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- An analytical-based methodology that computes the optimal length of block sections on ETCS L2 railway networks has been proposed.
- Starting from track layout, rolling stock information and headway scenario, and knowing the trains' features, an easy backward calculation defines the first signalling equipment position.
- The application to the main passenger and freight lines in Danish Fjernbane Infrastructure East area shows the significance of the proposed methodology.

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Abstract

This paper presents an analytical-based methodology that computes the optimal length of block sections and the marker boards' location following headway requirements, with the lowest amount of signalling equipment, for an ETCS L2 railway networks.

It is applied to the Danish Fjernbane Infrastructure East project, which aims at replacing the existing signalling system with a new one based on ETCS Level 2. Starting from track layout, rolling stock information and headway scenario, and knowing the trains features, an easy backward calculation, using OpenTrack tool, defines the first signalling equipment position (i.e. Marker Boards, Axle Counter) to fulfil the headway requirements.

The application to the main passenger and freight lines in Danish Fjernbane Infrastructure East area shows the significance of the proposed methodology able to define a robust signalling configuration which also provides a satisfying trade-off between total cost and railway operational performance.

Keywords:

Railway capacity; headway; simulation tool; signalling layout; railway network; ETCS Level 2; OpenTrack.

1. Introduction

Nowadays many railway lines are characterised by punctuality lacks due primarily to the clearly growing demand in railway transportation that invests most of European countries. Punctuality and time keeping of schedule are important both on operational and passenger side (Nagy and Csiszár, 2015; Sørensen et al., 2017).

The existing railway infrastructure, often, isn't used in an efficient way; so, for a high-quality transportation system, an optimization of its use is one of the principal aims for regional and national authorities, and for the owners of the infrastructure.

Efficiency depends on multiple factors such as track layouts, rolling stock performance, signalling systems, etc. Upgrading the existing signalling system is one of the best and cost-effective solutions both to increase capacity and to standardize the signalling system with ERTMS/ETCS standard, which aims to ensure railway interoperability throughout Europe.

Since all European Union member states must submit to European Commission a national implementation plan towards ERTMS/ETCS standard (European Commission, 2017), one of the crucial elements is to study adequate signalling design solutions, to solve the problem of identifying the position of signals and length of block sections that satisfy technical specifications and headway requirements and/or train energy consumption.

Designing the signalling layout is a complicated problem with different objectives and constraints. The main objectives are safety, high efficiency and low cost. A signalling system needs to be able to prevent train collisions, to achieve a certain line capacity with given headway and to have low installation and management costs (Baohau et al., 2006).

In scientific literature many design processes of railway signalling layout have been developed. They are mainly addressed to identify the design solution of the signalling system minimizing line headway (i.e. maximize network capacity) and/or train energy consumption (Hansen and Pachl, 2014). In this way the number of blocks increases as the investment costs for their installation. Another drawback is that candidate signalling layouts are evaluated disregarding the factors that are mainly responsible for degrading the capacity, the punctuality and the energy efficiency of the system, i.e.: the stochastic disturbances to operations and the interactions among trains on the network. The performances relative to each design solution are indeed assessed by considering that only a single train runs on the network (without the presence of other trains) in undisturbed conditions (i.e. no random perturbations) (Quaglietta, 2014).

To this purpose, this paper presents an analytical-based methodology for the design of railway signalling layout, which aims at identifying the length of block sections starting from contractual headway requirements. It can be used for every signalling layout design process with ERTMS standards, with reference to ETCS Level 2, with the same initial inputs required (headway, layout topology, train's characteristics). It is based on Blocking Time Model, developed for ETCS Level 2.

Starting from track layout, rolling stock information and headway scenario, and knowing the trains features, an easy backward calculation, using OpenTrack tool, defines the first signalling equipment position (i.e. Marker Boards, Axle Counter) to fulfil the headway requirements. These outputs are afterwards used by Signalling Engineer to find the correct position of Stop locations considering also signalling engineering rules and operational requirements and constraints. Every Stop location is placed only if it's necessary to achieve a headway requirement or to respect engineering rules; implicitly minimizing the cost. Every scenario (i.e. two consecutive trains) has been generalized and represents a real track on the planned timetable, for the specific case of study.

The proposed methodology is relatively simple and has a short computing time; it can be appreciated simply in a planning evaluation or in a dimensional set of possible traffic scenarios. The point of view of the proposed method is the one of the railway infrastructure managers that are interested in knowing how the capacity of the network changes starting from headway scenarios. This is a very frequent task since different transport service operators can request new train services in the same infrastructure. Therefore, further time slot windows should be allocated to new train operation; but before this operation is carried out, a check could help by speeding up decisions.

The main contributions that this document intends to give are:

- providing a summary of the existing research on optimal design of signalling systems;
- facilitating the early design of railway signalling layout with ERTMS standards, providing a tool which rapidly evaluates the first signalling equipment position in terms of Marker Boards and Axle Counter, able to fulfil the contractual headway requirements and respect engineering rules, minimizing costs;
- addressing the design of railway signalling layout to a different objective that is no more to get the maximum capacity possible for a given signalling system, but to match the infrastructure manager performance requirements in terms of contractual headways;
- overcoming the limits of the approaches proposed so far in literature, by developing an analytical-based methodology that is based on an operational tool, easy to use, which does not need complicated simulations;
- demonstrating the benefit brought from the implementation of the tool applied on a case study simulation of an upgrade of the main lines in Fjernbane Infrastructure East area (Denmark).

The document is organized as follows: Section 2 gives a review on scientific approaches proposed in literature for the optimal design of signalling systems. Section 3 depicts the backward calculation based on blocking time model and input data. In section 4 the application to the main passenger and freight lines in Fjernbane Infrastructure East area (Denmark) is illustrated. Conclusions and final comments are reported in Section 5.

2. Literature review

Different approaches are proposed in literature for the optimal design of signalling system.

Gill and Goodman (1992) have developed one of the first computer-based method to design a signalling layout, able to minimize the headway in metro lines. It is characterized by the same length of the block sections within stations. The algorithm firstly chooses speeds and positions of block joints which minimize the train break distance, and then adjusts them in order to economize on track circuiting.

Chang and Du (1998, 1999) have divided a railway line between two stations in three types of sections namely “constraint”, “stretchable” and “critical” section. Each one is prescribed with different headway design criterion. They have adopted different objective functions for each section, resolved separately by a genetic algorithm, to optimize the layout of block joints and their position depending on the train breaking distance or on the number of block sections to save on track circuiting costs.

Ke and Chen (2005) have proposed an approach for the design of fixed-block signalling system of mass rapid transit systems, by optimizing the block layout and running speed code of each signalling block between any two neighbouring stations. Considering the effect of gradients and the limits of minimum headway of an Automatic Train Operation system and average train speed, a genetic algorithm is applied to determine the shortest length, speed codes and positions of signalling blocks. The heuristic search is realized to find the speed codes combination which minimizes the energy consumption for each signalling block.

The concept of “optimal signalling layout” is often linked to the problem of minimizing also the energy consumption, identifying energy - optimal speed codes according to minimize the line headway.

Ke et al. (2011, 2009) have defined a method of block-layout design between successive stations for mass rapid transit systems able to minimize both energy consumption and headway. Differently from past research regarding the energy savings of train operation, the authors have proposed a combinatorial optimization model to reduce the computation time.

Harrod (2009) has evaluated fifty-four combinations of track network and speed differential within a linear, discrete time network model that minimized energy consumption and maximized an objective function of train volume, delays and idle train time.

Weik et al. (2016) have discussed a model for the capacity analysis of railway line relying on single channel queueing systems. By identifying knock-on delays (delay propagation) with waiting times, delays can be estimated using methods from stochastics and queueing theory. Mean knock-on delays are used as a quality-dependent indicator of capacity, allowing to determine the admissible number of trains for a prescribed level of service minimizing energy consumption.

Dunbar et al. (2017) have presented the development of a rapid railway simulation tool, designed to aid decision making at the conceptual stage of planning signalling upgrades. The railway simulation tool features a train simulator based on Brute Force Algorithm, which is capable of evaluating the capacity and the energy consumption of a section of track under European signalling standard.

These proposed approaches tended to minimize the length of block sections for reducing headway, but this is the major deficiency because, while the number of blocks increase, the installation costs increase (Grimes and Barkan, 2006). The performances relative to each design solution were also evaluated by considering a single train running on the network (without the presence of other trains) in undisturbed conditions.

In order to overpass these limits, Goverde et al. (2013) have proposed a new concept of dynamic infrastructure occupation to assess infrastructure capacity under disturbed conditions as a complement to the established capacity indicator of scheduled infrastructure occupation. This new indicator was applied in a capacity assessment study of a Dutch railway corridor with different signalling configurations under both scheduled and disturbed traffic conditions. For the analysis they have used the train dispatching system ROMA that combined the alternative graph formulation of train rescheduling with blocking time modelling of signalling constraints. The results have showed that the scheduled infrastructure occupation with ETCS Level 2 significantly improved.

Similarly Dicembre and Ricci (2011) have proposed a methodology for signalling layout design process which can be used like guideline to every design of signalling layout with Automatic Train Protection (ATP) system conforms to the specifications of the European Rail Traffic Management System (ERTMS), under disturbed conditions. Railway system’s performances were linked to timetable planning criteria, i.e. to the definition of appropriated recovery times and buffer times, which influenced the definition of available capacity.

Also Quaglietta (2014) have presented a new design approach addressed to identify the signalling layout which minimized the investment and management costs, respecting the required level of capacity. To solve this problem an innovative design framework was introduced which integrates a stochastic multi-train simulation model within a ‘‘black-box’’ optimization loop. Results obtained from an application to a real metro line confirmed the effectiveness of the method in finding the solution which minimizes total costs for the line manager.

The proposed research works highlighted that is important the use of advanced approaches able to represent the real behaviour of trains under conditions of real-time or ATC systems (i.e. ETCS level 2), avoiding undisturbed traffic conditions with only a single train running on the network, that can compromise the real behaviour of train running in real operational conditions.

In this context the analytical-based methodology proposed in this paper computes the length of block sections for each real circulation scenario, as consequence of signalling layout and starting from contractual headway requirements, through a simulation with OpenTrack tool.

3. The proposed methodology

3.1 The Blocking Time Model

The proposed methodology computes the optimal length of block sections and the marker boards’ location following headway requirements, with the lowest amount of signalling equipment.

