# DITTO Project Deliverable 3.2 Milestone 7

## Simulation and Control of ERTMS Level 2

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## 1. Introduction

The ERTMS (European Railway Traffic Management System) is aimed at providing a harmonised/standardised solution for the interoperability of trans-European railway operation. It is composed of ETCS (European Train Control System), GSM-R (Global System for Mobile Communications - Railway), ETML (European Traffic Management Layer) and operating policy. ETCS integrates the functions of signalling, train control and train protection, under the cooperation of on-board and trackside subsystems. GSM-R supports the bi-directional telecommunication between the on-board and trackside ETCS equipment and between train drivers and other railway staff. ETML provides the high-layer support for real-time information, supervision and management of the trans-European rail traffic, and the development of ETML so far includes OPTIRAILS[1] (optimisation of traffic through the European rail traffic management system), OPTIRAILS II[2], and EUROPTIRAILS (European online optimisation of international traffic through rail management system)[3].

The ERTMS/ETCS are categorized into different application levels, mainly based on the requirement on the infrastructure systems (SUBSET-026). The ETCS Level 2 and Level 3 are the two most advanced application levels under the existing categorization, and they are distinguished from other lower levels in the way that they are radio-based. The most obvious difference between ETCS Level 2 and Level 3 is that, the former is a fixed-block system while the latter is a moving-block system. We have discussed ETCS Level 3 in

[1] http://www.transport-research.info/project/optimisation-traffic-through-european-rail-traffic-management-system
[2] http://www.transport-research.info/project/european-online-optimisation-international-traffic-through-rail-management-system
[3] http://www.transport-research.info/project/europtirails-ongoing-activities

Deliverable 3.1; in this deliverable, we present simulation and control algorithms for modelling ETCS Level 2.

The ERTMS is expected to significantly increase the capacity of the railway systems, and the increased capacity means shorter train headways and more severe interference among trains using the same infrastructure, which may lead to longer delay and higher energy consumption. Therefore, it is important to investigate, in a practical train operating environment, whether the claimed capacity increase can be achieved and how the added capacity would influence the performance of the whole system. The simulation platform can provide convenience for such investigation before the ERTMS is widely implemented in practice.

The capacity increase brought by ERTMS relies on the new radio systems for communication between trains and radio block centre (RBC). As a critical component of the ERTMS/ETCS system, the RBCs' rules to determine the moving authority (MA) affect the operation of each train and thus the performance of the whole railway system. Also, the quality (e.g. delay) of the train-RBC communication would affect the operation of both trains and RBCs. Therefore, our simulation platform explicitly models the functions of RBCs and their interaction with the trains, and also provides flexibility to adopt different MA generation rules as well as to allow various non-ideal situations associated with the train-RBC information exchanging process such as communication delay/loss. Furthermore, since the real-time timetable adjustment and temporary speed regulation would affect the train operation, in our simulation platform, the RBCs are allowed to receive such information from other traffic management functions such as the control centres.

The shorter train headway coming with the higher railway capacity requires more advanced railway operation strategies, which includes not only the scheduling schemes in control centres and MA generation rules in the RBC, but also the safe and energy-efficient train control strategies. To keep the railway lines operating smoothly with short headways, such train control strategies should be obtained in short time once the train running condition changes, e.g. when the MA is extended or the schedule is adjusted. Also, more accurate train speed/location estimation and real-time telecommunication bring a chance to better coordinate the train controls in real time to further reduce energy consumption and improve sustainability of the railway system.

This deliverable presents the framework for simulating a railway system based on ECTS Level 2, with our proposed train control strategies. As a part of the DITTO project, the simulation platform could help to generate detailed train operation data for the capacity analysis of the railway network, and the analysis of time- and energy-efficiency of timetables generated by other scheduling tools. Section 2 summarises the features of ERTMS Level 2 that are incorporated in our simulation framework. Section 3 describes how the simulation framework works based on the interaction of the train and various trackside equipment under ETCS Level 2. The train simulator is introduced in Section 4, together with the methodologies for simulating the train advancing and calculating the train control strategy. The rules adopted for the generation of MA and the train (re)scheduling are introduced in Section 5. Case studies are demonstrated in Section 6.

## 2. Modelling features of ERTMS Level 2

The trackside system in ETCS Level 2 includes RBC, balises, interlocking, etc. RBC is a computer-based centralised unit in charge of the safe movement of all trains running on the area under the responsibility of this RBC. It delivers route and the associated track description to all supervised trains based on information received from external trackside systems and all trains. The balises (or balise groups) are spot transmission devices mainly for location referencing. Some trackside equipment (interlocking, track circuits, etc.) is not a function of ETCS Level 2, but is indispensable for fulfilling the functions of ETCS Level 2 such as the train detection and train integrity supervision, which is not performed by trains in ETCS Level 2 (SUBSET-026).

The on-board ETCS system is responsible for the train protection including speed supervision and prevention of overrunning the MA, which is the permission and distance to run for a specific train), as well as displaying cab signalling to the train driver.

Our simulation platform is established based on simplifications on the ETCS Level 2 features provided in the Functional/System Requirements Specification (ERA/ERTMS/003204, SUBSET-026). We assume that trains are operated under ETCS level 2 on lines equipped with ETCS Level 2, and the trains are operated according to the advised control/speed profiles from the driver advisory systems. The train is assumed to be connecting with at least one RBC anytime during the journey, so there is no connection loss between the train and the RBC. The following flow chart demonstrates the interaction among different components of ETCS Level 2.

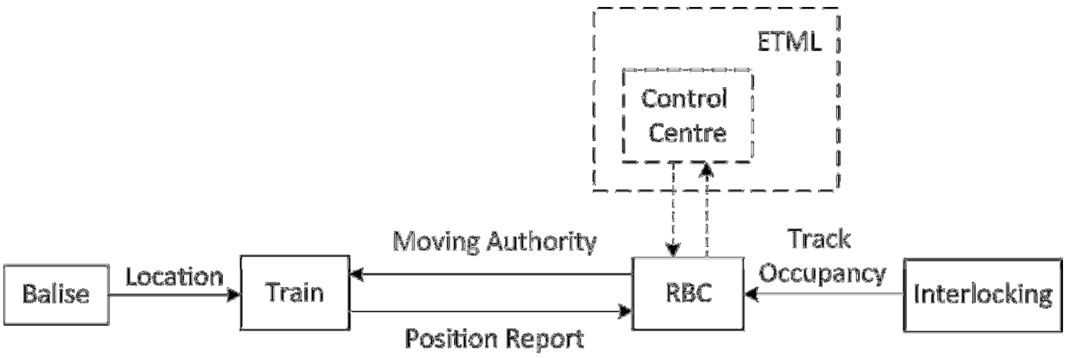


Figure 1: **Flow chart of ETCS Level 2**

The functions of the train include:

1) When running on the track, estimating current train position and speed based on the data from odometers, and correcting the position information based on the location referencing information on passage of the balise groups.
2) Sending position report to the RBC. Such report may contain, but not limited to, current location, running direction, current speed, and current End of Authority (EOA, i.e. the end location of MA).
3) Receiving the MA information from the RBC, selecting the most restrictive speed limit at each location ahead, and then calculating and following the speed profile/control strategy taking into account MA, track condition and train running/tractive/braking characteristics.
4) Monitoring actual train speed without overrunning the most restrictive speed limit, and applying brakes if necessary.

