BSc thesis Civil Engineering

Variable Static Speed Profiles

within ERTMS on the Dutch rail network

Investigation of the possibilities and implementation of variable static speed profiles based on external characteristics

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ARCADIS, Amersfoort

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BSc Thesis Civil Engineering

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Pictures front page

Top left: OVPro.nl (13-12-2018)
Top right: *ERTMS DMI*, Marten de Vries (19-06-2016)
Bottom: Frans Berkelaar (01-07-2017)

Preface

In front of you lies my bachelor thesis research on the topic of variable static speed profiles. This research focusses on the first steps towards variable static speed profiles within ERTMS on the Dutch rail network and investigates the characteristics and possible implementation of such variable static speed profiles. The research is conducted in the period from April until July 2019 at Arcadis in Amersfoort, at the department of Rail studies and advice.

In the short time working at Arcadis, I have learnt a lot about ERTMS and the rail sector in general, something that had not been discussed in detail during my bachelor. I want to thank all colleagues at Arcadis for answering all my questions and the good working environment. In special, I would like to thank my supervisor of Arcadis, Rikus Koops. Rikus provided me with good feedback and helped me in guiding the research. Furthermore, I would like to thank professor K. Gkiotsalitis for his feedback during the whole pre-thesis and thesis period.

I hope you will enjoy reading my bachelor thesis,

Kelt Garritsen

Amersfoort, July 5th, 2019

Summary [EN]

At this moment, every train on the Dutch network has to follow the same speed limits, except when there are temporary speed restrictions. These speed limits are communicated to the driver via speed signs next to the track. In the following years, the Dutch network manager Prorail wants to invest in the implementation of the European Rail Traffic Management System. ERTMS will no longer use these speed signs but communicates the static speed profile to the driver via a screen, called the Driver Machine Interface (DMI), inside the cabin. However, there are only a few static speed profiles available to choose from, differentiating per type of train, while it would possibly be beneficial if there would be more static speed profiles to choose from, variating for multiple other characteristics. Such a system does not exist in the current ERTMS implementation.

The goal of this research is to investigate which external characteristics determine the current static speed profile, how these characteristics could be variated and how these variable characteristics could be used to design variable static speed profiles. This research can be seen as an exploratory research on the topic of variable static speed profiles (VSSP's).

First, a literature review and expert interviews were conducted to investigate the workability of ERTMS and to determine the influential external constraints that influence the current static speed profile. These constraints are divided into two major categories: hard constraints that cannot be altered in different situations, and soft constraints that can be varied in different situations. The soft constraints provide room for variability of the maximum speed on a track section. The characteristics *noise and vibration nuisance, catenary system, railroad switches, passing a station* and *passing curves* have been identified as soft constraint. The identification as soft constraint is mostly due to the variability in condition of materials and different behavior of rolling stock types. All discussed constraints are combined in a Causal Relation Diagram, providing the relations between the constraints.

An assessment on the implementation of variable static speed profiles has been conducted on a micro and macro-level. The micro level discusses the variability of one constraint, namely the *catenary system*. A roadmap has been constructed, which can be used in determining the variability of a constraint and the determination of a decision model. The roadmap provides the steps needed to construct a VSSP. The decision model is a framework for the selection of the best VSSP, based on the key performance indicators: time of delay, capacity usage and energy consumption.

An experiment, using the Xandra simulation software, on the implementation of VSSP's showed that it can indeed decrease the time delay. However, the effect depends heavily on the VSSP of other trains on the network and the possible acceleration of the train itself. Increasing the speed from 140 km/h to 160 km/h did in potential safe 65 seconds of travel time, but this effect was accomplished over 20 kilometers of track. In a delayed situation, the decrease in travel time was 48 seconds, due to slow acceleration. Hence, the benefit of implementing VSSP's should not only be reducing delay, but also in increasing the capacity, and reducing energy consumption and wear-off when driving on time.

The macro-level assessment discussed, based on literature and interviews, the implementational options of variable static speed profiles are discussed. Two options are discussed in general; (1) implementation of VSSP's in the ERTMS software, making use of the data and sub-systems of the ERTMS level 2 and level 3 implementation. A computerized decision model should choose the best VSSP based on historical data and the defined KPI's. Another option (2) is letting the traffic controller actively adjust the VSSP of the train, according to the situation.

The implementation of VSSP is still far from reality. This research has tried to identify the most promising soft constraint that can be used to variate the now static speed profiles. Furthermore, the steps towards implementation and construction of VSSP's have been discussed. An experiment gave an idea on the effects of VSSP and the possible use in case of delays. What can be concluded from the research is that a lot of data on all different constraints is needed to select the right VSSP based on a decision model. It is therefore recommended to start with monitoring influential characteristics in a VSSP database and putting more research into the policy side of implementing variable static speed profile within ERTMS.

Samenvatting [NL]

Op dit moment moet elke trein op het Nederlandse spoornetwerk dezelfde snelheidslimiet volgen mits er geen tijdelijke snelheidsbeperkingen in werking zijn. Deze snelheidslimieten worden via borden die naast het spoor staan naar de machinist gecommuniceerd. In de komende jaren wil Prorail daar verandering in gaan brengen door het implementeren van het *European Rail Traffic Management System*, voornamelijk omdat met dit systeem treinen dichterbij elkaar kunnen gaan rijden. ERTMS zal niet langer gebruik maken van de snelheidsborden langs het spoor, maar zal een statisch snelheidsprofiel communiceren naar de machinist via een scherm in de cabine, genaamd de *Driver Machine Interface*. Er zijn maar een select aantal van deze statische snelheidsprofielen beschikbaar, deze profielen verschillen voor passagiers- of goederentreinen. Echter, het zou in theorie gunstiger zijn als er meer statische snelheidsprofielen zouden zijn, waarbij gevarieerd wordt op meerder andere karakteristieken. Een systeem waarbij het snelheidsprofiel wordt gevarieerd op basis van vele factoren bestaat niet in de huidige ERTMS-implementatie.

Het doel van dit onderzoek is dan ook om te onderzoeken welke externe factoren de maximumsnelheid in de spoorsector beïnvloeden, bij welke karakteristieken deze variabiliteit gehaald zou kunnen worden en hoe deze variabiliteit gebruikt kan worden om variabele statische snelheidsprofielen te ontwerpen. Dit onderzoek kan worden gezien als een verkennend onderzoek voor het implementeren van variabele statische snelheidsprofielen (VSSP).

Op basis van literatuuronderzoek en expertinterviews zijn eerst de werking van de huidige ERTMS-levels en invloedrijke externe karakteristieken op het statische snelheidsprofiel onderzocht. Deze karakteristieken zijn onderverdeeld in twee categorieën: harde beperkingen (*hard constraints)* vormen een grens voor de maximumsnelheid die niet te overschrijden is, en zachte beperkingen *(soft constraints)* die een variabele snelheidsgrens vormen en gevarieerd kunnen worden in verschillende situaties. Deze zachte beperkingen geven ruimte voor variabiliteit van de maximumsnelheid. *Geluids- en trillingen overlast, het bovenleidingsysteem, wissels, passeren van stations* en *het passeren van bochtstralen* zijn in dit onderzoek geclassificeerd als zachte beperking. Deze classificering is gebaseerd op de variabiliteit van de conditie van materialen en verschil in gedragingen van typen treinen. De besproken karakteristieken zijn samengevoegd in een causaal relatie diagram, die de verbanden tussen alle karakteristieken laat zien.

Hierna is een beoordeling van de VSSP-implementatie uitgevoerd op een micro- en macroniveau. Op microniveau is de variabiliteit van een zachte beperking geanalyseerd, namelijk het bovenleidingsysteem. Om tot een beslismodel te komen waarmee de variabiliteit van de maximumsnelheid bepaald kan worden, is een stappenplan ontwikkeld. Dit stappenplan geeft aan welke stappen nodig zijn om tot een variabel snelheidsprofiel te komen. Het beslismodel biedt een kader voor de selectie van een VSSP, gebaseerd op de kritieke performance indicators: vertraging, capaciteit van het netwerk en energiegebruik.

Een experiment op de effecten van VSSP's is uitgevoerd in Arcadis' Xandra simulatie software. De resultaten van het experiment laten zien dat invoeren van variabele statische snelheidsprofielen vertraging kan doen afnemen. Echter, het effect hangt zeer af van andere factoren, namelijk het VSSP dat is toegewezen aan andere treinen op het netwerk, én treinkarakteristieken, zoals de maximale versnelling van een trein. Het verhogen van de maximumsnelheid van 140 km/u naar 160 km/u heeft in het experiment de rijtijd met 65 seconden doen verminderen, maar hiervoor heeft de trein wel 20 kilometer spoor nodig gehad. In een vertraagde situatie kon de rijtijd maar met 48 seconden worden verminderd, omdat de trein meer tijd nodig had om op maximale snelheid te komen. Het voordeel van VSSP's moet dan ook niet alleen gezocht worden in het

verminderen van vertraging, maar ook in het vergroten van de capaciteit en het verminderen van energiegebruik en schade aan infrastructuur.

Op het macroniveau is op basis van literatuur en interviews de implementatie van VSSP's in ERTMS besproken. Twee opties worden als meest realistisch gezien, namelijk: (1) het implementeren van een beslismodel in de ERTMS-software, waarbij gebruik wordt gemaakt van de verzamelde data en subsystemen van ERTMS-level 2 en level 3. Een computer beslismodel zal op basis van de KPI's een keuze moeten maken voor het meest ideale VSSP. Een andere optie (2) is de keuze leggen bij de verkeersleiding, waarbij de verkeersleider het snelheidsprofiel van een trein actief kan bijsturen, afhankelijk van de situatie. De effecten van beide opties worden in het onderzoek besproken.

Het implementeren van variabele statische snelheidsprofielen is nog ver weg. Dit onderzoek heeft gepoogd om de meest veelbelovende zachte beperkingen op de maximumsnelheid in kaart te brengen. Verder zijn de stappen richting het implementeren van VSSP's uiteengezet. Een experiment heeft mogelijke effecten van de implementatie aan het licht gebracht, zodat hiermee rekeningen kan worden gehouden. Er kan geconcludeerd worden dat veel extra data nodig zal zijn; alle karakteristieken moeten in kaart worden gebracht per baan sectie, om de variabiliteit van een statisch snelheidsprofiel voor die specifieke sectie te kunnen bepalen. Er wordt daarom ook aanbevolen om de in dit onderzoek vastgestelde karakteristieken te gaan monitoren en bij te houden in een database. Verder zal nog meer onderzoek nodig zijn aan de beleidskant van de implementatie van VSSP's in ERTMS, aangezien dit met vele stakeholders vastgesteld dient te worden.

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List of abbreviations & definitions

ATB	*Automatische Trein Beïnvloeding*	Conventional Dutch train protection system. Two systems are used: ATB-EG (First generation) and ATB-NG (New generation).
ATC	Automatic Train Control	General class of train protection systems.
ATP	Automatic Train Protection	General term for a train protection system.
BTM	Balise Transmission Module	Onboard system that reads trackside balises and can determine the trains location based on the balises.
DMI	Driver Machine Interface	The screen in the cabin which informs the driver about the maximum speed and other characteristics.
DSP	Dynamic Speed Profile	Train specific speed profile, which modified the SSP using train specific characteristics, such as the braking capacity of the train.
ERA	European Railway Agency	An agency from the European Union that sets standards for the rail network in Europe.
ERTMS	European Rail Traffic Management System	Specification of the new European system, containing trackside, onboard and communication systems.
ETCS	European Train Control System	The products of the ERTMS specifications.
GSM-R	Global System for Mobile Communications – Railways	The communication system between the ETCS on board and the ETCS trackside material.
LEU	Lineside Electronic Unit	Will provide the balises with information of trackside signals, so that the ETCS system in the train can use the conventional signals. (ERTMS Level 1)
MRSP	Most Restrictive Speed Profile	Based on different speed limitations the most restrictive speed limitations are combined to MRSP. This MRSP is a static speed profile.
SSP	Static Speed Profile	The speed limitations the train must follow. These are static and cannot vary per train in the schedule. Different types for passenger and freight transport.
VSSP	Variable Static Speed Profile	The proposed new speed profile. Multiple static speed profiles to choose from, variable to all kind of conditions: weather, time of day, condition of infra, etc.

1. Introduction

The problem context and motivation of the research are discussed in this chapter. Furthermore, the research aims, and objectives will be set, before the methodology of the research is pointed out. This chapter will give an overall idea of the research and its significance to real problems.

1.1. Problem context

In the current situation, almost every country in Europe has a different train protection system. Resulting, for example, in the fact that running international trains is difficult. To replace the older systems and to end the differences in signalling systems and train protection systems between European countries, the European Rail Traffic Management System, ERTMS in short, has been introduced. ERTMS is an international standardisation for train protection. The train protection system within ERTMS is characterised by using signals in the cabin of the train driver. The system shows the train driver the maximum allowed speed on a special display in the cabin. Besides that, the ERTMS based system can take control of the train when the driver is speeding (Railway Signalling, 2014).

At this moment, ERTMS has been implemented in different countries throughout Europe and also in non-European countries (UNIFE, 2014). Safety and interoperability are the main reasons to implement ERTMS, as well as the current systems becoming too old and unreliable. For example, Belgium wants the complete network to operate under ERTMS in 2022. Denmark also tries to renovate the network with an ERTMS system before 2021 (Goverde et al., 2012). In the Netherlands, ERTMS will replace the older ATB train protection system at some specific places. (Ministry of Infrastructure and Environment, 2016). With this older ATB system, the maximum speed on the railways in the Netherlands is shown by signs next to the track. Three examples of such speed signs are shown in Figure 1.1.

Figure 1.1 - Examples of railway speed signals. (left = reduce speed to 40 km/h, center = maximum speed is 40 km/h, right = increase speed to free track section speed of 130 km/h) (source: P.Bech, 2007*)*

Most of the times it is unknown why a particular speed regulation is shown by a sign like the ones in Figure 3.1, and what it is based on. But when switching to ERTMS, all these speed regulations must be digitalised to a speed profile. Using the position of the train, train specific characteristics and this static speed profile, the system gives information to the train driver about the allowed maximum speed of the train and when the train has to start braking (Slootjes, 2013). The used ERTMS in the Netherlands provides the train driver with a static speed profile the driver must follow (Červenka, 2017).

1.2. Motivation

At this moment it is not possible to choose per train a specific speed profile, which would be the most optimal for that specific train. This is because the current ERTMS software does not allow for more than a few static speed profiles on the Dutch rail network, which are only differentiated per type of train, i.e. the difference between passenger or freight trains. It has also been introduced that the driver interface of ERTMS could show an advisory speed. This speed is not based on the timetable but can be given by the traffic control centre (Rookmaaker et al., 1998). The ERTMS system digitalizes the old traditional situation, having only a few static speed profiles.

However, with the new digital system, it could be possible to have multiple static speed profiles. These do not only differentiate per train type, but for other variables as well, such as weather conditions, time of day or the condition of infrastructural elements. This was not possible before due to static signs next to the track, but it would be theoretically possible to implement the idea of such variable static speed profiles (VSSP) when the system is digitalized.

For example, it would be beneficial if delayed trains could run faster than the maximum speed where possible, to reduce its delay. A faster and more stable flow of trains in case of delays will increase the capacity of the network (Goverde et al., 2012). To do so, it should be known when a speed can be increased and when a train should cope with the current maximum speed profile. Furthermore, trains that do not have delays can use the running time reserve to drive energy efficient (ten Siethof, 2016). Showing the driver a lower maximum speed when on time, could help in reducing energy consumption, making sure he or she will not drive faster than necessary to get to the next station on time (Scheepmaker, 2013). Also, noise nuisance is rated higher during night-time, causing more external effects. The maximum speed could be lowered in the nightly hours, reducing the nuisance for residents living close to the network. This idea follows from the variable maximum speeds per time of day on the Dutch highways. Comparable systems are currently not implemented on the Dutch rail network.

At this moment, it is not known when the maximum speed is a hard constraint and cannot be altered, or when it is a soft constraint where variation is possible. This is partly since it is not known why a maximum speed is currently in place. Both this information is needed to implement variable static speed profiles and to increase the maximum speed for some instances.

1.3. Research aim

The goal of this research is to (1) investigate which characteristics determine the current static speed profile in ERTMS, (2) investigate their possible variability and (3) investigate how this variability of characteristics can be used to design a variable static speed profile.

Characteristics that influence and restrict the static speed profile are for example: the centre to centre distance between tracks, movement of the overhead wire and cant (Goverde et al., 2012). A list of the most influential characteristics will be determined during the research and can be considered a sub-goal of this research.

1.4. Research questions

Based on the research aim formulated earlier, the main research question of this research can be formulated as follows:

How can a variable static speed profile be designed, based on variations in external constraints on the current maximum speed?

The main question is divided into different sub-questions (S1 to S4) and minor questions helping to answer the sub-question and give an idea of the direction of the answer:

S1. *How does the current ERTMS system select the most restricting speed profile (MRSP)?*

a. Which different constraints does the MRSP take into account?

S2. *Which external characteristics are the most influential hard and soft constraints to the maximum speed profile on the Dutch rail network?*

a. Which objectives determine the influence of the characteristics?
b. Are these characteristics hard or soft constraints on the maximum speed?

S3. *How can the most influential external characteristic be used to variate the speed limitations?*

a. Under which conditions can the soft constraint be varied?
b. How should be decided when the soft constraint should be varied?
c. What are the effects of varying the soft constraint on the delay of the train?

S4. *How could ERTMS cope with variable static speed profiles?*

a. How should be decided which speed limitations can be possible on a track section?

1.5. Methodological approach

From the research aim and questions follows the research approach. This paragraph starts with describing the methodological framework of the research. After that, the most important concepts of the research are defined.

1.5.1. Methodological framework

The methodological process of the research can be seen in Figure 1.2. It shows the framework for the study per sub-question. The orange boxes will form the end product, i.e. answer to the specific sub-question, whereas the blue boxes show intermediate steps. For sub-question S3, simulation software will be used to simulate possible effects of the variable static speed profiles.

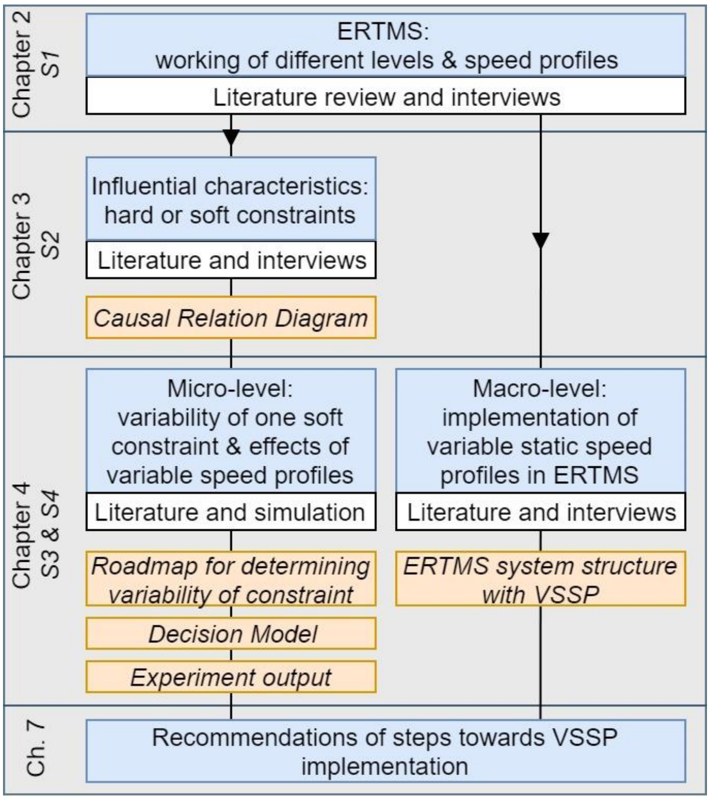

Figure 1.2 - Methodological framework of investigating variability of static speed profiles

The research methodology in Figure 1.2 describes from top to bottom all steps that are set for answering the main research question. It discusses: (S1) the description of the current static speed profiles in ERTMS, which will be done using literature research of policy documents and guidelines from the European Rail Agency and Prorail, and interviews with senior advisors on the topic of rail safety and ERTMS. Influential characteristics follow from this step and together with other external characteristics (S2), the characteristics are divided into multiple categories. These categories, hard or soft constraints, determine the variability of the maximum speed and make it possible to investigate the possible variability. Extensive literature study as well as interviews with experts are used to make this distinction. Afterwards, one influential soft constraint is identified and investigated in a case study on a micro level (S3), to determine how to decide on variability and its effects. This decision model and its effects are compared to the current situation using a simplified simulated situation. A comparison of the results along with a general conceptual model of the possible implementation on macro level (S4) will result in recommendations in the process towards more variable static speed profiles. The most important methods of the research are discussed and explained below.

Literature study
The literature review focusses on finding an answer to the first two sub-questions S1 and S2. It should provide a framework for the identification of constraints and the conceptual implementation model. Therefore, the literature study consists of (a) theory about train protection systems in general, (b) the workability of ERTMS and its sub-systems, (c) variability in other means of transportation and (d) the identification of influences on the maximum speed.

Decision model
Based on constraints and sub-constraints defined in the literature study, one constraint is pointed out and investigated in depth. Therefore, a causal relationship diagram is constructed, based on the literature and interviews, to understand and picture the causes and effects of the constraint. After that, the decision model will provide a conceptual model for the future implementation of the variable static speed profiles. This helps in answering the third and fourth sub-questions.

Simulation of experiment
The effect of one of the constraints on the driving time and performance of trains will also be evaluated in this research. Arcadis' simulation tool *Xandra* (see Appendix C) will be used to measure the effect of using a variable static speed profile instead of the current static speed profile. Different situations of delay will be simulated, providing a sensitivity analysis. The outcomes of this analysis should be used in the decision model, to make a discrete decision on when to implement one of the variable profiles. For the simulation model, data on the rolling stock is provided within the simulation software. Infrastructural and timetable data is simplified and fictional but based on a possible real-life situation. The outcomes of the simulations are used to answer S3 and give insights to answer sub-question S4.

1.5.2. Definition of concepts
The most important definitions within this research are provided in the list of abbreviations. However, some concepts used in the research need further explanation and delimitation. The definition of concepts will be the same in the whole report and can be verified in this paragraph.

Different speed profiles
In this research, a new kind of speed profile is proposed, replacing the existing static speed profile. The difference between these two, and the dynamic and most restricting speed profile is described below:

Static speed profile (SSP)
In the current situation, a static speed profile is communicated to the train (within ERMTS or with signs next to the track). This speed profile is based upon hard constraints and cannot be changed, with the exception that there are different static speed profiles for passenger or freight trains. The SSP provides the train the allowed maximum speed at a track section (Slootjes, 2013).

Most restricting speed profile (MRSP)
In general, the MRSP is equal to the static speed profile, but considers temporary speed restrictions. These temporary restrictions could be cause by maintenance work or dangerous situations (Červenka, 2017).

Dynamic speed profile (DSP)
The dynamic speed profile is a calculated speed profile, where the ERTMS system takes into account the SSP and the characteristics of the train itself, like the actual speed and braking capacity of the train. The DSP can be seen as a train specific SSP, giving the driver more information about the braking moment of her train (Goverde et al., 2012).

Variable static speed profile (VSSP)
This concept is introduced within this research and is currently not existing. The static speed profiles cannot be varied for different constraints, only for the type of train. The variable static speed profiles will change this: it provides a static speed profile, adapted to the real time situation. It is variable for all kinds of characteristics, e.g. the time delay or condition of the overhead wire.

Type of constraints
To find the variability within the static speed profile, a distinction between soft and hard constraints should be made. Below, the definition of both concepts is provided:

Hard constraint (HC)
Limits the maximum speed directly and cannot be varied nor exceeded in different situations.

An example would be the relation between the maximum speed and the centre-to-centre distance of two parallel tracks; when increasing the speed, too much air movement will occur, which will cause dangerous situations. Therefore, there is a hard limit to the maximum speed.

