Investigation of in-station coupling and decoupling effect on railway capacity using virtual coupling technique

Weiting Yang[a], Yuguang Wei[a*], Tao Han [a], Chuxuan Hu [a]

[a] Beijing Jiaotong University, Beijing, China
yangweiting2021@163.com, ygwei@bjtu.edu.cn, hantao202312@163.com, 22110299@bjtu.edu.cn
* Corresponding author

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1 INTRODUCTION

Virtual coupling (VC) technique separates trains by relative braking distances and can shorten train tracking intervals. It has been regarded as one of the important methods for effectively alleviating constraints and improving railway capacity (Quaglietta *et al.*, 2020). The advantages of VC have been validated and reported in both theoretical and experimental investigations (Schumann *et al*., 2016 and Felez *et al*., 2019). However, the degree of improvement in railway capacity using VC varies with different scenarios. For example, when considering complicated scenarios such as coupled trains approaching a turnout, the enhancement of railway capacity with VC is rather limited due to additional safety constraints. Many researchers have investigated such rail scenarios, for instance, in a “Y” shape railway train line where two lines merge into one, Chen et al. proposed a strategy for how these two trains running on different lines after merging to couple with each other according to their running orders and departure times (Chen *et al*., 2024). Wang et al. considered train delay conditions to determine the trains’ running order and the initial coupling position of the train after merging (Wang *et al*., 2013). However, current investigations primarily focus on strategies for coupling or decoupling trains when they encounter turnouts in the railway section other than railway station (Xun *et al*., 2022). Solving this problem can effectively enhance railway capacity. On one hand, it shifts the coupling and decoupling positions from in-section to in-station, thus increasing trains’ running distances during coupled. On the other hand, it reduces the loss of railway capacity arising from train departure intervals. This work mathematically describes and analyzes the scenario when coupling and decoupling occur after trains pass through a turnout at a railway station. Different scenarios when trains encounter turnouts at railway stations are compared and presented, and the connection of VC to railway arrival and departure tracks applications is revealed.

2 PROBLEM DESCRIPTION AND METHODOLOGY

In this section, first, the scenarios of in-station coupling and decoupling are described. Then methodology for in station coupling and decoupling is proposed and given.

2.1 In-station coupling and decoupling scenario

In traditional common scenario when trains run in section and encounter turnouts there are more uncertain factors. For example, it is difficult to determine arrival time, velocity and acceleration values of these two trains when they arrive at turnouts. In this case, it is reasonable to adopt the absolute braking distances as “defensive distances” to ensure safe railway operations. When considering coupling in station, there are less uncertainties. Under known conditions (distances from trains to turnouts, velocity and acceleration values and train operation states) in railway station, it is only needed to determine the proper departure time of two trains to save much coupling time thus can improve railway capacity. In decoupling process, it is the same story as coupling process as stated.

The in-station coupling and decoupling process is presented in this section. Figure 1 gives the schematic diagram of in-station coupling process. When two tracks parking trains in the station are close to each other as shown in figure 1a, the distance from merging switch to the boundary of station can cover the distance for coupling. In this case, the two close trains can complete coupling in the station. When two tracks are far away from each other and the merging switch is near the boundary of station as seen in figure 1b, the front train has already run out of the station when the rear train arrives at the merging switch. It can be divided into two cases (denoted as case one and case two shown in figure 1b) depending on the behaviors of the front train. In case one, the front train runs out of the station but keeps the velocity as the station limit speed to wait for the coupling with the rear train, and then they accelerate to the section limit speed together. In case two, the front train runs out of the station and immediately accelerates to the section limit speed, and then the two trains are difficult to coupling since they run in the same manner.