The functions of RBC include:

1) Receiving and storing the train position report.
2) Obtaining track occupancy information from the interlocking.
3) Calculating and sending MA to the train. The detailed information sent from RBC to train may include, but not limited to, the MA and the track description covering the whole MA (such as speed restrictions and gradient profile).
4) Additionally, the RBC may have interaction with the (regional, national or international) control centre. The control centre is a function of ETML but not a function of ETCS. The information from RBC to the control centre may be used to support the sophisticated (re)scheduling procedure in the ETML, while the new schedule resulted from the (re)scheduling process will be used to determine the MA.

Furthermore, ETCS Level 2 is still a fixed-block system, where each block can be occupied by at most one train at a time. The number of balise groups contained in different block sections can vary.

# 3. Simulation framework

## 3.1. Platform structure

The system components and information transmission we considered in the simulation framework are respectively represented by the solid rectangles and solid directed lines in the following Figure 2, while the dash rectangles and dash directed lines are those features that have not been considered. The simulation platform consists of three major components, which are the train simulator, the RBC simulator, and the control centre.

We assume no errors for speed and location measures from odometers, so the location reference information from the balises is not necessitated for the train. The track occupancy information provided by the interlocking is important for the RBC to determine the MAs. We use very simple rules for train (re)scheduling in the control centre, and our framework is also able to accept the (re)scheduling plans from other advanced (re)scheduling tools. In addition, although the location and speed information may be useful for the sophisticated (re)scheduling process, here they are not considered by the control centre in the simple scheduling rules, so this information transmission is also omitted in our simulation.

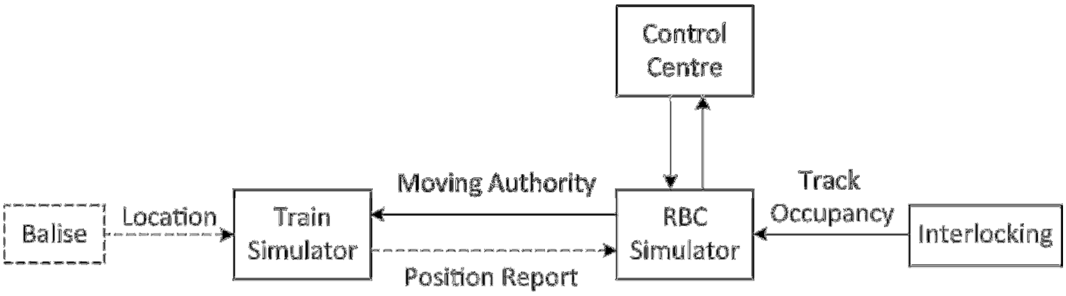


Figure 2: **Flow chart of the simulation platform for ETCS Level 2**

The train simulator consists of two major modules: the advancing module and the control advisory module. The former calculates how the train moves forward under a specific control profile, while the latter provides time-efficient or energy-efficient control profiles to the advancing module based on the MA as well as other track and train information either received from RBC or stored on board.

The RBC simulator determines the MA based on the track occupancy information from interlocking, and the control centre calculates the scheduled arrival time at EOA based on simple (re)scheduling rules.

The procedure of information transmission/processing is not explicitly simulated, and the transmission failure or system failure is not considered either. However, in a very coarse way, we consider the uncertainties in the processes of data transmission, system response, information processing, message delay, programme execution, etc. With such consideration, we use a random variable to model the time interval between the two adjacent attempts of the RBC to recalculate the MA.

# 4. Train simulator

## 4.1. Procedure of train simulator

The train simulator works through the interplay of the two train modules as well as the RBC and control centre. The control advisory module calculates the control profile when necessary and the train advances according to such control profile. For the control advisory module, its input includes:

- Current train location and speed.
- Location of the EOA.
- Targeted speed at the EOA. We request the train to stop before the EOA, so the target speed at the EOA is set to be zero. In other words, the case allowing a non-zero permitted speed at the EOA, i.e. Limit of Authority (SUBSET-026), is not considered.
- Scheduled arrival time at the EOA (or equivalently, the scheduled running time from current location to the EOA).
- Profiles of gradient and speed limit from current position to the EOA.
- Train aerodynamic/tractive/braking characteristics.

The output of the control advisory module would be the advisory control profile as well as an associated flag value, as shown in the following table.

Table 1: **Output of the advisory control module**

| Flag | Situation | Output control profile |
|---|---|---|
| 1 | Train cannot stop at or before the EOA with immediate full brake | Full brake |
| 2 | Time budget is less than the time-efficient plan | Time-efficient plan |
| 3 | Time budget is above the time-efficient plan and the energy-efficient plan is successfully obtained | Energy-efficient plan |
| 4 | Time budget is above the time-efficient plan but the energy-efficient plan cannot be obtained, while the time-efficient plan is successfully obtained | Time-efficient plan |
| 5 | Fail to obtain any plan | No advisory plan |

The train will follow the existing advisory control plan when running on the track, or keep dwelling at the stations, unless the following two situations happen:

- The MA is extended.
- The MA is not extended but the flag for the existing advisory control is 4.

When either of the above two situations happens, the control advisory module will be called. The train will accept and follow the new advisory control strategy unless the advisory module fails to obtain any feasible plan (i.e. flag=5).

## 4.2. Train dynamics

The core of the train advancing module is the train movement dynamics. Given a specific control profile, the train advancing can be described by a set of dynamical equations. The following assumptions on train characteristics and track condition are made:

- The train is a rigid body with a positive length.
- The forces applied on the train include: (i) the instantaneous tractive force applied by the train engines, and the instantaneous braking forces applied by the braking system; (ii) the speed-related running resistance, consisting of mechanical and aerodynamic resistances; and (iii) the component of the gravitational force along the track caused by the track gradient.
- The speed-related running resistance takes the Davis formula, i.e. the resistance is a quadratic function of speed with train-specific constant coefficients.
- The tractive/braking forces applied on the train are bounded from above, and the corresponding upper-bound functions are decreasing with respect to speed.
- Both the speed limit and track gradient are piecewise constant w.r.t. location. Therefore, we can divide the track into a finite number of subsections such that both the speed limit and track gradient are constant on each subsection.
- Factors, such as the correction factors for rolling stock and gradient, are omitted.

## 4.3. Energy-efficient driving strategy for an individual train

The control advisory module is to provide train control command to the automatic train operation system for driving the train in a time-efficient or energy-efficient way under the real train and track conditions. The core of this module is the algorithm/method for obtaining such control strategy. This problem (especially for obtaining the energy-efficient control) is called the optimal train control problem, which is usually modelled as an optimal control problem involving ordinary differential equations and integrals (Albrecht et al., 2015a, 2015b). Here we convert the optimal control problem into the nonlinear programming problem so as to reduce the computation effort for obtaining the solutions and/or to increase the operability of the solutions by reducing/eliminating the fluctuation on the suggested control profile. As assumed before, the track gradient and speed limit are both constant on each subsection. We introduce two different methods to solve such train control problems. They are briefly explained subsequently, and their performance will be compared later in Section 6.1.

**Method 1**

According to the optimal control theory (Albrecht et al., 2015a, 2015b), the train optimal control profile on each subsection can be realised as a sequence of (at most) four stages, which are: maximum traction (MT), cruising (CR), coasting (CS), and maximum braking (MB), as illustrated in the following figure. Following this idea, to find the optimal control strategy, we only need to figure out the time duration of each of these four stages on each subsection.