Soft constraint (SC)
Influences the maximum speed directly, but limit is variable for different situations, due to differences in, for example, condition of materials, train parameters or other external parameters.

An example would be the relation between the catenary system and maximum speed: where the condition of the overhead wire, which depends of the situation, is a soft constraint on the maximum speed. Per situation should be identified what the maximum speed can possibly be.

1.6. Readers guide

This research follows the structure of the methodological framework, as proposed in paragraph 1.5.1. Chapter 2 presents theoretical background information on the workability of ERTMS and speed profiles. Furthermore, it discusses the differences between implementation levels of ERTMS. Chapter 3 discusses the influential characteristics on the maximum speed and provides a causal relation diagram, which is used to have clear understanding of the relations between different characteristics. In chapter 4 the connection between ERTMS and variable static speed profiles is made. The implementation of such variable static speed profiles is discussed on a micro-level, including simulations results and a possible decision model, and a macro-level, where the integration within ERTMS is discussed. After that, chapter 5, 6 and 7 discuss the discussion, conclusion and recommendation of the research.

An extended list of definitions and abbreviations can be found on page 9.

2. Background theory on train protection

As an introduction to train protection and to answer the first sub-question: '*How does the current ERTMS system select the most restricting speed profile?*', literature has been reviewed and experts have been interviewed. This chapter will provide the answer to this question but will start with discussing background theory on the current train protection system and the ERTMS system in the Netherlands.

2.1. Introduction to train protection

The Netherlands have a complex rail network with more than seven thousand kilometres of track and 164 million train kilometres per year, considering intercity, stop service and freight trains (ProRail, 2019). To keep all those trains operating correctly, a traffic management system is in place to manage all trains in the network. The trackside system detects the position of trains on the network, checks if there are no conflicting routes between two trains and sets the correct switches. In the current situation, the movement authority for a train is communicated via trackside signals to the train driver. Furthermore, on-board train protection systems can influence the train in case of a human failure (e.g. overspeeding or passing a red signal). The most used train protection system in the Netherlands is the ATB system in combination with NS'54 trackside signals. In the future, more sections of track will switch to new the *European Railway Traffic Management System* (Van Es, 2018).

2.2. The European Railway Traffic Management System

Due to the commitment of the European Commission to have more international trains in Europe, a new interoperable operational system for the European rail network has been developed. This system is called the *European Railway Traffic Management System*, in short *ERTMS* (Schuitemaker & Rajabalinejad, 2017). Its goal is to increase the interoperability and safety in rail transport across Europe (Forsberg, 2016) and according to the Dutch Ministry of Infrastructure, it is expected that the implementation of ERTMS will indeed reduce the number of red signal passes significantly (Ministry of Infrastructure and Environment, 2016). At this moment, the system is implemented on some parts of the Dutch rail network, including the HSL and the rail section between Amsterdam and Utrecht (Ministry of Infrastructure and Environment, 2016).

ERTMS is considered to reduce the risk of human errors by continuously verifying the speed of the train and comparing it to the maximum speed allowed (Schuitemaker & Rajabalinejad, 2017). In general, the system therefore makes use of two different programmes: *ETCS (European Train Control System),* which is the signalling system of ERTMS, and *GSM-R (GSM-Railways)*, the standard for wireless communication. GSM-R works in the background whereas the ETCS shows the signal to the train driver in the cabin, via the DMI *(Driver Machine Interface)*. ERTMS will implement these systems (e.g. the ETCS) in different steps, called levels. The highest ERTMS levels will no longer use the speed signs and signals next to the track, but will communicate the speed profile on the display of the driver using the GSM-R to track the location of the train (Railway Signalling, 2014).

2.3. Technical implementation of ERTMS

As previously stated, ETCS is the system that directly controls and protects the train. Different so-called levels of ERTMS are developed with different roles for the current protection and detection systems. Higher levels will have more advantages, like higher capacity and faster travel times, but their sub-systems are also more expensive and difficult to implement (Slootjes, 2013). Which system is implemented will be determined by the demands and wishes of the network manager and the capabilities of the current ERTMS software (Van Es, 2019). In this paragraph, the different application levels of ERTMS are compared with the current Dutch train protection system.

2.3.1. Current system: ATB-EG

The current system used on almost all rail sections of the Netherlands, uses static block sections with NS'54 trackside signals. At a given point in time, only one train is allowed in a block section. When a train is positioned in one of these block sections, other trains are not allowed to enter this section. The signal at the beginning of this section will show red. The section before the occupied section will show a yellow sign, because of the long braking distance of a train. This obligates the train to reduce its speed to a maximum of 40 kilometres per hour. When a train will drive faster than this maximum speed, the *Automatic Train Control* system (ATB-EG) will warn the driver and, when he does not intervene, stop the train to a standstill (ten Siethof, 2016).

The maximum speed on a certain piece of track is also controlled by the ATB system. Train drivers must spot and act accordingly to trackside sign that communicate the maximum speed. For example, by an yellow 8 sign, which means that the train has to slow down to 80 kilometres per hour (Van Es, 2019). When the driver does not comply, the ATB system will first warn and when there is no response, intervene with an emergency braking to a standstill (ten Siethof, 2016). One remark should be made here, as the ATB system can only secure a few maximum speeds, that are 40km/h, 60km/h, 80km/h, 130km/h and 140km/h.

There are some disadvantages when using the ATB-EG system. The block sections used in the system are mostly longer than modern (passenger-) trains need to brake before a standstill. This causes for a longer following distance between trains than needed in the optimal situation. Furthermore, using track circuits for detection is not precise. The precise location of the train is not known by the system, while this would be important for optimal operation of the rail network. The systems used in ERTMS can partly solve these shortcomings, because it uses smaller block sections with more precise detection systems (Slootjes, 2013).

2.3.2. ERTMS Level 1

Level 1 of the ERTMS implementation does not differ a lot from the current ATB-EG system and the system is mostly combined with the current system of trackside signals. Detection of the train is done with axle counters, and balises will provide the train with its static speed profile and signals. These electronic units are found at the beginning of each block section where also a trackside signal is present. The difference with the ATB system is that signalling can occur via cabin signalling or trackside signals (Goverde et al, 2012). The state of the trackside signals is communicated to the ETCS system through the balises. The DMI will show the state of the signals and the maximum speed but will not show detailed information specific for the train. It is only one-way data to the train, whereas the train does not communicate its position itself (Van Es, 2019).

2.3.3. ERTMS Level 2

ERTMS Level 2 does not make use of the trackside signals and the ATB system. The system can use shorter static block sections and cabin signalling using the ETCS sub-system. The following distance between two trains will depend on the braking distance of the second train towards the position of the first train's last block section. This is a much shorter distance than with the current system, because the location of the train is monitored more precisely, using smaller block sections and axle counters (Slootjes, 2013). The moving authority and maximum speed of the train is communicated via the ETCS communication system instead of the trackside signalling (Van Es, 2018).

To summarise, the second level uses the on-board ERTMS systems, but the conventional trackside detection and interlocking systems. With level 2, the GSM-R train positioning and train integrity is not trusted, so the system relies on the trackside detection (ProRail, 2013). Level 2 is currently the most popular and most integrated ERTMS version. Figure 2.1 shows the difference between the different implementation levels of ERTMS. The left train is following the train on the right and the figure shows the difference in used trackside and train board technique. One remark should be made that with higher ERTMS levels, riding closer together is possible, which is not shown by the figure of Ter Beek et al. (2018).

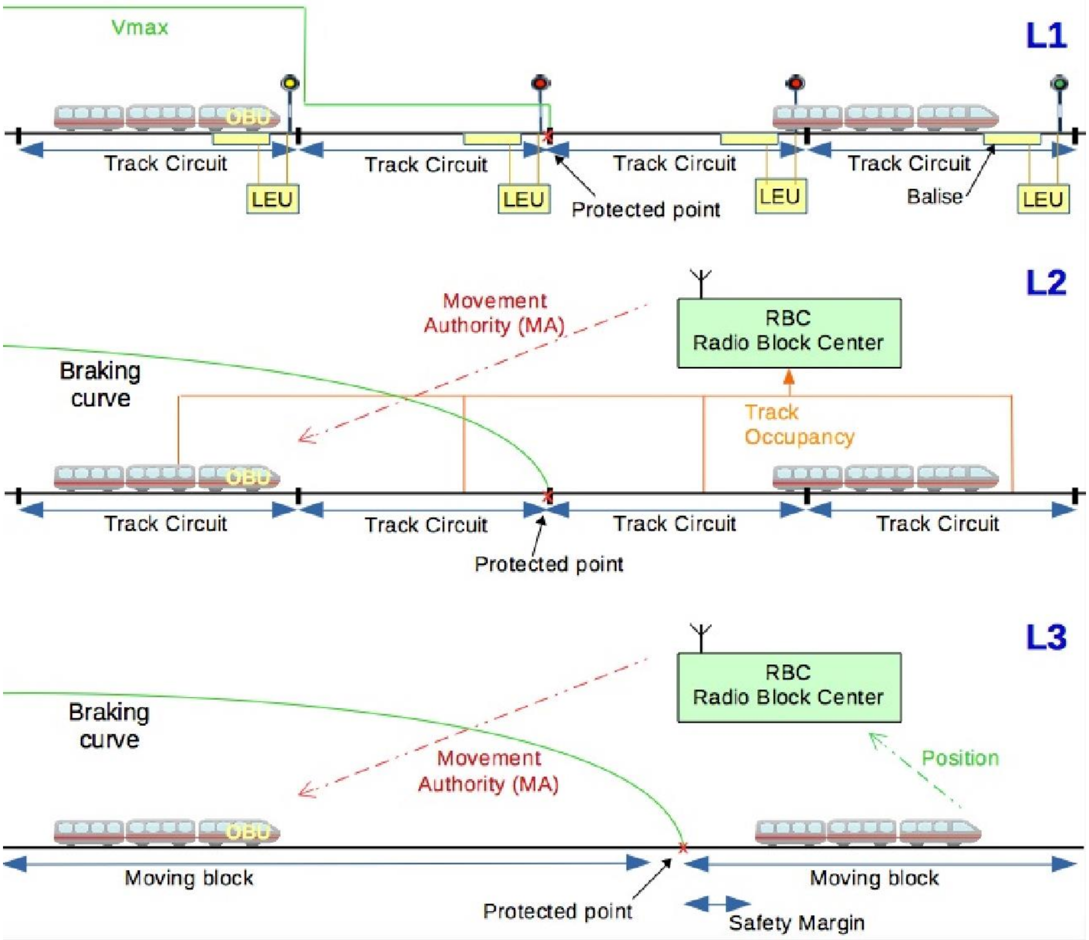

Figure 2.1 - Difference between the three ERTMS implementation levels (source: Ter Beek, Fantechi and Gnesi, 2018*)*

2.3.4. ERTMS Level 3

Level 3 of ERTMS uses virtual block sections between two following trains. Positioning of the train depends only on the GSM-R radio communication and not on trackside systems. Statistics of the train – like the speed, length and position – are communicated with the RBC *(Radio Block Centre)* every approximately 10 seconds. The location of the train is validated using electronic beacons next to the track. The system will create a moving block around the first train (Railway Signalling, 2014). By doing so, a second train can follow the first train with only the absolute braking distance spacing between them, instead of using the static block sections (Slootjes, 2013).

In the third level of ERTMS, there will not be trackside detection of the train. This causes the problem of train integrity. When a train loses a car, this car will no longer be detected by the trackside detection and can cause problems for oncoming traffic. A solution for this problem is the implementation of an ETCS system in the rear end of the train, which most passenger trains have already, but freight trains do not. Only when it is known that the train is fully complete, the train will be integer. Not-integer trains, mostly freight trains are the problem with the roll out of ERTMS Level 3 at this moment (Van Es, 2019).

2.4. Comparison of ERTMS levels

The levels of ERTMS discussed in the previous paragraph are not all versions of ERTMS that are available. There are some more overlay or hybrid levels, where the functionality of the new and conventional is combined (Slootjes, 2013). These levels are not considered in this review. The three levels of ERTMS are compared on their effects on the capacity and train, and on their subsystem architecture.

Comparing the different implementation levels of ERTMS will show how the system becomes smarter in higher levels and what the abilities are of the systems. The application of the different levels depends on the requirements and demands from the network, operation and existing infrastructure (Kalvakunta, 2017), but the on-board systems are almost identical for the different levels; changing between different levels will therefore automatically occur within the on-board ETCS (Van Es, 2019).

2.4.1. Effects of ERTMS levels

Implementing ERTMS Level 1 does not have a significant effect on the current capacity of the rail network. The system must use the current protection system with its subsystems to function correctly. The only main difference is that the signals are now displayed in the cabin instead of outside, which could be easier to detect for the train driver and therefore is safer (Van Es, 2018). Increasing the capacity within Level 1 is possible when extra balises are installed on the track section (Kalvakunta, 2017).

Application Level 2 is clearly different from Level 1, because lineside signals are not required anymore. Trains have on-board equipment to calculate real time the optimal speed of the train The ETCS evaluates the speed continuously and is able to protect the moving authority at every possible speed, also above 140 km/h (Kalvakunta, 2017). Because of the smaller (virtual) block sections, trains can travel closer together, increasing the capacity on the network (Van Es, 2018).

Using ERTMS Level 2 or Level 3 has clear advantages when comparing them to the current ATB-EG system. The systems are safer, because they can influence the speed of the train between 0 km/h and above 140 km/h, whilst this is not the case with the ATB system. Furthermore, the more detailed location of the train will allow the system to calculated where to start braking before the stopping point is reached (Slootjes, 2013). With this more detailed location known, the trains can drive closer, improving the capacity of the rail network. Also, the Level 3 implementation does not require any lineside signalling or detection, which will reduce the cost of maintenance significantly (Van Es, 2018).

2.4.2. System architecture of ERTMS

The different applicational levels consist and make use of different operational sub-systems. The most general systems that are needed within the different levels are shown in Figure 2.2. Not all systems occur in all application levels and the figure shows the differences in sub-systems between the levels.

It can be derived from Figure 2.2 that the difference between Level 1 and Level 2 is the biggest. Level 1 does not have many ERTMS standardized trackside systems and still uses the excising systems, connecting the on-board systems with the signals via the Eurobalises and line side electronic unit. The speed profile of the train is received by these units, that ‘reads’ the signals and signs (Kalvakunta, 2017). Variability of the speed profile is therefore difficult to implement because of this. Only when the *RBC (Radio Block Center)* is in use – which is the case in Level 2 and Level 3 – variations in the speed profile can be made.

The RBC will communicate track data and the speed profile via the GSM-R Euroradio with the train in a data telegram (Van Es, 2018). This telegram is received by the ETCS computer that will combine this data with its exact position on the track, based on the balises and the on-board odometer. In Level 3, the train will communicate its position back to the RBC, while in Level 2 the position of the train is detected by trackside systems (Van Es, 2019). Furthermore, in Level 3 the integrity meter is on-board to make sure the train remains complete, which is not the case in Level 2 of ERTMS.

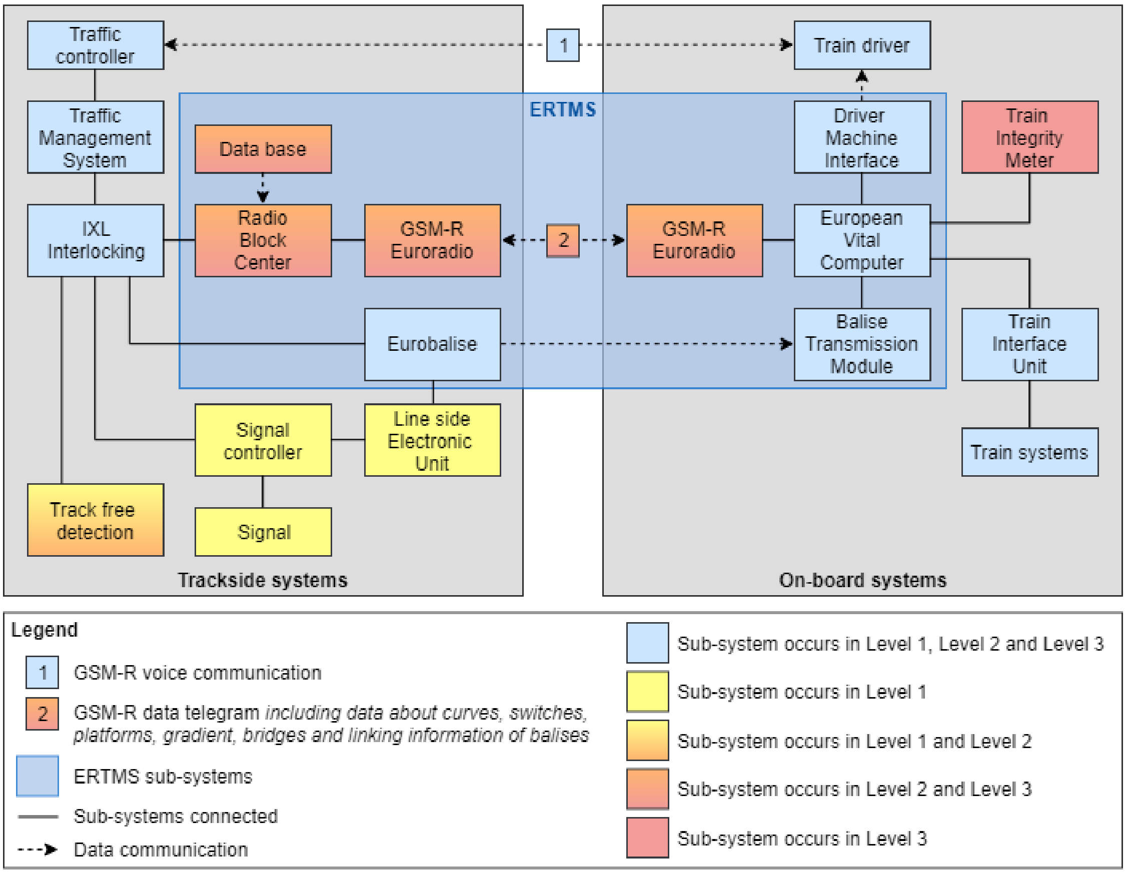

Figure 2.2 - System architecture of different ERTMS application levels (based on Van Es, 2018*)*

The subsystems differ significantly between the application levels. The system gets more sophisticated in higher levels, with less trackside and lineside systems and giving more intelligence to the train itself. But in general, all ERTMS levels provide more safety than the conventional systems (Kalvakunta, 2017).

2.5. The Most Restrictive Speed Profile

In the previous paragraph, the different levels of ERTMS have been reviewed. One of the main tasks of ERTMS is to keep a safe distance between two trains. Another main task of the ERTMS system is to make sure a train does not overspeed the maximum speed set on the rail network.

The ERTMS system can influence the speed using the pre-set static speed profile and the location of the train, which is determined using a combination of balises and GSM-R, as stated before. The ETCS computer will control the speed and can influence the train behaviour (Slootjes, 2013). It therefore uses the *MRSP (Most Restrictive Speed Profile)*, which is the static speed profile the train must follow. It considers the static speed profile and temporary speed restrictions and based upon them, the ETCS computer will calculate the MRSP. When a train is overspeeding or cannot brake on time before a closed (moving) block section, the system will automatically stop the train (Červenka, 2017).

The static speed profile depends on different characteristics, which can be seen in Figure 2.3. The most influential are the track constraints, also called the civil technical constraints. Example of such characteristics are the centre to centre distance between tracks, movement and type of the catenary and cant of the tracks (Goverde et al., 2012). Environmental constraints also influence the static speed profile. For example, vibrations to the ground construction below the tracks. Hence, the environmental constraints are also influenced by the static speed profile; higher maximum speeds have impact on the environment (Van Os, 2019). Based on these characteristics, a static speed profile is designed. This static speed profile is put into the ETCS software and together with temporary speed restrictions, the ETCS will calculate the MRSP.

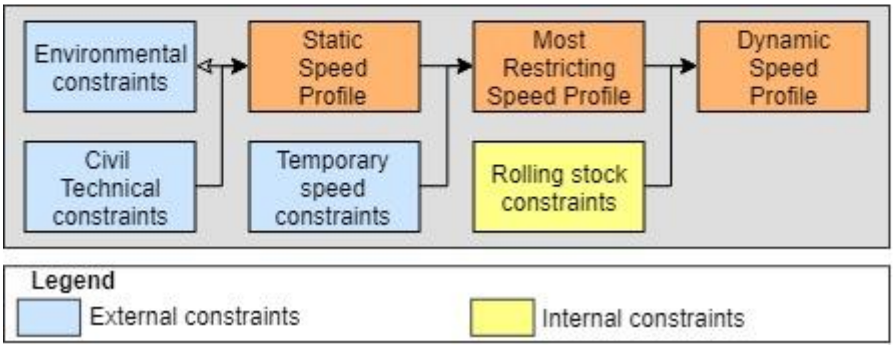

Figure 2.3 - Influences on speed of train

Based on the most restricting static speed profile, the ERTMS system is also capable of calculating a dynamic speed profile. This dynamic profile is based on the most restricting speed profile and characteristics of the specific train itself (i.e. rolling stock constraints), like the actual speed and braking capacity of the train. The dynamic speed profile gives the train driver information about the most optimal braking moment and deceleration (Goverde et al., 2012).

3. Influential characteristics on the maximum speed

The maximum speed on the Dutch rail network is presented by signs next to the track. Of course, these signs do not provide information on the reason behind a speed restriction. However, chapter 2 showed that there are different constraints influencing the static speed profile. This chapter will provide the most common and influential external characteristics that influence the maximum speed to answer the sub-question: *'Which external characteristics are the most influential hard and soft constraints to the maximum speed profile on the Dutch rail network?'*.

3.1. The maximum speed on the rail network

The visualization of the maximum speed on the Dutch network has already been introduced in the previous chapter. The current ATB system communicates the speed restrictions and movement authority to the train driver using trackside signals of type NS'54 and speed signs (Van Es, 2018). The maximum speed on a track piece is typically shown by simple speed signs with a number, corresponding with the maximum speed accordingly. The maximum speed can be different per track section, for example due to passing a sharp bend.

However, the maximum speed is not primarily based upon such infrastructural restrictions. The network has been designed for a specific maximum speed, most of the times the conventional free speed of 130 km/h or 140 km/h, based on the demands of the network manager. For instance, the catenary is designed for the requested maximum speed. When a higher speed is requested, a different catenary system has to be designed (Van Os, 2019).

Nevertheless, the speed on a track sections does not always meet the requested speed. Due to earlier mentioned infrastructural restrictions, the final maximum speed can possibly not be in line with the pre-set maximum speed. This is caused by multiple different constraints that are discussed within this chapter. Figure 3.1 shows as illustration some of the rail assets that form a possible constraint on the speed of a train.

Figure 3.1 - Illustration of some influential characteristics on maximum speed (picture of Van Lieshout, 2014*)*

It was also pointed out in the previous chapter that the current ATB system can only control and secure the speed at five different levels. This means that the current train control system cannot interfere at any given maximum speed on the rail network, as there are more maximum speed levels present than there are ATB control levels (Van Es, 2019). These different levels occur due to the multiple restrictions there are. In fact, the maximum speed between two signals can be 90km/h, caused by curve in the track. Hence, the ATB system is not able to control the train at this speed. However, ERTMS could control the train at any given speed. Putting more effort into these restrictions is therefore interesting when ERTMS will be implemented.

Since the current speed profile is based on a request of the network manager and is static throughout the whole train service, there has not been elaboration on these constraints. This is needed when transitioning towards a variable static speed profile, based on multiple parameters.

Some characteristics influence the maximum speed, meaning that the speed profile cannot be higher than the given restrictions based on the characteristics. In other words, these characteristics can be seen as constraints on the maximum speed. Effects on the other hand, do not influence the maximum speed themselves, but are influenced by the maximum speed. They are not taken into account during the design of a track section beforehand but are considered afterwards. If the effect is too negative, measures are taken to improve the situation. The effects can be seen as a key performance indicator of the rail network. The environmental characteristics can be seen as a combination of the two. They influence the maximum speed but are also influence by the maximum speed requested by the network manager during the design phase of the track section.

