A Tutorial on Blocking Time Theory and Strategic Extension with Virtual Coupling Principles

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Abstract

Blocking time can be employed to precisely represent the infrastructure usage. The well-known blocking time theory forms the foundations for capacity allocation, conflict detection, and timetabling. By focusing on the microscopic models for calculating the precise track blocking times, the stability and feasibility of railway schedules/timetables can be guaranteed from the operation point of view. In order to be used as a strategic guidance to scheduling train path with blocking time theory over the given infrastructure under virtual coupling, this study focuses on the blocking time and its elementary components, the formal basic definition of virtual coupling, the headway policy, and how to include the extended blocking time theory in conflict detection and resolution during the coupling process. The motivation for extending the blocking time theory with virtual coupling principles is to adapt all methods based on blocking time theory/model that can be pote ntially applied also for virtual coupling.

Keywords

Blocking Time Theory; Virtual Coupling; Headway Policy; Conflict Detection and Resolution; Timetabling; Capacity Allocation.

1. Introduction

Blocking time can be employed to precisely represent the infrastructure usage. Fundamentally, blocking time theory models the moment that a train blocks/claims a track section since the moment the track section is setup for a train until the track section is released again. As one of the most frequently and generally used models for describing minimum headways, blocking time theory has been implemented as the basis/function in the development of the advanced tools for train operation and capacity assessment, e.g., RailSys, and UIC Code 406[1-2]. Also, blocking time theory forms the foundations for capacity allocation, conflict detection, and timetabling, including several well-known associated methods, e.g., UIC infrastructure occupation computation [2], train path modelling [3], conflict detection and resolution for railway traffic management [4], and conflict-free timetabling [5-6]. Capacity occupation (the time that the compressed timetable of a sequence of train operations occupies the infrastructure) is regarded as one measure to quantify capacity, which is defined as the utilization of the infrastructure along a given section over a defined time period [2][7]. In fixed blocking system, the timetable determines the sequence of block sections that a train passes through, i.e., the route of a train. And most of the published researches assume that trains drive according to the blocking time theory [8].

The nature of blocking time theory is to manage the time and space slot for train operations, e.g., representing infrastructure usage/occupation as blocking time or blocking time stairway, and study the behaviour of individual trains in the railway environment [6], which offers a very accurate description of infrastructure occupation for conflict-free timetabling from the microscopic perspective. Also, blocking time theory or blocking time model can be used as a significant means to analyze/assess railway capacity under fixed/virtual blocking system[9-10], with the timetable-dependent UIC(International Union of Railways) Code 406 compression method (fully analytical) [11]. Based on blocking time theory, [12] provided an event-based simulation of train operations for traffic flow properties on unidirectional railway lines with two-aspect fixed-block signaling.

Together with the moving blocking signaling, virtual coupling (VC) is regarded as one of the most advanced concepts/techniques from the railway industry. By taking it as a next-generation train-centric signaling technique, [13] comprehensively assessed the impact of virtual coupling with regards to the performance, security, and feasibility for various rail market segments. Compared with the case in conventional railways, one of the biggest differences for the train-centric virtual coupling signalling system is that the track is not segmented into various physical fixed blocks, at least in the plain track section. The implications of the term train-centric refer to that all the operational and associated functional signalling procedure of the trains occur onboard of the train, rather than using the trackside associated train detection and signalling equipment. Under virtual coupling, due to the incorporation of relative braking distances and therefore the reduce path conflicts, certain extensions on blocking time theory have to take place for conflict detection and resolution, capacity assessment, and timetabling, in the context of connected and automated environment. The motivation for extending the blocking time theory with virtual coupling principles is to adapt all methods based on blocking time theory/model that can be potentially applied also for virtual coupling [14].

2. Blocking Time and its Elementary Components of Each Individual Train

2.1 Blocking Time in General

The blocking time refers to the time duration that a train occupies the block section excluding other trains, which is the time interval a specified infrastructure resource (track detection section or block section) is exclusively assigned to a single train or train unit and hence blocked for any other trains. The classical blocking time theory [15] can be used to calculate the blocking times. Consistent with the known definitions from [16-19], UIC Code 406 [1-2] describes the time elements that construct the blocking time of a train movements, which is significant for getting a standardized data basis for building the blocking time.