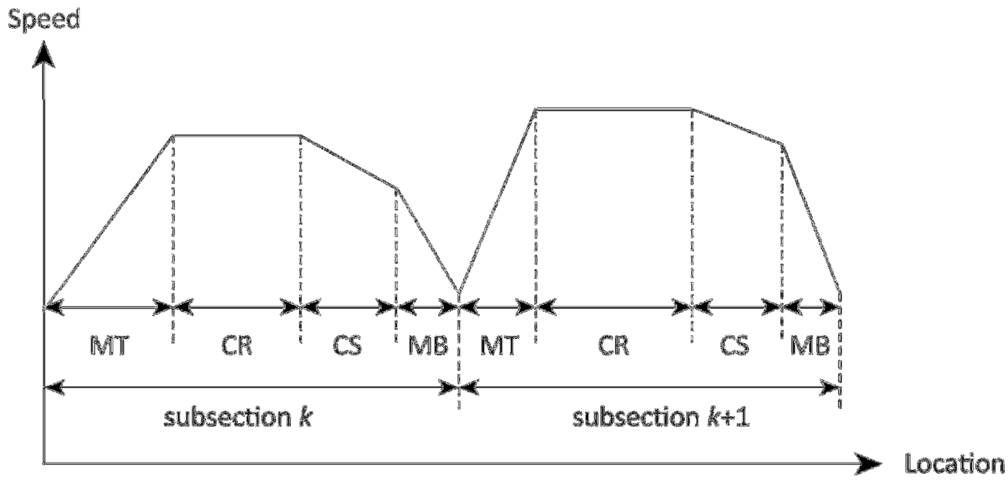


Figure 3: **Illustration of Method 1 with four-stage operation.**

In this method, we assume that the maximum tractive function and maximum braking function are piecewise-linear with respect to train speed, as illustrated in the following figure.

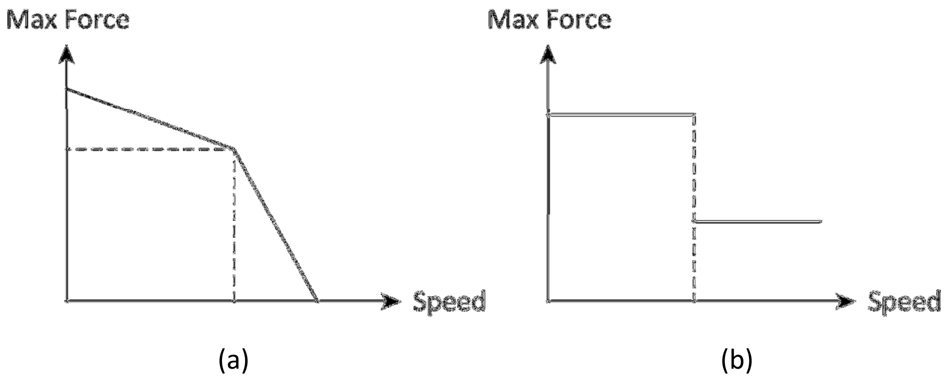


Figure 4: **Illustration of maximum tractive/braking force function.**

With this assumption, as well as those made in Section 4.1, given the time duration of each stage on each subsection, as well as the initial train speed at this stage, we can work out the closed-form expressions of various variables in this stage, including (i) the distance traversed, (ii) the final train speed, and (iii) the energy consumption (only for MT and CR), by solving the ordinary differential equations (regarding train dynamics) and integral (regarding energy consumption) in the original train control problem. As a result, we replace the differential and integral formulations in the original train control problem with the closed-form equations and form an equivalent nonlinear programming problem, with the following constraints:

- Train speed at the beginning of each stage should be equal to the terminal speed of the previous stage.
- Train speeds at the beginning and terminus of the journey should respectively be equal to the current train speed and the target speed at EOA (which is zero).
- The train speed should not exceed the speed limit applied on the corresponding subsection.
- The sum of the time duration of all stages over all subsections should be equal to the scheduled journey time.
- The travel time on each subsection should be no less than the length of the subsection divided by the upper speed limit applied on it.
- The sum of the distances traversed during the four stages of each subsection should be equal to the length of the corresponding subsection.
- The force applied in a cruising phase cannot exceed the range given by the maximum tractive and maximum braking forces under the corresponding cruising speed.

**Method 2**

In Method 1, the maximum tractive/braking force functions are restricted to be piecewise linear. To relax this restriction, we introduce the alternative method by assuming that the tractive/braking force applied by the train keeps constant on each specific subsection, but can vary from subsection to subsection. Under the constant applied force, the train’s speed will be monotone on each subsection, either increasing or decreasing. The operator will then only need to determine the sign and quantity of the constant force applied on each subsection. The process for constructing the nonlinear programming formulation in this method is similar to that in Method 1. Besides allowing more flexible function forms on the maximum tractive and braking forces, Method 2 also requires less computation effort due to the smaller number of decision variables and constraints; the side effect is that the energy-consumption obtained by this method will be higher than that by Method 1. To further reduce the energy consumption, one may cut each subsection into several ones so that the forces can be applied more flexibly.

## 4.4. Simultaneous control optimisation of multiple trains

When a track segment allows multiple trains running on it at the same time, the movement of a train running on it may be affected/obstructed by another train running in front of it on the same track. Under this circumstance, it is meaningful to consider all these trains together and optimise their control strategies simultaneously to improve the time and/or energy saving. Such simultaneous train control optimisation was investigated in Deliverable 3.1 and our recent publication (Ye and Liu, 2016) in a moving-block system such as ETCS Level 3, and here we continue to discuss its implementation in a fixed block system like ETCS Level 2. For this purpose, the methods proposed in Section 4.3 for the single-train control optimisation can be extended. Still, each of the concerned trains follows the four-stage operation (or the constant-force operation) on each subsection. Additionally, the safety train separation should be maintained between each two adjacent trains and described as constraints in the corresponding nonlinear programming formulation. Such safety consideration is satisfied by requiring that, for each block (which can contain more than one subsection), the time that the following train enters the block should be no earlier than the time that the leading train leaves it plus a safety time headway.  Advantages of the simultaneously control optimisation will be illustrated in Section 6.3.

# 5. Moving authority generation and train (re)scheduling

In our simulation framework, the information contained in the MA relies on RBC and control centre, where the former  generates MA and the latter calculates train schedules.

The MA generation scheme needs to handle two different situations: (i) when the train is running on the track, and (ii) when the train is waiting for departure at the station. We do not consider the possibility of MA revocation in our simulation, i.e., EOA of the new MA could not be closer to the train than the current EOA.

When the train is running on the track, the EOA will be chosen in such a way that:

- The EOA should be between the train (inclusive) and the particular station platform (inclusive) that the train is heading to.
- The EOA always locates at the end of a block section.
- The track between the train and the EOA is fully unoccupied.
- The EOA is the furthest location to the train that satisfies the above three requirements.

When the train is waiting at a station for departure, the MA will be given to the train that simultaneously satisfies the following three conditions:

- The train’s scheduled departure time at this station is no later than current time.

