**WP3 – Modelling**

**Towards Model Based Design of the ETCS Speed and Distance Monitoring**

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# Introduction: Approach of the University of Rostock

One major objective of the openETCS project is the development of a reference system software of the ERTMS/ETCS on-board unit. Therefore the methods of model-based system engineering are used to achieve this goal. The functionality of the overall system is defined in the System Requirement Specification (SRS).

Within the WP3, the functionality of the system shall be implemented in the form of a (semi-)formal model and afterwards transformed into executable source code to make it runnable on an appropriate platform. Within WP4, the created models are examined to ensure that they are specification compliant, what is generally known as verification.

The University of Rostock will be contributing to both modelling and verification activities. We are concentrating on the SRS Subset-026 baseline 3 especially on modelling the chapter 3.13 “Speed and Distance Monitoring”. This specification subset describes the realization of TI and DMI commands by calculating several modules with inputs form train side, track side and odometry. Initially the University of Rostock focuses on the modelling of calculation parts, which are used for safety critical cases using emergency brakes. This especially includes the EBD (emergency brake deceleration) curves. Later on we will expand our modelling activities on other parts of the chapter 3.13.

The added value will be gained by testing extra-functional aspects. We will perform performance and scheduling analyses on our models to give evidence which hardware system is sufficient to meet the system requirements. We want to discover which hardware resources (e.g. number of processors) will be needed for the OBU. This is important to avoid excessive delays to ensure adequate response times in critical situations. Therefore the University of Rostock will do model based simulation using different tools and methods (such as SysML, Simulink and Esterel Scade for modelling and SystemC for simulation). Furthermore we want to build additional system models for comparison and verifying behavior. The following figure summarizes the above described activities of the University of Rostock.

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| Figure 1: Approach of the University of Rostock |

# Short overview of the ETCS Speed and Distance Monitoring

Due to low static friction between wheel and track the brakes of a rail vehicle requires special attention. Compared to a car, a train has a much lower deceleration performance and thus a very long stopping distance. Since danger points (e.g. level crossings) are therefore not visible, the driver is supported by ETCS, which ensures the monitoring of the exact speed and position of a train. To ensure maximum safety, ETCS provides driving information and generates safety-critical braking commands. The chapter 3.13 "Speed and Distance Monitoring" of the requirements specification of the ETCS standard [UNI12] describes the necessary functional units (modules) and calculations. Figure 2 gives a first overview of the relevant inputs, modules and outputs of the (sub)system.

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| Figure 2: Speed and Distance Monitoring, Modules: Acceleration due to Gradient (AdtG), Calculation of Deceleration (CoD), Calculation of Brake Build Up Time (CoBBUT), Most restrictive Speed Profile (MrSP), Determination of Supervised Targets (DoST), Determination of Brake Deceleration Curves (DoBDC), Supervision Limits (SL), Speed and Distance Monitoring Commands (SaDMC) |

## **Train related Inputs**

The train related inputs are locally presented by the train. These mainly include: *Braking Models*, *Special Brakes*, *Brakes Status*, *Onboard Correction Factors*, *Train Specific Parameters*, *Traction Model* and *Fixed Values*.

To calculate the stopping distance the brake performance has to be present. There are two types of mathematical representation, the first is the *brake percentage* and the second type is represented by a *step function*.

The ETCS standard provides four different types of special brakes. Besides the always present pneumatic brakes, the regenerative brake, eddy current brake, magnetic shoe brake and elektro-pneumatic brake may be present. These could be used in different combinations. The actual brake combination also depends on the current state of the brake.

Another important aspect is the consideration of the time which passes until a brake unfolds its full braking force.

In operation, the braking models can serve three different purposes. In case of emergency, the full braking power is calculated, which guarantee the safe operation of a train. In the other two cases, not all input parameters and correction factors are used, because they are not safety-critical calculations.

Correction factors for brake models are necessary because of the braking behavior which depends on changing track conditions (dry, wet or icy).

The deceleration is a subject to statistical variation, which is determined by the train manufacturer on empirical test scenarios and which is indicated with a confidence level.

In addition, even the train length, the maximum speed, the axle load and the train category is of great importance. In all cases the train category defines what speed restriction is applied.

The traction model describes the influence of the motor while performing an automatic emergency brake because there is a time delay after a brake command is given, so the train keeps accelerating.