Causal Relation Diagrams per characteristic | Appendix A

The characteristics discussed in the upcoming paragraphs provide guidelines for constructing variable static speed profiles. It helps in answering questions like: which characteristics should be taken into account? Which other effects should be monitored? To help within this construction process even further, the causal relation diagram (CRD) per characteristics is discussed in Appendix A. It provides an understanding on the relevant characteristics that should be taken into account when implementing variable static speed profiles.

3.2. Environmental characteristics

The two most important environmental characteristics are the nuisance of noise and vibrations. Trains driving with high speeds produce a lot of sound and also vibrate the ground and air, causing problems to buildings and the basement of the tracks.

3.2.1. Noise nuisance

Trains produce sound and driving faster causes more noise nuisance to the environment (ProRail, 2017). Therefore, noise caused by passing trains has to be below a pre-determined limit, following legislation of the government. These limits are set as yearly maximum sound levels and are measured per 24 hours (Abrahamse, 2019). Besides that, the noise value should be below 70dB, but is preferably below the value of 55dB. Rides during night-time are weighted more heavily in the yearly norms, as people perceive them causing more nuisance (Ministry of Infrastructure and Environment, 2012). To conclude, too much noise is not permissible, but it is not evaluated per individual train ride.

The constraint of noise nuisance is soft constraint. It could have an impact on the speed of the trains in theory, when there are no other constraints, but in practise it is not. When the sound level is too high, measures are taken to the environment, not to the train schedule. Measures would include sound barriers next to the tracks or sound absorbing surroundings (Van Os, 2019). Increasing the speed however can have an impact on for instance the stability of the sound barriers due to heavier pressure waves on the walls, so this would be an effect that should be monitored (Abrahamse, 2019).

When implementing ERTMS with variable static speed profiles, this could change. Although the speed limit cannot be altered for all trains, it is possible for some of them. For instance, a lower speed limit for night and evening trains, to keep the sound level below the limit. Another example would be to different the speed for older and newer, respectively noisy and quieter, rolling stock. So, noise nuisance is a soft constraint, which can be altered per ride to higher and lower maximum speeds.

Conclusion

The environmental constraint of noise nuisance is a soft constraint. The speed profile of a single train does not have to comply with the sound limit (only the average over a whole day). Therefore, the maximum speed can be altered accordingly, depending on the time of day and characteristics of the train itself. If the noise of all trains is on average below the sound limit, some trains could drive faster. It should be monitored how much buffer room there still is in making more noise.

3.2.2. Vibrations

Vibrations of trains are a difficult problem. Past examples have shown that vibrations can cause damage to the basement of the tracks or to nearby buildings. The problem is that the legal guidelines for vibrations are not very detailed. For the nuisance to people, there is currently no such thing as maximum vibration (ProRail, 2017). Because of this, the vibrations of trains passing a house can be seen as effect and not as constraint when looking into the effects for neighbours of the rail network.

There are however guidelines for the damage to buildings. These guidelines follow the SBR-A vibration guideline. The vibrations caused by passing trains cannot be higher than the maximum value. This maximum value can be determined when parameters like the construction of the building, status of the building and type of vibration, are known. When the maximum value is exceeded, the owner of the building can take legal steps in order to receive compensation (Ostendorf, 2017).

Of course, when designing the track layout, vibrations are considered. This is mostly the case for the condition of the subsoil below the track section. When vibrations are too high, the maximum speed needs to be lowered, due to safety issues. But when vibration seem too high for surrounding buildings, other measures will be taken, comparable with the measures against noise nuisance: placing under sleeper pads or installing anti-vibration walls (ProRail, 2017). In other words, it will not affect the maximum speed of the trains. Furthermore, research showed that other factors, like the condition of subsoil, have a much higher correlation with the amount of vibrations than the maximum speed. Therefore, vibrations are not the most important constraint to consider when increasing the maximum speed (Connolly, et al., 2014)

Conclusion

Vibrations can be seen mostly as an effect of trains passing, especially for surrounding buildings. When vibrations damage the subsoil, maximum speed will be altered. In general, the effects of vibrations are different for every train and rail combination and are therefore variable, being a soft constraint. Vibrations can be seen as sort of the same constraint as noise nuisance, where some trains could drive faster if the average of trains will comply to the legal rules.

3.3. Track characteristics

Track characteristics influence the maximum speed directly and follow from the requested track design. The civil technical, i.e. track characteristics that influence the maximum speed on the network the most, are considered in this paragraph.

3.3.1. Catenary system

The catenary system is a railway electrification system that provides the train with electricity energy. Via the train's pantograph, electric current is collected by pressing the pantograph at the overhead wire. In the Netherlands, multiple different catenary types are present on the network. These systems are designed for a specific speed, requested by the network manager (Van Os, 2019). The most frequently used systems are shown in Table 3.1.

The speed is restricted due to these design choices. In addition, incoming wires from other track sections or height variations in the overhead wires influence the possible maximum speed. When driving with higher speeds than the maximum design speed, the damage to the overhead wires will become too extensive. Of course, the system will not immediately breakdown when higher speeds occur, but it cannot be assured that the system will remain working. However, some tests have been performed with increasing the maximum speed under the conventional catenary system (Van Os, 2019).

Table 3.1 - Most common catenary types

System type	Maximum design speed	Information
B1	140 km/h	Conventional, static system
B3 (DAB)	160 km/h	Newer, movable system
B4	180 km/h or 200km/h	High speed, movable system for 1,5kV (180km/h) or 25kV (200km/h)

Furthermore, trains driving with a higher speed will collect current from the overhead wire for a longer period of time. Eventually this could influence the heat stress of the electrical substation – which provides the overhead wire with the electrical power – causing the station to shut down (Schrage, 2010). So, the (heat stress) capacity of the substations influences the possible maximum speed on the network.

To conclude, the catenary system is of important influence on the maximum speed. First of all, due to the design of the construction which limits the maximum speed on the network. Second, the power capacity of the overhead wires in combination with the substations is constraining for the maximum speed. However, when the substations satisfy the power demand, higher speeds could be possible under the conventional catenary system.

Conclusion
The type of catenary system influences the maximum speed, but tests showed that driving faster than the design speed could be possible. This is only the case when all substations comply with the power demand. Therefore, the catenary system is a combination of hard and soft constraints. When the substations satisfy the demand, the catenary is a soft constraint: most trains should oblige the design maximum speed, but it is acceptable if some trains overspeed those restrictions. To do so, the condition of the catenary construction as well as the pantograph should be monitored.

3.3.2. Track positioning

The positioning of the track is important when trains are passing each other at higher speeds or when there is work in operation on the network. Following the guidelines from legislations, every train needs a safe space surrounding the train. With higher speeds, this safe space needs to become larger (Van Os, 2019). Therefore, the centre-to-centre distance of parallel tracks is an important constraint. The current norms state the centre-to-centre distance should be over 4 metres (Van Houwelingen, 1984).

When only a single train is travelling on the track section, no problems should occur. However, passing another train with higher speeds can possibly cause problems, due to the higher air pressure. Especially in tunnels, this could be a problem. At this moment – similar to the catenary system – the position of the track is designed based on the requested maximum speed. It is unclear how the flow of trains is altered when travelling with higher speeds with the same centre-to-centre distance.

Other problems with the track positioning that could occur is when maintenance is in progress next to the track section. If trains pass with higher speeds, the distance from the centre of the track to the so-called *safe zone* is larger. With 140 km/h, this is 2,25 m. But when passing with 160 km/h, this becomes 2,40 m. Higher speed therefore can affect the possibility of working close to the tracks (Schrage, 2010).

Conclusion

It is still unclear what the detailed effect is of the track positioning on the maximum speed. The current situation is designed for a specific, safe maximum speed and cannot be altered. Therefore, this is a hard constraint on the maximum speed. Only when the speed could possibly be higher, it should be considered a soft constraint. To do so, it should be known what the different effect is of different trains on the air movement. The centre-to-safe zone distance is considered an effect of higher maximum speeds, not as a restriction.

3.3.3. Railroad switches

A railroad switch is used to guide trains from one track section towards another. The simple, general switch consists of two fixed rails and two movable, switch rails, i.e. point blades. The position of the point blades determines if the train will be directed on the main line or the diverging route. Because of those turning movements, switches get damaged quite fast. Furthermore, passing a switch with too much speed can cause derailment of the train.

There are different types of switches in the Netherlands. The general switch is a simple switch from one track to another, either right- or left-handed. There are also symmetrical (wye-) switches – connecting two adjacent tracks – and crossover switches, connecting four track sections. These types of switches also have different tangents, which is the tangent between the main and diverging track. The railroad switches, with different types and tangent, that are used on the Dutch network, are shown in Table 3.2 (Van Houwelingen, 1984).

Each type of switch has a different maximum design speed. The most used switches are the 1:15 and 1:18 new generation switch, with a maximum passing speed of 80 km/h. Other switches can be more expensive (e.g. the high speed switches) or produce more noise nuisance (e.g. 1:9 switch) (Hofstra, Huisman, & Westgeest, 2014).

Table 3.2 - Railroad switches on Dutch network (source: Van Houwelingen, 1984)

Switch type	Switch tangent	Maximum design speed	Information
General	1:9	40 km/h	Used on rail yards or side-tracks
General	1:12	60 km/h	Used only when needed on rail yards
General	1:15	80 km/h	Standard used switch for less used track sections
General	1:18	80 km/h	Standard used switch for heavily used sections
Symmetrical	1:20	110 km/h	Not preferable to use
General	1:29	140 km/h	Only when needed for travel time requirements
General	1:34,7	140 km/h	High speed switch
General	1:39,2	160 km/h	High speed switch

The different types of switches all have a different design speed (Van Houwelingen, 1984). This speed is currently a hard restriction for the maximum speed of the train. However, this is based on different sub-constraints, such as the chance of derailment (which also depends on the type of train), tangent of the switch and condition of the point blades. Every switch has its own combination of these constraints, making it variable and a soft constraint. The different sub-constraints should be monitored or calculated to make sure higher speeds are possible.

Furthermore, there are some other measures possible to increase the maximum speed. When installing better and longer guard rail – an extra rail making sure the wheels follow the right track – higher speeds are possible. The risk of riding with higher speeds is the chance of collision with the point blades, caused by damage (Schrage, 2010).

Conclusion

The maximum design speed of a railroad switch is currently determined by the network manager and legislation. However, when all sub-constraints should be monitored and known within the ERTMS system, the railroad switches can be seen as soft constraint. Every switch has of course its own chance of derailment, determining the maximum speed, but now this is generalized to a worst-case scenario. When all aspects behind the chance of derailment at a switch would be known, the speed could be varied in the variable static speed profile.

3.3.4. Stations

The Dutch rail network is full of stations. Approximately, there is a train station every 18 kilometre of track (ProRail, 2019). Due to legislation, trains passing a station cannot drive faster than 140 km/h. This means that trains driving faster than this limit are forced to slow down. For some stations other norms are applied. For instance, passing the station Leiden Central is possible with speeds of 160 km/h (Schrage, 2010).

The maximum speed will assure safe conditions for the people waiting on the station. When trains drive with higher speeds next to the platform, the pressure of the train will cause dangerous air movement (Schrage, 2010). These speed restrictions only apply on the tracks that are located directly to the platform. Passing with higher speeds is not obliged, due to the safety issues. Therefore, variability is possible for the time of day: when there are no passengers waiting on the station (i.e. the station is closed), trains could driver faster.

When there is also a passing track available, for instance when intercity trains pass stopping sprinter trains, those trains are allowed to drive faster. Hence it is important to know the exact location of the train using GSM-R when implementing the variable static speed profiles in ERTMS. Otherwise, the maximum speed of the wrong track section can be communicated to the driver.

Conclusion

The passing speed of a station's platform is determined in legislation and cannot be altered at this moment. However, the passing speed depends on the safety for the passengers. So, when there are no passengers waiting, higher speeds could be possible. The presence of passengers should be monitored and could be determined using the time of day. If that is done, stations are a soft constraint to the maximum speed.

3.3.5. Level crossing

The Netherlands has more than 2000 level crossings (ProRail, 2019). This means that the allowed maximum speed at those crossings form an influential constraint on the maximum speed, because there are so many level crossings. These crossings are designed for a specific maximum speed. The detection distance is determined for this maximum speed. This is important for the proper workability of the level crossing. When driving slower, the crossing will be closed for a longer time. When driving faster, the crossing will not close in time.

Due to the design speed, driving with higher speeds is not always possible. Furthermore, a higher speed also causes a longer closing time of the crossing. Most of the times, higher speeds compared with higher capacity on the track section could cause crossing to be closed more than to be open. This is not desirable for the network manager and the surrounding stakeholders. With higher speeds, the risk that for derailment in case of an accident is also much bigger. Therefore, when increasing the maximum speed, most level crossings are closed and reconstructed using separated roads (Van Os, 2019).

Each level crossing is designed for the specific speed. When introducing ERTMS with variable speed static profiles, these specific maximum speeds would remain the same. Driving faster would not be possible, as the level crossing will not be safely closed in time. However, there have been some tests with increasing the maximum speed from 140 km/h to 160 km/h between Eindhoven and Venlo. Another example is the line between Zwolle and Amsterdam, where the track speed is above 140 km/h. On this track section, there are no more level crossings, because of the allowed high speed (Van Es, 2019).

Conclusion

The level crossing maximum speed is restricting when increasing the maximum speed on a track section. Therefore, the level crossings can be seen as a hard constraint on the maximum speed on the train. Increasing this maximum speed is not possible with the current design of the level crossings. Changing the maximum speed is only possible when level crossings are replaced by crossings where the road and track are separated.

3.3.6. Curves and cant

The rail network cannot exist only out of straight track sections, curves are needed to connect the straight track sections together. Curves are not ideal, because of possible speed restrictions. To make a better conversion between the curve and the straight section, transition curves are used. Those provide a smooth transition between the straight track and the curve. Multiple guidelines determine the bend of the curve and the transition curve. Generally, when the radius of the curve becomes smaller, the maximum speed allowed for trains traveling through the curve indeed becomes lower too. For instance, when the radius (R) of a curve is smaller than 630 m., the maximum speed cannot be above 40 km/h. These guidelines are determined using a worst-case scenario for the worst performing train (Mininsty of Traffic and Water Management, 2005).

When the speed in a curve needs to be higher, it is possible to add cant to the track. This occurs when both rails do not have the same elevation. The effect of cant is shown in Figure 3.2. The resultant force keeps the train onto the rails, allowing for higher speeds. It improves the comfort for the passengers, and it reduces the wear-off on the rail and wheels of the rolling stock. With higher cant, higher speeds are possible. On the Dutch network for mass transit, cant of 90 mm is allowed (Mininsty of Traffic and Water Management, 2005).

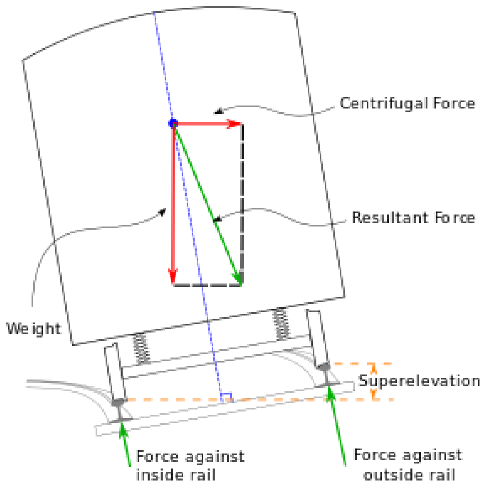

Figure 3.2 - Effects of cant on railway tracks (B. Marquis, 2015)

The transition from the straight track to the curve with cant is conducted by the transition curve. There is a twist in the track and this twist is restricted to a maximum speed. For instance, when the track is twisted with 20 mm over a distance of 6 meters, the maximum speed allowed is 50 km/h. (Mininsty of Traffic and Water Management, 2005). Concluding, the speed is currently restricted when the curve and cant are designed for a specific maximum speed. It will be unsafe to increase the maximum speed even further for the worst performing train, but it could be different for different train types: the derailment in curves is restricting for the maximum speed, but this is caused by different characteristics of the train itself.

Conclusion

The maximum speed influenced by a curve or the cant is a soft constraint. If the speed is higher, situations become unsafe. However, when it becomes unsafe depends on the characteristics of the train. Therefore, the maximum speed of a curve should be determined per train type, instead of a generic maximum speed. Furthermore, it can be possible that the speed limitations next to the track are lowered because of the restricted ATB-EG control levels (Van Es, 2019). This will most of the times not be the case but should be considered.

3.3.7. Bridges and tunnels

Tunnels and bridges are the most common civil engineering works on the Dutch rail network. These constructions have their own guidelines and restrictions, due to different facts. For instance, driving through a tunnel with higher speeds can cause dangerous air pressure movements. This can be dangerous for passengers of the train. An example of this is the tunnel near the station of *Best*, where increasing the speed caused pressure problems (Schrage, 2010).

Increasing the maximum speed on bridges can also cause more vibrations and more noise nuisance. Additionally, those vibrations could possibly cause faster wear-off of elements on the bridge or tunnel. The restricting factor therefore is the design speed of the tunnel or bridge. There are enough examples however of tunnels with very high maximum speeds, for example the *Lötschbergtunnel* in Switzerland. The maximum speed in this tunnel is 250 km/h. Parameters on the location and specific restrictions of each construction are needed when introduction variable speed static profiles in ERTMS. The maximum speed is most of the times determined on the stability of the bridge. Introducing variable static speed profiles is only possible when the stability of the bridge and the effects of the passing train is known at any given moment (Abrahamse, 2019).

Conclusion

For bridges and tunnels, the same applies as for the catenary system. They are designed for a pre-specified speed and increasing the maximum speed can cause problems. As said by Schrage (2010), investigations in situ are needed to check if increasing the maximum speed is possible for every situation. The discussed constructions can currently be hard constraints on the maximum speed, but when the condition is known at any moment as well as the wear-off by a passing train, they could be considered soft constraints.

3.4. Classification of characteristics

The classification of the identified characteristics is based on the expert opinion of senior rail specialists and literature review. Are the characteristics hard constraints or soft constraints on the maximum speed or are they influenced by the maximum speed, classifying them as effects? The classification of every influential characteristic is already discussed previously in the *Conclusion* section. In this paragraph, the rail assets are classified.

Three different classifications are distinguished, namely the (a) hard constraint, (b) the soft constraint and (3) effects of the maximum speed. An effect does not influence the required maximum speed on the network but is influenced by the maximum speed. Therefore, it is not a constraint or boundary on the maximum speed. However, if the effects become too affecting for the environment, measures could be taken. In general, the maximum speed is not influenced by the effects. Figure 3.3. shows the classification of the previously discussed characteristics.

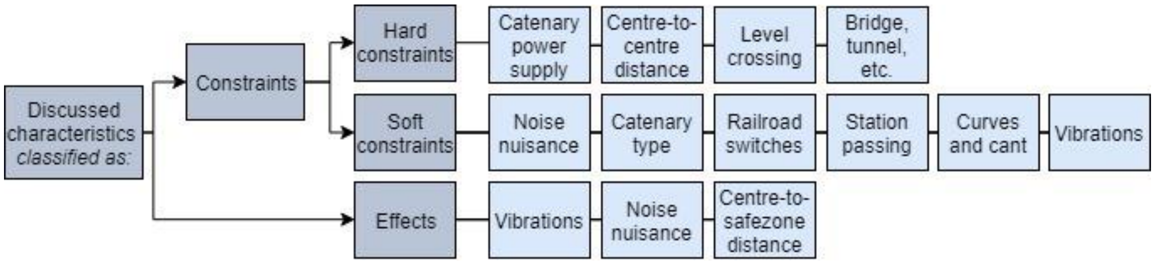

Figure 3.3 - Classification of influential characteristics on maximum speed

It can be seen in Figure 3.3. that a large amount of the constraints is considered a soft constraint. Most of the times this is due to the fact that the current design speed is based on a worst case scenario for failure of the track piece or derailment of the train (Van Os, 2019). When the sub-constraints behind this worst-case scenario are monitored or calculated per train, variability is possible per situation.

3.5. Causal Relation Diagram

Variable static speed profiles should take into account a lot of different characteristics to determine the maximum speed possible. With the use of a decision model, a computerized model within the ERTMS software should decide what the maximum speed is. To provide a framework for this decision model, it should be clear what the causal relation is between the different factors and characteristics.

Figure 3.4 on page 30 provides the causal relation (loop) diagram (CRD) of the maximum speed. From the diagram can be conducted which characteristics are causally connected which each other and what the relation is. It shows also the relation between the sub-characteristics from different main characteristics as discussed in Paragraph 2.2 and 2.3. Furthermore, it provides feedback loops that "control" the maximum speed; they are influenced by the maximum speed and also influence the maximum speed themselves.

The relations between the characteristics that follow from the CRD should be used in the construction of a decision model, which will be done in Chapter 4 for one of the constraints. The CRD provides a clear structure on the relations and when a decision should be made on, for instance, the maximum speed due to the condition of the overhead wire, it can be seen that the crosswind speeds and outside temperature should also be taken into account. Appendix B does offer a more detailed description of the Causal Relation Diagram with positive and negative links as well as the identification of the sub-characteristics.

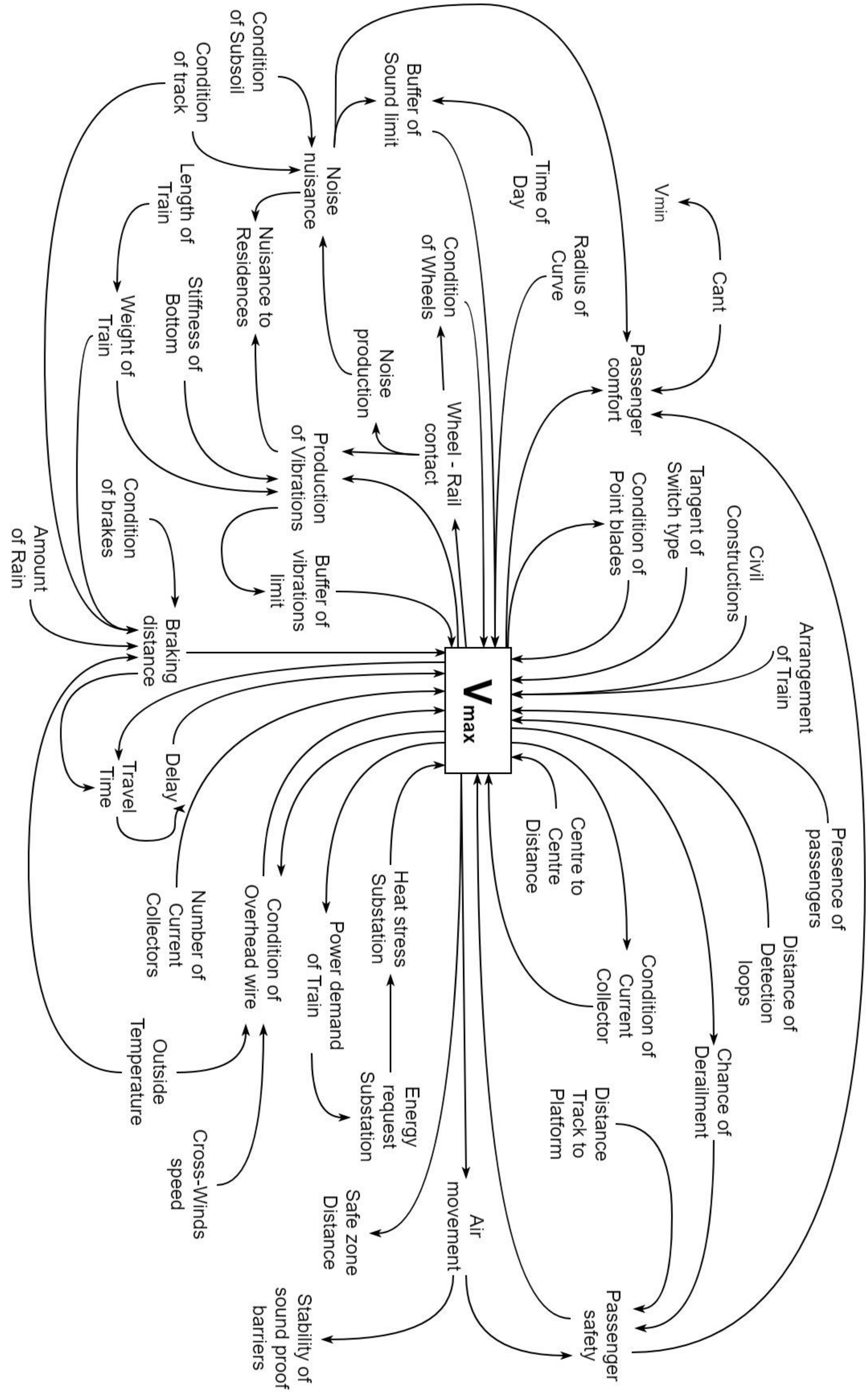

Figure 3.4 - Causal Relation Diagram of influences on the maximum speed

4. Variating speed profiles

The previous chapter provided the most important factors that influence the maximum speed on the rail network. In the case of variable profiles, it should not only be known which factors could be varied, but also how that should occur. This chapter will go deeper into the topic of variating the speed profiles, to figure out how it is decided if a train should drive differently and what is needed for this decision.