- If the train is dwelling at an intermediate station, it has dwelled no shorter than the required dwell time for it at this station.
- The train's scheduled departure time at this station is the earliest among the trains that (i) are currently dwelling at this station and (ii) satisfy the above two conditions.

The (re)scheduled arrival time at the EOA for a particular train is calculated as follows.

- If current time is earlier than the scheduled arrival time at the train's frontal station (i.e. the nearest station that is on the train's route but haven't been visited by the train yet), then the arrival time at the EOA is scheduled as

$$current\ time\ + \frac{location\ of\ EOA - current\ train\ location}{location\ of\ frontal\ station - current\ train\ location} \times (scheduled\ arrival\ time\ at\ \ frontal\ station - current\ time)$$

- If current time is no earlier than the scheduled arrival time (i.e. the train is delayed), then the scheduled arrival time at the EOA is set to be current time (i.e. the scheduled time budget to arrive at the EOA is zero), so the control advisory module will try to calculate the time-efficient control strategy.

# 6. Case studies

The case studies are based on a single-track railway line across four stations (A, B, C, D), as shown in the following Figure 5. The locations of stations A, B, C and D are respectively 0km, 30km, 60km and 90km. Two different network structures are used: one with no extra loop at each intermediate station B and C, and the other with one extra loop at B and C each. The profiles of speed limit and track gradient are shown in the following tables, based on which the whole track from A to D is divided into 90 subsections, each of which is 1km long. Each subsection is defined as a block. The MA recalculation interval is assumed a random integer varying from 30 to 60 seconds.


Figure 5: **Network structure: (a) without loops, (b) with loops.**

Table 2: **Speed limit (SL)**

| Start location (km) | End location (km) | SL (km/h) | Start location (km) | End location (km) | SL (km/h) |
|---|---|---|---|---|---|
| 0 | 1 | 100 | 44 | 45 | 120 |
| 1 | 4 | 170 | 45 | 49 | 170 |
| 4 | 6 | 130 | 49 | 50 | 120 |
| 6 | 10 | 170 | 50 | 54 | 170 |
| 10 | 11 | 120 | 54 | 55 | 120 |
| 11 | 13 | 170 | 55 | 59 | 170 |
| 13 | 15 | 150 | 59 | 60 | 140 |
| 15 | 17 | 170 | 60 | 61 | 140 |
| 17 | 18 | 120 | 61 | 63 | 170 |
| 18 | 24 | 170 | 63 | 64 | 120 |
| 24 | 26 | 150 | 64 | 70 | 170 |
| 26 | 27 | 120 | 70 | 71 | 120 |
| 27 | 30 | 170 | 71 | 77 | 170 |
| 30 | 33 | 170 | 77 | 78 | 120 |
| 33 | 34 | 120 | 78 | 82 | 170 |
| 34 | 38 | 170 | 82 | 83 | 120 |
| 38 | 39 | 120 | 83 | 88 | 170 |
| 39 | 44 | 170 | 88 | 90 | 120 |

Table 3: **Track gradient**

| Start location (km) | End location (km) | Gradient (‰) | Start location (km) | End location (km) | Gradient (‰) |
|---|---|---|---|---|---|
| 0 | 2 | -2 | 47 | 48 | -3 |
| 2 | 3 | -3 | 48 | 51 | 0 |
| 3 | 5 | 10.4 | 51 | 52 | 3.5 |
| 5 | 7 | 3 | 52 | 53 | -1.8 |
| 7 | 8 | -8 | 53 | 56 | 0 |
| 8 | 9 | 3 | 56 | 57 | -0.5 |
| 9 | 12 | -2 | 57 | 58 | 1.5 |
| 12 | 14 | -3 | 58 | 60 | -1 |
| 14 | 16 | 8.2 | 60 | 62 | 6 |
| 16 | 19 | 2 | 62 | 65 | 0 |
| 19 | 20 | -20.4 | 65 | 66 | -8 |
| 20 | 21 | -24 | 66 | 67 | -3 |
| 21 | 22 | 0 | 67 | 68 | 5 |
| 22 | 23 | -2 | 68 | 69 | 1.4 |
| 23 | 25 | -3.2 | 69 | 72 | 0 |
| 25 | 28 | 0 | 72 | 73 | 15.5 |
| 28 | 29 | 3.3 | 73 | 74 | 24 |
| 29 | 30 | 2.8 | 74 | 75 | -3 |
| 30 | 31 | -15.6 | 75 | 76 | 10.1 |
| 31 | 32 | 9 | 76 | 79 | 2 |
| 32 | 35 | 0 | 79 | 80 | -3 |
| 35 | 36 | 5 | 80 | 81 | 3 |
| 36 | 37 | -2 | 81 | 84 | 2 |
| 37 | 40 | 0 | 84 | 85 | 20 |
| 40 | 41 | -2 | 85 | 86 | 3 |
| 41 | 42 | 5 | 86 | 87 | -18.9 |
| 42 | 43 | 3 | 87 | 89 | 2 |
| 43 | 46 | 0 | 89 | 90 | 0 |
| 46 | 47 | 2 | | | |

There are two types of trains, the fast train and the slow train, which vary in the maximum tractive force $\bar{F}(v)$ (in kN) and maximum braking force $\bar{B}(v)$ (in kN) but are identical in other characteristics such as mass (278 ton), length (200m), and resistance function $R(v)$ (in kN) (Wang et al., 2014), where $v$ is the train speed in km/h[4]. The forms of these functions are given as follows.

$$\left.\begin{aligned} \bar{F}(v) &= \begin{cases} 550, & 0 \le v \le 90 \\ 550 - 5(v - 90), & v > 90 \end{cases} \\ \bar{B}(v) &= \begin{cases} 500, & 0 \le v \le 100 \\ 500 - 5(v - 100), & v > 100 \end{cases} \end{aligned}\right\} \text{Fast train}$$

$$\left.\begin{aligned} \bar{F}(v) &= \begin{cases} 400, & 0 \le v \le 60 \\ 400 - 5(v - 60), & v > 60 \end{cases} \\ \bar{B}(v) &= \begin{cases} 350, & 0 \le v \le 80 \\ 350 - 5(v - 80), & v > 80 \end{cases} \end{aligned}\right\} \text{Slow train}$$

$$R(v) = 2.2294 \times 10^{-3} v^2 + 3.9476$$

## 6.1. Comparison of Methods 1 and 2

Assume a fast train is scheduled to run from Station A to Station B with a time budget of 14 minutes. For Method 2, we further cut each subsection into *n* segments with equal length, *n*=1,2,3,4, thus each new subsection is $1/n$ km long. So we have five different cases to investigate, one is Method 1 with subsection lengths of 1km, and the other four are Method 2 with subsection lengths of 1km, 0.5km, 0.33km and 0.25km, respectively. We adopted the MATLAB built-in solver *fmincon* to solve the nonlinear programming problems. An initial point is needed as a "seed" to start the solver, and the choice of such an initial point would influence the computation time and solution of the solver. Therefore for each case, the optimal train control is repeatedly solved for 100 times, each starting with a random initial point. The results are illustrated in Table 4 and Figures 6 to 9. The two methods are compared as follows.

1) The solution obtained by Method 1 is globally optimal, which is evident based on two reasons. On one hand, all the 100 initial points lead to almost identical energy consumptions (Table 4) and speed profiles (Figure 6). On the other hand, the optimal control (Figure 7) is consistent with the sequence of MT-CR-CS-MB on each subsection.