The ETCS standard specifies all necessary algorithms and defines required constants, so-called "Fixed Values". For example, the nominal reaction time of the driver is enshrined there. For example, the nominal reaction time of the driver is set there.

## Track related Inputs

The track related inputs are the Movement Authority, trackside related speed restrictions and other speed restrictions, the Gradient Profile, track conditions and national values.

The "Movement Authority" is the permission of a train to be able to move in a certain piece of track or section.

From varying track conditions and landscape characteristics different speed restrictions shall be derived. These can be divided into static and dynamic restrictions and are received from the trackside via train equipment. The static speed restrictions arising from the geometry of a specific track section. The dynamic speed restrictions depend on temporary track uncertainties, a possible train category and a specific axle load.

The gradient profile provides information about the track up- and downslopes.

Beside specific track properties, which cause speed limits, there are conditions which affect train operations directly, e.g. in situations with limitations in usage of special brakes and/or sections with reduced adhesion.

The National Values are default values for various calculations or settings and may be defined differently for each track or section.

## Speed and Distance Monitoring Modules

Different modules realize the calculation of the braking commands and driver display information, which are briefly outlined in this chapter. A first high level architectural overview is given in figure [number].

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| Figure 3: High Level Architecture and Data Flow of the ETCS Speed and Distance Monitoring |

The module *“Acceleration due to gradient” (ADTG)* calculates the acceleration of the train caused by an elevation profile of the track (upslope and downslope). Necessary operations in that module are the calculating of the Train length Compensation and the calculation of the acceleration based on the rotating mass of the train wheels (rotating inertia of the wheels).

The module *“Calculation of Deceleration” (CoD)* summarizes/combines the brake model data for the emergency brake and the various influences on the acceleration values to a function, resulting in a position-dependent deceleration function.

The period of time it takes for the brakes to unfold their full braking force is calculated in the module “*Calculation of Brake Build Up Time” (CoBBUT)*.

Due to the variety of different speed limits there is the necessity to identify to any position on track its most restrictive speed limit. This functionality is achieved in the module “Most restrictive speed profiles” (MRSP).

The speed and distance monitoring system has to supervise different targets simultaneously. The module *“Determination of Supervised Targets”* (DOST) shall maintain a list of these targets with exact position and its associated speed.

Braking curves are very important elements in the speed and distance monitoring. They enable the prediction of the stopping distance in relation to a certain speed. They are calculated in the module “*Determination of Brake Deceleration Curves”* (DoBDC). This document focuses on the *“Emergency Brake Deceleration Curve”* (EBD) which represents braking in case of emergency.

The results of all previous functional units (modules) are considered in the module *“Supervision Limits” (SL)*. This module will aggregates all necessary data and calculates a series of supervision limits.

Within the module *“Speed and Distance Monitoring Commands”* (SaDMC) concrete train commands, such as automatic braking are computed. In essence, the monitored targets with its position and allowed speed are compared to the current position and speed of the train. In case of leaving allowed limits interventions are initiated.

# Model-based design of the Speed and Distance Monitoring

## Overall Architecture of the Speed and Distance Monitoring

It is planned to have complete SysML model of the chapter 3.13 of the SRS. The following picture gives an overview of internal architecture of a possible Speed and Distance Monitoring data flow model [draft].

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| Figure 4: Architecture of the Speed and Distance Monitoring Model |

## SystemC Modelling

* The SystemC model is available on Github: [https://github.com/openETCS/model-evaluation/tree/master/model/  
  SystemC\_TWT\_URO/3.13\_Speed\_and\_distance\_monitoring](https://github.com/openETCS/model-evaluation/tree/master/model/SystemC_TWT_URO/3.13_Speed_and_distance_monitoring).
* It is an executable model written in C++/SystemC.
* It calculates an Emergency Brake Deceleration Curve of a given input.
* The results can be plotted with Gnuplot

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| a) | b) | c) |
| Figure 5: Gnuplot visualization of two input step functions (piecewise constant function):  a) A\_gradient(d), b) A\_safe(V,d)  and one output: c) calculated EBD-curve by a SystemC implementation | | |

* More details will follow soon

## SysML Modelling

### Architecture Modelling

* Block Definition Diagram
* Internal Block Diagram

Work in progress. Results will follow soon.