Under fixed blocking system, according to the physical attributes of the specified resource (block section), the blocking time T_{li} of the train l associated with block i can be achieved as formula (1).

$$T_{li}=t_{setup}+t_{sight}+t_{approach}+t_{block}+t_{clear}+t_{release} \tag{1}$$

Where:

t_{setup} denote the time for route formation for the approaching train.

t_{sight} denote the sight and reaction time for visual distance of the train driver to view and response to the indication of the signaling system.

$t_{approach}$ denote the time for crossing the approach section after that a movement authority has been issued.

t_{block} denote the train journey time of the occupied block interval (the time duration the train head completely crosses the section), which depends on the block length and the train speed.

t_{clear} denote the time for clearing which depends on train length and speed.

$t_{release}$ denote the time for route release after the train clearance and ready for the next train's occupancy.

The input to formula (1) can be classified into the infrastructure features, the driver behavior, and the running times of trains. The term t_{setup}, t_{sight}, and $t_{approach}$ compose the safety margin of the time required before the train physically runs into the block. In more generally, let B_{bli} denote the beginning occupation of train l on block section i (the instant the movement authority is issued), B_{eli} denote the end occupation of train l on block section i (the moment the section has been totally released.), i.e.. blocking time is introduced as $T_{li}=(B_{bli}, B_{eli})$, then the blocking time T_{li} can also be expressed as formula (2).

$$T_{li}=B_{eli}-B_{bli} \tag{2}$$

In the space-time diagram, the blocking times along a train's path form the blocking time stairway under fixed blocking system. Let n denote the number of block sections along the route of train l, the associated list of blocking times T_l for each train l can be expressed as formula (3) from the microscopic perspective.

$$T_l=\{T_{l1}, T_{l2}, \cdots, T_{\ln}\} \tag{3}$$

The blocking time reflects the capacity consumption/occupation of the train movements on the train operation line. In the blocking time theory, each block section is a piece of railway infrastructure element/resource, which is usually divided by the block signals under fixed blocking system, i.e., the track sections or interlocking route section going from a stop signal to the next stop signal in the same direction [7][20], including one or more switches or crossings. A set of consecutive resources/infrastructure elements consists a train route, which can be used by a train to traverse between two stations/points. From the time-distance perspective, the train route is extended with the time the path is used, which forms the blocking time stairway under the fixed blocking system.

2.2 Blocking Time under Virtual Coupling

However, under virtual coupling conditions, the vital systems, e.g. track-free detection elements, and signals, have been migrated from track-side to on-board, or cab signalling. Thus, the typical rectangular block or the blocking time stairway maybe disappear under virtual coupling [16], which would transformed into the approximately continuous and smooth bandwidth (except for the switch sections that offer discontinuities associating to a given time to set and lock the switch.) to form the virtual block (or no sections at all[21]) wrapping around the time-distance diagram of trains when crossing the elementary resources of the railway network, i.e., the blocking time bandwidth, and the block sections exist no longer [9]. Thus, the basic concept of blocking time requires to be modified from a section to a dimensionless point of the infrastructure, which can be called as location [9]. The way how to divide the railway network into pieces of elementary resources under virtual coupling can be in the same manner as for the conditions under fixed blocking system and ERTMS/ETCS Level 3 [22] according to UIC Code 406. Meanwhile, the blocking time components for virtual coupling have to be adapted accordingly. Based on the analysis of [9], under virtual coupling, the occupation time of the train unit on the portion of the infrastructure depends on the associated location. For the infrastructure resource locations associated to level crossings and switches, or interlocking areas[23], the formula (1) for computing the blocking time for fixed blocking signalling is still suitable for virtual coupling. For the plain track locations, the blocking time T_{bl-vc} of train l for a virtual block under virtual coupling can be expressed as formula (4), whereas the blocking times have a zero-setup time(setup time does not apply to non-movable portions of plain track) and a null running time (the running time for a location with an infinitesimal length is zero). Moreover, virtually-coupled trains have to adapt their speed profile, together with their time-distance path, to that of the train ahead in a convoy. Hence, before blocking times can be calculated under virtual coupling, a joint calculation of time-distance train paths(trajectory) within convoys is entailed [14].

$$T_{bl-vc} = t_{sr} + t_{coap} + t_c + t_{rel} \tag{4}$$

where:

t_{sr} denotes the time for the ATO (Automatic Train Operation) system to response to the instructions offered by the on-board computer.

t_{coap} denotes the coordinate approaching time, which consist of two terms, i.e., the coordination time, and the safety margin crossing time.

t_c denotes the clearing time.

t_{rel} denotes the release time, which is the communication delay for the RBC to acknowledge that the location has been cleared by the train.