2) Method 2 can only give the locally optimal solution, which can be seen from both the energy consumptions (Table 4) and the speed profiles (Figure 8). The energy consumptions obtained by Method 2 are always higher than that by Method 1, regardless of the lengths of the subsections. However, as the subsection shortens in

[4] The empirical values used here are based on the Beijing subway (Ye and Liu, 2016), For comparison, on the East Coast Main Line, a Class 91 locomotive weighs around 80 tons and is 19.4 m long, a Mark 4 coach is around 40 tons and 23 m long, whilst the driving van trailer weighs 43 tons and is 18.8 m long. A typical formation includes nine coaches.

Method 2, the energy consumption may reduce, and at the same time the corresponding computation time quickly increases and eventually exceeds that of Method 1.

Table 4: **Results of Methods 1 and 2**

| | | Method 1 | Method 2 | | | |
|---|---|---|---|---|---|---|
| | | | k=1 | k=2 | k=3 | k=4 |
| Computation Time (s) | Max | 33.2 | 10.5 | 41.0 | 122.6 | 227.1 |
| | Mean | 20.7 | 5.1 | 21.6 | 55.8 | 106.7 |
| | Min | 15.1 | 2.4 | 6.2 | 16.2 | 30.9 |
| Energy Consumption (kJ/kg)* | Max | 4746 | 5912 (+24.6%) | 5182 (+9.2%) | 5010 (+5.6%) | 5094 (+7.3%) |
| | Mean | 4746 | 5560 (+17.1%) | 5061 (+6.6%) | 4918 (+3.6%) | 4886 (+3.0%) |
| | Min | 4746 | 5525 (+16.4%) | 5039 (+6.2%) | 4895 (+3.1%) | 4825 (+1.7%) |

* The percentages are based on the energy consumption of 4746kJ/kg from Method 1.

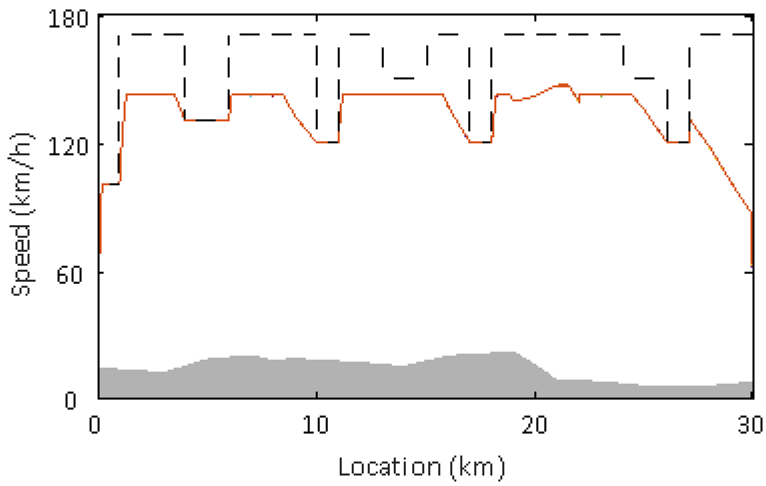


Figure 6: **Speed profiles of the fast train with all 100 initial points by Method 1**

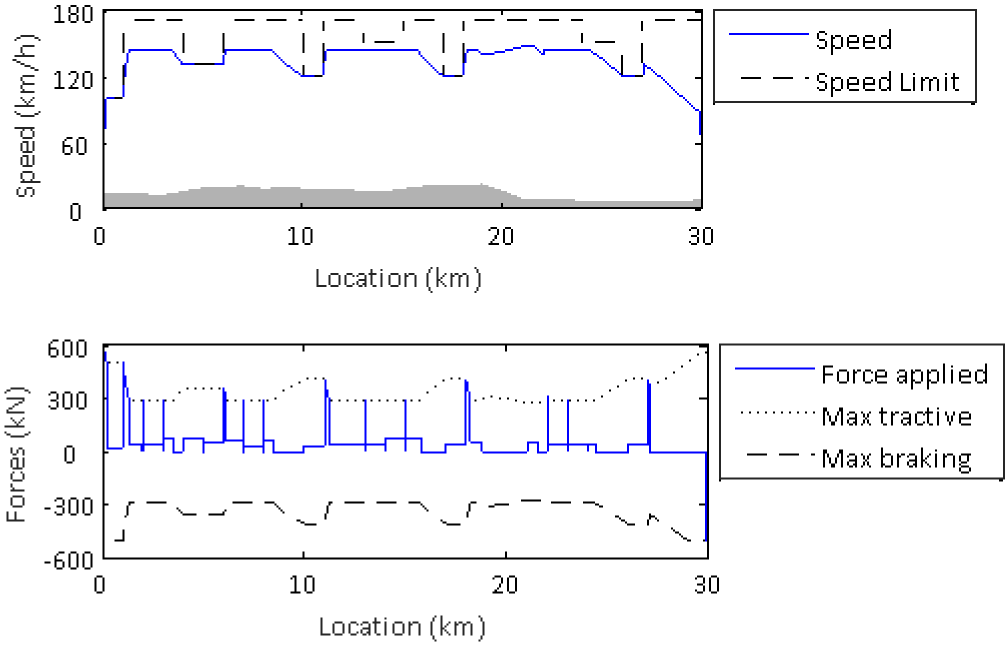


Figure 7: **Speed and force profiles of the fast train with a particular initial point in Method 1.**

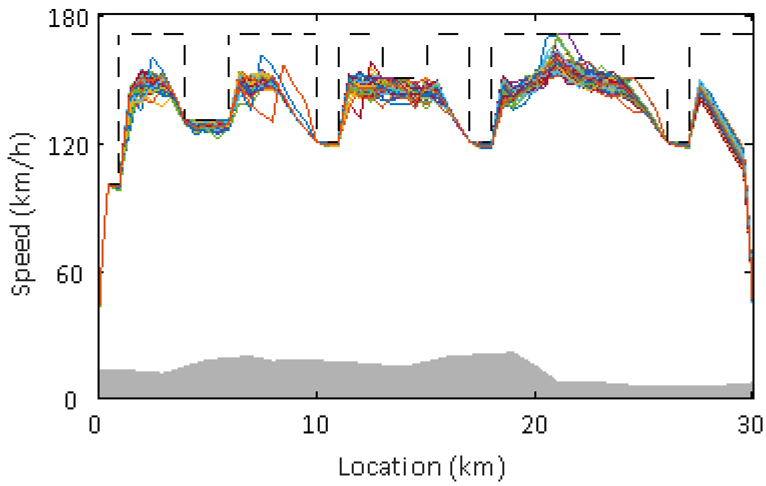


Figure 8: **Speed profiles of the fast train with all 100 initial points by Method 2 with 0.5km-long subsections.**