4.1. Variating on different levels

As previously discussed, variable static speed profiles cannot be implemented immediately, due to some different factors; (**1**) The most parts of the Netherlands still use the ATB system, which does not use cabin signalling (ten Siethof, 2016), (**2**) lower ERTMS levels do not use two way communication with the train, while feedback of the train is needed for the variating the speed limit (Van Es, 2019), and (**3**) ERTMS software does not support a lot of different or parameter based speed profiles (Van Es, Interview on ERTMS and influences on maximum speed, 2019).

To make the first of many steps towards variable static speed profiles and overcome these problems, the needed changes to the current situation are assessed on different levels. From micro level up to macro level, the workability is discussed. On the micro level, the variability of one constraint is discussed as this will bring clarity on how the future system should decide when a trains speed should be different. On a more macro level, recommendations will be done on how to handle the data and implementation of these variable static speed profiles in the sub-systems of ERTMS. Figure 4.1. provides an overview of the micro and macro level first assessment of the upcoming challenges and implementation steps for variating the speed profiles.

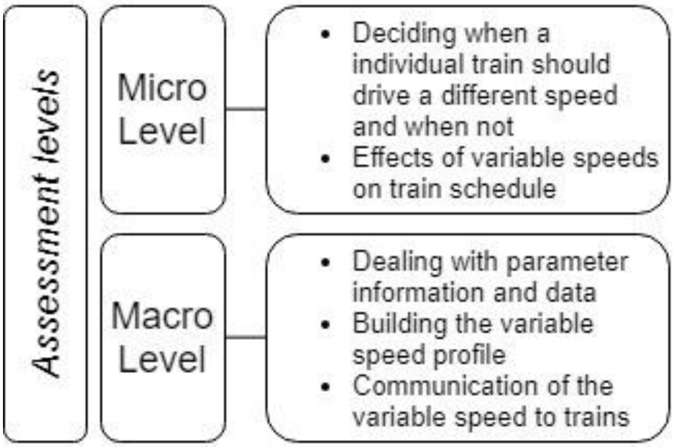

Figure 4.1 - Assessment levels on implementation of variable static speed profiles

Obviously, there will be more steps into the implementation of the idea of variable static speed profiles into ERTMS. However, assessing these first steps will give a good picture of the needed changes in the current system as well as the opportunities the system offers.

4.2. *Macro level* – Communicating variable static speed profile data

On a macro level, recommendations will be done on how to handle the data and implementation of these VSSP's in the sub-systems of ERTMS. Currently, there is no way of implementing the variable static speed profiles in the ERTMS software environment. Figure 4.2 describes this system structure in a simple way. The arrows with numbers describe communication between the different sub systems and discuss the possible implementation of the VSSP system in the structure of ERTMS.

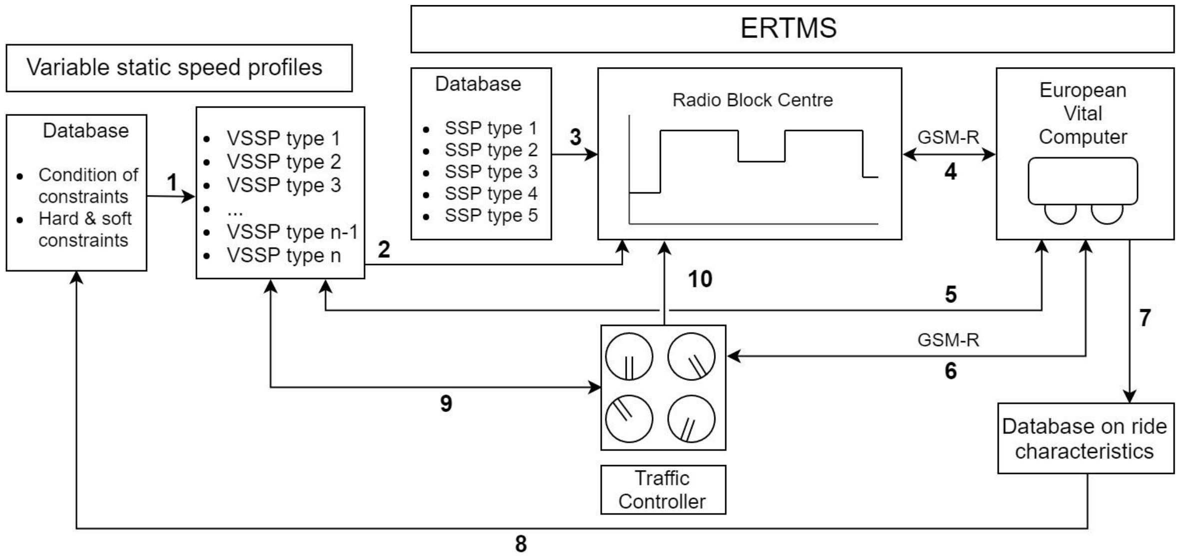

Figure 4.2 - ERTMS system structure with variable static speed profiles

The VSSP's in Figure 4.2 of different types will be based on a decision model as discussed in paragraph 4.3.5. For example, a type of VSSP can be the normal static speed profile, but the speed constraint by the catenary system is increased, due to delay of the train. Numbers 1, 2, 5, 7 and 9 in Figure 4.2 are options for implementation of variable static speed profiles. The numbers describe the following:

1. Data on the condition of hard and soft constraints is communicated to the decision models, to determine a variable static speed profile (VSSP) of different types, variating per time of day, type of train, etc. Different from the standard SSP is that the VSSP is based on real time data, specific for the situation of the train and the current condition of infra structure.
2. Chosen by the ERTMS system itself or by the traffic controller (via link 9), the selected VSSP is communicated to the ERTMS Radio Block Centre.
3. This is the current workability of ERTMS, an SSP type is selected, based on the type of train: passenger or different types of freight train.
4. Current communication between the ERTMS RBC and the board computer EVC of train.
5. Possible implementation of VSSP's in the EVC of the train. The decision model within the board computer of the train will decide which VSSP is selected, based on constraints and KPI's of the train itself. The VSSP database is used to define the soft constraint parameter values.
6. Current communication between the traffic controller and the train and train driver.
7. Data of the train, i.e. condition and speed of wear-off of certain parts, should be monitored and stored in a database. In that way, the data can be used in a later stage to estimate the condition and possible VSSP for the situation.
8. The data of this database is communicated to the database of the VSSP, to improve upon the VSSP types and the selection of these types. This contains the speed of the train but also the condition of, for example, the pantographs of the train.
9. Another possible implementation would be that the traffic controller could decide, seeing the situation of the train, which VSSP would fit the best. The controller selects the VSSP and sent this towards the ERTMS system of the explicit train, via the RBC.
10. The traffic controller communicated the new VSSP towards the RBC, which will communicate this VSSP to the train, using GSM-R (link 4). The traffic controller will base its decision upon the current situation of the train. This is a form an active adjustment by the controller.

How this new system with a VSSP will change from the current system with static speed profiles can also be seen in Figure 4.3. It describes the difference with the current system in Figure 2.3.

The civil technical and environmental constraints for the specific track section will again be used to determine the limits on the maximum speed.

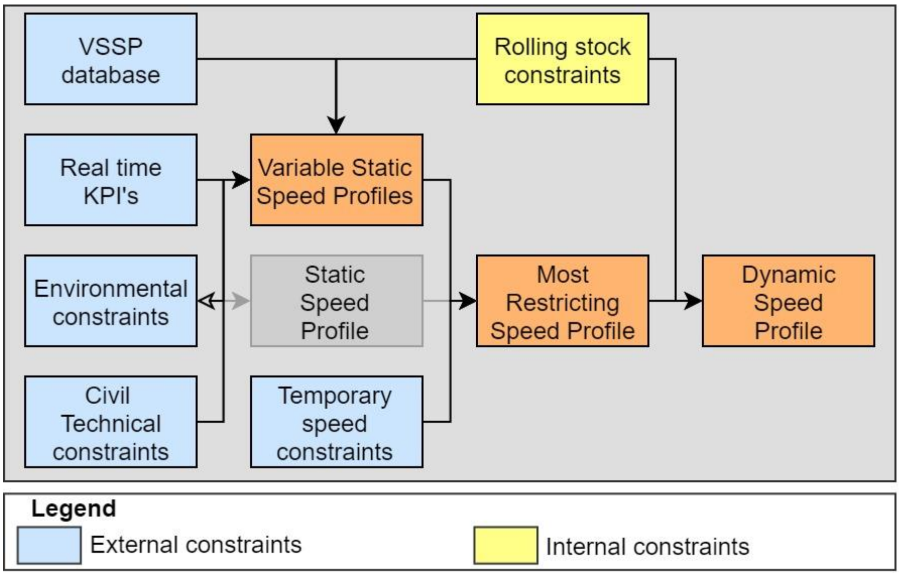

Figure 4.3 - New system of determining the final speed profile

But the VSSP will initially use more input data than the SSP: the data from the VSSP database provides the current condition of the hard and soft constraints or buffers of noise and vibration limit, and the real time KPI's are monitored to make the decision for the optimal VSSP of the train. The rolling stock constraints will determine for instance the noise production or condition of the pantograph. The difference between the dynamic speed profile and the VSSP is that the dynamic speed profile can be adjusted for a disturbed condition, in case of limited moving authority, but not for other constraints. The VSSP can be altered for all other constraints and can differ not only for disruptions, but for other factors as well (Goverde, Corman, & D'Ariano, 2013)

Conclusion – Macro level

There are multiple options for implementing the variable static speed profiles. But a few things should be clear from the beginning. First of all, a lot of additional data is needed before implementation could occur. Dealing with parameter information and monitoring all these constraints will be the first difficult asset towards the implementation of variable static speed profiles. A new database should be designed were all these parameter data is saved. An example of the data that is needed for one single constraint can be seen in Table 4.2 to 4.4. The most difficult part is the monitoring of the condition of infrastructure, but determining it mathematically will be even more difficult, due to all different factors (Wang, et al., 2018).

The VSSP database, displayed in Figure 4.2, will not have a sufficient amount of data, primarily because it is currently not tracked what the precise effect is of different speeds on the condition of infra and train (Többen, 2019). This data should be stored in a trackside database, before implementation of the VSSP could occur. Starting with the gathering of such data should start as soon as possible. Hence, there will be a sufficient starting point for the construction of the VSSP's.

Furthermore, decision making within the new idea of the VSSP's could occur in multiple ways. First of all, the best VSSP can be chosen by the ERTMS computer system, based on the data of constraints and the current situation (link 2 in Figure 4.2) or by the traffic controller as 'active adjustment' (Többen, 2019), who is able to adjust the VSSP of the train based on a decision model and his own judgement (link 9 and 10 in Figure 4.2).

4.3. *Micro level* – Making a decision for an individual train

On the micro level, one of the previously discussed characteristics is investigated further on the topic of variability to figure out (as stated in Figure 4.1); (**1**) how the decision on variating the speed should be made, and (**2**) what possible effects of variable speeds should be taken into account. To do so, a decision model for the characteristic *catenary system* has been constructed and simulations in Arcadis' Xandra software are performed to simulate the effects. This has been done for a specific reason, as research has pointed out that failure of the overhead wire (and feeder lines) causes the most delays on the network. Probability because maintenance of damage to these elements costs a lot of time (Nyström & Kumar, 2005).

For every characteristic that has been identified as constraint on the maximum speed, the steps shown in Figure 4.4 should be taken to decide on the variability options of the characteristic. This is (partly) based on Winston (2004) and Pieter Bots (2014), where it also follows the general steps of the *behavioral model of rational choice* by Herbert Simon (1953): First gather information, determine alternative solutions and then select and implement the chosen option (Simon, 1953). Furthermore, the steps partly follow the first step in the performance measurement system developed by Stenström (2012), based on maintenance key performance indicators set by the European standardization committee (CEN, 2007).

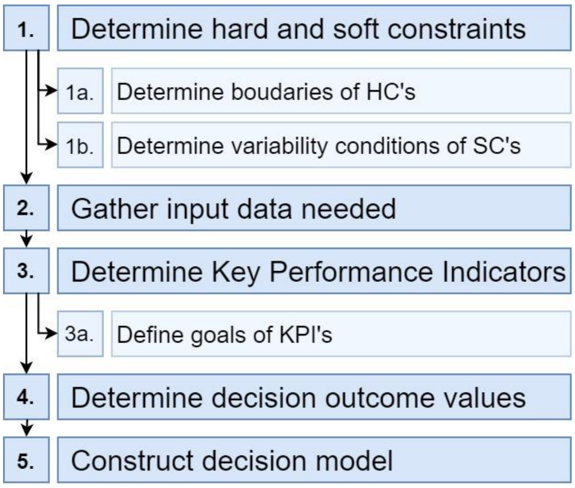

Figure 4.4 - Steps to follow in constructing a decision model for a single characteristic

In this paragraph, the steps shown in Figure 4.4 are followed to construct the decision model for the *catenary system* characteristic. This will be used to show how the ETCS sub-systems could handle the variability of one characteristic. A note should be made that not all numeric values are available, because they heavily depend on the location, and this report discussed the general situation. The decision model provides a VSSP specific for the characteristic. When done for all characteristics, one should be able to construct a variable static speed profile with the feasible region to choose from.

4.3.1. Step 1 – Determine hard and soft constraints

This step has already been performed in the previous chapters, so it will be discussed briefly. The causal relation diagram of the catenary system can be seen in Figure 4.5. The effect of increasing the maximum speed on the comfort of passengers is not considered, because it does not form a constraint on the maximum speed. The sub-constraints of the catenary system are discussed in detail in Appendix A.4. The following hard and soft constraints are the most important for the catenary system:

- The *power demand* in combination with the heat stress in the substations will form a hard constraint, as the power demand cannot be higher than the capacity of the substations. This capacity should be known for every track section.
- The *number of current collectors* (i.e. pantographs) will form a hard constraint with two boundaries: having no pantograph makes sure that the catenary constraint does not play only role, while having more than one pantograph will cause problems due to shockwaves for the second pantograph in line.
- *The quality of the contact point between pantograph and overhead wire*, influences the electric transmission. It depends on the following soft constraints:
    - The *condition of the overhead wire*, as less damage is done to the construction when in good condition, as well as a better electric transmission. The condition could be monitored by the number of train passages with a certain speed and condition of train specific material.
    - The *condition of the current collector*, the pantograph of the train. This is also influenced by crosswinds, which can push the pantograph with 50N extra to the overhead wire. When the condition is less, electric transmission is more difficult and the damage of on other constructions will increase.

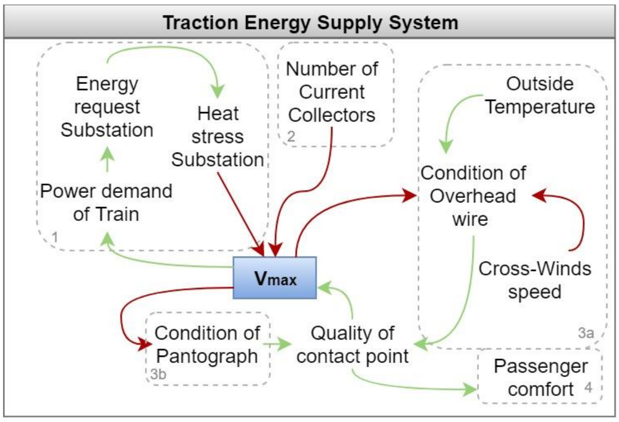

Figure 4.5 - Causal Relation Diagram of the pantograph-catenary system

Table 4.1 shows the sub-constraints for the overhead electric power system. Besides that, it provides the parameters for the constraints. The parameter values should be determined using the input data gathered in step 2 of the process. The boundary conditions provide a short explanation of how the constraint influences the variability of the maximum speed.

Table 4.1 - Sub-constraints of overhead electric power system

Constraints	Id.	Boundary conditions	Parameter
Power demand / heat stress substation	HC	Depends on the situation at a specific track section. With higher speeds, more amperage is needed (Schrage, 2010).	Per track section should be determined what the maximum speed is for the substations. We call this $V_{max,ss}$.
Number of current collectors	HC	When 0 pantographs, catenary does not form constraint. With more than 1 pantograph, more damage due to shockwaves in wire (Többen, 2019)	Number of pantographs in use could be derived from the train itself. We call this N_{panto}.
Quality of contact point	SC	Depends on the condition of the overhead wire and pantographs (Karaköse & Gençoğlu, 2013)	Quality of contact point should be monitored. The quality is presented as $C_{contact}$
Condition of overhead wire	SC	The better the condition, the faster the maximum speed. We state that with good condition, +20 km/h on maximum speed is possible (Többen, 2019)	Condition should be monitored and provided with value between 0 – 1. This value is presented as C_{wire}

Condition of pantograph	SC	The better the condition, the faster the maximum speed. We state that with good condition, +20 km/h on maximum speed is possible (Többen, 2019)	Condition should be monitored and provided with value between 0 – 1. This value is presented as C_{panto}

4.3.2. Step 2 – Gather input data needed

When the constraints are identified, data on their parameter values should be gathered. Furthermore, some other input values are needed for the decision model. Data on this input is also necessary. The input data needed for the decision model is discussed per constraint. Note that the input values that would be needed per track section are discussed, not the real values. The condition of parts of the railway infrastructure is important in decision making and can also be seen as performance indicators for the network.

Power demand / heat stress in substations

Substations deliver the electric current from the network towards the overhead wire and each substation has to cover a specific track section. The current and voltage in a substation – and thus the maximum speed allowed –depends on the requested power demand (Barrero, Van Mierlo, & Tackoen, 2008). When these values get too high, heat stress can occur in the station (Schrage, 2010). Table 4.2. provides the input values needed for determining the substation constraint. The power demand of a single train (P_{train}) depends on the factors in Equation 4.1, but then per time step, as the equation describes the total power demand (Jong & Chang, 2005).

$$W_T = \left[\frac{2.725}{0.814}\left(\sum T_A \times d_A + \sum T_B \times d_B\right)\right] + \left[\frac{P_a}{0.964} \times \left(\frac{\sum d_C}{v_C} + \frac{\sum d_D}{v_D}\right)\right] \qquad \text{Equation 4.1}$$

Where: W_t is the power demand of the train (kWh)

T is the traction force due to Acceleration, Balancing, Coasting and Deceleration of the train

d is the distance travelled of the train (km)

P_a is the power consumption by all systems of the train (kWh)

v is the speed of the train (km/h)

From Equation 4.1 follows the influence of the trains speed on the power demand, but also other factors such as the trains acceleration and deceleration that should be monitored. In ERTMS these factors are already monitored by the train onboard vital computer or the radio block center (Van Es, Interview on ERTMS and influences on maximum speed, 2019). The power demand of a train fluctuates heavily during a long distance ride, mostly due to the difference in acceleration and deacceleration, causing different values for each substation (Molina, Valero, & Garcia, 2009).

Table 4.2 - Input values and functions of substation constraint

Parameter	Input data		Source within ERTMS infra
$V_{max,ss}$	$V_{max,ss} = f(V_{design,ss}, P_{train}, P_{network}, \sigma_{heat})$		*The maximum speed is based on a function of different factors, saved in a database in the Radio Block Centre.*
	$V_{design,ss}$	The speed the substations is designed to be able to handle	The design speed should be known in the *RBC.*
	P_{train}	The power demand of the train	Real time in vital computer of the train
	$P_{network}$	Power demand of the further train network on the track section	Communicated from the other trains' board computer to the *RBC.*

	σ_{heat}	Heat stress within the substation on the track section	Measured in the substation or derived from function, communicated to *RBC.*

Number of pantographs

The number of raised pantographs that make a connection with the overhead wire is easily derived from the onboard vital computer of the train. When there are no pantographs, e.g. in case of a diesel train, there is no constraint from the catenary system. Multiple pantographs can cause a shockwave, causing the quality of the contact point to decrease (Többen, 2019). Table 4.3 shows the parameter of the pantograph.

Table 4.3 – Input values of number of pantographs constraint

Parameter	Input data	Source within ERTMS infra
N_{panto}	The number of pantographs in use on the specific train and also the position of the pantograph on the train, i.e. first or second in driving position.	Derived from the *train board computer* how many pantographs are up.

Quality of the contact point: condition of overhead wire and pantograph

The condition of the overhead wire and the condition of the pantograph influence the quality of the contact point, which determines the quality of the whole catenary system and thus the maximum speed (Pombo, et al., 2009). The quality of the contact point depends on the force between the overhead wire and pantograph: a high contact force means high wear-off and abrasion, causing electric arc. A low contact force, caused by wear-off and destabilization of the wire, causes formation of electric arc (Karaköse & Gençoğlu, 2013). Table 4.4 shows the input values that are needed to determine the condition of the overhead wire and pantograph.

Table 4.4 - Input values of condition of overhead wire and pantograph

Parameter	Input data		Source within ERTMS infra
C_{wire}	$C_{wire,d} = C_{wire,d-1} - f(N_{passages,d}, v_{cross-winds}, T_{outside}, v_{train})$		*The condition of the wire is monitored for a period of time and will decrease in that time period.*
	$N_{passages,d}$	Number of times the wire is passed on the day d.	Derived from database in *Radio Block Centre*.
	$v_{cross-winds}$	The speed of crosswinds on the overhead wire	Derived from measure points next to track section.
	$T_{outside}$	The outside temperature	Derived from measure points next to track section.
	v_{train}	The speed of the specific train	Current speed, derived from *train board computer*
C_{panto}	$C_{panto,d} = C_{panto,d-1} - f(s_{panto}, N_{passages,d}, v_{cross-winds}, T_{outside}, v_{train})$		*The condition of the pantographs is monitored for a period of time and stored in the database within the train.*
	s_{panto}	*If applicable*, distance between first and second pantograph	Static data, known within *train onboard computer.*
	$N_{passages,d}$	Number of times the wire is passed on the day d	Derived from database in *Radio Block Centre*.
	$v_{cross-winds}$	The speed of crosswinds on the overhead wire	Derived from measure points next to track section.
	$T_{outside}$	The outside temperature	Derived from measure points next to track section.
	v_{train}	The speed of the specific train	Current speed, derived from *train board computer*

The condition of the overhead wire and pantograph depend on different factors, that it becomes difficult to determine it mathematically. But the conditions need to be monitored, as the wear-off has great impact on the quality of the contact point, which influences the maximum speed possible (Wang, et al., 2018). Another way of determining the quality of the contact point is by monitoring the horizontal positioning of the overhead wire on the contact strip of the pantograph. The difference contact point regions can be seen in Figure 4.6. Contact point monitoring determines if the contact point remains in the safe region or moves to the dangerous or even fault region, due to bad weather conditions or other disturbances (Karaköse & Gençoğlu, 2013). It can be said that raising the maximum speed is possible when the contact point is in the safe region.

