity loss caused by OGT running on double-track railway blocking zone.

In the end, railway stations with complex layouts and limited throat capacity are basic supports for OGT running. Thus, our future work will focus on the influencing mechanism of station carrying capacity due to OGT running and the comprehensive assessment of both stations capacity loss and BS capacity loss caused by OGT running based on cellular automata.

Notations

N: Total number for all cells
l_0: Length for each cell (m)
L: Total length for all cells or distance between two depot stations (m), $L = Nl_0$
$v^n_{\max}$: Maximum running speed for the nth train, while $v^o_{\max}$ is maximum running speed for the oth OGT (m/s)
$v_n(t)$: Instantaneous speed for the nth train at t moment (m/s)
$x_n(t)$: Cellular position for the nth common train at t moment, while $x_o(t)$ is cellular position for the oth OGT at t moment
$d_n(t)$: Preceding train distance for the nth train and its closest preceding train at t moment (m)
t^n: Average time for the nth train passing through a cellular space (s)
$\Delta v_{\max}$: Difference between maximum running speeds for two adjacent trains at certain direction
$\Delta x(t)$: Displacement difference for two adjacent trains with certain direction at t moment (m)
$\Delta v_n(t)$: Instantaneous speed difference for the nth train at t and $t+1$ moment (m/s)
$d_{\min}$: Minimum security cellular interval for two adjacent trains at the same direction
$t_{\min}$: Minimum security time interval for two adjacent trains at the same direction (s)
$t^s_{\min}$: Minimum stop time at cellular station (s)
t_s: Update time interval in the simulation situation (s)
p_{tk}: Stop chance for running trains
p_{qd}: Starting chance for stop trains
c_{on}: The total cellular number ran by the closest opposing train in the opposite direction while the OGT o is running on the NCBS at certain direction
$\text{gap}(n, c_{tk}, t)$: Cellular interval between the cellular positions for the nth train and its closest preceding cellular station c_{tk} at t moment, denoted by $\text{gap}(n, c_{tk}, t)$.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

Yinggui Zhang and Qiong-fang Zeng contributed equally to this work.

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