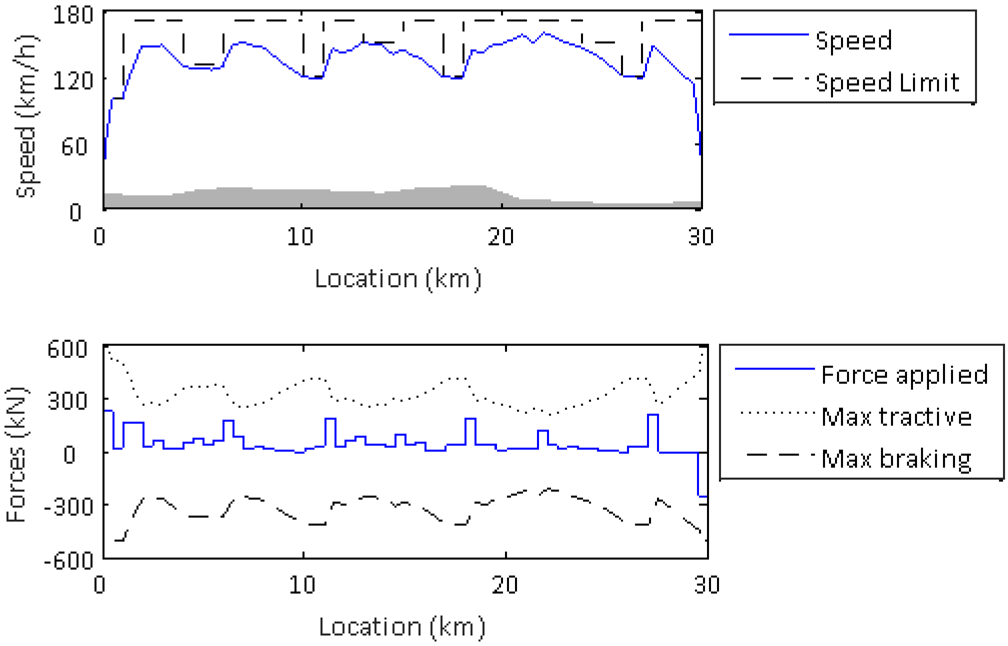


Figure 9: **Speed and force profiles of the fast train with a particular initial point by Method 2 with 0.5km-long subsections.**

## 6.2. Simulation of ETCS Level 2

Assume 10 trains are scheduled to travel from Station A to Station D, where the (2x+1)th train is a fast train and the (2x+2)th train is a slow train, x=0,1,2,3,4. The schedules of the first two trains are shown in the following table, and the schedules of the (2x+1)th and the (2x+2)th trains are respectively 10*x minutes later than that of the first and the second trains.

Table 5: **Timetable**

| Train | Type | Station A | Station B | | Station C | | Station D |
|---|---|---|---|---|---|---|---|
| | | Departure | Arrival | Departure | Arrival | Departure | Arrival |
| 1 | Fast | 08:00 | 08:13 | 08:16 | 08:30 | 08:34 | 08:50 |
| 2 | Slow | 08:05 | 08:25 | 08:32 | 08:52 | 09:59 | 10:19 |

The train trajectories in the network without loops (Figure 5(a)) are illustrated in the following figure.

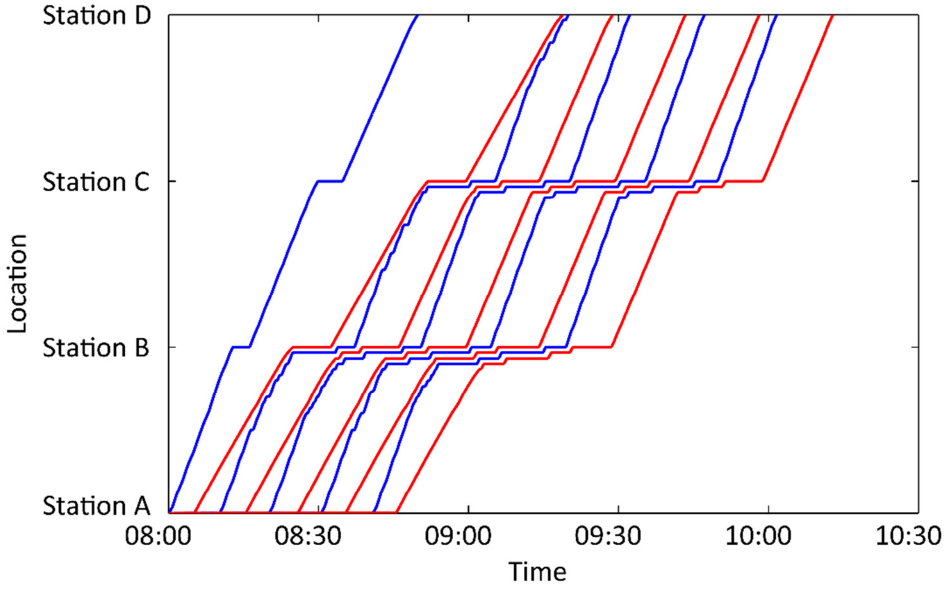


Figure 10: **Train trajectories without overtaking.**

In particular, we show the speed profiles of Trains 1 to 3 between stations A and B, where the blue circles indicate the time points when the control strategy of the corresponding train is calculated. The speed of Train 2 is fairly stable since it is far from the train in front of it (i.e. Train 1), although it has to frequently recalculate its control strategy along the journey. The situation is different for Train 3 since it is very close to the train in front of it (i.e. Train 2), which causes it to stop and recalculate the control frequently.