It is based on Blocking Time Model, described for the first time by Potthoff Gerhart (1980), that is here developed for ETCS Level 2, which is a radio-based train control system in which movement authority is generated from trackside and transmitted via Radio Block Centre to the train and Eurobalises are used as spot transmission devices mainly for location referencing (UIC 406, 2013). While in a conventional signalling system the approaching time is determined by the position of sighting point ahead of distant signal (Figure 1), in ETCS Level 2 approaching time depends on the location of the Indication Point (IP) by Indication curve (Figure 2) (UIC, 2010). For a conventional signalling system, the position of the sighting point is not necessarily identical to the point at which braking is initiated, because the sighting point is located up ahead of the initiate braking point for safety reasons. In ETCS system Level 2, instead, the approaching time depend on IP that isn't a "fixed point" as it is related to the braking distance (Indication curve) which depends on train braking characteristics, line speed and rolling stock's features.

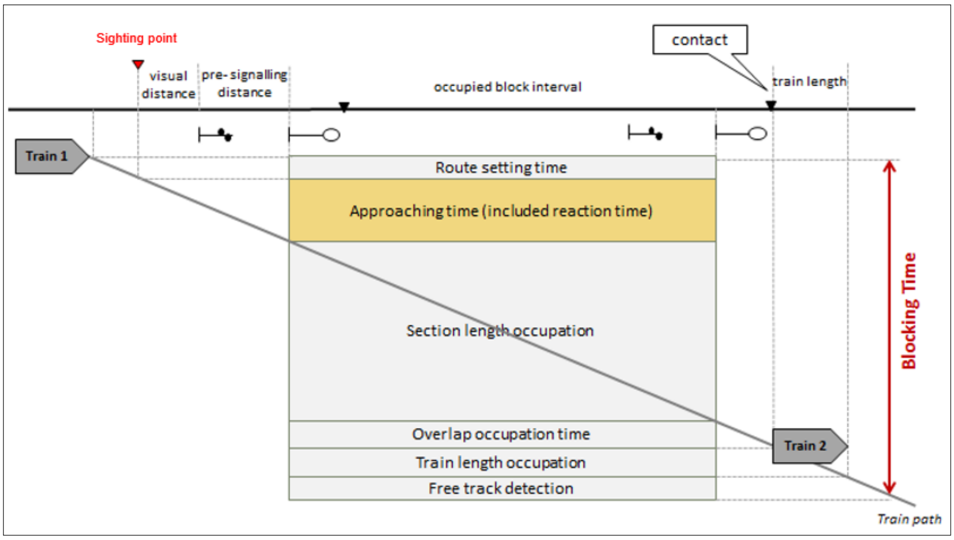


Figure 1: Blocking time model components in case of conventional signalling system

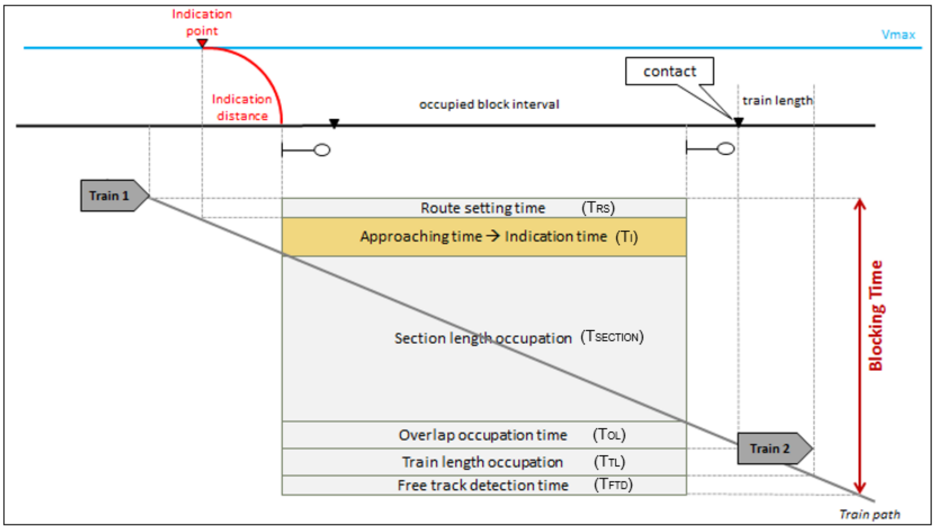


Figure 2: Blocking time model components in case of ETCS Level 2

Comparing the figures 1 and 2, it's clear that the Blocking Time, i.e. the time during which one block section is reserved exclusively for a train and is not available to other trains, in case of conventional signalling system is longer than in case of ETCS Level 2, due to the longer approaching time.

For ETCS Level 2 the blocking time for a running train consists of the following parts (Figure 2, refer to Train 1):

- Route setting time (T_{RS}): that is the sum of Traffic Management System (TMS) command time, time of implementation of the route by IXL (Interlocking) and time of elaboration because dispatch of MA by RBC includes transmission delay (s). Route setting shall occur before the train reaches the Indication Point related to the EoA at the beginning of block section;
- Indication time (T_I) that is the time to travel the Indication braking distance (i.e. from the Indication Point to the stopping point at the beginning of block section) (s);
- Section length occupation ($T_{SECTION}$) that is the time to travel the block section (s);
- Overlap occupation (T_{OL}) that is the time to travel the overlap length at the end of block section (s);
- Train length occupation (T_{TL}) that is the time to travel the train length (s);
- Free track detection (T_{FTD}) that is the time to detect the track free within the block section (s).

The minimum headway is the minimum distance allowed between two consecutive trains with specified speed profiles and, comprising the blocking time sequences, is defined by Blocking Time Model in the critical section with hindrance free train running (i.e. usually the longest section of the others, or the section corresponding at the train stop because there is, also, the dwell time).

The block section length ($L_{SECTION}$) derives from the section occupation time ($T_{SECTION}$), calculated subtracting from the headway technical value (T_H) all the other Blocking Time components according to the following equations:

$$L_{SECTION} = T_{SECTION} \cdot V_{MAX} \tag{1}$$

$$T_{SECTION} = T_H - T_{RS} - T_I - T_{OL} - T_{TL} - T_{FTD} = T_H - T_{RS} - \left(\frac{D_I}{V_{MAX}}\right) - \left(\frac{D_{OL}}{V_{MAX}}\right) - \left(\frac{D_{TL}}{V_{MAX}}\right) - T_{FTD} \tag{2}$$

where D_I, D_{OL} and D_{TL} are respectively the Indication distance, the Overlap length and train length (m).

3.2 Design Phase: The backward calculation

The proposed signalling layout design process follows the backward calculations illustrated in Figure 3.

The basic concept of the backward calculation is the definition of block section length as a time in which the headway requirement defines the maximum occupation time.

Starting from few input data (rolling stock, operational plan and infrastructure), according to infrastructure operational and performance requirements (headway), the signalling layout is submitted to the headway assessment using OpenTrack tool, which uses UIC method to compute trains movements. If the signalling layout fulfils each headway scenarios, it is considered a candidate final solution; otherwise it is re-designed based on Blocking Time Model and the headway assessment is carried out again up to the achievement of all headway scenarios required. When the signalling layout is assessed in OpenTrack tool, also the engineering and operational rules shall be considered, since they block the signal position with respect to safety and/or constraints by the owner of each railways infrastructure. For example, engineering rule define that the exit Markers Board in a station, must be placed at certain distance from the edge of platform in both directions (e.g. 80 meters or 0 meters), as shown in Figure 4. Also, all the elements must be renamed with a specific form like <object type>-<station abbreviation>-< serial number > (e.g. Mrk-Lu-331), according to the operational rules.

The users enter input information (rolling stock, infrastructure, signalling system response time, headway scenario) into different modules and then start the signalling sections length calculation; the output is a list of Axle counter and Marker Boards kilometric position.

The first design of block sections length based on backward calculation using Blocking Time Model is carried out by a tool (Dimola et al., 2016, 2017). Starting from a reduced set of input data, it defines the cinematic profile of both trains that are linked by the headway value along the track topology. According to instantaneous speed along the line, the Indication Time is calculated at each instant and consequently the theoretical second train position is defined. The output contains the signals positions along the track layout based on the Blocking Time Model, then it is able to calculate the signalling sections length. Along the line, various headway requirements must be fulfilled because different sequences of train (i.e. different train's categories or different train's path) can circulate at the same time; this tool can help to identify the worst headway case on specific track layout, because the sections length are the tool output and the worst case needs the shortest length of block sections to respect the requirements.

The headway achievable, for every track layout, is strictly dependant on input data which therefore influence railway capacity; it's important to define these inputs clearly and on a general level so they can become the "defined step" necessary for the signalling design process.