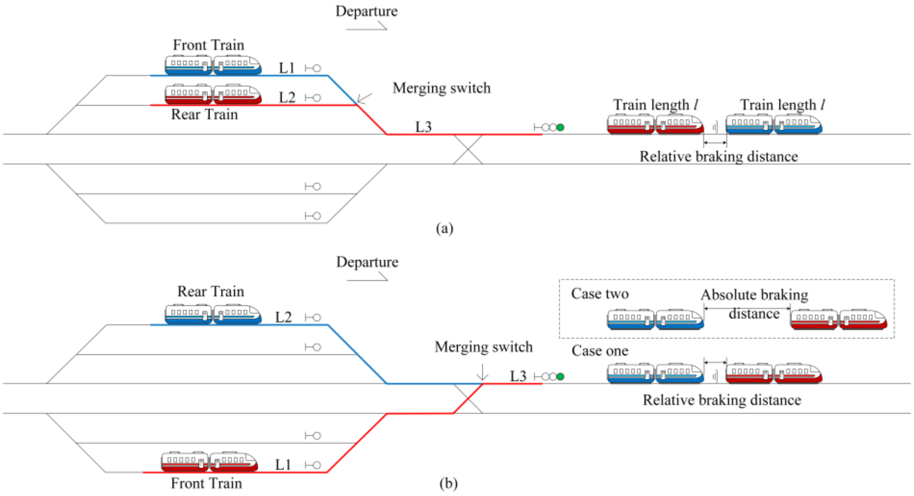

Figure 1 – *In-station coupling scenario*

The discussion for decoupling process is similar to the above mentioned detailed coupling process. Separate cases can be also divided and discussed as coupling section does. The schematic diagram of in station decoupling process and detailed illustrations are omitted. In following section, both the in station coupling and decoupling behaviors are described mathematically.

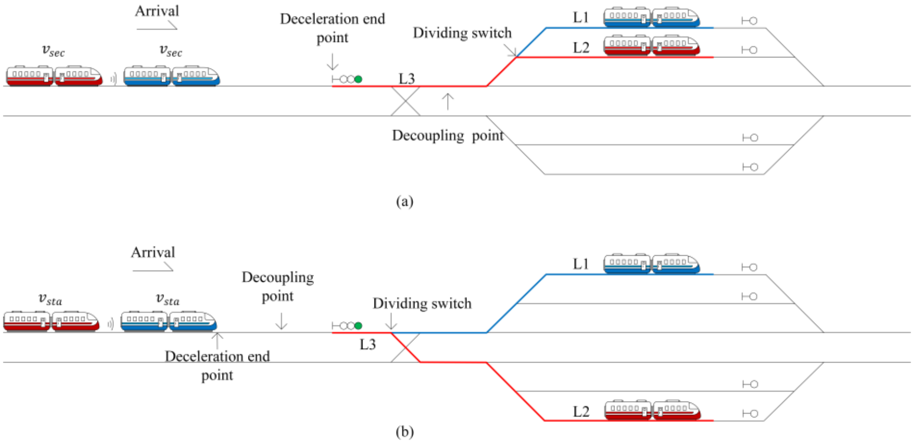

Figure 2 – *In-station decoupling scenario*

2.2 Methodology for coupling and decoupling in station

This section gives the mathematical illustration for in station coupling and decoupling process mentioned in section 2.2. The critical points when trains accelerate and decelerate are calculated and marked shown in figure 3.

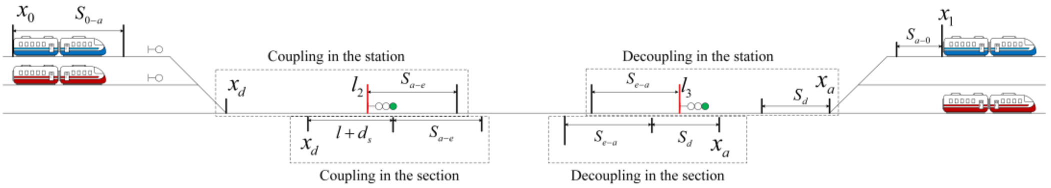

Figure 3 – *In station coupling and decoupling definition with mathematical description*

In figure 3, $l_2$and l_3 are the positions of exit signal and entrance signal. X0 and x1 are the initial position and stop position, respectively. x_d is the position of merging switch and x_a is the position of dividing switch. Based on the discussion in section 2.2 we know that whether coupling (or decoupling) in station or in section is determined by the relative distance between merging (or dividing) switch and entrance (or exit) signal (boundary of station). When $l_2 - x_d \geq l + t \cdot v_{sta}$, they will couple in station. Similarly, when $x_a - l_3 \geq S_d$ they will decouple in station. t is the time for turnout changing directions. S_d is the distance from decoupling point to dividing switch. S_{0-a}, S_{a-e}, S_{e-a}, , S_{a-0} are four distances and can be defined with equation 1.