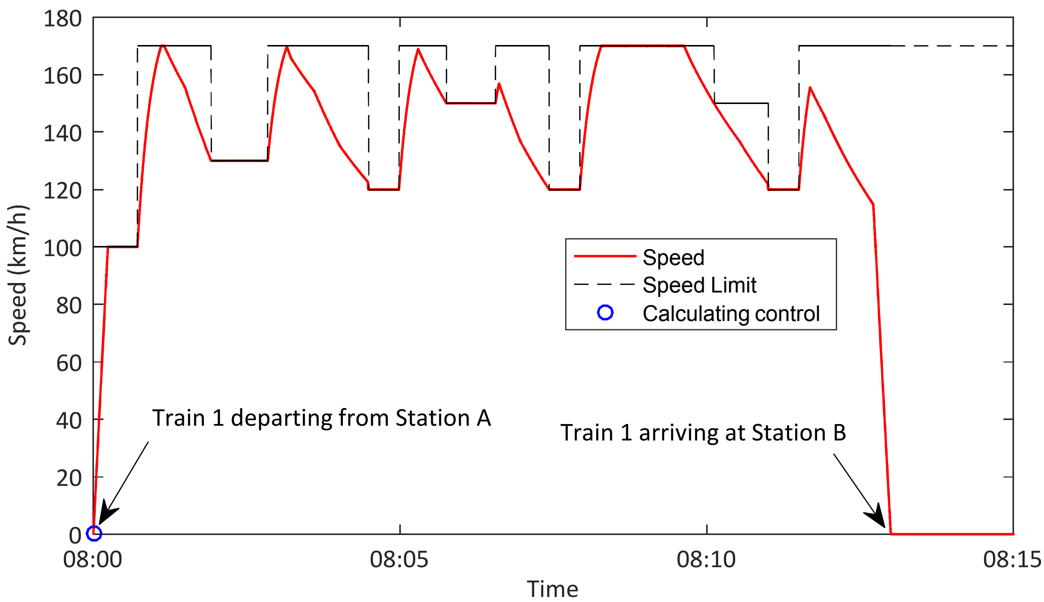


Figure 11: **Speed profile of Train 1 from Station A to Station B.**

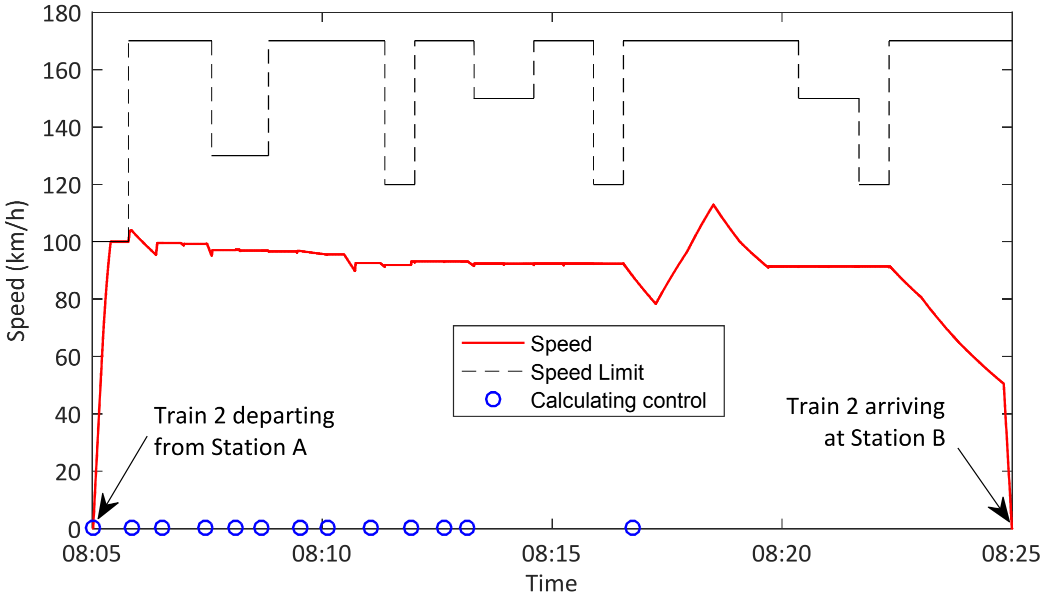


Figure 12: **Speed profile of Train 2 from Station A to Station B.**

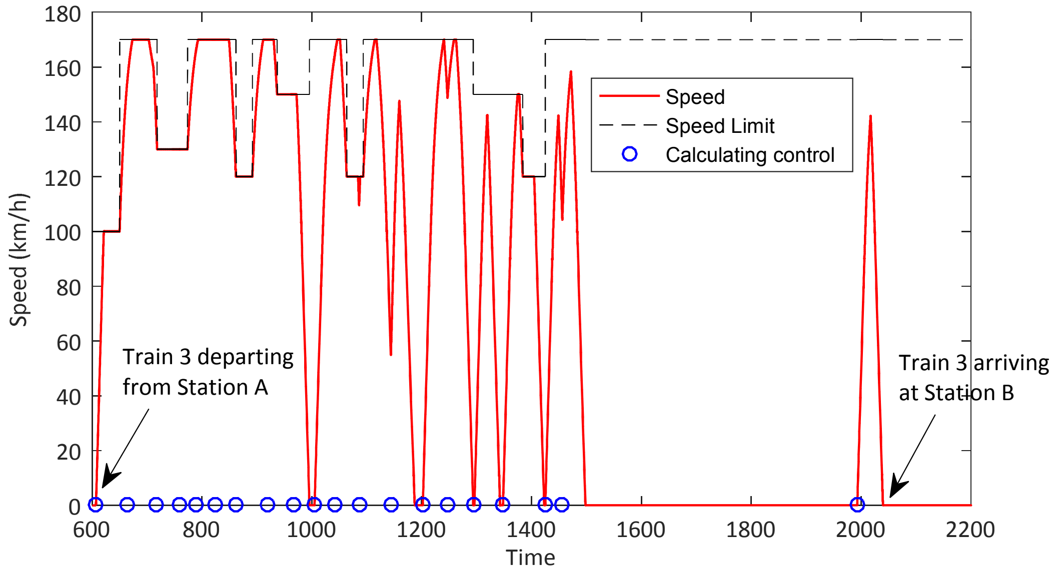


Figure 13: **Speed profile of Train 3 from Station A to Station B.**

The train trajectories in the network with loops (Figure 5(b)) are demonstrated in the following figure. Compared with the case without loops, in this case with loops, the time for all 10 trains to travel from origin to destination decreases from 2 hours and 15 minutes to 2 hours, which is equivalent to a 12% time saving.

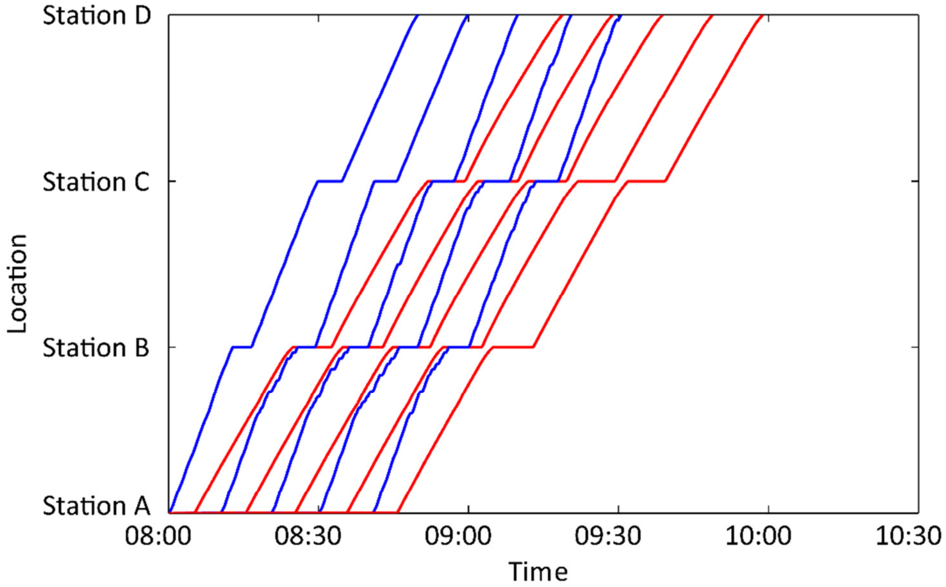


Figure 14: **Train trajectories with overtaking.**

## 6.3. Simultaneous control optimisation of multiple trains

It is evident in Section 6.2 that, when a train is close to its frontal train, it may be forced to stop outside the station and its speed may fluctuate, which will increases the energy consumption and decrease passengers' comfortability. In this case, the simultaneous control optimisation of multiple trains may show its advantage. We consider a case that two trains are scheduled to run from Station A to Station B in the network in Figure 5(b), where the leading train is a slow train and the following train is a fast train. The schedules of these two trains are given in the following table. The optimisation is based on Method 1 and formulated as a nonlinear programming problem involving both trains under consideration. The control profile of each individual train follows the four-stage control strategy, and additional constraints are added that the following train is forbidden to enter a block section unless the block is cleared. We also assume that once the leading train leaves a block, the following train can immediately enter it without waiting for an additional time. The train lengths are set to be zero.

Table 6: **Timetable**

| Train | Type | Departing from Station A | Arriving at Station B |
|---|---|---|---|
| 1 | Slow | 08:00 | 08:18 |
| 2 | Fast | 08:02 | 08:20 |

We first simulate the case when the train controls are calculated separately, as in Section 6.2. The MA is recalculated every 30 seconds, and the train trajectories and speed profiles are illustrated in the following figure. In this case, the energy consumptions are respectively 2885.0kJ/kg and 3506.7kJ/kg for the leading and following trains.