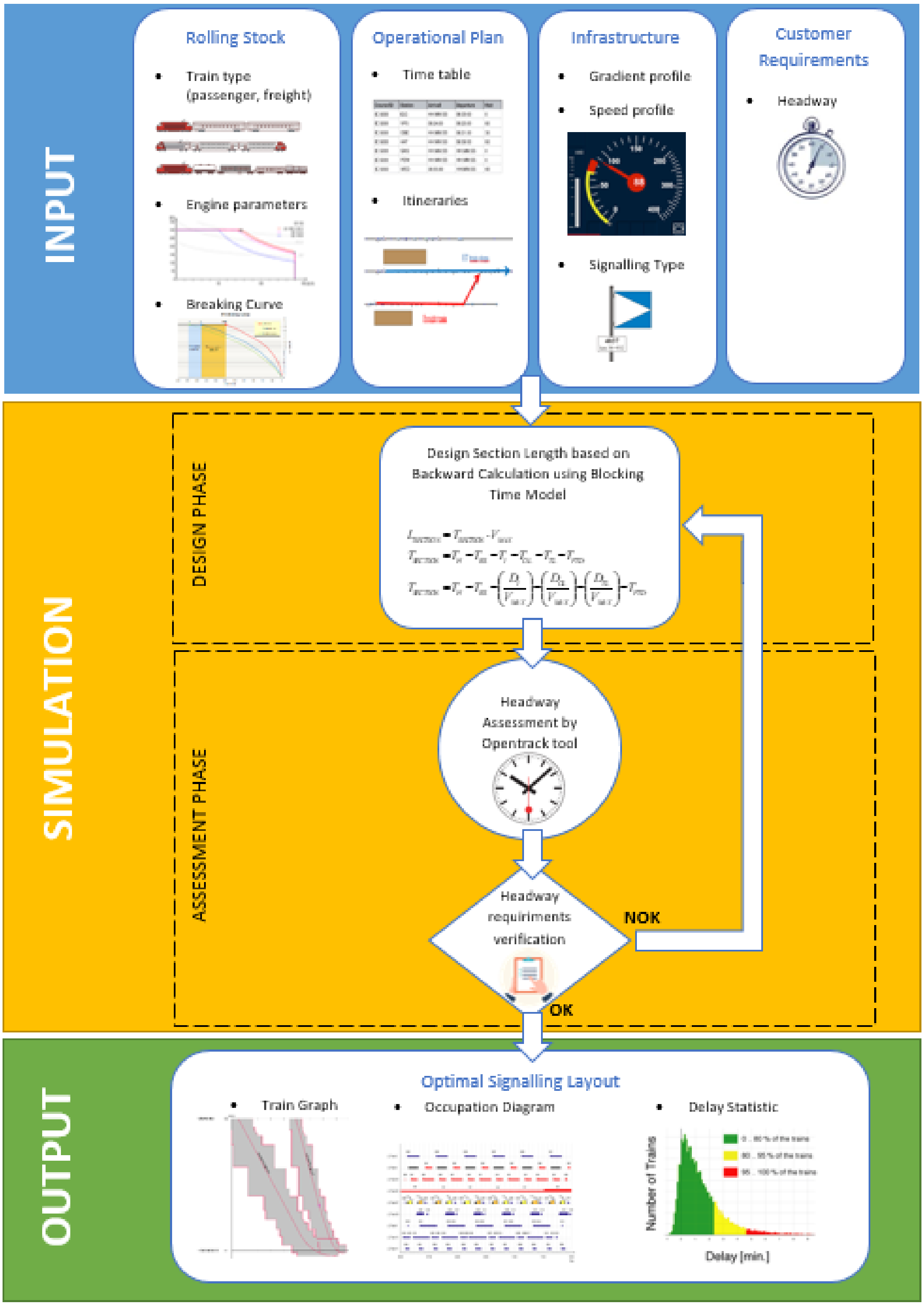


Figure 3: Flow chart of the proposed signalling layout design process

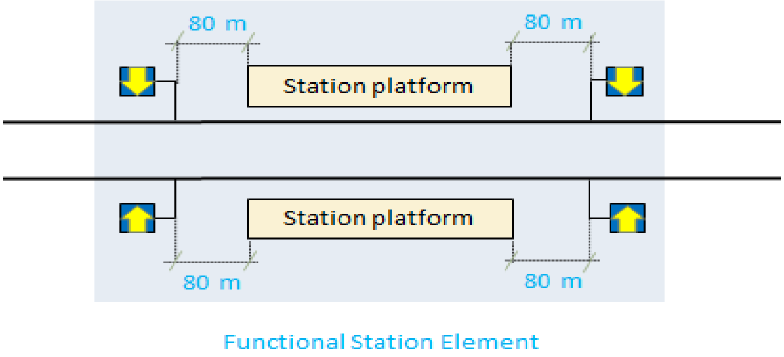


Figure 4: Example of engineer and/or operational requirements

3.3 The input data

The input data of the proposed signalling layout design process, requested by the infrastructure manager, are: headway requirements, track layout features, trains features and the signalling system configuration.

Combined Headway requirements

The required headway defines the time between two consecutive train runs, so that the second train is not slowed down due to the presence of the first train ahead. This concept is, however, strictly dependant both on the position where the headway is requested and on the features of the two trains. For this reason, elementary circulation scenario (i.e. only two trains) have been defined. Every elementary scenario can be used in all cases of study regardless of specific operation conditions (e.g. rolling stock, traffic topology, service model).

Case A: continuous headway requirement in line, same train graph.

In “Case A” the two trains have the same characteristics (e.g. length, mass, breaking features), speed and service trains patterns. So, the headway time is the same time interval between two consecutive fronts of the two trains that don’t obstruct each other. Using the Blocking Time definition, the headway time is evaluated from the beginning of the first train’s blocking time to the beginning of the second train’s blocking time. The headway time shall be fulfilled along the entire line (Figure 5, Case A).

Case B: continuous headway requirement in line, different train graph.

In “Case B” the two trains have different service patterns (i.e. stopping train and non-stopping train). The headway is related along the entire line, in particular:

- “Case B at start”: a stopping train follows a non-stopping train, the headway increases along the line, so the minimum headway is applicable at departure station (Station 1). The specific point, where it’s measured, is following passenger platforms at depart station. The headway value is detected on the splitting point; progressively the derived headway is obtained along the line (Figure 5, Case B at start);

- “Case B at end”: a non-stopping train follows a stopping train, the headway decreases along the line, so it’s applicable at destination station (Station 2), generally preceding passenger platforms on the splitting point (Figure 5, Case B at end).

Case C: headway at the splitting point.

In “Case C” the couple of train is composed by freight and through train and the headway is applicable at the splitting point. The train’s features are completely different so is important to define the correct sequence:

- “Case C at end”: freight train followed by through train, freight train is caught up by a through train in front of passing loop (Figure 5, Case C at end);
- “Case C at start”: through train followed by freight train, the trains depart from different tracks, so the minimum headway value is applicable at splitting point at the start station. The feasible headway is constrained by the section length at the splitting point (Figure 5, Case C at start).

Case D: continuous headway requirement in line, same train graph

The “Case D” is similar to “Case A” but both trains stop at the same platform with the same dwell time and then the headway shall remain unchanged along the entire line section if the two trains has got the same characteristics. The dwell time shall be bound to maximum dwell time to prevent station bottleneck section (Figure 5, Case D).

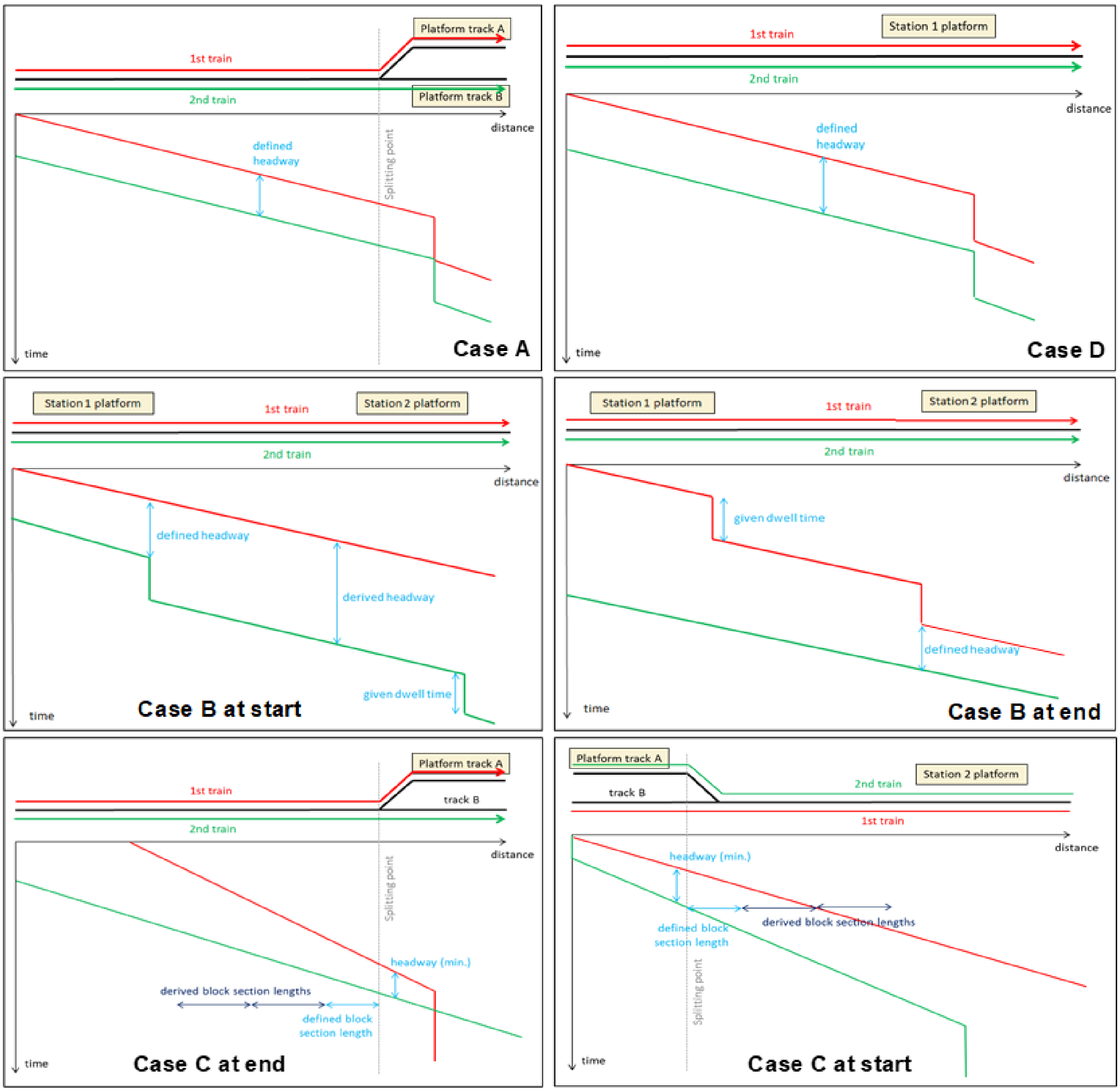


Figure 5: Headway in the elementary circulation scenario object of study

Along the typical railway line, different headway values are required. Therefore, different train sequences and different train category must be taken into account to define the block section lengths along the line. The section length at a given location on the line is defined by the worst-case headway requirement (minimumheadway) at that location. The search of worst-case headway requirement, between the multiple headway requirements defined for the same location, shall be done manually by the user (i.e. the worst case is to be identified by experience of Signalling Engineering or by Backward calculation tool). Usually, the minimum headway is defined between the following overlapping headway requirements:

- the continuous headway requirement in line (two trains with the same speed);
- the headway requirements at the splitting point (start of separated track);
- the continuous headway requirement between trains with different service patterns;
- the continuous headway requirements, two following trains at lower speed than the line speed.

Track layout features

Track features define the railway structure and the position of equipment along the line. They are: line length; functional splitting element length; infrastructural constraint; stopping point location; deviation speed on splitting points; maximum speed profile of the line; overlap length.

The maximum speed profile of the line and the deviation speed are necessary because train's speed constraints the minimum headway and thus the capacity of network; the maximum speed depends on the track layout while the deviation speed depends on the switch point geometry. The gradient (based on ATC Diagram gradient profile) and curve radius are considered.

Trains Features

The headway is dependent on the trains' features: braking capabilities (i.e. train deceleration), acceleration, length and maximum speed.

For each train following characteristics are taken into account (Figure 6):

- Emergency Braking Curve (EBD) deceleration values, calculated based on the trains EB deceleration profile;
- Permitted Braking Curve (P), calculated applying a time deceleration delay to the EBD (adding the EB build-up time and the service brake (SB) built-up time and the driver's reaction time);
- Indication Braking Curve (I), calculated applying and additional delay between the P and I curves (depends on the service brace build-up time of the train.