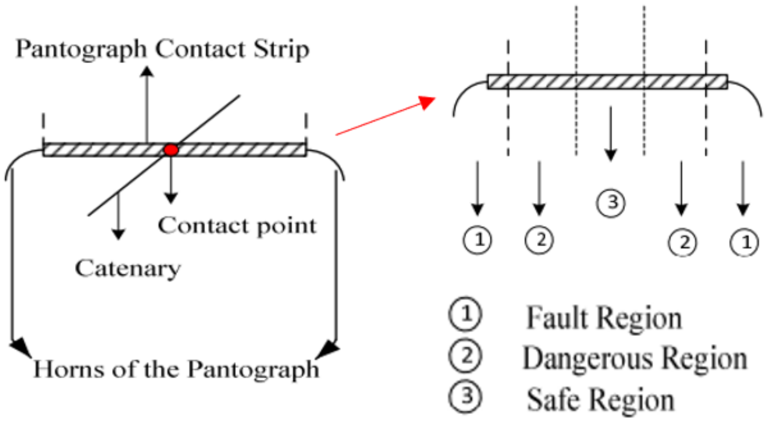

Figure 4.6 - Representation of pantograph (left) and pantograph regions (right) (source: Karaköse & Gençoğlu, 2013)

4.3.3. Step 3 – Determine Key Performance Indicators

As the importance of railway traffic is increasing over the last years and will also become more important in the upcoming years, it is required to have an optimal performance on the network. VSSP's could be helpful in a more optimal workability on the network as long as the performance is measured correctly. Key performance indicators (KPI's) help in making the best decisions for the specific situation of the train (Stenström, Parida, & Galar, 2012). For the decision model these KPI's will form the base for the decision criteria.

Stenström et al. (2012) came up with a structure of railway performance indicators, which has been produced for sake of monitoring the status of railway assets. The structure of the performance indicators is depicted in Figure 4.7. On these performance indicators, the key performance indicators for the catenary system can be based.

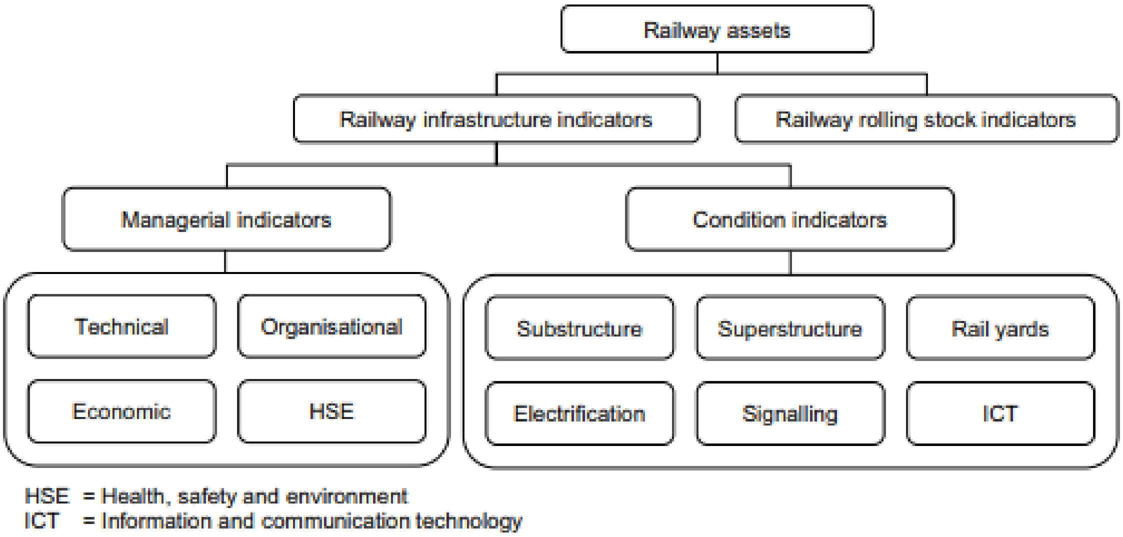

Figure 4.7 – Structure of railway infrastructure performance indicators (source: Stenström et al., 2012*)*

The *Managerial indicators* monitor the state of the complete network, whereas the *Condition indicators* focus on the condition of infrastructural characteristics, as discussed in this report in Chapter 3. The technical indicators are mostly related to the availability, reliability and maintainability of the network, which is in line with the ERTMS goals discussed in this research. Other indicators focus more on the costs of maintenance and safety issues, which is outside the scope of this research (Stenström, Parida, & Galar, 2012).

The condition indicators are already taken into account within the sub-constraints of the catenary system, which is called the *superstructure* within the model of Stenström et al. (2012). The condition of the overhead wire and pantograph are therefore constraints of the maximum speed (higher damage, lower speed), but also KPI's on the decision-making process (no too high speeds, because too much damage). This represents the balancing feedback loops mentioned earlier.

The KPI's that are taken into account are mostly focused on the technical management and the superstructure condition part of the indicators. Performance indicators for the rail network should follow from the network manager and the overall ambitions. These ambitions are broken down into sub-goals and these goals are supported with performance indicators (Åhrén & Kuman, 2004). The following goals are derived from the Dutch network manager's ambitions: (**1**) Capacity for the mobility of the future, (**2**) Trustworthy mobility on the rail network, and (**3**) Sustainable rail mobility (ProRail, 2019). Based on these goals, the following KPI's and decision criteria are identified for the variable static speed profiles:

1. The first KPI is the *time delay* [min] of the individual train, which can also be seen as the arrival punctuality of the train. It is described as one of the most important performance indicators of the rail network, as improving punctuality will be beneficial for customer satisfaction and the capacity on the network (Nyström & Kumar, 2005). It follows from the ambition on reliable public transport and high quality of transport.
   - *Goal of KPI:* The lowest time delay possible.

2. The second KPI will be the *capacity utilization* [%] which is the percentage of used capacity over the total capacity on the network. For future proof capacity it is of importance that the full capacity is used. When scheduled trains cannot drive due to delay or capacity issues, capacity is not fully used (Stenström, Parida, & Galar, 2012).
   - *Goal of KPI:* The highest capacity utilization possible.

3. From the ambition of sustainable rail mobility follows the indicator of *energy consumption* [kJ/area]. Less energy use is not only good for the environment and sustainability of the network, but also for less power demand and heat stress in the substations, allowing other trains to drive faster and consuming more energy (Åhrén & Kuman, 2004).
    - *Goal of KPI*: The lowest energy use possible.

The KPI's above are listed in order of importance (Åhrén & Kuman, 2004). Making sure the delay of a train is overcome is of more importance than respectively fully optimizing the capacity and sustaining the energy usage. When determining the variable maximum speed, the delay will be optimized first, before looking into the other two KPI's. Therefore, the KPI's are also used as decision variables in the decision model.

4.3.4. Step 4 – Determine decision outcome values

Before being able to make a decision on the speed profiles, it must be known what the effect of any decision would be. The effect is based on the KPI's determined in the previous step. For instance: there is a delayed train and it is possible to increase its maximum speed. Then it should be known what the effect of increasing the speed is on the travel time and the delay of the train.

In this paragraph, a small fictional experiment has been conducted to investigate the possible effect of implementing variable static speed profiles. This experiment is again based on the constraints of the catenary system.

Experiment

The effect on the KPI *time delay* is determined by simulating a train flow on a certain track section. This simulation is conducted in Xandra. Xandra is a simulation application developed by Arcadis, used to simulate the functionality of rail network track sections and timetable designs (Vooren, 2016). In this research Xandra will be used to evaluate the effects of variable static speed profiles (see Appendix C – Xandra info). Therefore, multiple runs with different delays will be simulated.

Experiment setup

The experiment will simulate the variable static speed possible for the soft constraint *Catenary system.* In short, trains could drive faster than currently allowed under the catenary system. This research investigates the effect of the variable speed on the *time delay* KPI. For this research, also some sub-KPI of the time delay are identified, to get a better view on the problems and situations that occur.

The following parameters play a role during the simulations in Xandra:

- *Decision variable:* Delay of specific train.
- *Variable parameter:* Maximum speed profile.
- *KPIs:* Travel time, delay of specific train, delay of following trains

The goal of the experimental simulations is to investigate the effect of variable static speed profiles on the delay of the specific train and to find other possible effects. It is expected that when implementing the variable static speed profile, the delay of the trains will decrease.

Methodology

Multiple simulations will be conducted to investigate the sensitivity of the system on the delay and variable speed. A specific train will get a delay, due to a standstill in front of a red signal at chainage 45,500. After that the specific train will be allowed to drive faster, because of its delay. The speed will not be increased further than 160 km/h, because this would not be a realistic situation (Többen, 2019). This simulates the decision of selecting a different speed profile. The effect of this will be measured. The simulation will be repeated with a longer period of delay and giving variable higher speed to multiple trains.

The simulation runs can be seen as *Sensitivity Analysis*. The effects of variable speeds with different variations in delay on the final delay are tested in this research. The output will show how sensitive the time delay is for the variation in maximum speed. It should be mentioned that this experiment only focusses on a small experimental setup, leaving out a lot of factors that play a role in real life, such as freight trains, other trains series, weather conditions, etc.

Input

Xandra needs certain different inputs to eventually run the whole simulation. These input variables are discussed below and are partly based on the Xandra guide (Vooren, 2016):

- *Track layout*. Information on the track, connections and location of the track. In this simulation, a fictional piece of single track including a station is simulated. Figure 4.8 displays the track layout. It consists of three sections: a station approach section of approximately 25 km (100), a station section of more than 2 km (STS) and a station departing section of 20 km (101). The station will simulate a bigger station where both the intercity and sprinter service will stop.

- *Speed profile*. The static speed profile that is simulated can also be seen in Figure 4.8. This is the basis for variating the speed profiles for the specific trains. Rolling stock adheres this static speed profile accordingly in *block section* mode. Furthermore, trains keep enough distance from each other to be able to brake to a standstill in time, which is in line with the ERTMS Level 2.

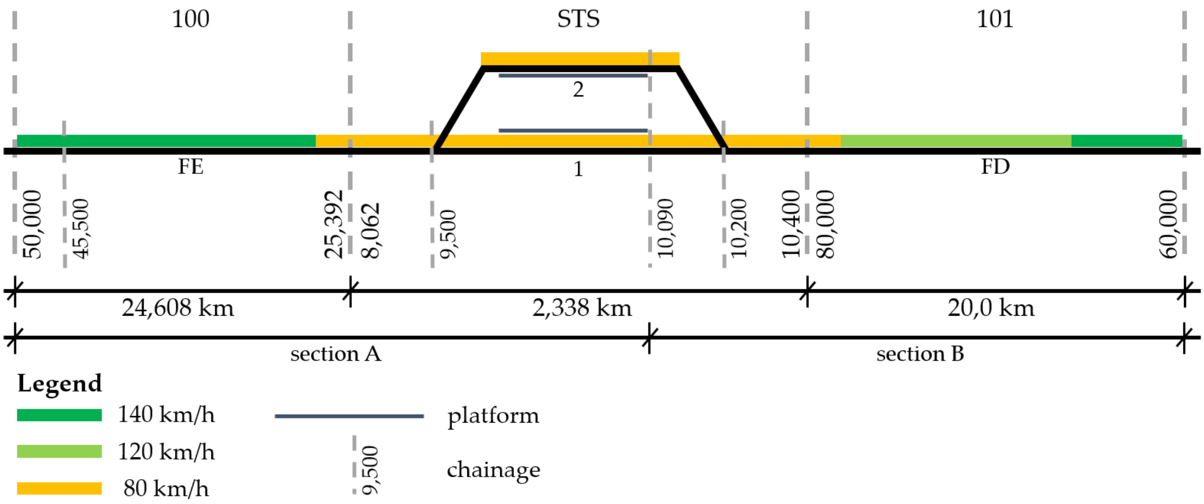

Figure 4.8 - Simulation rail network infrastructure layout (figure is not on scale in both x and y direction)

- *Rolling stock and Timetable*. From the Xandra software, multiple types of rolling stock can be selected. In this simulation, there will be an *intercity* (VIRM-train) and a typical *sprinter* (SLT-train) service, where the sprinter follows the intercity closely. The timetable with the corresponding rolling stock can be found in Table 4.5. The stop time at a station is based on the most common stop time on the Dutch network, where the Intercity needs more time than a Sprinter. This difference is in line with the current situation on the Dutch network. The departure time in Table 4.5 is the departure from the start of the track section, at chainage 50,000. Delta shows the time between departures, which is 15 minutes for each. See Table C.1 in Appendix C for more information on the rolling stock characteristics.

Table 4.5 - Input data Timetable and Rolling stock

Train series	Timetable data		Rolling stock
1000 – Intercity	*Departure*	06:00:00	VIRM VI + IV
	Delta	00:15:00	
	Stop time	120 seconds	
2000 – Sprinter	*Departure*	06:05:00	SLT IV + IV
	Delta	00:15:00	
	Stop time	60 seconds	

Results and conclusion

The results of the experiments can be seen in Table 4.6. To simulate the increase of the maximum speed due to the catenary system, the speed has only been increased on the free sections where the current maximum speed is 140 km/h (see Figure 4.8) *Section A* is the beginning to the stop at the stations, *section B* is from the stations to the end of simulation.

From the results it can be concluded that implementing variable static speed profiles will decrease the delay in this situation. In this case, increasing the maximum speed (from 140 to 160 km/h) for the intercity (1000 series) has the potential to decrease the travel time in section A with 65 seconds, from 739 seconds to 674 seconds. This follows from the difference between run 0.0 and 0.3, highlighted in green. When increasing the speed to 150 km/h for the sprinter train, the potential decrease in travel time is 41 seconds, also in green. This depends on the speed given to the previous intercity; when the headway becomes too little, the sprinter has to slow down, increasing the travel time of the sprinter again.

Table 4.6 - Results experiment simulations Xandra

Run id.	Delay time at chainage 45,500	Train 1000 (intercity)					Train 2000 (sprinter)				
		Max. speed (km/h)	*Travel time section A*	*Diff. with run 0.0*	*Travel time section B*	*Diff. with run 0.0*	*Max. speed (km/h)*	*Travel time section A*	*Diff. with run 0.0*	*Travel time section B*	*Diff. with run 0.0*
0.0	0 min	140	739s	-	614s	-	140	742s	-	599s	-
0.1	2 min	140	876s	+137s	614s	-	140	794s	+52s	599s	-
0.2	4 min	140	996s	+257s	614s	-	140	872s	+130s	602s	+3s
0.3	0 min	160	674s	-65s	603s	-11s	140	737s	-5s	599s	-
0.4	0 min	150	702s	-37s	607s	-7s	140	730s	-12s	599s	-
0.5	0 min	150	702s	-37s	607s	-7s	150	704s	-38s	590s	-9s
0.6	0 min	160	674s	-65s	603s	-11s	150	701s	-41s	590s	-9s
1.1	2 min	160	828s	+89s (-48s)[1]	603s	-11s (-11s)	140	773s	+31s (-21s)	599s	-
1.2	4 min	160	948s	+209s (-48s)	603s	-11s (-11s)	140	847s	+105s (-25s)	599s	-
2.1	2 min	150	848s	+109s (-28s)	607s	-7s (-7s)	140	783s	+41s (-11s)	599s	-
2.2	4 min	150	968s	+229s (-28s)	607s	-7s (-7s)	140	847s	+105s (-25s)	599s	-
3.1	2 min	150	848s	+109s (-28s)	607s	-7s (-7s)	150	758s	+16s (-36s)	590s	-9s (-9s)
3.2	4 min	150	968s	+229s (-28s)	607s	-7s (-7s)	150	841s	+99s (-31s)	596s	-3s (-3s)
4.1	2 min	160	828s	+89s (-48s)	603s	-11s (-11s)	150	752s	+10s (-42s)	590s	-9s (-9s)
4.2	4 min	160	948s	+209s (-48s)	603s	-11s (-11s)	150	816s	+74s (-56s)	603s	+4s (+1s)

[1] The number between brackets is the difference between the delayed situation without VSSP, in this specific case the difference between run 1.1 and run 0.1.

However, when there are 4 minutes of delay, the travel time has only been decreased with 48 seconds (in orange) for the intercity when the speed is increased to 160 km/h. This effect can be explained by the time needed to accelerate from standstill to the maximum speed. It should be noted that when implementing the variable static speed profiles, the travel time profit will possibly not be as large as expected and will also depend on the type of delay, whereas accelerating from a standstill will take more time than acceleration from coasting or cruising trains. The simulated decrease of the travel time is accomplished with a VSSP on a track section of 20km. Hence, the average distance between two stations is 18km, bringing up the discussion if increasing the speed is effectively.

Another notable effect is the impact on the following sprinter trains. The travel time profit of the sprinter profoundly depends on the variable static speed profile that is assigned to the intercity. When comparing run 2.2 and 3.2. (in blue), the speed of the sprinter is increased from 140 km/h to 150 km/h. This could potentially decrease the travel time with 31 seconds, but only decreases by 6 seconds. Causing this effect is the close intercity in front of the sprinter. Hence, the sprinter must wait before accelerating fully. It is therefore important to take this effect into account when increasing the speed of the following sprinter.

Figure 4.9 shows the time-distance diagram of one intercity and one sprinter train. The path of both trains in run 0.2 (normal speed with 2 minutes delay) is displayed in yellow (intercity) and blue (sprinter). The green line displays run 1.2 and shows the effect of the implementation of the increased variable static speed profile.

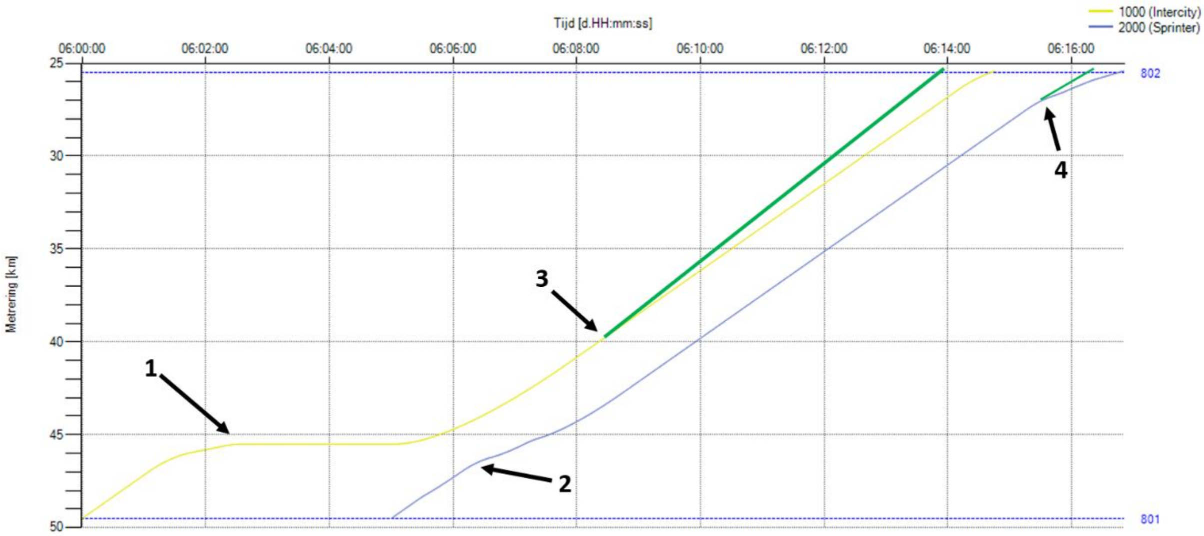

Figure 4.9 - Time-distance diagram of run 0.2 (yellow and blue) and run 1.2 (green) in section A

The following phenomena from Figure 4.9 seem interesting to discuss more in depth:

1. The intercity has come to a standstill from approximately 06:02:30 to 06:05:30, 180 seconds. However, this has caused a delay of 257 seconds, because accelerating back to the normal speed of 140 km/h also costs time. This is important to consider when increasing the maximum speed: no full potential benefit is used because of the acceleration phase.

2. The sprinter must start braking because of the delay of the intercity in front. When the delay will be even more, this will cause a shockwave through the train schedules.

3. After the delay, the intercity is allowed to increase its speed to 160 km/h (green) instead of 140 km/h (yellow). The intercity will go faster through section A and is 48 seconds earlier at the station, decreasing the delay (of 257 seconds) with 18,68%. It can be concluded from this

that increasing the speed with 20 km/h over 20 kilometres of track can decrease the speed with 18,68%.

4. In the normal situation (blue), the sprinter train must slow down, because it gets too close to the intercity train. This sounds logical because the sprinter can accelerate faster than the intercity ($0{,}8 m/s^2 > 0{,}66 m/s^2$), mostly caused by the difference in mass (288ton < 653ton) (see Appendix C for details of rolling stock). With the implemented VSSP for the intercity, the sprinter does not have to slow down and can keep its speed for a longer period. This shows that increasing the speed of one train (the intercity) can also influence other trains positively.

4.3.5. Step 5 – Construct decision model

To select the specific speed per train the decision tree will help in selecting the most profound speed. A decision model is needed, if the system is integrated in the ERTMS software of if the system is used by the traffic controller. Both should make a decision structurally, based on decision values and KPI's. Figure 4.10 shows such a decision model that is developed for the constraint of the catenary system. It describes the input needed and the needed monitoring of other constraints, such as the condition of the infrastructure.

The KPI of delay has been used as a decision variable in the decision model, since it has been ranked as the most important KPI. Decision are based on the delay of a train but take into account the effect on the other KPI's. For instance, when the train is on schedule or even too early, the speed is lowered. Hence, the KPI of energy consumption is satisfied, because of lower energy demand by the train. Furthermore, the other KPI's are constantly monitored to see if the decision model can be improved. The *overall condition* is based on the combined condition of the pantograph and overhead wire, which can be seen as the quality of the contact point of the catenary system (Wang, et al., 2018).

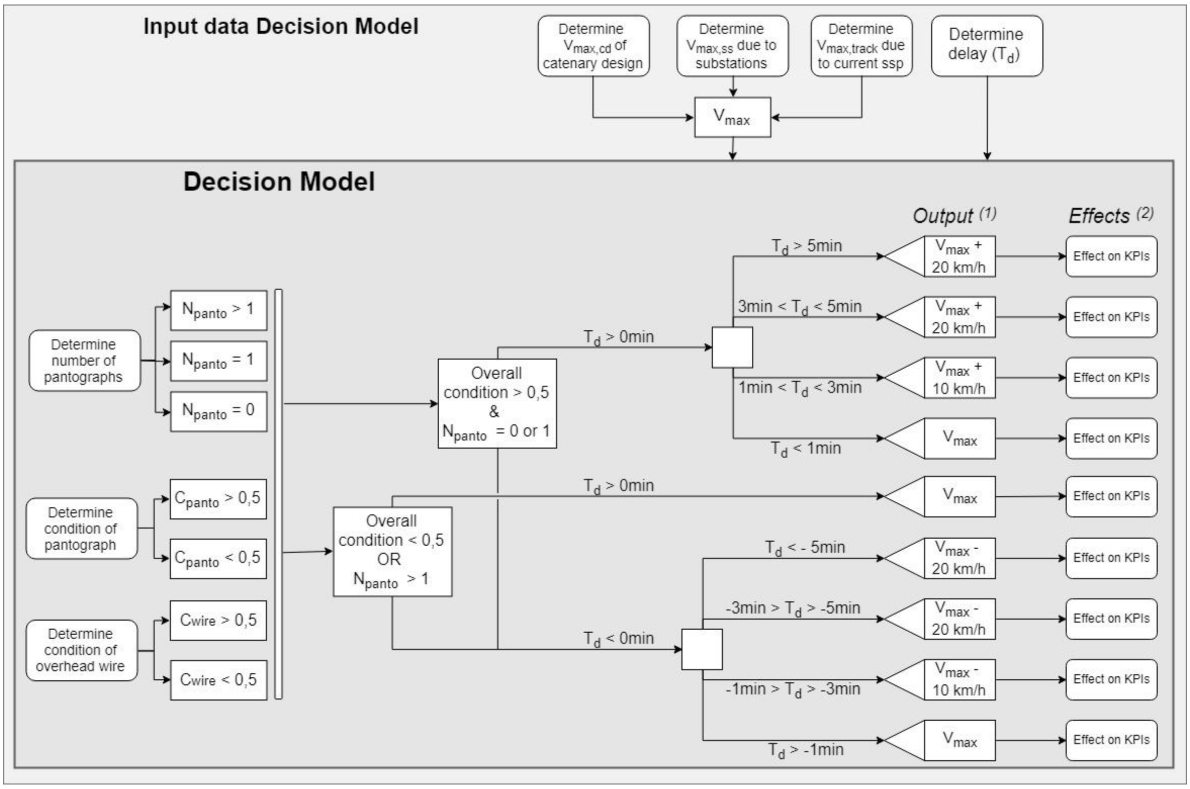

Figure 4.10 - Decision model on catenary system

The decision model is not definitive, but provides a framework for the making of a decision. It provides the steps needed for such a process. Firstly, the hard constraints determine the maximum speed currently possible. After that, the condition of the infra is determined, to define if it is possible to drive faster than the maximum speed. Based on the condition of the overhead wire and pantograph, and the number of pantographs, the decision model starts. Based on the KPI of the delay, the output values are determined (1). These decide if a train can drive faster or slower than the current maximum speed, based on the constraints and KPI. This output is the selected VSSP for the specific train. The effects (2) show, for instance, what the effect of the higher speed is on the KPI's, such as the delay. These values are determined using the simulations in Step 4 (paragraph 4.2.4.).