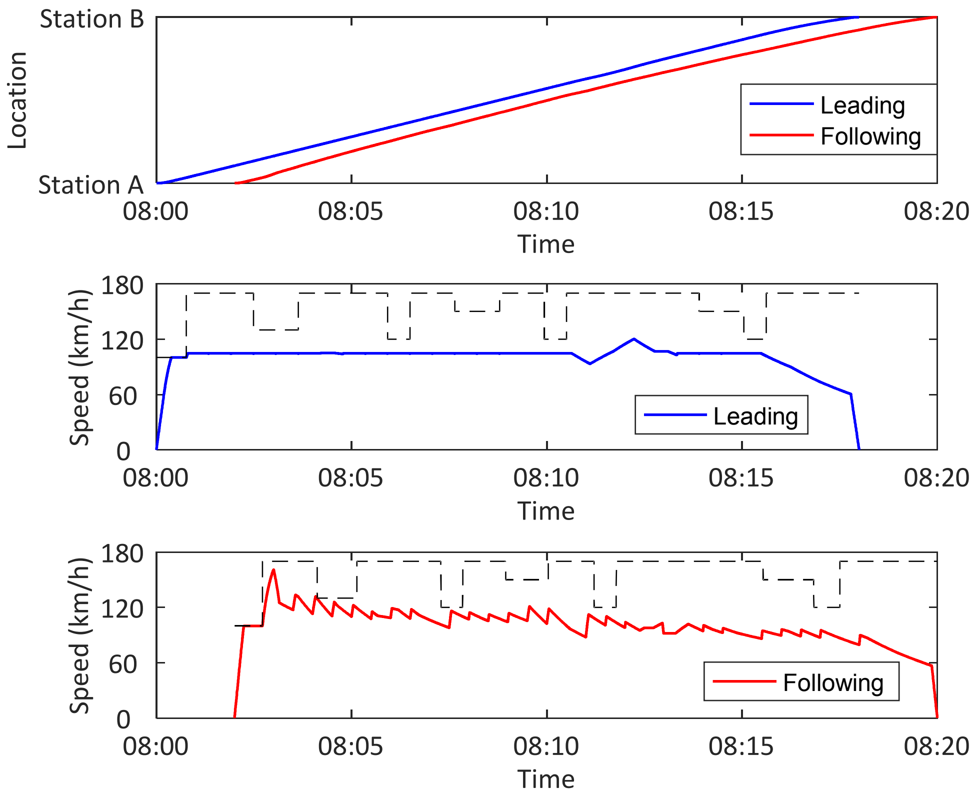


Figure 15: **Trajectories and speed profiles of both trains when their controls are optimised separately.**[5]

Now we consider the situation when the train controls are optimised simultaneously. Again the trajectories and speed profiles of both trains are illustrated in the figure below. The energy consumptions are respectively 2885.2kJ/kg and 2864.3kJ/kg for the leading and following trains. Here, such coordination doesn't change the speed profile (or say the control strategy) and energy consumption of the leading train, but it greatly reduces the speed fluctuation and energy consumption (by 18.3%) of the following train.

[5] The following train's jagged profile results because the following train is very close to the leading train (due to the close departure times). When the leading train leaves a block, the following train's MA is extended, so it recalculates its control profile. On the other hand, since the following train is close to the leading train, so its MA is not very long, which means that soon after accelerating, the train will go to the coasting and braking stages to decelerate. As the MA repeatedly extends, each time for a short distance, the train repeats the traction-coasting-braking operations, which cause the jagged speed profile.

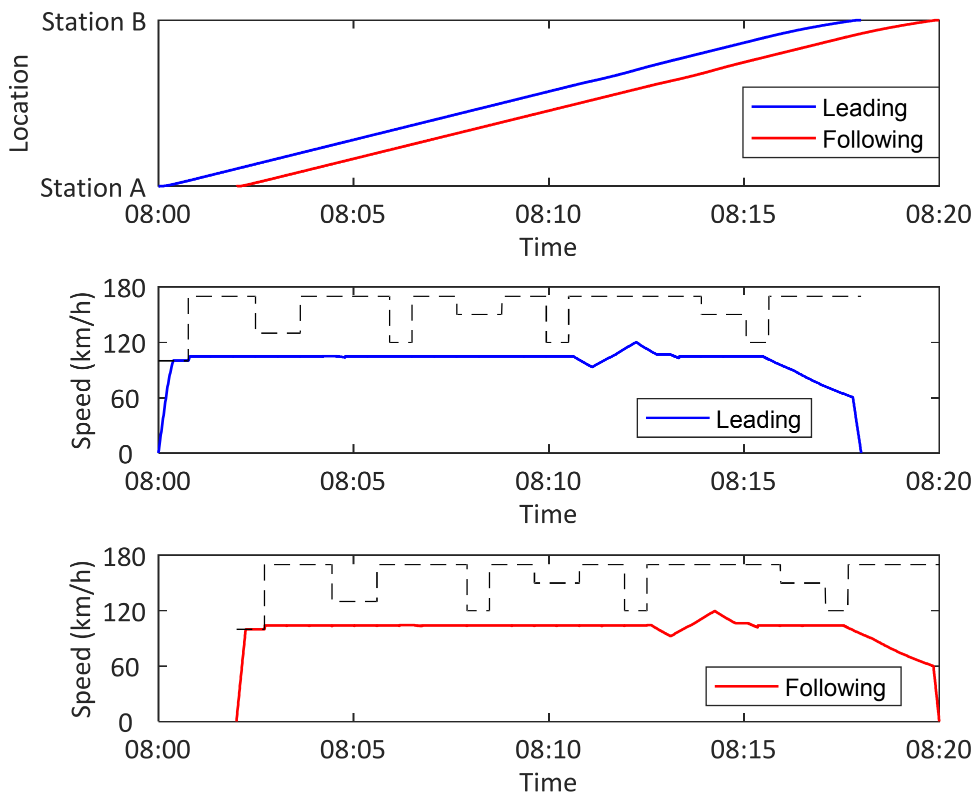


Figure 16: **Trajectories and speed profiles of both trains when their controls are optimised simultaneously.**

# 7. Summary

In this deliverable, we presented the simulation platform for ETCS Level 2. The key features of ETCS Level 2 were summarized, based on which the simulation platform was established. The platform is driven by the interaction among four components: the train simulator, the RBC simulator, the control centre, and the track circuit and interlocking for track occupancy detection. The train simulator consists of the advancing module and the control advisory module, where the former is for simulating the train movement, and the latter is for calculating train control strategies. Two methods (four-stage method and constant-force method) for calculating the train controls were introduced. The RBC simulator and the control centre are respectively in charge of calculating MA and train schedules, based on specific rules. Three case studies were conducted. The first case study compared the two methods for calculating train controls, which showed the advantage of the four-stage method in better energy-saving, and the advantage of the constant-stage method in lower computation effort. The second case study demonstrated the feasibility of our simulation framework in simulating two four-station rail lines, one with loops and overtaking, and the other without them. The third case study illustrated the advantage of simultaneously optimised train control in stabilizing train speed and reducing energy consumption.

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