The EBD curve is related to the speed decrease due to emergency brake and depends on both train (e.g. braking percentages) and track characteristics (e.g. overlap behind the Marker Board). For each specific target location (i.e. speed reduction or stop location) ETCS on-board computers calculates a fully deterministic EBD curve and other two supervision limits: Indication (I) and Permitted (P) which are locations that, when crossed by the train, will trigger some information to be given to the driver through appropriate graphics, colours and sounds on the Driver Machine interface (DMI).

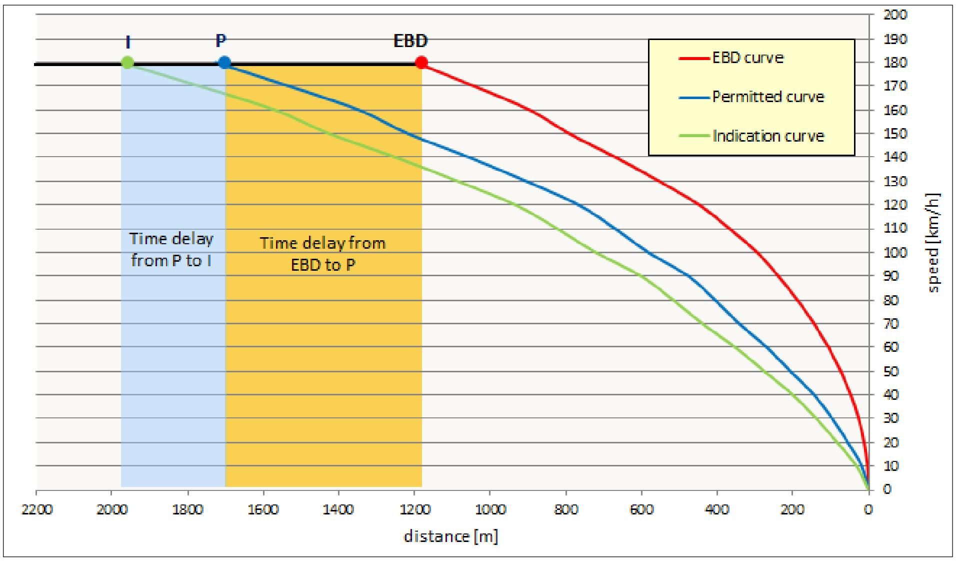


Figure 6: ETCS Braking Curves

Signalling system configuration

In addition to the infrastructure elements, interlocking routes (i.e. from one Marker Board to a following Marker Board) are needed to model trains run. Each route, according to Blocking Time Model, is characterized by a route setting time (reserve time) and route release time (free track detection).

4. Application of the proposed methodology to a case study

4.1 Case study description

The proposed approach has been applied to the main passenger and freight lines in Fjernbane Infrastructure East area (Denmark).

The current signalling systems has overrun its technical service life, causing an increase in errors and delays for passengers and a general decrease in the train traffic service level.

So Banedanmark, the Danish infrastructure manager, has committed to an ambitious and radical upgrade of its signalling system by totally replacing it with a new system based on ERTMS Level 2.

The railway lines in Fjernbane Infrastructure East areas are subdivided in Roll Out (from R1 to R11) and for each one general and detailed headway requirement have been defined (Figure 7).

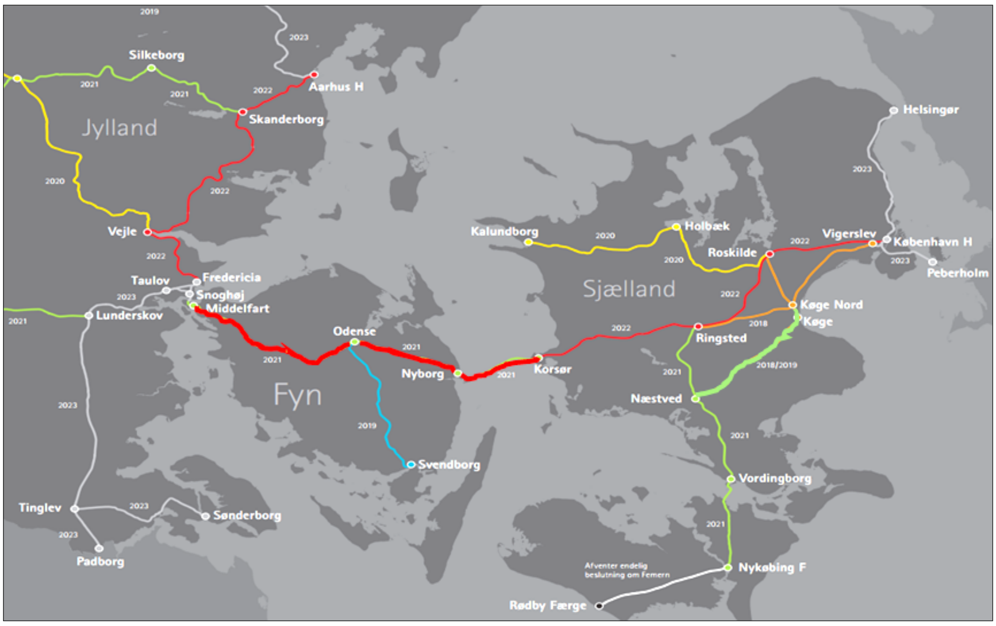


Figure 7: The lines for Fjernbane Infrastructure East (Banebranchen, 2016)

The case of study is the signalling design process in Roll Out 7, which is part of the renovation project Ringsted – Rødby Færge, and it includes double track up to Nykøbing Falster and single track from Nykøbing Falster to Rødby Færge (in green in Figure 7).

There are two different kind of trains, from headway requirement point of view, that run on Roll Out 7: Freight Train (EG) and Passenger Train (ET).

The EG Freight Train is composed by EG loco (length of 21 m), plus trailers for a total length of 1000 m (Figure 7). The maximum acceleration at start is 0.22 m/s^2 (Banedanmark, 2014). The EG (1000 m) ETCS braking curves, dependant on the length, is showed in Figure 8.

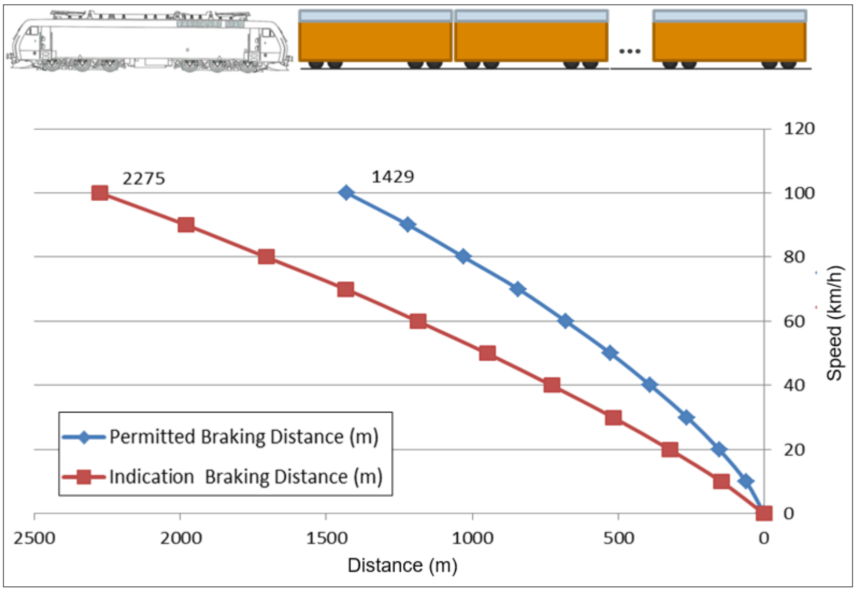


Figure 8: Freight train (EG loco plus trailers) and EG (1000 meters) ETCS braking curves

The ET passenger train is a theoretical train having the maximum allowed length of passenger trains, with dynamic characteristics of one multiple unit (Figure 9) (Banedanmark, 2014). It is composed by five trainsets of 70 m, for a total length of 350 m. The maximum acceleration at start is 0.78 m/s^2. The ET (1000 m) ETCS braking curves, dependant on the length, are showed in Figure 9.

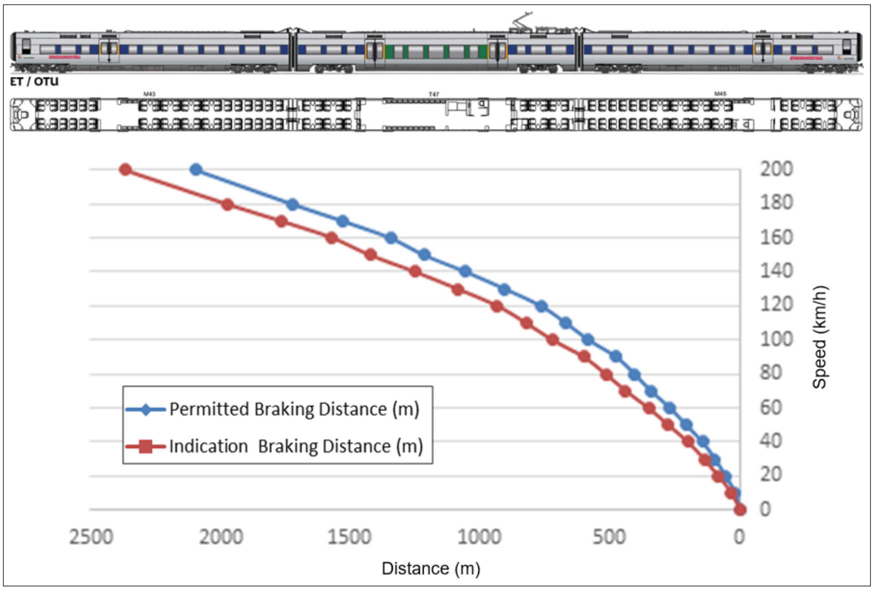


Figure 9: Passenger train (ET) and ET (1000 meters) ETCS braking curves

Figure 10 shows the line overview. The capacity simulation has been carried out from Lundby to Nykøbing Falster, considering the new Storstrøm double track fixed bridge. The capacity scenarios are not applied from Nykøbing Falster to Rødby Faerge because of the single track line.