### Behavior Modelling

* Activity Diagram
* State Machine Diagram
* Sequence Diagram

Work in progress. Results will follow soon.

## Simulink Modelling

### Context delineation of the model

Figure 1 on page 7 illustrates that the University of Rostock is dealing with a subset of requirements. This subset contains the following Requirements:

* 3.13.8.1.1
* 3.13.8.1.2 🡪 3.13.6.2.1
* 3.13.8.1.3
* 3.13.8.3.2

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| Figure 6: Context delineation of the model: focused module of the Speed and Distance Monitoring |

### Functionality of the model

* Calculating the EBD-Curve depending on a target location (d\_target), target speed (V\_target) and d\_est\_front [SRS: 3.13.8.1.1]
* based on safe deceleration A\_safe(V,d) where the train reaches zero speed at the target [SRS: 3.13.8.3.2]
* the functionality of the model will be shown by test case data provided by the ERA Braking curves tool (Version 3.0)
* the input data is based on the simplification of piecewise constant functions (step function) containing all relevant information which are condensed to one specific deceleration value in relation to a certain speed of the train and position on the track (or target distance)

### Assumption made

The University of Rostock has made the following assumptions. Given inputs:

Target Speed Monitoring, with:

* d\_target : double = 200 [distance unit]
* V\_target : double = 0 [velocity unit]
* D\_est\_front : double = 0 [distance unit]
* A\_safe(V,d):
  + two dimensional matrix which represents data of the SRS function A\_safe(V,d), containing deceleration values of the train  
    🡪 named: a\_safe\_data (gray)
  + one dimensional vector as distance category (blue)  
    🡪 named: distance\_val = [0 15 30 45 60 … 210]
  + one dimensional vector as speed category vector (orange)  
    🡪 named: velocity\_val = [0 5.55 11.1 16.7 … 44.4]
  + left axes 🡪 speed category index (i)
  + upper axes 🡪 distance category index (j)

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| Figure 7: given A\_safe(V,d) test case data by ERA Braking Curve tool V3.0 (Excel spreadsheet) |

* these data is loaded by a MATLAB script (m-file) in to Simulink for the calculation process:

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| Table 1: MATLAB m-file code example for loading relevant data |
| d\_target=200;  v\_target=0;  d\_est\_front=0;  [num\_data] = xlsread('A\_safe\_data.xlsx');  [a\_safe\_data] = num\_data(2:end,2:end);  [distance\_val] = num\_data(1,2:end);  [velocity\_val] = num\_data(2:end,1); |

### The EBD calculation

#### Introduction

* The EBD curve is called the parachute of ETCS because this is the braking curve in case of emergency
* If there is a position on track where the train has to stop, e.g. a changing speed limit, where the train have to reach zero speed (stop position)
* In case of emergency and from a certain speed the system has to use all available brakes to stop against that location
* There exist several constraints, e.g. the system is not allowed to use all brakes but only a specific combination of brakes or there is a slippery track which reduces the brake performance
* The system has to calculate the position of initiating the braking to reach the stop position under all circumstances
* By a lower brake performance the train will not stop at the desired position on track, that means the system has to brake earlier to stop at the desired position
* in contrast to that, by a higher brake performance the train will stop earlier or the initial braking can be done later, so the braking distance depends on brake deceleration value (brake performance) which is given from A\_safe(V,d), see Figure 8

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| Figure 8: Brake performance and its influence of the brake distance |

* So when the stop position on track and the brake performance on each section of the track are known, the latest possibility of braking can be calculated to stop at the desired position
* so there is a need of backward calculation algorithm, starting from the target location and calculating backwards to estimated front end of the train, see Figure 9
* The result of the algorithm is the maximum speed of the train on a specific position on track
* by exceeding this speed limit the train will never stop on the desired location
* after knowing the maximum speed in comparison to the actual speed, the EVC can intervene and brake automatically

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| Figure 9: Backward calculation of the braking initiation depending on brake performance |

#### Simulink Model for the EBD Calculation

For the calculation of the EBD curve a Simulink model has been implemented. The algorithm for the calculation process can be seen in Figure 10. For a given target distance the algorithm calculates the maximum allowed speed of the train to stop at that target location. The Simulink model use numerous inputs, provided by a balise, which is integrated in the rail bed in front of a possible target. The inputs are: the distance to the target location (d\_target), the desired speed at the target location (V\_target) and the estimated front end (d\_est\_front) of the train (distance covered yet).