$$S_{0-a} = \frac{{v_{sta}}^2 - 0}{2 \cdot a_{max}}, S_{a-e} = \frac{{v_{sec}}^2 - {v_{sta}}^2}{2a_{max}}, S_{e-a} = \frac{{v_{sta}}^2 - {v_{sec}}^2}{2a_{brake}}, S_{a-0} = \frac{0 - {v_{sta}}^2}{2 \cdot a_{brake}} \tag{1}$$

where v_{sec} is the speed limit in section and v_{sta} is the speed limit in station.
When all conditions are prescribed in station, the distance from trains' initial positions to merging switch is known. Therefore, the time for train arriving at merging switch can be calculated and the rear train departure time can be properly obtained.

3 RESULTS

As stated in section 2.2, two cases (denoted as case one and two) can be divided according to the behaviors of the front train. We compared the parameter variations (train displacement, velocity and relative distances between two trains) between case one and two and plotted them in figure 4.

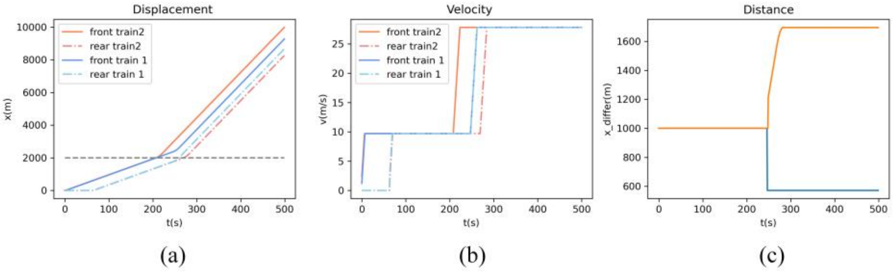

Figure 4 – *Parameter results of coupling in the railway section (a) displacement (b) and velocity (c) distance between two train heads*

It can be seen from figure 4a that for case two (denoted as front train 2 and rear train 2) the two trains (front train and rear train) start to accelerating to the section speed limit when they arrive at the boundary of the station. However, in case one the start accelerating when they are coupled. It can be clearly observed that it take less departure time between two adjacent trains in case one.

Figures 4b and 4c show the same behaviors as indicated in figure 4a but with variations of velocity and relative distances of the two trains.

We consider the whole process which includes both coupling and decoupling processes. Coupling behavior can be divided into coupling in the station (CA) and coupling in the section (CE) depending on the distance from merging switch to the boundary of station. Similarly, the decoupling behavior can be divided into decoupling in the station (DA) and decoupling in the section (DE). The entire behaviors which are considered both coupling and decoupling are plotted and shown in figure 6.

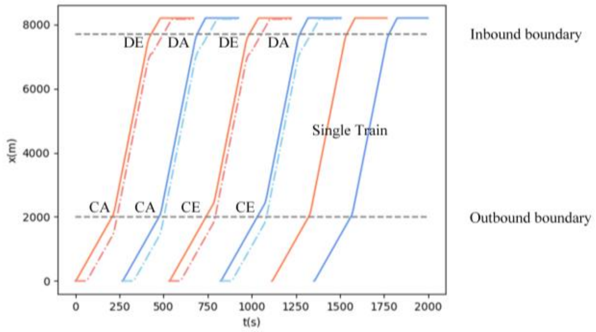

Figure 5 – *Behaviors of train operations considering the combinations of different coupling and decoupling schemes*

4 DISCUSSIONS AND CONCLUSIONS

In this work, the behaviors of trains coupling and decoupling in station are investigated in depth. It can be seen from generated results that when the distance from merging switch to the boundary of station is small (not enough to cover the coupling process in station) the two trains can still couple with proper operation scheme. In this case, it shows that the optimal scheme for these two trains operation is when they are coupled and accelerate simultaneously. This will save more time compared to that when the front train runs out of the station and accelerates immediately. When considering the whole coupling and decoupling process, one can see that coupling operation manner can utilize the railway resources effectively compared to operating trains one by one. In all four coupling and decoupling schemes, the CA pluses DA is the best mode to reduce time intervals between two adjacent trains. This work can provide useful guidelines for the applications of virtual coupling technique in trains arrival and departure.

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