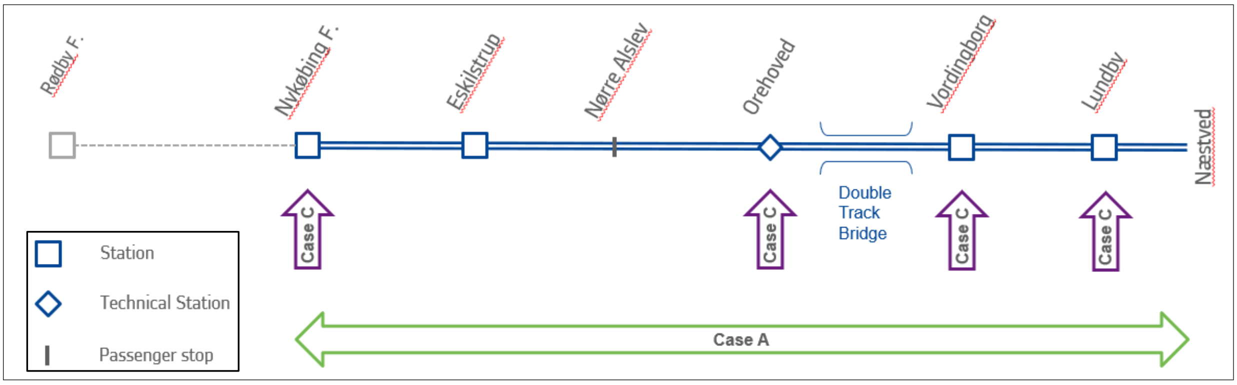


Figure 10: Line graphic overview

The main defined capacity scenario is “Case A” (ET no stop train followed by another ET no stop train) at the maximum allowed speed (200 km/h) (requirement); this scenario defines the maximum signalling section’s length in main line; however, the sections are designed also to avoid perturbations for the arrival/departure case C scenarios.

The signalling section's length are shorter close to the splitting point of Lundby, Vordingborg, Orehoved and Nykøbing Falster to reach the minimum headway for "Case C", where EG freight trains (1000 m length) take the overtaking track followed by the ET passenger train (Dimola et al., 2017).

In accordance with Banedanmark, the maximum value of the operational headway (defined as the sum of the technical headway, which is the required headway, plus a tolerance of 15 seconds) is evaluated for each scenario (Table 1):

- for "Case A" (two passenger trains that don't stop at any stations) it is 180 sec (165 +15 sec);
- for "Case C at end" (first freight train that stops at a station followed by a passenger train) it is 145 sec (130 +15 sec);
- for "Case C at start":
    - if first passenger train departing from a station, followed by a freight train departing from the same station, the headway is 100 sec (85 +15 sec);
    - if first passenger train crossing a station, followed by a freight train that is waiting to depart from the same station, the headway is 40 sec (25 +15 sec).

Table 1: Overview over the Operational Headway requirements

Line Sections		Required headways [s]
From	To	A / C at end / C at start
Næstved	Lundby	180 / 145 / 40
Lundby	Vordingborg	180 / 145 / 100 / 40
Vordingborg	Orehoved	180 / 145 / 100 / 40
Orehoved	Nykøbing Falster	180 / 100 / 145 / 40

In the scope of modelling trains braking behaviour, the use of Indication Curve for the following train is too much conservative and impactful on the headway achieved in line. So, for headway scenarios "Case A" and "Case C at end" for the first train (Train 1) and for the second one (Train 2) the Permitted Braking Curve (P) is used (Figure 11).

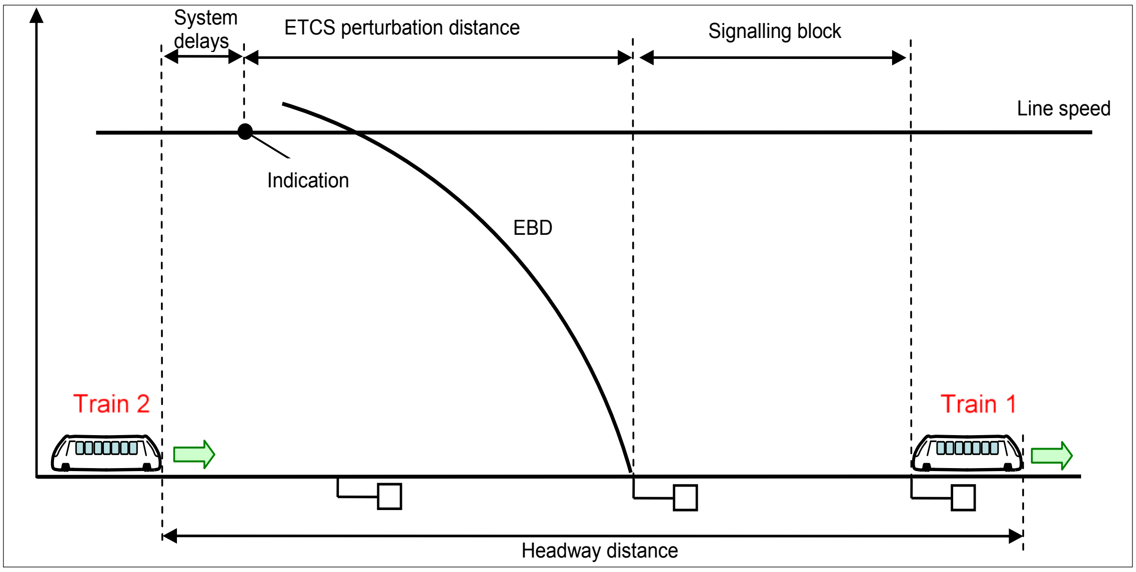


Figure 11: Contribution of ETCS braking curve to the headway

However, in accordance with this assumption, the simulation with railway tool doesn't reflects the real behaviour on the following train: the release time of block section, using an Indication Breaking Curve, is set to 4 sec (i.e. IXL release time), but using a Permitted Breaking Curve and 4 sec of release time, the following train would display on its Driver Machine Interface (DMI) the yellow Indication preannouncing the entering into braking curve, not the Normal Status (i.e. the DMI turns from grey to white indicating the driver that he is entering target speed monitoring). This situation shows that the following train run is disturbed and then the train circulation isn't hindrance free. So, the route release time is increased, for each route, by 5 sec if the follower train is a passenger train, because the value of 5 sec is the typical time difference between the P and I curve.

For "Case C at start", instead, the release time is only the Interlocking (IXL) release time (4 sec), because the follower train departs as soon as the first Movement Authority (MA) is available, that is for each Marker Board close to the station is needed to check if the MA length, for the follower train, is longer than the Indication distance calculated at the follower train's current speed. In this contest, the MA check has been lead in the following steps (Figure 12):

- calculated t_1, that is the instant one second before the route is released and set to the freight train after the first passenger train (ET) release the axel counter (start/end of each section);
- calculated d, that is MA available of freight train (distance between the freight train head position and axel counter position);
- calculated $I_d(V_{t1})$, that is the Indication distance of the freight train calculated at the current speed;
- check that $d > I_d(V_{t1})$ at the time t_1.

These steps are repeated for several instant times (i.e. t_2, t_3) until the ET train is far away of departure station.

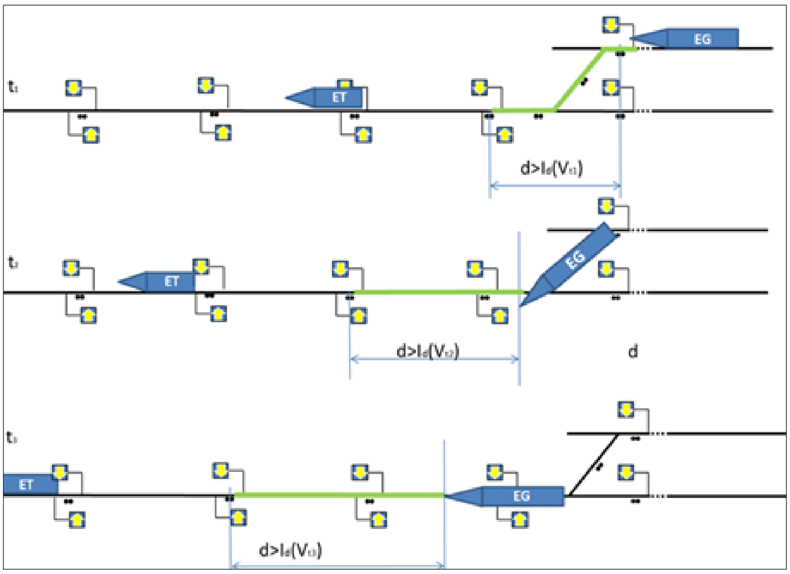


Figure 12: Movement Authority check for “Case C at start”

In terms of interlocking routes, the route setting time is assumed as follows: 8 sec for routes without points to move (e.g. routes sections without switches) or 15 sec for ones with points to move (e.g. routes sections with switches). These route setting timers are estimated considering the contribution of TMS (Traffic Management System), IXL (Interlocking), RBC (Radio Block Center) processing and transmission time (Movement Authority) and GPRS transmission delay. The section clearing is assumed, as above, in 4 sec.

4.2 System Capacity Simulation

For Fjernbane Infrastructure East area the headway cases have been fulfilled for each scenario and for each track in both directions. For each one has been defined:

- the Headway cases (“Case A” or “Case C at start/end”);
- the Technical Headway specific position and the headway value required;
- the use of station track (i.e. overtaking or main track);
- the first and second train and the trains type (freight or passenger);
- the train’s pattern.

Roll Out 7 has got 18 scenarios between Næstved and Nykobing Falster, which shall be fulfilled in bidirectional use of track (36 total simulation cases). From Næstved to Nykøbing Falster there are different headway required for different headway scenarios, but the signalling design shall fulfil all the requirements. So the first signalling sections lengths (output of backward calculation tool) allows to identify the shortest block sections lengths related to worst circulation scenario and the higher number of block sections along the line from Næstved to Nykøbing Falster. The block sections length has a tolerance of 20%, so the Signalling Engineer has a safety margin that can be used to insert Marker Board respecting the operational/engineering rules.

This is an iterative approach: starting from the input, the designer gets different topology output applying a trial and error procedure, which will stop when the obtained result is closed to the real traffic requirements given by Banedanmark, as reported in Figure 3.

By the backward calculation tool the “Case C” scenario results the worst case.

Figure 13 describes “Case C at end” related to the Vordingborg station: the peculiarity of this scenario is the restricted deviation speed (100 km/h) for freight train (ET), that influences the headway requested (145 sec) and so short block sections near the Vordingborg station is needed (Dimola et al., 2017). Figure 13 illustrates the first block sections lengths by backward calculation, starting from Mrk-0 (Marker Board 0) close to the slitting point in Vordingborg station to Mrk-3 near Orehoved station. It’s clear that the length of the section near Vordingborg is the shortest to reduce the “section length occupation time” by followed train to travel the block section, in Blocking Time Model.