3. Formal Basic Definition of Virtual Coupling

Analogous to what has been described for moving blocking system [24], let f be a train following/succeeding its leader/predecessor counterpart train l running on the same track. For a position p on the track, we denote t_p^f the time when f passes p, analogously for l. Additionally, let $x(f,p)$ denote the position where f comes to slow down from its current speed to the one of the leading/predecessor train when performing a relative braking at p. Then the virtual coupling block condition is that for any position p holds as formula (5).

$$t_p^f > t_{x(f,p)}^l \tag{5}$$

Note that $x(f,p)$ might depend on several parameters, most notably the current speed, but also track gradients and train-specific braking parameters. Moreover, this fundamental model disregards the train lengths and further safety margins such as, e.g., the time required for detecting and communicating train positions. These time supplements can be either integrated into $x(f,p)$ or added to $t_{x(f,p)}^l$, but we will stick to the above fundamental definition for the sake of simplicity. Stipulating (5) for any point of a train trajectory is the formal description of operating trains in a virtual coupling system with relative braking distance.

Both in fixed-block signaling and moving-block signaling, the overlapping blocking times will incur conflicts of train paths. However, if two trains are virtually coupled and operate at a relative braking distance on the plain track section, the overlapping blocking times are allowed which are not conflicts [14], i.e., relative braking distance allows for overlap between the follower train and its predecessor. This is due to the principle of relative braking, i.e., a track/resource will already be claimed by a train when its predecessor is still occupying it under virtual coupling. Meanwhile, the absolute braking distance between trains is still required for diverging movements at switches so as to guarantee the safety in the event that the switch fails to be locked.

4. Headway Policy

The application of blocking time theory on headway modelling requires a microscopic level of infrastructure representation. As illustrated by [21], the infrastructure modelling options for EoA(End of Authority) and IP(brake Indication Point) for maximum/scheduled speed can be either discrete(e.g., equidistant discretization into train length) or continuous (considering the dynamic set of the point EoA and IP) under virtual coupling. Based on the blocking time stairway, by shifting two adjacent trains blocks blocking sequence until they touch in the graph, the minimum headway time can be determined using the blocking time sequence, i.e., the blocking time is as close possible without overlapping in the fixed blocking system. The minimum line headway time is defined as the gap from the beginning of the first train's blocking time to the beginning of the second train's blocking time in the first block section as the case under fixed blocking signalling. A max-plus matrix has been used to represent the blocking time stairway under fixed blocking system for capacity assessment [20]. The representation method of max-plus matrix can give the gap between the end of the blocking time on one resource and the beginning of the blocking time on another resource (if both used by the train).

Usually the minimum headway between two adjacent trains is determined by the deployed signalling system. Under virtual coupling, the dynamic timing point of the following train can be considered as the EoA (End of Authority), and brake indication point (IP), whereas EoA refers to the position behind the tail of its preceding train plus a safety margin, and IP refers to the position where an approaching/following train gets the indication to start braking to stop at EoA (usually IP depends on the scheduled speed alternative of the approaching train and the preceding train under virtual coupling). The headway is associated with the IP and EoA depending on the braking dynamics. In virtual coupling signalling systems, minimum headways are on the basis of relative braking distances. The necessary headway time/distance can be explained as the time/distance between the controlled train and its preceding train. When trains with homogeneous braking rates running in the platoon state, the minimum headway distance within the virtually coupled train convoy is the safety margin, due to the consensus velocity and relative braking distance of the train unit. As the headway can be expressed in the units of space and/or time [25], there exist two alternative categories of headway policies for trains under virtual coupling[26-27], i.e., the constant time gap, and the spacing gap between the adjacent trains. As the tracking distance between trains in a virtually coupled train set with the relative braking distance is quite a significant content, the latter one (i.e., the spacing gap policy) is strongly recommended [28], so as to guarantee the necessary spacing between trains for safety and improve the throughput for capacity.

In the graphical timetable (time-distance diagram), the virtually coupled train convoy are displayed as a single train path from the converging point. When reaching the diverging point, the uncoupled trains are separated as individual train path. For successive trains in the virtually coupled train convoy [29], the minimum train separation $\triangle x_{k+1}^{vc}(t)$ (i.e., the relative braking distance plus the safety margin) can be defined as formula (6).

$$\triangle x_{k+1}^{vc}(t) = \left(\frac{(v_{k+1}(t))^2}{2b_{k+1}^{\max}} - \frac{(v_k(t))^2}{2b_k^{\max}}\right) + SM \tag{6}$$

where:

$v_{k+1}(t)$ denotes the velocity of the following train $k+1$.