Conclusion - Micro level

Deciding which VSSP a train should follow is not an easy task, because there are a lot of different parameters that should be considered. First of all, the VSSP's should be designed, following the proposed steps in Figure 4.2; the hard and soft constraints on the VSSP should be determined, and to do so, input data on all parameters should be gathered. This data needs to be monitored real time or needs to be predicted, using historical data. After gathering the information, a decision model is needed to determine under which conditions the speed can be varied from the current static speed profile. When these decision models are conducted for each constraint, the VSSP's can be constructed, because it is now known what the options for variation are.

The possible effects of an introduction variable speed limits are tested in an experiment. It is concluded from the experiment that variable static speed profiles can decrease the travel time and therefore the delay, but the influence of varying the speed depends heavily on the speed of other trains on the network. Hence, it is important to also take into account the VSSP of other trains, to make sure, for instance, that a train does not accelerate to 160 km/h, and thereafter must slow down because there is a slower train in front of it.

5. Discussion

In this chapter, the outcomes and conclusions of this research are discussed. The discussion is divided into different paragraphs, debating different topics and parts of this research and comparing them to the reviewed literature.

Influential characteristics

A lot of different external characteristics that influence the static speed profile have been encountered during this research. Nine different main constraints and over 40 of their sub-constraints have been identified. The most general characteristics are discussed during this research, but it is possible that for specific track sections other characteristics apply. As said in an interview with F. Többen; it should be checked what goes wrong if the speed limit is increased, to get a clear view on the influential characteristics (Többen, 2019). To overcome the possibility of missing some important constraints, lot of data needs to be collected and monitored on increasing the maximum speed. This will also help in overcoming the current problem in not knowing for sure why a speed limit is in place, i.e. what the reason is behind this speed limit. Furthermore, train characteristics, such as the braking curve or noise production, are not within the scope of this research. Hence, they are not discussed in detail.

This research maps out the most important influential characteristics but does not guarantee that all these apply on each individual track section. Further research per track section is necessary to identify the restraining characteristics for that specific section. Only when this has been done, variability within the speed profiles is possible.

Data collection

As pointed out above, this research alone identified almost 40 sub-constraints on the maximum speed. When introducing a VSSP, data on these constraints should be monitored and collected within a database, as discussed in paragraph 4.3. This data collection has not been a part of the research. When gathering information on a constraint, even more constraints could be identified or discussed in detail, which was not possible for all characteristics now; they are discussed in a more general way and not in detail. Wang et al. (2018) describes that there are so many factors influencing the maximum speed, that it becomes difficult to describe them mathematically. Condition based modelling or monitoring is therefore a good solution (Wang, et al., 2018).

Experiment results

The results of the experiment show only one of the possible implementations of a VSSP and do only apply for such a situation, whereas the options and capabilities of VSSP's are considered much larger than shown in the experiment. Only delays of 2 and 4 minutes are simulated, as such small delays are much more common than larger delays, but it only shows a narrow range of possible results. Also, the increase in speed had a maximum of 20 kilometers per hour. This was in line with the outcomes of the interviews, who stated that increasing even further would most likely cause more problems (Többen, 2019).

The experiment still has not discussed a lot of other factors, which would be necessary to get an accurate picture of the possibilities and shortcomings of VSSP's. For instance, a defect train, larger delay time or different trains riding close together with different VSSP are options for future experiments. ERTMS level 2 and level 3 makes it possible to let trains driving with smaller headways (Červenka, 2017). This already increases the use of the total capacity significantly (Goverde, Corman, & D'Ariano, 2013). Hence it is needed to experiment further with VSSP when there is a higher frequency of trains on the network.

Furthermore, the Dutch rail network is a complex system. For instance, four hundred stations, 7114 kilometers of track and 6795 railroad switches are presented on the Dutch rail network (ProRail, 2019). The experiment is a very simplified situation and the implementation of a VSSP will be much more complicated. Where the experiment shows that increasing the speed from 140 km/h to 160 km/h can potentially decrease the travel time with 65 seconds, there is no certainty that this is also possible when there are for example more trains on the network. More research is needed on different situation, representing the real-life system more than the current performed simulation runs. Also, more simulations on changing the VSSP's based on other constraints are needed.

Benefits of VSSP

The experiment showed that the decrease in travel time was 65 seconds when increasing the speed with 20 km/h for over 20 kilometers of track. With a station on the Dutch network approximately every 18 kilometers (ProRail, 2019), it is possible to discuss what the total benefit would be of implementing variable static speed profiles, as a travel time profit of 1 minute is not that much. Other research showed that rescheduling – where the static speed profile was adjusted to the new moving authority – increased the capacity on the network (Goverde, Corman, & D'Ariano, 2013)

More research is needed to investigate other possible benefits of VSSP's, for instance the effect on the other two discussed KPI's, namely the capacity usage and energy consumption. Only when it is clear what the effects on all three KPI's, a clear picture on the benefits of implementing VSSP's can be given, which is not the case at this moment (Stenström, Parida, & Galar, 2012). To do so, more real-life data and more complex situations than currently used in the Xandra simulation are needed. Another possible benefit of VSSP could be the better tracking of the condition of elements, making maintenance easier to conduct. This has also not been discussed within the research.

VSSP implementation on macro-level

It is clear from research that the total implementation of VSSP's is at this moment not possible. Ideas on the possible workability of a VSSP based system are provided and discussed upon in paragraph 4.3. Nonetheless, it has not been discussed with a good amount of ERTMS experts at other departments, like the European Rail Agency or Prorail. Moreover, the current rail sector has focused on trackside systems for over 150 years. A 'migration of the mind' within this sector is needed to work variable with train-based data (Van Es, 2019). It is a completely new system that should be executed and extended research towards implementing the VSSP's has not been conducted.

One of the visions on the implementation of VSSP's given in this research focusses on the traffic controller, giving them the possibilities to reassign a new VSSP to, for example, a delayed train. However, previous research showed how each traffic controller acts differently when rescheduling trains in case of delays; some try to maintain the capacity while others try to restore the disruption as soon as possible (Hirai et al., 2006). This makes it more difficult to understand what the effects will be of implementing VSSP's via the traffic controller, making it a less optimal option.

The other vision on the implementation showed the use of a decision model in the ERTMS software. This vision is supported by literature, for instance Goverde et al. (2013) and Hirai et al. (2006). Nevertheless, it is computationally difficult to search for an optimal solution in real time, if many factors play a role. It is therefore better to identify a good solution, based on the pre-defined KPI's, as this is possible in the limited time (Rodriguez, 2007).

This study gives an idea on the future use but has not quantified the benefits and costs of the whole system. A future cost benefit analysis on this topic is needed as addition to the findings of the research. The current subsystems of ERTMS already cost a lot to implement, and the scope of the ERTMS network in the Netherlands is deceased because of the difficulties of implementation and costs (Slootjes, 2013). With the VSSP system, this will most likely be the same. Furthermore, one of the sub goals of ERTMS is the interoperability between countries. Making differences to the current software or change the way ERTMS works, will cause discussions between countries and this will also take time and make extra expenses (Goverde et al., 2012). Hence, the question arises in what timeframe VSSP's could be implemented. More research is needed on the political and policy side of the implementation.

6. Conclusion

This research has focussed on a new idea in the rail sector, namely the possible implementation of variable static speed profiles (VSSP). This new terminology describes multiple different speed profiles, altering on different characteristics and offering a more variable selection in speed profiles within ERTMS. To investigate which factors should influence these VSSP's and how ERTMS could handle these in the future, the following research question has been formulated:

How can a variable static speed profile be designed, based on variations in external constraints on the current maximum speed?

The reasoning behind the current static speed profile is missing for the most situations. That is why – to be able to answer the research question – different external constraints were investigated to determine their influence on the maximum speed of the train. It can be concluded that the current static speed profile is designed for a specific design speed, which is requested by the network manager. Systems, like railway switches and the catenary system, are designed for the requested speed. However, research showed that these speed limits are not as hard as it seems; the system's design speed is based on a worst-case scenario, which does of course not apply for each situation, where type of train, wind speeds and other conditions can vary.

The external constraints that are investigated during the research are divided into different classes. Hard constraints form a hard boundary on the maximum speed and cannot be varied for different situation. Characteristics identified as such are the power supply of the catenary system, maximum speed at level crossings and the stability of bridges and tunnels. These factors depend on the safety for passengers. Soft constraints can be varied for different situation and are the most interesting when constructing variable static speed profiles. Characteristics identified as soft constraints are the nuisance caused by noise and vibrations, the condition of the catenary system, railway switches and others (Figure 3.3). The identification as soft constraint is mostly due to the variability in condition of materials and different behavior of rolling stock types.The sub-parameters that influence these soft constraints should be determined per situation to be able to determine the maximum speed specifically adjusted for the situation of the train. A causal relation diagram has been constructed to help identifying parameters that influence the maximum speed on the rail network (Figure 3.4).

A case study on the catenary soft constraint has been conducted. It is found that the condition of infrastructural and train bound materials determine the variability of the maximum speed. Data on these conditions should be monitored per train and per track section, otherwise variability is not possible. To select the most appropriate variable static speed profile, a decision model has been constructed, providing insight in the steps that need to be set. First hard and soft constraints should be determined, after which a decision should be made in increasing or decreasing the speed, based on key performance indicators. The KPI's that should determine the selection of the VSSP are the time of delay, capacity usage and the energy consumption. These KPI's are in line with the goals of the Dutch network manager.

To quantify the possible effect of variable static speed profiles an experiment has been performed on a single-track section. From these experiments was found that the travel time could be decreased by increasing the maximum speed. However, the effect depends heavily on the VSSP chosen for other trains on the network. When a train in front of the delayed train has a slower VSSP selected, the delayed train can get stuck behind the slower train. This will cost a lot of extra energy, whilst the effect is almost null. Furthermore, increasing the speed to overcome delay only has a limited impact. Increasing the speed from 140 km/h to 160 km/h over approximately 20 kilometres of track did only safe 65 seconds for the intercity. Thus, the benefit of variable static speed profiles should not only be found in decreasing delays, but also in increasing the capacity or reducing negative external effects, like for instance noise nuisance for older, noisier trains.

Before it is possible to implement variable static speed profiles, a lot of additional data will be needed. The data could partly be collected by ERTMS trains and should be used to determine how trains and the condition of infrastructure, like the overhead wire or a switch, reacts to driving with different speeds for a longer time. The earlier discussed KPI's can be used to determine the effects. For the implementation of VSSP's in the ERTMS structure, two different visions are discussed. Selection of the VSSP can take place via the traffic controller or via the ERTMS Radio Block Centre. With the first procedure, the traffic controller can actively adjust the speed profile of the train, according to the situation. When communicating the VSSP via the RBC, the decision should be based on a computerized decision model, for what more historical data on the effects is needed.

To conclude, a variable static speed profile can be designed when all external parameters per track section are identified and divided into soft and hard constraints. It should be known how much room for variability there is, and on which factors it relies. After that, the effects of increasing or decreasing the speed should be determined, using the KPI's. An example on how to do so is provided in this research (paragraph 4.1). When it is known what the effects are of each different VSSP, a decision model should be made to determine structurally what the best VSSP is for each specific train.

7. Recommendations

The recommendations chapter is divided into two sections. First, an advice on future steps towards ERTMS with the VSSP are provided. After that, more general recommendations based on future research are made on what should be done next that has not been done thoroughly in this research.

7.1. Advice on the implementation of VSSP

It is now known how variable static speed profiles should be designed and how they should be handled. For the future implementation of these variable static speed profiles in ERTMS, a list of recommendations has been made. The points discussed in this list follow from the conclusion and discussion:

- Legacy systems should be replaced by newer, up to date software systems like ERTMS. This is not only because of the already presented advantages, like higher capacity and better safety against red light crossings, but also to make the rail network more futureproof for new ideas. Basing the system upon software and not one-track systems requires a new way of thinking, but gives a lot of new opportunities. Variable selection of static speed profiles is one of these.
- When ERTMS is in place, statistics of the train and its systems can be monitored. Before even implementing the VSSPs, it would be preferable that the systems monitor the behavior and safe this in a database. This data can be used later on to determine how trains react to driving with certain speeds and how their mechanical parts' condition reacts.
- Gather data on current speed restrictions to make a better plan in the future for speed restrictions. Now we say; worst case is 140km/h, but when monitoring the trains behavior, we can say in the future: well, this type of train can easily drive 160km/h with the same effect. ERTMS systems can help in monitoring exactly the speed, location and storing the condition of train elements in its on-board computer vital system.
- Specific recommendations for the monitoring at specific influential characteristics on the maximum speed;
    - Monitor or calculate the effect of different speeds on the condition of the overhead wire and pantograph.
    - Monitor the sound and vibrations used by different types of trains. Also, for freight trains, base these numbers on data collected in the past.
    - Monitor and test the behavior of different train types per curve and safe this data to determine in the future how fast every train can drive through the specific curve.
    - Track and monitor the presence of passengers at the platform and stations and communicate this to the RBC. In this way, the system can determine if there are safety issues if a train passes a station with higher speed and maybe (on smaller stations) if a train should stop at all.
    - Determine the effects of two trains passing each other, which influence the air pressure on both trains and other structures.
    - Monitor the effect of different trains passing through different tangents of railroad switches on noise and chance of derailment.
- Gather information on the effect of different variable static speed profiles on the identified key performance indicators. The values of the KPI's are needed to be able to make a decision on which VSSP a train will get. These results will form the base for a decision model implemented in ERTMS or for the active adjustment strategy of a traffic controller.
- Implementation of VSSP in ERTMS will be difficult. A VSSP database should be constructed to gather all parameter data to construct the VSSP's. The database of SSP in ERTMS should be increased to allow for more speed profiles.

7.2. Research recommendations

More future research should be put into the work of identifying the influential characteristics, i.e. hard and soft constraints. The network of characteristics could and should be increased with more factors, to get a better picture of all characteristics that influence the maximum speed. Besides that, the identified characteristics form a general picture for the Dutch rail network. It should be determined per track sections what the constraining characteristics are. Most likely other explicit factors are discovered when investigating specific track sections.

Simulating and experimenting on a real-life track sections will also be a good next phase in the investigation. Following the steps discussed in paragraph 4.2 on a real situation, determining the effects on all KPI's. Currently, only the effects on a small, simple delay on a single line have been determined. Effects of more complex situation could be different and should be determined, to have a complete image on the benefits and cons of variable static speed profiles.

The macro-level section of this research has focussed on the implementation of variable static speed profiles in ERTMS. However, this has not been discussed in detail. More work should be put into the implementational phase of VSSP's: how should the best VSSP be selected? Where should data on constraints be saved? What extra systems are needed for the implementation? Those questions should be answered in future research. Furthermore, two visions on the VSSP implementations have been discussed: a computerized decision model within the ERTMS system or active adjustment by the traffic controller. It is recommended to clarify the possibilities, costs and implementational steps of those options, to be able to determine the best option. Also, more research should be conducted on the policy field of implementing VSSP in ERTMS.

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Appendix A – Causal Relation Diagrams of Characteristics

This Appendix provides the CRD (Causal Relation Diagrams) of all characteristics that influence the maximum speed as discussed in Chapter 2 of this report. Every paragraph corresponds these characteristics. The discussed CRD as well as the identification of the sub-characteristics provides help in framing the characteristics that are needed to monitor when introducing VSSP's.

A.1. Introduction to the CRDs

The Figures A.2 to A.9 show the Causal Relation Diagram of the corresponding characteristic. Figure A.1. provides the legend of all CRD. The arrows show the relation between the sub-characteristics and show what happens if the previous sub-characteristic in the chain increases or decreases.

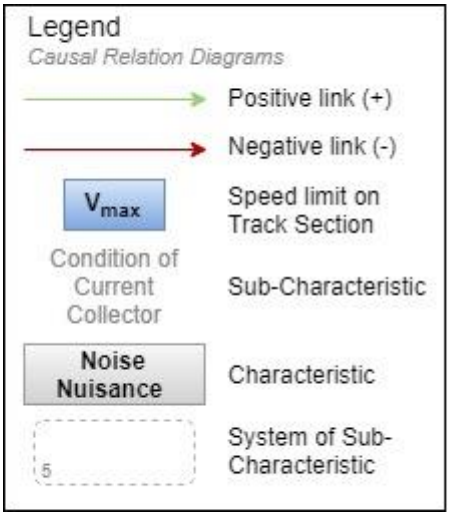


Figure A.0.1 - Legend of Causal Relation Diagrams

Table A.2. to A.9 provide the explanation and identification of the sub-characteristics. The identification of the sub-characteristics includes; *effects, causes, soft-* and *hard constraints.* Explanation on this identification is provided below in Table A.1.

Table A.1 - Legend on identification of sub-characteristics

Identification	Meaning
Effect	Sub-characteristics is influenced by the maximum speed and has no direct impact on the maximum speed itself.
Cause	A sub-characteristic that influences another sub-characteristic, but not the maximum speed directly. Can influence the maximum speed indirectly.
Hard Constraint	Influences the maximum speed directly and cannot be altered, varied in different situations. Forms an upper barrier for the speed of the train.
Soft Constraint	Influences the maximum speed directly and can be altered, varied in different situations. It is desirable to meet the constraint, but it is not mandatory for the specific situation.

A.2. CRD – Noise Nuisance

Noise nuisance of trains in general has been identified as a soft constraint on the maximum speed, whereas a single train does not have to comply with a sound barrier, but the total batch of trains does. Figure A.2. shows the sub-characteristics that play a role in the noise nuisance characteristic. Measures that decrease noise nuisance, for instance sound absorbing barriers, are not considered, because they are of no importance to the speed of the train. The noise nuisance that is measured obviously takes these measures into account. Table A.2 discusses the sub-characteristics in detail and provides an identification of the sub-characteristics.

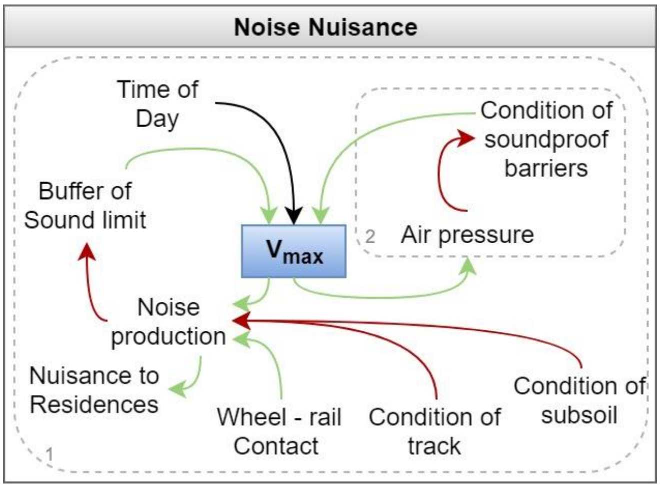


Figure A.0.2 - CRD of Noise Nuisance

The sub-characteristic *Time of Day* is a special case, where indeed there is neither a positive nor negative link with the buffer of the sound barrier. It depends specifically on the time of day which type of link it is. During evening and nightly hours, it decreases the buffer, because sound effects are affected by a multiplying factor. During daytime, nothing happens.

Table A.2 - Identification of sub-characteristics of Noise Nuisance

ID	Sub-Characteristics	Identification	Numeric value	Explanation
1	Wheel-Rail contact	Effect	-	Increasing the maximum speed has a lot of effects according the production of sound. Condition of track and subsoil influence the production of noise. The wheel-rail contact decreases, and this will produce more oscillations, producing more sound and increasing the noise nuisance. The limit of sound buffer is based on legislation; how many noise is permitted in one day? When more noise has been made, there will be less buffer for other trains to produce noise, influencing the speed to decrease. Therefore, noise nuisance is a soft constraint providing a **balancing loop** on the maximum speed**.**
	Noise production	Effect	-	
	Noise nuisance	Effect	-	
	Buffer of sound limit	Effect & Soft Constraint	-	
	Nuisance to residences	Effect	Above 55 dB	
	Time of day	Cause	21:00 – 04:00	
	Passenger comfort	Effect	-	
	Condition of track	Cause	-	
	Condition of subsoil	Cause	-	
2	Air pressure	Effect & Cause	-	Higher speeds cause more air pressure on the noise cancelling barriers. When this

Condition of soundproof barriers	Effect & Soft Constraint	-	becomes too much, the condition of the barriers will decrease. When the condition becomes too low, speed should be lowered for construction safety. This provides a **balancing loop** on the maximum speed.

A.3. CRD – Vibrations

Vibrations caused by running trains are a difficult problem to address, due to the lack of legislation and information. This also influences the case that vibration is primary identified as effect of trains and not as constraint, as it is not mandatory to provide measures to decrease vibrations. Figure A.3 provides the most important sub-characteristics that form the effects of vibrations. Note that not all characteristics that play a role are taken into account.

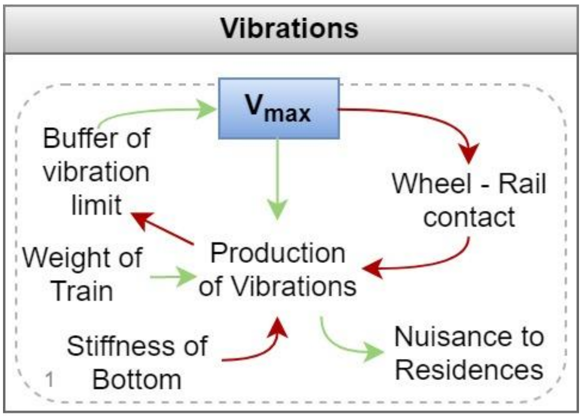


Figure A.0.3 - CRD of Vibrations

Table A.3 shows the identification of the sub-characteristics. All characteristics can influence each other, but do not have any control over the maximum speed of the trains. Vibrations can however influence structures of the track section, but this is so specific per section, that this is not taken into account in the Causal Relation Diagram.