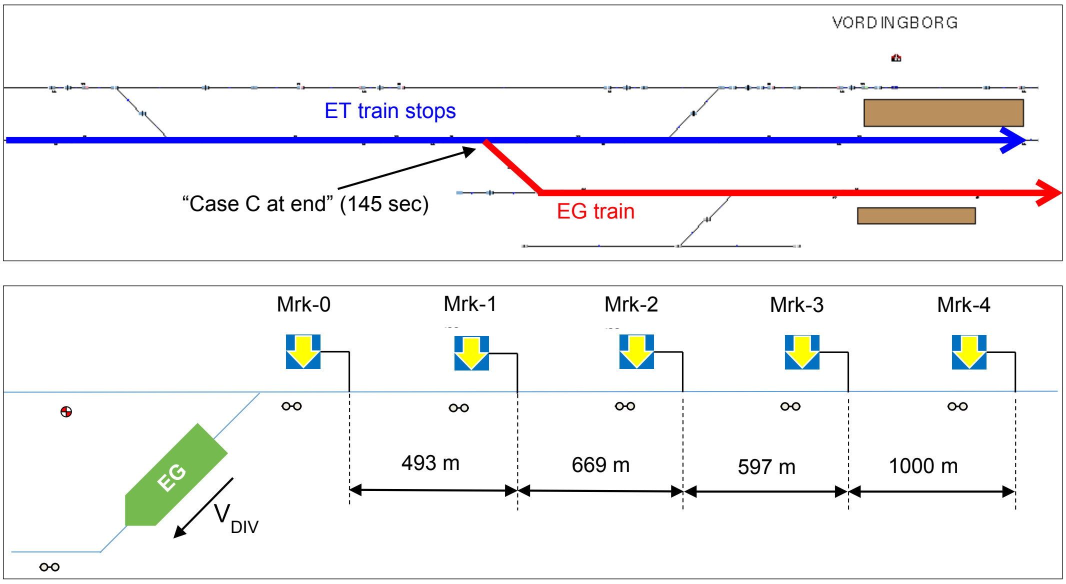


Figure 13: Scenario “Case C at end”, Vordingborg station use of track and signalling layout

To control if the signalling layout fulfils the headway requirements, it’s necessary to check the cascade braking. When headway is being found, it’s possible to reduce the departure time value of the second train to verify the optimal length of each sections. If the length is correct, reducing the departure time by 1 second would result in train braking at the Mrk-0 close to the splitting point. Reducing several times this value allows to verify the cascade braking over Mrk-1, Mrk-2, etc... This means that the second trains it’s perturbed by the first one.

The train’s entry speed in every simulation is the maximum allowed speed on the line, taking into account the maximum train’s speed and the track speed profile. For this reason, the trains will enter in the simulation at some stations before Vordingborg. The headway between the two trains calculated at the spitting points is 129 sec (2:09 min) and it satisfies the headway requirement (130 +15 sec).

Now it is necessary to evaluate the cascade braking verification: reducing the departure time of the second train by 1 sec, the ET train will brake at Mrk-0. The headway at the splitting point is 129 s (Figure 13a). Reducing one more time the departure time by 13 sec, the ET train will brake at Mrk-1 (headway 118 sec) (Figure 14b) and finally further reducing the departure time of 25 sec, the ET train will brake at Mrk-2 (headway 110 sec) (Figure 14c).

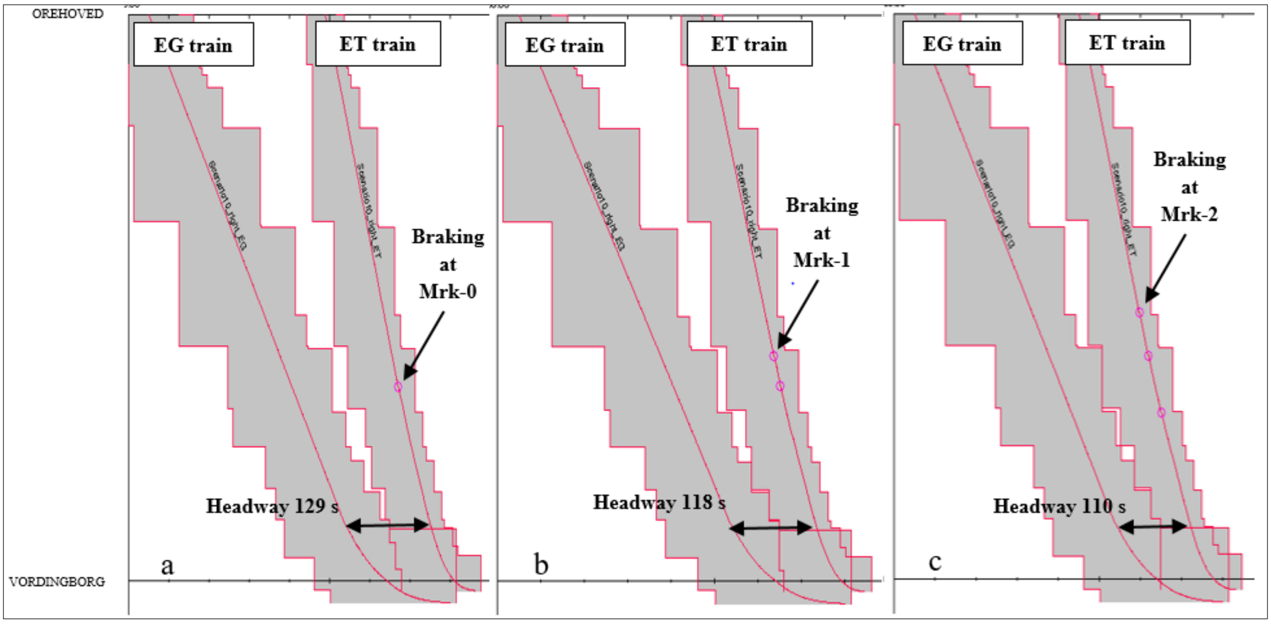


Figure 14: Scenario “Case C at end”, train graph with perturbations

Now considering “Case C at start”, where ET passenger train departs from Vordingborg on main track followed by EG train that departs from the same station on overtaking track, the headway is detected on the splitting point as shown in the Figure 15.

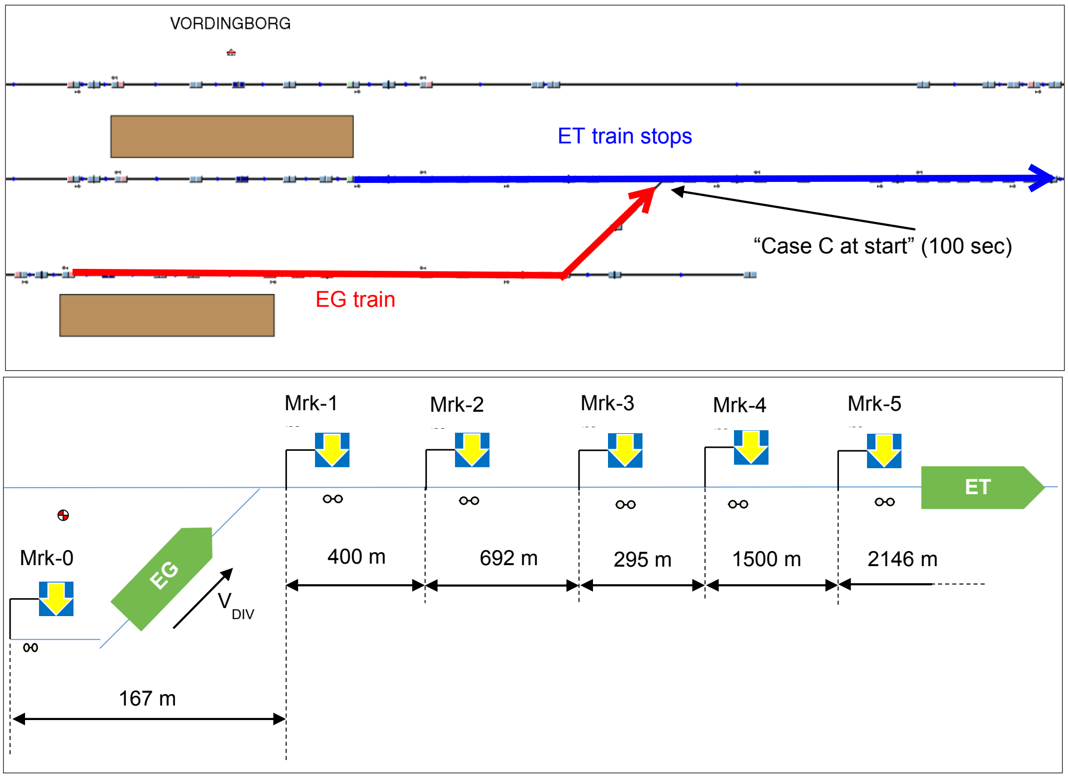


Figure 15: Scenario “Case C at start”, Vordingborg station use of track and signalling layout

This scenario needs to be checked, by OpenTrack tool, regarding the distance of Movement Authority at any given point for the follower EG train. This distance must be longer than the Indication distance calculated at the follower EG train’s current speed (the release time for each route is only 4 seconds).

The headway between the two trains, calculated, as a requirement, at the spitting points, is 71 sec (1:11 minutes) and satisfies the requirement headway (85 +15 sec) (Figure 16).

Now it is necessary to calculate the MA verification, as reported in Figure 12:

- time t_1, that is the instant one second before the route is released and set to the freight train after the first passenger train (ET) release the axel counter (start/end of each section), is equal to 01:05 min;
- distance d, that is the MA available of freight train equal to the length of section 0 minus the space already travelled after the departure, is equal to 164 m;
- the Indication distance of the freight train calculated at the current speed at time t_1 ($I_d(V_{t1})$) is equal to 59 m;
- to satisfy the verification, MA remaining length must be greater than stopping distance at the time t_1 ($d > I_d(V_{t1})$). In this case the requirement is verified because 164 m > 59 m.

With the same rational mentioned above, it is necessary to verify at least 3 sections after the first one because usually, after this number of sections, the first train is far enough from the second; consequently the movement authority of the second train (EG) is always greater than the required braking distance. The difference between MA and Indication distance shall be greater than 100/150 m to allow a reasonable margin.