$v_k(t)$ denotes the velocity of the preceding train k.

$b_{k+1}^{\max}$ denotes the maximum braking rate of the following train $k+1$.

$b_k^{\max}$ denotes the maximum braking rate of the preceding train k.

SM denotes the safety margin between the tail of the preceding train and the point of EoA (End of Authority).

5. Include the Extended Blocking Time Theory in Conflict Detection and Resolution During the Coupling Process

The main features for the modelling of railway traffic under virtual coupling signaling is the minimum train headway based on relative braking distance. Using blocking time theory to determine the headways is one of the alternatives, and all blocking time components should be included by the minimum headways in order to model both physical conflicts and signaling conflicts. Once the infrastructure modelling and speed modelling under virtual coupling have been determined [21], the blocking time stairways in terms of max-plus algebra [7], the minimum headway time computation, the procedure algorithms for conflict detection, and the procedure algorithms for the conflict resolution [30] can be considered to be adapted and extended according to the cases in the fixed-blocking signaling for virtual coupling system with relative braking distance.

Based on the conflict detection and resolution (CDR) model presented in [31], [32] proposed the extended alternative graph with virtual nodes, associated fixed arcs, and pairs of alternative arcs for the development of the moving block CDR model. Particularly, by discretizing the line into the train length, the virtual nodes are obtained from the corresponding discrete grid points in the literature [32]. And the weights of the fixed arcs (connecting the virtual nodes) is equivalent to the time it takes the train to traverse its length when operating at maximum speed, i.e., the minimum train clearing time. This extension of the alternative graph can be considered to transfer to the development of the virtual coupling CDR model.

Considering the pros and cons in terms of the trade-off between solution quality and computational efficiency, [21] performed a systematic comparative analysis modelling approaches for moving-block CDR, including Alternative graph(AG), Disjunctive MILP(Mixed Integer Linear Programming), Time-indexed MILP, and Dynamic system, with various combination of infrastructure modelling options and speed modelling options, i.e., discrete infrastructure and discrete speed, discrete infrastructure and continuous speed, continuous infrastructure and discrete speed, and continuous infrastructure and continuous speed. Among these, the modelling approach of dynamic system[33] is recommended to be applied to timetabling with relative braking distance under virtual coupling, over the proposed modelling options of continuous infrastructure and continuous speed.

6. Conclusion

Blocking time theory/model lays the foundation for scheduling train path over the given infrastructure and train speed. With regards to the level of extension considered in blocking time theory for virtual coupling, three approaches can be recognized and distinguished, i.e., microscopic, mesoscopic, and macroscopic. By focusing on the microscopic models for calculating the precise track blocking times, the stability and feasibility of railway schedules/timetables can be guaranteed from the operation point of view. Considering the UIC Code 406 compression method, under fixed blocking system, the first and critical step of the UIC Code 406 capacity evaluation is the division of railway line and station area into sections by block signals. And the segmentation of infrastructure has to be positioned at each point of changing number of trains, where significant traffic operation or timetable differences occur. In contrast, under virtual coupling system, it is unnecessary to physically divide the infrastructure into sections (except the interlocking area), when adopting UIC Code 406 for capacity estimation, more focus should be put on dynamic timing points (e.g., EoA, and IP) under virtual coupling, due to the virtual block and self-organization nature of the train-centered virtual coupling signaling system. Macroscopic traffic state refers to the collective behavior of trains in terms of speed, density, and flow, and is typically represented by their trajectories and macroscopic fundamental diagram, regardless of the accurate car following behavior. The interest attracted in fundamental diagrams for rail traffic have been only lately increased. Emerging signaling systems with virtual coupling and very short train separations (relative braking distance) are natural applications for macroscopic traffic flow theory, e.g., macroscopic fundamental diagram for railways. From the mesoscopic perspective, the coupling and uncoupling procedure among the virtual coupling enabled train convoy is approximate to the Brownian motion to a certain extent. Due to its complexity, the blocking time model is hard to be applied manually in practice. For the establishment of the conflict-free train paths, the computer-generated blocking time stairways are usually embodied in the associated timetabling systems. From this perspective, the digitalization of the railway infrastructure is indispensable. And the collection of train running trajectories in various operational scenarios can be leveraged/ facilitated to assess the associated blocking time distributions.

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