Table A.3 – Identification of sub-characteristics of vibrations

ID	Sub-Characteristics	Identification	Numeric value	Explanation
1	Wheel-rail contact	Effect & Cause	-	The sub-characteristic production of vibrations caused by trains is influenced by the maximum speed, and also the stiffness of the bottom, weight of the train and wheel-rail contact are important causes of vibrations, which are dependent on the situation. Vibrations are mostly a problem to residences and the people living there, causing nuisance and damage to structures. When there are too much vibrations, there is no buffer left to produce more vibrations: the speed needs to be lowered. Vibration also are a soft constraint on the maximum speed, forming a **balancing loop**.
	Production of vibrations	Effect	-	
	Stiffness of bottom	Cause	-	
	Weight of train	Cause	Different per train type (kg)	
	Nuisance to residences	Effect	-	
	Buffer of vibration limit	Effect & Soft Constraint	Different per situation	

A.4. CRD – Catenary system

The traction energy supply system, here is short catenary system, is a complex constraint on the speed of trains. Not only the visible systems of the overhead wire and current collector have a role, also the substations providing the system with energy. The whole system is identified as soft constraint on the maximum speed. Figure A.4. provides the CRD of the traction energy supply system, with different sub-systems in place.

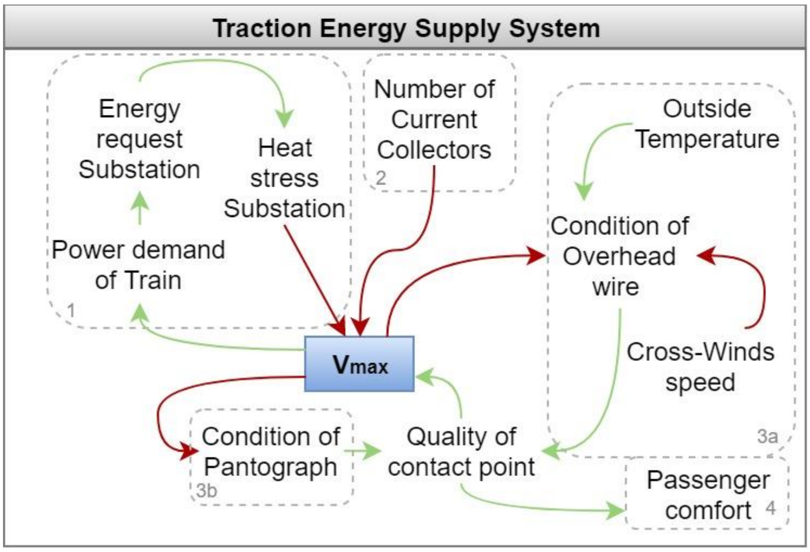


Figure A.4 – CRD of Traction Energy Supply System

Table A.4. shows the identification of the sub-characteristics and provides the hard and soft constraints that are needed to consider when driving with higher maximum speeds. The balancing loops control the maximum speed and need to be monitored per train ride, to be able to determine the maximum speed allowed.

Table A.4 – Identification of sub-characteristics of Traction Energy Supply System

ID	Sub-Characteristics	Identification	Numeric value	Explanation
1	Power demand of train	Effect	-	The three sub-characteristics form a **balancing loop** to the maximum speed. When the speed is increased the train needs more power, requesting more energy from the substation. If this get to much, the heat stress in the substation increases. To make sure no damage is done, the maximum speed should be decreased.
	Energy requested of substation	Effect	-	
	Heat stress in substation	Effect & Hard Constraint	Depends on substation	
2	Number of current collectors	Hard Constraint	0 or 1 or more than 1	When the train has more than 1 current collector, shockwaves in the overhead wire could cause damage to the second collector. Therefore, lower speeds are advised.
3a	Outside temperature	Cause	Critical below 0°C	The condition of the overhead wire will decrease with higher speeds, or when there are lower temperatures and high-speed crosswinds. When the overhead wire is in bad condition, the energy transport through the contact point is
	Crosswinds speed	Cause	-	

	Condition of overhead wire	Effect & Soft Constraint	Should be monitored	less efficient and lower speeds are needed. This process forms a **balancing loop** between the maximum speed and the condition of the overhead wire.
	Quality of contact point	Soft Constraint	Should be monitored	
3b	Condition of current collector	Effect & Soft Constraint	Should be monitored	The condition of the current collector determines in combination with the condition of the overhead wire if driving faster could be possible. Higher maximum speed also damages the collector more, allowing for less high speed, because the contact point is less efficient. This is a **balancing loop** between the maximum speed and condition of the current collector.
	Quality of contact point	Soft Constraint	Should be monitored	
4	Passenger comfort	Effect	-	When driving faster under the overhead wire, flames or noise can occur and this could influence the comfort for passengers or people waiting on platform.

A.5. CRD – Track lay-out

The track layout consists of two elements, the centre to centre distance of two parallel track sections and the safe zone distance when working next to the track. The current situation of the centre to centre distance cannot be altered and was therefore identified as a hard constraint. Figure A.5 shows the CRD of the track layout with only the most important sub-characteristics. For instance, the *Air movement* also influences the safety, but this is not specific for the track layout and is thus not displayed in the CRD.

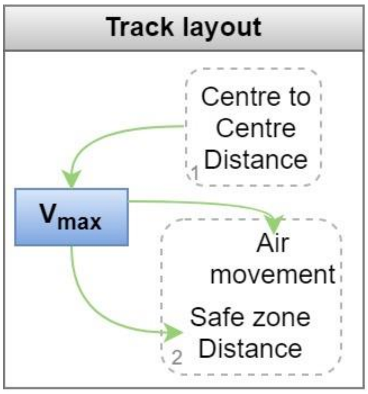


Figure A.5 – CRD of Track layout

Table A.5. provides the identification of the track layout sub-characteristics and offers an explanation on the working of the characteristics on the maximum speed.

Table A.5 – Identification of sub-characteristics of Track layout

ID	Sub-Characteristics	Identification	Numeric value	Explanation
1	Centre to centre distance	Hard Constraint	Centre to centre distance should be higher	The positioning of the tracks is a hard constraint on the maximum speed, as it cannot be altered variable. The positioning has effect on the air movement, especially when two trains

			than 4 metres.	will pass each other. With higher speeds, this will become dangerous and the centre to centre distance should be increased, but as said, this is not possible on a short notice. However, when it is known that trains will not pass each other, the maximum speed could be increased.
2	Air movement	Effect	-	Both these sub-characteristics are effects of increasing the maximum speed and should be considered if the maximum speed is increased.
	Safe zone distance	Effect	Higher than 2,40 metres	

A.6. CRD – Switches

Switches are regularly used within the rail network, especially on rail yards and station areas. Railroad switches are present in different types, all with a different design speed. It is dangerous to pass such a switch with a higher speed and therefore the switches are identified as hard constraint. Figure A.6 shows the CRD of railroad switches with the most important sub-characteristics.

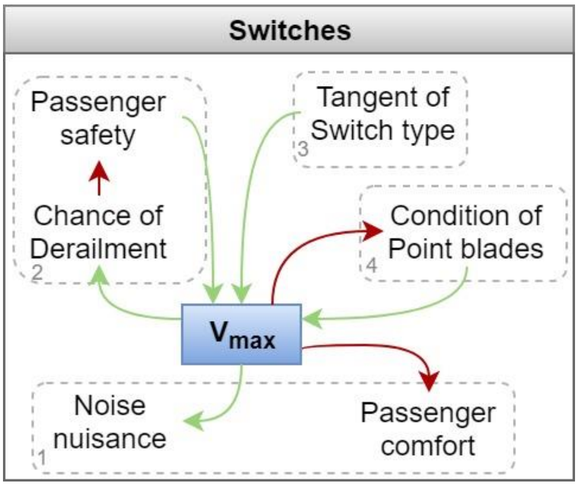


Figure A.6 – CRD of Switches

The identification of the sub-characteristics follows from Table A.6. Most sub-characteristics have their own sub-system and do not influence each other directly. Hence the sub-characteristics are discussed separately in Table A.6.

Table A.6 – Identification of sub-characteristics of Switches

ID	Sub-Characteristics	Identification	Numeric value	Explanation
1	Noise nuisance	Effect	55 dB	Both these sub-characteristics are effects of increasing the maximum speed and should be considered if the maximum speed is increased. Noise can occur when passing a switch too fast, when the wheels touch the moving parts. This can also cause the train to move to an amount passengers dislike it.
	Passenger comfort	Effect	-	
2	Chance of derailment	Effect & Cause	-	When passing the switch with higher speeds, the chance of derailment

	Passenger safety	Effect & Soft Constraint		increases, because the tangent of the switch is too small to pass with such speeds. Furthermore, collision with the point blades could cause derailments. This decreases the safety of passengers. Because these conditions are different for every situation, this forms a soft constraint in a **balancing loop.**
3	Tangent of switch type	Hard Constraint	See Table 3.2. of Paragraph 3.3.3.	The switches on the Dutch network all have different tangents and are therefore designed for different speeds. Higher speeds are currently not allowed and are dangerous, thus the maximum speed is restricted to the design speed of the switch, which is a hard constraint.
4	Condition of point blades	Effect & Soft Constraint	Should be monitored	When passing the switch with higher speeds, the train could collide with the point blades of the switch. When this happens, the point blades get damaged. When the condition of the point blades is lower, chance of accidents increases, and lower speeds should be advices to not damage the point blades even further; here a **balance loop** is in place between the condition of the blades and the maximum speed that should be allowed.

A.7. CRD – Station passing

Passing a station without stopping has impact on the passengers waiting on the platform and can cause dangerous situations. That is why speed restrictions are in place with passing the station, most of the times already caused by the presence of switches. Increasing the speed causes safety issues and is therefore considered as hard constraint. The sub-characteristics of this constraint are presented in Figure A.7.

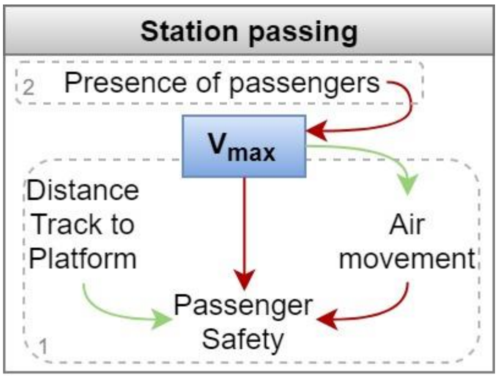


Figure A.7 – CRD of Passing a station

Table A.7 provides the identification of the sub-characteristics when a train passes a station with higher speeds. No sub-characteristic has direct influence on the maximum speed, but the station passing has a speed restriction in the Netherlands, as discussed earlier in Paragraph 3.3.4.

Table A.7 – Identification of characteristics of Passing a station

ID	Sub-Characteristics	Identification	Numeric value	Explanation
1	Distance Track to Platform	Cause	Adjacent to platform or not	When passing with higher speeds, generally the air movement increases, and this is dangerous for passengers. Also, higher speeds decrease the safety when passenger will fall on the tracks or stand close to the platform edge. The distance from the track to the platform is of importance, because if the train travels on the track that has no adjacent platform, the safety issues decrease, and the maximum speed could possibly be increased.
	Air movement	Effect	-	
	Passenger safety	Effect	-	
2	Presence of passengers	Soft constraint	-	When a lot of passengers are present at the stations, passing at lower speed is better for the safety of those passengers. On the other hand, when no one is present, it does not form a constraint on the maximum speed. That is why the presence of passengers, which is variable, is a soft constraint.

A.8. CRD – Level Crossing

Crossing a railroad is possible with the use of level crossings. A level crossing should be closed in time and to do so, detection loops on a right distance of the crossing will detect the train going to pass the crossing. These systems are designed for a specific speed and that is why the level crossing was judged as a hard constraint. In Figure A.8 the level crossing's CRD is presented with the most important sub-characteristics.

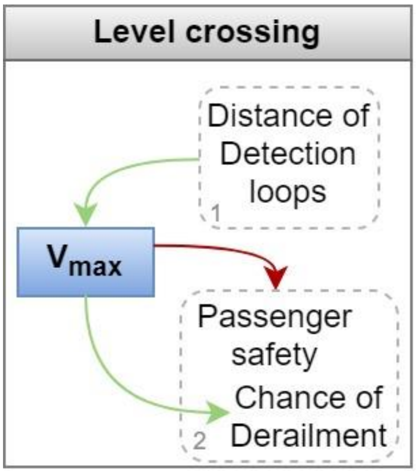


Figure A.8 – CRD of Passing a level crossing

Table A.8 presents the identification of the sub-characteristics that take a role in passing a level crossing. Here the distance of the detection loop to the level crossing is the most important for the level crossing to be a hard constraint, but it also has some effects that could indirectly have influence on the other characteristics.

Table A.8 – Identification of characteristics of passing a level crossing

ID	Sub-Characteristics	Identification	Numeric value	Explanation
1	Distance of detection loops	Hard constraint	Different max. speed	When passing the detection loop with higher speeds, it is possible that level crossing is not closed for road users in time, causing unsafe circumstances. Therefore, the design speed for the level crossing is a hard constraint on the maximum speed.
2	Passenger safety	Effect	-	Both these sub-characteristics are effects of increasing the maximum speed and should be considered if the maximum speed is increased. Higher speeds are not only a negative effect on passenger, but more on other road users that wait at the level crossing.
	Chance of derailment	Effect	-	

A.9. CRD – Curves and Cant

When travelling through a curve, the train should have a lower speed to make sure the train can travel safe through the curve. The radius of the curve therefore determines how fast the train could travel, but other characteristics influence the maximum speed too. These sub-characteristics of curves are presented in Figure A.4. In general, curves are identified as a hard constraint.

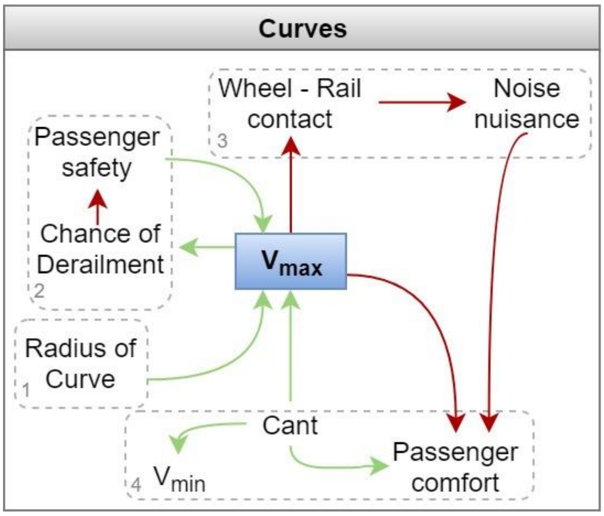


Figure A.9 – CRD of Curves

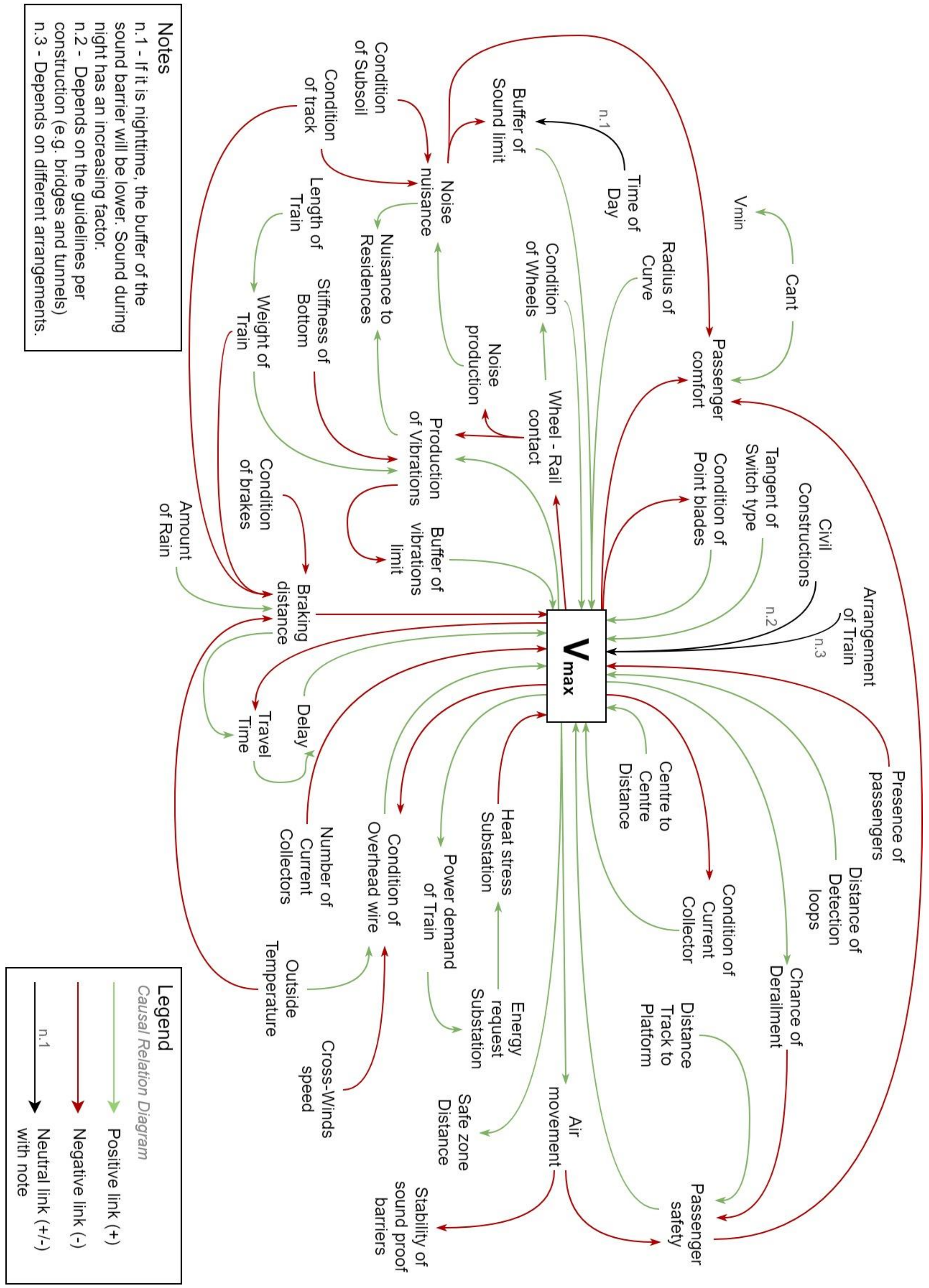
Table A.9. shows the sub-characteristics' identification. The table provides explanation on the influence the sub-characteristics have on the maximum speed and how the curves are identified as hard constraints.

Table A.9 – Identification of characteristics of Curves

ID	Sub-Characteristics	Identification	Numeric value	Explanation
1	Radius of curve	Hard constraint	R < 630 meter -> v < 40 km/h	The radius of the curve has influence on the safe travel of the train through the curve. A curve is designed for a specific speed and increasing the speed is not

				possible, because it can cause unsafe conditions. The radius determines the maximum speed of the train.
2	Chance of derailment	Effect & Cause	-	When travelling faster through a curve, derailment chance will increase. The wheels will no longer follow the tracks and the train will 'shoot' straight ahead, causing damage. This decreases the safety of passengers. Because these conditions are different for every situation and train type, this forms a soft constraint in a **balancing loop.**
	Passenger safety	Effect & Soft Constraint		
3	Wheel-rail contact	Effect & Cause	-	With decreasing wheel-rail contact comes more noise nuisance. Specific in curves, the wheel-rail contact can decrease with higher speeds, making it more difficult to keep the wheels on track, causing noise nuisance. This noise also causes squeezing sounds, which is not ideal for passenger comfort.
	Noise nuisance	Effect & Cause	-	
4	Passenger comfort	Effect	-	Cant of the curve is needed when wanting to travel with higher speeds through the curve. It makes travelling through the curve also more comfortable for passengers. Only the minimum speed needs to be increased, because standing still could case the train to bend over.
	Cant	Cause & Hard Constraint	-	
	Minimum speed	Effect	-	

Appendix B – Causal Relation Diagram: influences Vmax



Appendix C – Xandra simulation software

Xandra is an application developed by Arcadis and is used to simulate and predict the functionality of rail network track and time table designs. This appendix will briefly discuss the options of Xandra on the aspects of input, simulation and output (Vooren, 2016).

General functionality

A *project* in Xandra consists out of different elements, called *variants*. The project contains one or more *infrastructure* variants in which the *track layout* and *signalling system* can be defined. Furthermore, the infrastructure variant contains information about *traction* and the *timetable* and also *rolling stock* info is needed. When enough information is obtained on the variants, *simulation* can take place. From a single simulation run, different *output* variables can be obtained and verified.

Input

As said before, Xandra needs different input to eventually run a simulation. These already have been discussed in Chapter 4.3, focussing on the inputs for the specific experiment that influence the conclusions. This appendix' paragraph discusses the input variant on the workability of Xandra more in detail.

Track layout

Information on the track, its connections with other tracks and the precise location of the track. Geocodes are used to give each track section a code. The track layout is based on nodes and links; endpoints of track sections need to be added and Xandra will link the two points. Two different track sections are connected via a track link or switch. Based on the chainage of locations of specific joints, crossings and timetable points, these points are added to the layout. Timetable points are used to guide trains and mark location needed for stops.

The station approach section used in the experiment in Chapter 4.3 is displayed in Figure C.1. It shows the visualization of the track section within Xandra. The intercity train (1000 series) is running from the left to the right. Link A connects track section FE with section 1. At the same chainage, there is a speed sign (which communicates the maximum speed to the intercity in the simulation). At switch 503 the intercity will be directed on to track 1, where the platform is. Switch 507 reconnects the track 2 and 1 before link B connects track 1 with section FD behind the station area. See also Figure 4.8 for the full layout of the track section.

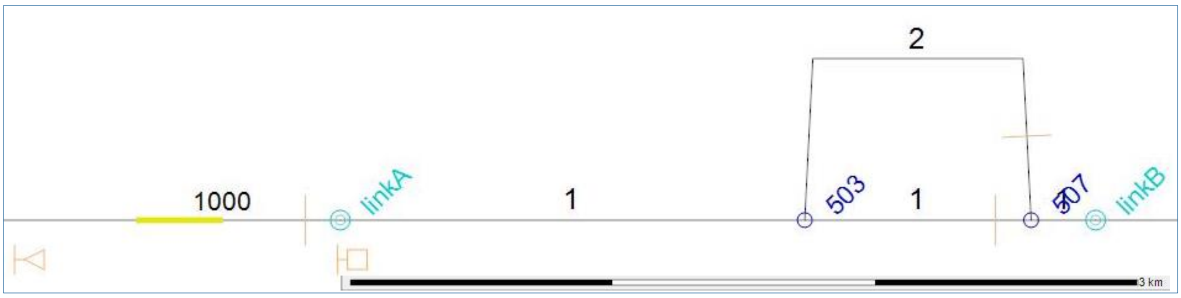


*Figure C.1 - Visualization of station approach section in Xandra (*Xandra, 2019*)*

Signalling and Speed profile

Only relevant signals for the route of the train in the simulation must be added. Consists out of signal positions, speed signs, relations between signals, and detection joints. Different signalling systems can be simulated with different interaction and relations:

- *None* -> No train interaction, trains adhere the *ssp* and timetable

- *BB21* -> Moving block system (like ETCS L3) with train interaction, adhere *ssp* and try to adhere the timetable.
- *Block* -> Fixed block sections, train adhere signals (trackside or cabin), adhere *ssp* and try to adhere timetable. Select specific model: ATB-EG, ETCS L2, etc.

Also, a static speed profile has to be defined. For speed signs, the specific speed and type of sign is added. The static speed profile is influenced by the *max. simulation speed, max. rolling stock speed, max timetable speed, speed at first timetable point, current static speed profile and the braking model (e.g. braking to lower signal aspect)*.

The speed profile used in the experiment differs per simulation run, but the general speed profile can be found in Figure 4.8. Figure C.2. shows the sprinter (2000 series) on the station approach section, where (in orange) two speed signs can be seen. The left signal tells the train to slow down to 80 kilometres per hour and that speed has to be reached before the right signal.