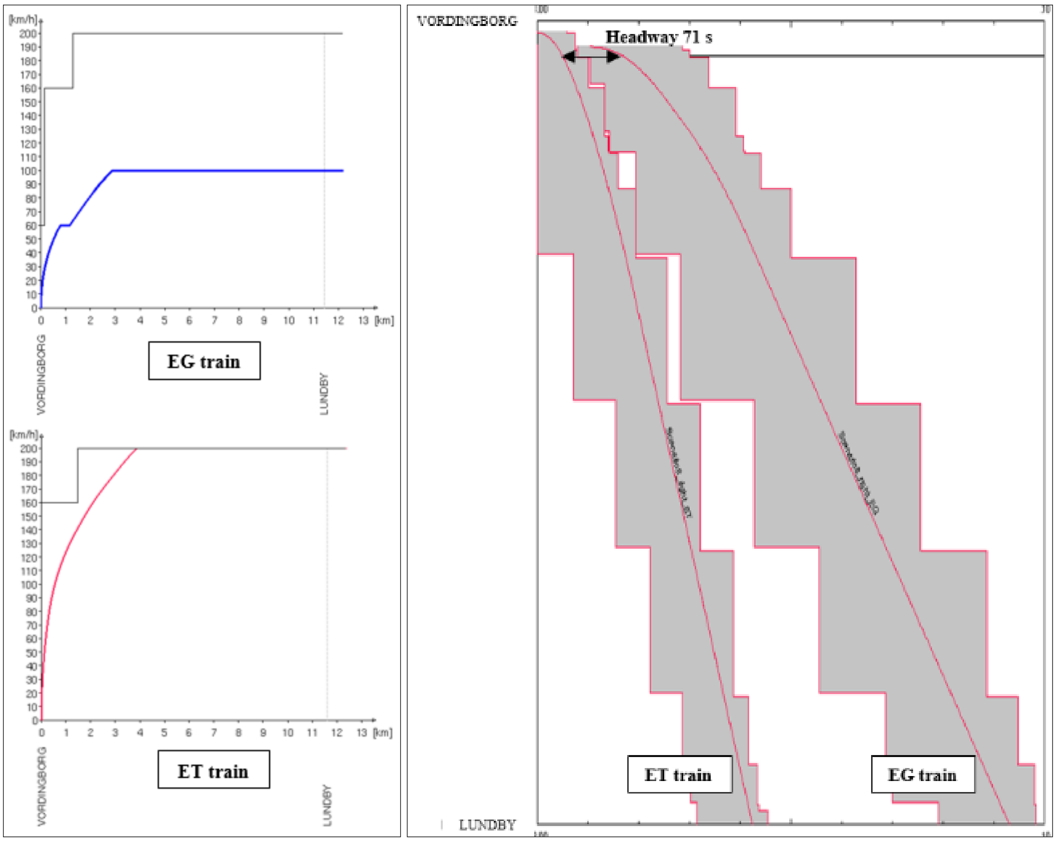


Figure 16: Scenario “Case C at start”, speed profile of EG and ET trains and train graph

After checked the “Case C” it’s necessary to analyse the “Case A”, which is easier to check than other cases, because the bottlenecks identified along the line are related to changes made by “Case C”, that is more binding from the signalling point of view.

Figure 17 describes the train graph related to “Case A” (two no stop ET passenger trains running along the entire line). The headway between the two trains calculated, as a requirement, in line is 109 sec and satisfy the requirement headway of 180 sec (165 +15 sec).

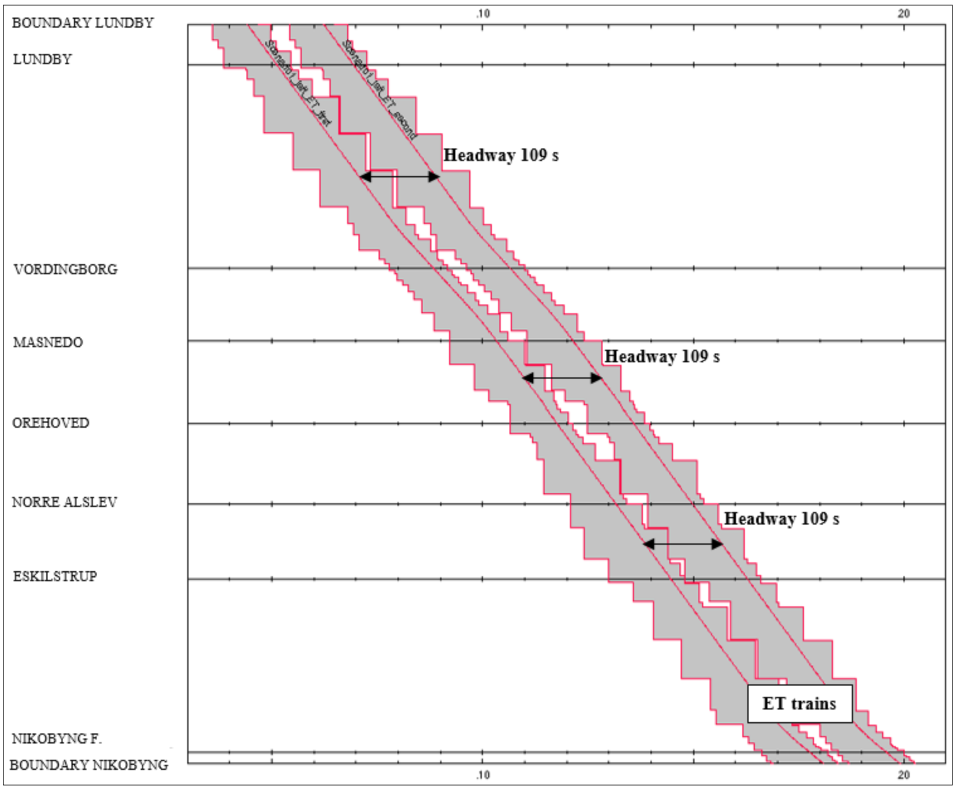
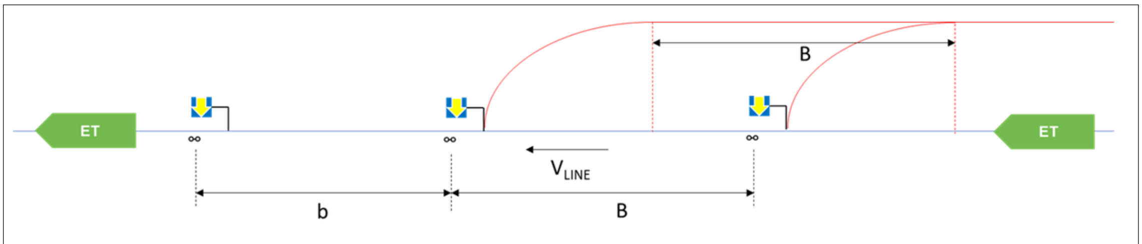


Figure 17: Scenario “Case A”, train graph

In order to justify the obtained results, in agreements with Banedanmark, an analytical calculation through simple mathematical formulas based on uniformly accelerate/decelerate motion has been developed (Galasso, 2012).

“Case A” (continuous headway requirement in line, same train graph)

According with the proposed backward calculation, the maximum length of the section is calculated through a relation between the time required for the ET train to travel in the section “b” (T_b) and the time necessary for the second ET train to travel in the section “B” (T_B) (Figure 18).



$$T_b = \frac{b}{V_{ET}} \qquad T_B = \frac{B}{V_{ET}} \qquad V_{ET} = \min(V_{LINE}; V_{TRAIN}; V_{AVG})$$

$$T_B \leq T_b \rightarrow \frac{B}{V_{ET}} \leq \frac{b}{V_{ET}} \rightarrow B \leq b$$

Figure 18: Scenario “Case A”

"Case C at end" (ET train departing from a station, followed by a EG train departing from the same station)

According with the proposed backward calculation, in first section before splitting point the maximum length of the section is calculated through a relation between the time required for the EG train to travel in the section "a" (T_a) and the time necessary for the ET train to travel in the section "A" (T_A) (Figure 19).

T_a is evaluated as a function of the diverging track speed (V_{DIV}), the route setting time of diverging track (T_{set_div}), the route setting time of straight track ($T_{set\_straight}$) and the length of the section "a" (a).

T_A is evaluated as a function of the length of the section "A" (A) and the ET train speed (V_{ET}), that is the minimum among the line speed (V_{LINE}), the train speed (V_{TRAIN}) and the train average speed (V_{AVG}).

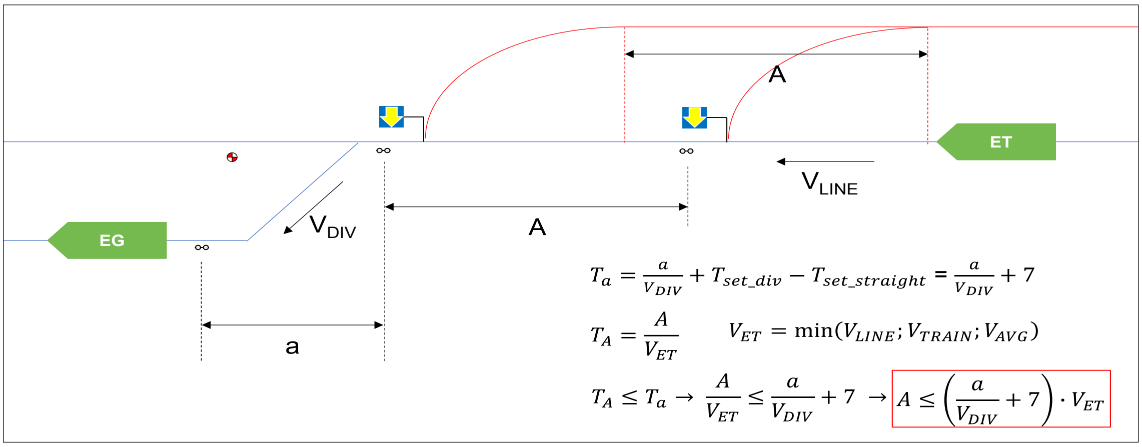
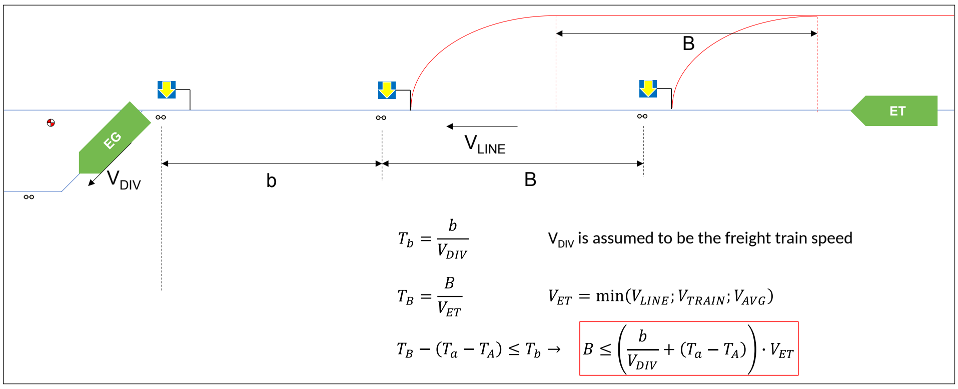


Figure 19: Scenario "Case C at end", first section before splitting point (in red train ETCS braking curve)

In the section above the splitting point the maximum length of the section is calculated trough a relation between the time required for the EG train to travel in the section "b" (T_b) and the time necessary for the ET train to travel in the section "B" (T_B) (Figure 20).