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| Figure 10: Calculation of the ETCS Emergency Brake Deceleration Curve (flowchart of data and control flow) |

Another input is a two dimensional step function organized as an array named A\_safe(V,d) containing information about deceleration values (curAcc) of the train depending on the track position (curDis) and the speed of the train (curVel). Therefore a specific deceleration value depending on both, a particular speed and position category (dis\_cat, vel\_cat) is returned. Based on the given inputs the Simulink model calculates iteratively the maximum allowed speed of the train regarding to a specific position on track, which must not been exceeded by the train to stop at the desired target location. The structure of an example A\_safe-data-set is depicted in Figure 11. This function contains a matrix (gray) which represents the deceleration values of the train in m/s2, for a distance category in m (blue) and a speed category vector m/s (orange). Additionally, the left axes represents the speed category index (i) and the upper axes represents the distance category index (j).

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| Figure 11: Example A\_safe-data |

Now the EBD calculation starts as follows. The deceleration value in the target region has to be determined at first. Therefore within a Simulink look-up-table the given target distance in the distance vector is approximated (A\_safe\_data.to\_index(curVel, curDis), realized in Simulink with pre-look-up blocks) and also the relevant index is returned.

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| Figure 12: Determination of the deceleration value of A\_safe-data using Simulink prelook-up-blocks and a look-up-table | |

Because zero speed at the target is considered, the first deceleration value can be derived at the speed index zero and the distance category index selection which depends on the target distance. Thereafter, the the maximum allowed speed is calculated by the formula which is given in Figure 8. The resulting speed (newVel) is calculated until the next lower distance category index because at this position may the deceleration value change and consequently the brake performance also change. Due to the two dimensional characteristic of the A\_safe-data the brake performance also depends on speed. The Algorithm has to check whether the new calculated maximum speed matches into the related speed category, which has been realized through a Simulink If-Condition-Block. There are two possible scenarios. If the calculated maximum speed is lower or equal to next speed stage, the speed category index is incremented by one, the distance category index will be decremented and its value represents the new distance as input to the next iteration of the algorithm. The else case is triggered if the calculated maximum speed is greater than the next speed stage. It must be assumed that there is change in deceleration value on that speed level. In consequence of that, the concrete position regarding to the actual speed level have to be calculated by transposing the formula which is given in Figure 8. The results are saved in a table and the backward calculation algorithm processes as long as the actual train position is reach.

#### Case Study: Train Movement Simulation

In this section, the Simulink model of the EBD calculation is used to simulate the braking behavior of a moving train in case of a speed limit change to zero speed Figure 13. The simulation is interactive, therefore the user is able to manipulate the train movement by setting the actual acceleration value of the train. A positive value will accelerate the train to a desired speed, zero acceleration leads to a constant speed and a negative acceleration is used to decelerate the train until zero speed is reached and the train stands still. The outputs of the train movement block are the actual train speed and the actual train position on the track.

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| Figure 13: Train movement simulator block diagram |

At the start of the simulation, the braking curve of the whole track is calculated. This curve represents the upper speed limit of the train to really stop at the desired location. By reaching the EBD curve the train will automatically brake by using the deceleration of the A\_safe-data, which depends on the actual speed and track position of the train. The output of the EBD Calculator is a matrix which consists of 4 column vectors: start and end position of a deceleration section, its corresponding deceleration value and the calculated maximum speed at the end of each section.

The EBD Sampler calculates, corresponding to actual train position, a maximum speed value by using the formula which is presented in Figure 8. The maximum speed regarding to a specific position is given as an output to the Speed Limiter. The Speed Limiter compares the actual speed of the train with the braking curve speed limit and feeds back a boolean value to the train movement.

In case of equality of both values, the boolean is set to one. The acceleration input switches from manual user acceleration control to automatic braking. Consequently the train slows down and stops at the target location. The result of an example test case is depicted in. Due to several impacts like the brake built up time and possible other tractional acceleration a certain safety margin is subtracted from the EBD. Therefore the both curves are not congruent while the automatic intervention.

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| Figure 14: Simulation result of an example test case |

## Scade Suite Modelling

Work in progress. Results will follow soon.

## Code Generation

Work in progress. Results will follow soon.