T_b is evaluated as a function of the length of the section "b" (b) and the diverging track speed (V_{DIV}), which is assumed to be the freight train speed.

T_B is evaluated as a function of the length of the section "B" (B) and the ET train speed (V_{ET}), that is the minimum among the line speed (V_{LINE}), the train speed (V_{TRAIN}) and the train average speed (V_{AVG}).



$$T_b = \frac{b}{V_{DIV}}$$

V_{DIV} is assumed to be the freight train speed

$$T_B = \frac{B}{V_{ET}}$$

$$V_{ET} = \min(V_{LINE}; V_{TRAIN}; V_{AVG})$$

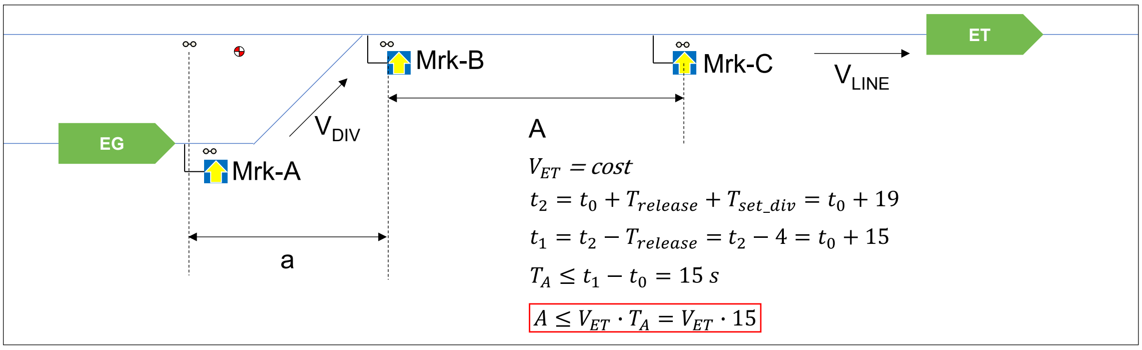
$$T_B - (T_a - T_A) \leq T_b \rightarrow \boxed{B \leq \left(\frac{b}{V_{DIV}} + (T_a - T_A)\right) \cdot V_{ET}}$$

Figure 20: Scenario “Case C at end”, section above the splitting point (in red train ETCS braking curve)

<u>“Case C at start” (first ET train departing from a station, followed by a EG train departing from the same station)</u>

According with the reported backward calculation, in first section before splitting point the maximum length of the section “A” (A) depends on the ET train speed over “A” (V_{ET}) which can be a constant speed for a non-stopping train, or an accelerating speed (or at least partially) for a train starting from standstill.

In the first case, the maximum length of the section is evaluated as a function of the ET train speed over “A” (V_{ET}) and the time T_A. This last is the difference between the time t_1, which is the time when section “A” shall be cleared by the ET train to be detected clear by signalling system at time t_2, and the time t_0, which is the time when ET train clears section “a” (signalling system can set the route for EG train after $T_{release}$). t_2 is the time when MA is available for EG train up to Mrk-B and signalling system can set the following route over “A” for EG train (the system sets the route up to Mrk-C as soon as the route is set up to Mrk-B) (Figure 21).



$$V_{ET} = cost$$

$$t_2 = t_0 + T_{release} + T_{set\_div} = t_0 + 19$$

$$t_1 = t_2 - T_{release} = t_2 - 4 = t_0 + 15$$

$$T_A \leq t_1 - t_0 = 15\ s$$

$$\boxed{A \leq V_{ET} \cdot T_A = V_{ET} \cdot 15}$$

Figure 21: Scenario “Case C at start”, first section before splitting point, V_{ET} constant speed

The second case, instead, is characterized by an ET train starting from standstill, which has a speed over “A” (V_{ET}) that can be (Figure 22):

- an accelerating speed over “A” (a): in this case the time related to the train acceleration phase (t_{ACC}) is longer than t_1;
- a partially accelerating speed over “A”, because the ET train partially accelerates and partially moves at constant speed. In this case the time related to the train acceleration phase (t_{ACC}) is included between time t_0 and time t_1. D_{ACC} is the distance related to the ET train acceleration phase.

If ET train is starting from standstill, time to travel over section “A” depends on the distance between starting point and beginning of section “A” (d_0).

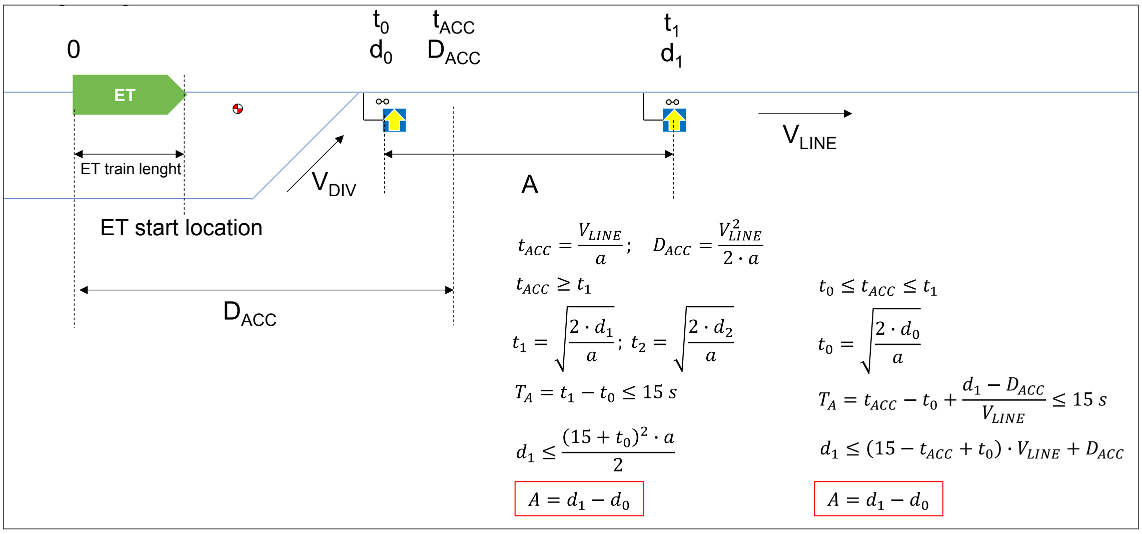


Figure 22: Scenario “Case C at start”, first section before splitting point, V_{ET} accelerating speed (or at least partially)

In the section above the splitting point the maximum length of the section is calculated as a function of the line speed (V_{LINE}), the maximum acceleration of EG train (a) and the Indication distance (d_{IND}) calculated for a speed double than the one at time t_1 (worst case estimation). This last is the time when EG train gets the MA extension up to Mrk-C (Figure 23). Section B shall be less or equal than the distance travelled by ET train in $t_{IND} - t_1$.

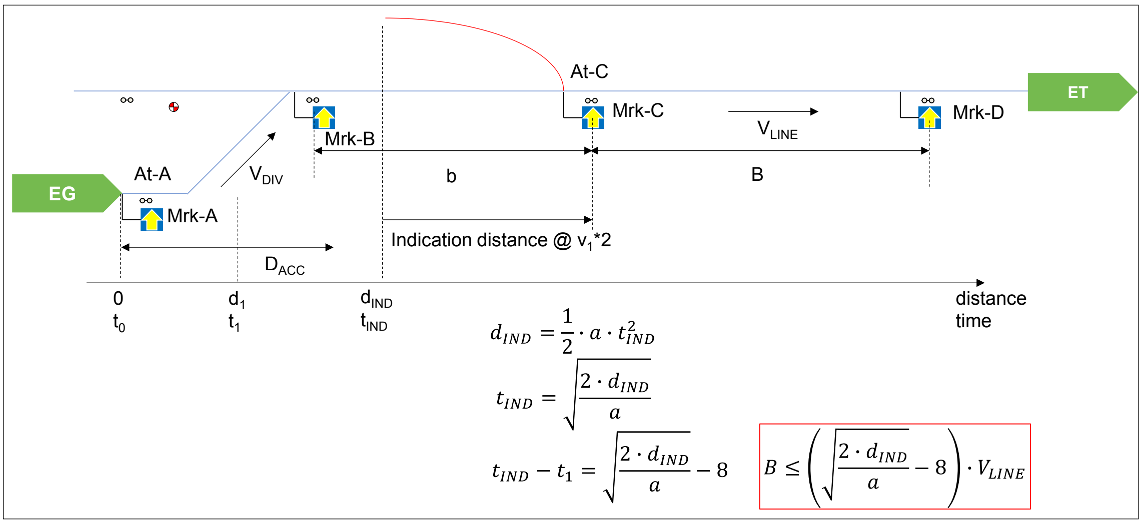


Figure 23: Scenario "Case C at start", section above the splitting point (in red train ETCS braking curve)

The proposed formulas have been used to justify the obtained results as requested by Banedanmark.

5. Conclusions

The proposed methodology is used to evaluate the first signalling equipment position, in terms of Marker Boards and Axle Counter, to fulfil the expected headway requirements and respect engineering rules, minimizing costs. It is supported by a tool that allows to obtain consistent results in a relatively short working time. On the other hand, if obtained signalling layout doesn't fulfil each headway scenarios, it is possible to modify and re-design it, reiterating the procedure. In this way the methodology permits to the signalling engineer to analyse the results sensitivity by turning specific parameters related to infrastructure and trains, ensuring the fulfilment of operational and performance requirements applying a given headway in a commercial turn-key contract.

The obtained results, in the case study of rollout 7 from Næstved to Nykøbing Falster in Denmark, are a robust signalling configuration which also provides a satisfying trade-off between total cost and network performance.

So the application to the Danish case of study shows that it is possible to pursue a different objective that is not merely to get the maximum possible capacity for a given signalling system, but to evaluate the right trade-off between headway requirements, infrastructural constrains, operational constrains and technological constrains. These last are defined at the beginning of the process and the entire signalling layout is built based on these requirements, so the capacity of the railways lines is an implicit result.

Acknowledgments

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