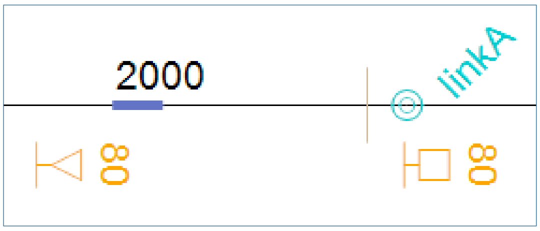


*Figure C.2 - Example of speed signs in Xandra (*Xandra, 2019*)*

Rolling stock

From a database, different single and combined train types can be selected. Characteristics as length, width, acceleration and rolling resistance are provided. For each train series, a set rolling stock has to be selected. The rolling stock used in the experiment and its characteristics can be seen in Table C.1. It describes the most important characteristics of the trains for the experiment.

*Table C.1 - Characteristics of experiment rolling stock (*Xandra, 2019*)*

Characteristic	VIRM VI + IV	SLT IV + IV
Used in	Intercity – 1000 series	Sprinter – 2000 series
Length	270 m	138 m
Weight	653000 kg	288000 kg
Acceleration	max. 2,0 m/s^2	max. 2,0 m/s^2
Deacceleration	0,66 m/s^2	0,80 m/s^2
Cabins	10	8

Timetable

Timetable consists of services with specific rolling stock type (a train series) including information about first and last departure time, route of the train passing timetable points, minimum stopping time and alignment of the train at the platform. From these train series, a timetable can be generated, showing all specific trains in the timetable. The settings for the timetable can be found in Table 4.5.

Simulation

A simulation run can be performed when infrastructure, timetable, traction and signalling variants are known. The simulation can be done in a specific timeframe, for all trains or separate per train. Also, different delay options can be changed, using the events simulator.

The simulation calculates the location, speed and acceleration at discrete time steps. The execution of the simulation is deterministic and will not change if parameters are constant.

Appendix D – Interview A. van Es.

The transcript of this interview will be in Dutch because the interview has been conducted in Dutch on the 29th of April at Arcadis in Amersfoort. Below, an English summary of the meeting is provided.

English summary
Andre van Es works on integral plans in the rail sector and is also teacher on the minor Rail Transport in Utrecht. He tells about the functionality of the different ERTMS Levels; where level 0 is not allowed by Prorail, level 1 is approximately the same as the Dutch ATB and level 2 is the most common integrated ERTMS system. Differences in ERTMS can be found in the communication between train and wall. The static speed profile within ERTMS is based on the current signage next to the track. The dynamic speed profile is based on train specific characteristics, for instance the braking capacity of a train. Using variable speed profile asks for a new mindset, where we do not depend on trackside systems. In the future, the environment will play a much bigger part, so acting on this is important. A train based; tailor made speed profile (Andre calls it ERTMS Level 4) would be the future. The train will take into account different norms and also the speed and braking of the train in front of it.

0.	**Kunt u kort iets vertellen over uw functie, achtergrond en werkzaamheden bij Arcadis? Wat zijn uw ervaringen met ERTMS?**
André van Es werkt op de afdeling integrale plannen en werkt op het moment aan verschillende projecten, waaronder de East Coast Main Line in het Verenigd Koninkrijk. Ook is hij docent op de Hogeschool Utrecht bij de minor Rail Transport. Hij omschrijft zijn bezigheden als ‘alles wat met rails te maken heeft’, dus tram, metro en trein. Meestal is hij betrokken in de vroege plan en onderzoeksfase van opdrachten en dan voornamelijk in de breedte, aansluitend bij de rol van projectleider.	
1.	**ERTMS heeft verschillende implementatie levels; wat is het verschil tussen de verschillende levels? Specifieker; wat is het verschil in het *ssp* tussen de verschillende levels?**
ERTMS kent de levels 0 tot en met 3, met daarnaast verschillende modes. Level 0 is niet toegestaan door Prorail. Level 1 is bijna gelijk aan het bestaande beveiligingssysteem in Nederland en wordt uitgerold als er geen goed ATP-systeem aanwezig is, dit gebeurt nu in België. Bij L1 is er geen RBC en geen train/wall communicatie. Level 2 is op dit moment het meest gangbare systeem, waarbij gebruik wordt gemaakt van het on-board ETCS-systeem met daarnaast het huidige trackside systeem voor de treindetectie. Level 3 is wat je eigenlijk wil; de trein meldt zelf waar hij is en de positie van de voorkant en achterkant van de trein is bekend. Het probleem waardoor L3 nu niet kan worden uitgerold ontstaat door niet-integere (meestal) goederentreinen, waarbij niet zeker kan worden gezegd dat er geen wagons zijn afgekoppeld, i.e. zijn los geraakt. Zonder trackside detectiemateriaal kan dit niet worden vastgesteld en daarom is L3 niet operationeel op het moment. Het verschil tussen de verschillende systemen zit hem in de communicatie met de trackside systemen. Binnen alle levels is het on-board systeem eigenlijk hetzelfde. In L1 komt de maximumsnelheid binnen via balises die gekoppeld zijn met het sein beeld. Bij L2 en L3 wordt dit gecommuniceerd via het RBC.	
2.	**Hoe beland het *ssp* in de ETCS? Waarop is dit *ssp* gebaseerd?**
Zie ook antwoord vraag 1. Het statische snelheidsprofiel is gebaseerd op de huidige snelheidsrestricties die ook op de borden naast het spoor staan. Volgens mij is dit gewoon 1 op 1 overgenomen. Waarop de snelheidsrestricties naast het spoor zijn gebaseerd heeft men weleens proberen te achterhalen, maar dit blijkt erg ingewikkeld, aangezien dit lang geleden is gebeurd.	
3.	**Wat is het verschil tussen het *ssp* en het Most Restrictive Speed Profile?**
Het statische snelheidsprofiel kan je zien als de bovengrens, meestal gebaseerd op civieltechnische restricties, die harde begrenzingen blijven natuurlijk altijd erg belangrijk. Bij	

bijvoorbeeld een tijdelijke snelheidsverlaging wordt dit ook aan het ETCS doorgegeven. Het ETCS kijkt dan wat de laagste maximumsnelheid is en baseert daar het MRSP op.	
4.	**Hoe wordt door de ETCS het statische profiel omgezet in het dynamische profiel?**
Dit is puur gebaseerd op trein specifieke karakteristieken. Niet langer gebaseerd op de slechts remmende trein. ETCS weet de rem capaciteit van de trein, maar bijvoorbeeld ook hoe lang de trein is. Na een snelheidsbeperking weet het systeem dus ook precies wanneer weer versneld kan en mag worden.	
5.	**Is deze "variabiliteit" ook het voordeel van ERTMS? Meer algemeen; hoe is ERTMS meer op de individuele treinen gericht?**
De trein zelf geeft nu dus zijn positie door, waardoor veel specifieker de locatie van de trein bekend is. Verder is het een kwestie van overgaan op een nieuwe mindset: *migration of the mind*. Meer dan 150 jaar is gewerkt met trackside systemen en dat werkte ook zeker goed, alleen om de voordelen van ERTMS te benutten, is eerst een nieuw beeld nodig dat men variabel kan omgaan met alle data die vanuit de trein nu binnen komt.	
6.	**In het algemeen, waar ziet u/ waar liggen de voordelen van ERTMS? Wat is hiervan de keerzijde, i.e. slechte punten en nadelen van ERTMS?**
Doordat de trein (in ETCS-level 3) zelf de positie doorgeeft, kunnen treinen dichter op elkaar rijden dan in het huidige systeem. Er valt dus capaciteit te winnen. Met zo'n statement moet je wel voorzichtig zijn, omdat als men zoals in Nederland al een goed werkend systeem heeft er niet zo heel veel capaciteit te winnen heeft. Het is dan lastig om de voordelen uit te leggen aan bijvoorbeeld beleidsmakers. Andere voordelen die langskomen zijn dat men meegaat met Europese wetgeving, de systemen vernieuwd met de huidige trend en er minder onderhoud nodig is aan de trackside systemen, omdat er nou eenmaal minder trackside systemen nodig zijn.	
7.	**Door ERTMS kan de maximumsnelheid op een aantal trajecten naar 160km/u. Is dit waarom ERTMS nodig is of zijn er andere belangrijkere redenen?**
Het huidige ATB-systeem werkt met beveiliging in trappen. De laatste trappen zijn 80km/h, 130km/h en daarna 140km/h. Het systeem kan de trein dus niet beveiligen boven 140km/h, terwijl de infrastructuur dit vaak wel aankan. Het ERTMS-systeem kan wel beveiligen met deze hogere snelheid.	
8.	**Welke andere parameters bepalen volgens u de maximumsnelheid het meeste?**
Het meest beperkende element bepaald de maximumsnelheid. Meestal zijn dit civieltechnische kenmerken, maar dit kunnen ook regelgeving of misschien omgevingskenmerken zijn, zoals bijvoorbeeld geluid of trillingen. Die omgeving zal in de toekomst nog meer in rol gaan spelen. Regelgeving speelt ook vaak mee, omdat in de wet vaak gewoon staat vastgelegd hoe hard gereden mag worden.	
9.	**Stel: *baanvaksnelheid op lang traject wordt nu beïnvloed door een enkel kunstwerk of bochtstraal.* Hoe wordt dit anders als men met ERTMS-gebruik gaat maken?**
Laten we als voorbeeld een bochtstraal nemen waar men met 80km/h doorheen mag. Bij het sein voor het baanvak met de bocht zal een wit 8 bord staan. Bij aanvang van het baanvak daarvoor zal een geel 8 bord staan, gebaseerd op de slechts presterende trein. Voor de nieuwste treinen betekent dit dat er al heel vroeg geremd moet worden, terwijl zij ook pas veel later kunnen remmen om op tijd 80km/h te rijden. In ERTMS zal dat gele 8 bord verdwijnen en zal het dynamische snelheidsprofiel precies laten zien op de DMI wanneer de machinist moet gaan afremmen. Ander voorbeeld is een bestaande bochtstraal in de buurt van Naarden-Bussum, waar de maximumsnelheid op 90km/h lag. Deze snelheid valt tussen twee trappen in het huidige ATB-systeem, waardoor een probleem ontstaan: laat je de te lage snelheid beveiligen of de te hoge snelheid, waarbij je maar hoopt dat de machinist het bord ziet en toch afremt naar 90km/h. Uiteindelijk is de maximumsnelheid op 80km/h gesteld. In ERTMS is dit probleem er niet en kan men gewoon beveiligen voor 90km/h.	
10.	**Deze factoren die de maximumsnelheid beïnvloeden, zijn deze ook te variëren per trein of rit? Welke parameters zijn volgens u variabel per trein of rit?**

Civiele beperkingen zullen de overhand hebben en als harde grens blijven gelden. Variëren is waarschijnlijk het meest mogelijk bij omgevingskenmerken. Ander vreemd voorbeeld zou zijn dat de bovenleiding beperkend is op 120km/h, maar dat geldt natuurlijk niet voor dieseltreinen. Nu moeten alle treinen het statisch profiel van 120km/h aanhouden, maar de dieseltreinen zouden hier dan prima 140km/h kunnen rijden, om maar een idee te opperen.	
11.	**Waar zit volgens u het voordeel/ nadeel van variabele snelheidsprofielen in plaats van statische snelheidsprofiel?**
Door de denken vanuit de trein is er nog meer mogelijk dan nu wordt uitgevoerd. Een *tailor made* snelheidsprofiel moet mogelijk zijn, aangezien ook veel data van de specifieke treinen beschikbaar komt. Denkbaar is een “level 4” ETCS-optie, waarbij de trein veel beter kijkt naar de remcurve van de trein voor zich en niet uitgaat van een rem naar abrupt 0km/h.	
12.	**In hoeverre zou het gebruik van variabele profielen al mogelijk zijn in de huidige ERTMS-software?**
Kijken naar trilling en geluid of andere invloeden op de omgeving. Hier valt waarschijnlijk wel in te differentiëren, bijvoorbeeld door een soort buffer op te stellen. Geluid wordt per jaar gemeten, je zou dan kunnen zeggen dat de treinen in december toch maar langzamer moeten gaan rijden omdat er anders te veel lawaai wordt gemaakt.	

Appendix E – Interview D. van Os

The transcript of this meeting will be in Dutch because the language during the meeting was Dutch. The interview does not follow the complete interview setup, because of the short time span of the meeting. The interview has been conducted on the 3th of May at Arcadis in Amersfoort. An English summary of the meeting is provided below.

English summary
Dick van Os is a senior advisor on the department of integral plans. Before, he has worked a lot on the catenary system. He told about the static speed profile and how it is based on a design speed. The speed is not based upon the constraints from infrastructure, but infrastructure is designed for a specific pre-determined maximum speed. But, driving faster under the current catenary system will not cause immediate issues. Only you should not do this with every train, because of the wear-off of the overhead wire. Other important constraints on the maximum speed are level crossings (we do not want those if we drive faster than 140 km/h), bottom construction and centre-to-centre distance of parallel tracks. Noise and vibration are effects of high speeds, but not as important constraint on the maximum speed: we do not change the speed, but we change the effect. For instance, by placing sound proof walls. Variating speeds is a difficult topic, because there are so many constraints.

0.	**Kunt u kort iets vertellen over uw functie, achtergrond en werkzaamheden bij Arcadis?** Wat zijn uw ervaringen met ERTMS?
Aangevuld door Kelt Garritsen. Dick van Os is senior-adviseur binnen de afdeling Spoor & Baan, Integrale Plannen. Hij heeft zich vroeger gefocust op de bovenleiding, maar houdt zich nu bezig met meerdere verschillende dilemma's en projecten.	
2.	Hoe beland het *ssp* in de ETCS? **Waarop is dit *ssp* gebaseerd?**
Het ssp is ingericht op een vooraf besloten ontwerpsnelheid. De snelheid voor het desbetreffende baanvak is ooit vastgesteld op, stel, 140 km/h. De installaties en overige civiele werken, zoals worden dan ingericht op die 140 km/h. De snelheid wordt dus niet achteraf vastgesteld, maar vooraf bepaald en als doel gezet voor een bepaald baanvak. De bovenleiding is meestal dan ook ontworpen voor 140 km/h. Uitzonderingen zijn de Hanzelijn en de HSL, die hebben dan ook andere systemen.	
8.	**Welke andere parameters bepalen volgens u de maximumsnelheid het meeste?**
Bovenleiding is een harde grens die de snelheid beperkt. Bovenleiding zijn wel proeven geweest voor het rijden met een hogere snelheid onder het huidige systeem, door sommige treinen harder te laten rijden dan de huidige grens. Dit was volgens mij geen probleem, maar je moet dit niet met alle treinen doen omdat de slijtage van de bovenleiding anders te veel wordt. De bovenleiding zal er ook niet meteen uitklappen bij 141 km/h, maar de ATB zal dan ingrijpen als een trein deze snelheid rijdt. Een andere snelheid willen rijden op zo'n traject zal vaak leiden tot het moeten doen van aanpassingen aan de installatie van de bovenleiding; nieuw systeem, kabels iets anders vastmaken, etc. Op het traject Eindhoven - Deurne is ooit een proef geweest met harder rijden onder de conventionele bovenleiding. Overwegen zijn nog veel bepalender. Bij 140 km/h zeggen we, dit kan nog met spoorbomen (conventionele overgang), maar bij hogere snelheden niet meer. Dit komt omdat de overweg anders nog langer dicht is, ook omdat je bij hogere snelheden waarschijnlijk met meer treinen (per uur) gaat rijden. Zoals je ook ziet op de HSL, worden bij hogere snelheden geen overwegen meer gebruikt. Geluidsnormen zijn niet technisch beperkend voor de maximumsnelheid, maar zijn er een gevolg van. Tegen dit gevolg worden maatregelen genomen (geluidsschermen e.d.), maar de geluids- productie van de treinen wordt niet beperkt. Heeft ook weer te maken met de	

vergunningen langs het spoor volgens mij. Er moet voldaan worden aan het geluidsplafond, maar als dit overschreden wordt gaan er niet treinen zachter rijden maar worden er meer maatregelen genomen. Hart-tot-hart afstand is ook getest met hogere snelheden, eigenlijk hetzelfde als het voorbeeld met de bovenleiding; spoor is ontworpen op een bepaalde snelheid, 4 meter afstand bij 140 km/h, maar zou dit ook hoger kunnen. Beperkend is hierbij wanneer twee treinen elkaar tegemoetkomen. Het harder gaan rijden met treinen kan ook invloed hebben op de druk op de bodem. Als de grond te zacht is kan de grond verzakken. Kijk maar naar de situatie bij Zwolle Stadshagen tussen Zwolle en Kampen. Kijk ook naar de beperkende factoren door het spoor zelf; bogen, verkanting en ook bruggen en kunstwerken.	
10.	**Deze factoren die de maximumsnelheid beïnvloeden, zijn deze ook te variëren per trein of rit?** **Welke parameters zijn volgens u variabel per trein of rit?**
Variatie is wel een lastig ontwerp, zeker omdat er zoveel verschillende invloeden zijn. Stel je zou de snelheid verhogen bovenleiding technisch, dan zijn er weer andere factoren die deze verhoging toch beperken. Denk aan een bochtstraal of een overweg. Het zou dan maar om een snelheidsverhoging gaan op een klein stuk spoor.	

Appendix F – Interview F. Többen

The transcript of this meeting will be in Dutch because the language during the meeting was Dutch. Because of the specific topic of the interview, a new interview setup has been introduced. Some questions are the same as in the other interviews with A. Van Es and D. Van Os. The interview has been conducted on the 3th of June at Arcadis in Amersfoort. An English summary can be found below.

English summary
Frans Többen works at the Asset Management department for the rail sector and has worked on catenary questions in the past. The design of the catenary system is combined with the substations, which deliver the power for the trains, via the pantograph. ProRail can choose between different types of catenary, which they think will fit the goal of the "new" section. The new system is designed for this speed and is tested for the most extreme conditions. The speed that follows is strict for the substations, but not that strict for the catenary system itself: it is designed for the worst-case scenario, and when the condition of the wire and pantograph are good, higher speeds should be no issue. Currently this is not possible with the legislation, but in theory it should be possible. For variable speed profiles, a lot of different parameters play a role (e.g. cant, curves, tractions of the wheels, layout of the train, number of pantographs, etc.). The benefit of variable profiles would be active control of the traffic controller for different scenario's, like delayed trains or extreme weather conditions.

0.	**Kunt u kort iets vertellen over uw functie, achtergrond en werkzaamheden bij Arcadis? Wat zijn uw ervaringen met ERTMS/ bovenleiding projecten? Wat is uw taak/ positie?**
Frans Többen werkt bij Arcadis op de afdeling Asset Management in de rail sector. Hij houdt zich verder bezig met Systems Engineering en Rail Infra vraagstukken, in de planvoorbereiding. Ook weet hij veel van de tractie-energievoorziening systemen. Frans heeft Werktuigbouwkunde gestudeerd aan de Universiteit Twente. Hij is ook betrokken bij de Rail Transport minor aan de Hogeschool Utrecht. In zijn eerste jaren bij Arcadis heeft hij vooral veel aan de bovenleiding gewerkt en onderzoek gedaan naar het harder rijden onder de bestaande bovenleiding, bijvoorbeeld met de Thalys en een ICM bij Schiphol.	
1.	**Hoe gaat het ontwerp van de bovenleiding in zijn werk?**
De bovenleiding gecombineerd met de onderstations wordt in vaktermen de TEV genoemd; de tractie-energievoorziening. De onderstations leveren energie wat naar de trein wordt getransporteerd. Dit gebeurt door het contact van de pantograaf met de draad van de bovenleiding. Er zijn op dit moment verschillende typen bovenleiding aanwezig in Nederland. De klant (in Nederland is dit ProRail) kiest het een van de typen bovenleiding uit die zij geschikt achten voor het baanvak waar het om gaat. Ze kunnen kiezen uit acht systemen, die voor verschillende snelheden het meest geschikt zijn.	
2.	**Hoe wordt de bovenleiding ontworpen voor een specifieke snelheid?**
De acht verschillende typen bovenleiding zijn dus ontworpen voor een specifieke snelheid. Die snelheid is de snelheid waarop we tijdens het ontwerp hebben gezegd: als we de snelheid nog meer verhogen, worden de effecten te negatief. Stel je zou 500 km/h gaan rijden bij een bovenleiding die is gebouwd voor 160 km/h – en we gaan ervan uit dat de onderstations dit aankunnen – dan zal de bovenleiding draad heel snel slijten en schade oplopen. Ook zal de draad een golfbeweging gaan maken, waardoor het contact met de pantograaf niet meer goed is. Hierdoor ontstaat ook mechanische slijtage en ontstaan vlambogen. De maximumsnelheid van de bovenleiding is erop gebaseerd dat een bepaald aantal passages moet kunnen plaatsvinden voordat onderhoud nodig is, het is dus ook een life cycle casus.	
3.	**Hoe streng is die specifieke snelheid? Waarop is dit gebaseerd?**
Verschillende factoren hebben dus invloed op de maximumsnelheid als we kijken naar de bovenleiding. Allereerst de onderstations, als die niet voldoende energie kunnen leveren, kan	

niet harder worden gereden. Ook de hoeveelheid treinen op een baanvak speelt hierbij een rol; meer treinen, meer energie nodig. Op dit moment hebben we in Nederland 1,5kV op de bovenleiding staan, maar men wil dit verhogen naar 3kV. Op de HSL is dit nu al 20kV. Hoe hoger het voltage, des te harder gereden kan worden. Lagere spanning levert meer problemen op. Ook de dikte van de bovenleiding kabel speelt een rol. Al deze factoren worden getest voor het worstcasescenario, waaruit een snelheid voortkomt waarvoor de bovenleiding geschikt is. Het is op dit moment een harde grens in de wet, maar bijvoorbeeld 160km/h rijden bij een 140km/h bovenleiding zou geen probleem zijn, mits de onderstations en de pantograaf dit aankunnen.	
4.	**Is sneller rijden mogelijk over de bestaande bovenleiding?**
Qua regelgeving is het op het moment dus niet mogelijk, omdat voor het type bovenleiding een norm snelheid ligt. Ook zou het misschien wel mogelijk zijn, maar dan zou de bovenleiding ook sneller kapotgaan dan nu de richtlijn is. Maar het is mogelijk, mits je dit dus niet met alle treinen doet. Als enkele treinen harder zouden rijden en sommigen ook weer langzamer, dan zou dit te doen moeten zijn. Eigenlijk moet per trein gekeken worden: is de pantograaf in een goede staat? Is het nodig om deze trein harder (of zachter) te laten rijden? Zijn er andere bezwaren? Etc. Als dit dan goed is, dan kan harder rijden worden toegestaan.	
5.	**Hoe variabel is het rijden onder de bovenleiding?**
Op dit moment is het dus niet variabel. De maximumsnelheid per type bovenleiding staat vast. Voor het type B4, het moderne Europese bovenleiding type, is dit bijvoorbeeld 160 km/h. Het is eigenlijk dus wel een soort grijze grens (gebaseerd op een worstcasescenario), maar in de regel mag het niet overschreden worden. Het gaat alleen niet mis als het wel overschreden zou worden, we vinden de gecombineerde kans dan te groot.	
6.	**Op welke manieren is variabel rijden met de bovenleiding mogelijk?**
Zie antwoord vraag 4. Het moet dus een combinatie zijn van factoren. Het is mogelijk als rekening wordt gehouden met de op zijn minst: de pantograaf van de trein, het aantal pantografen op de trein, staat van de bovenleiding, staat van de infrastructuur, energievoorziening onderstations.	
7.	**Wat zou het effect zijn op de bovenleiding van het gebruik maken van variabele maximale snelheidsprofielen in ERTMS?**
De schade op de bovenleiding zou dan vooral goed gemonitord moeten, aangezien deze op dit moment is gebaseerd op een vaste snelheid.	
8.	**Ziet u de bovenleiding als grote beperkende factor op de maximumsnelheid, of moet dit worden gezocht in andere parameters?**
Er zijn heel veel parameters waarmee rekening moet worden gehouden. Je zou moeten kijken naar het volgende: als je de snelheid zou verhogen, wat gaat er dan allemaal fout. Bijvoorbeeld, als de snelheid omhooggaat, gaat de geluidproductie naar boven. Maar dit is ook weer afhankelijk van het type trein. Zo zou je een heel schema kunnen maken met verbanden tussen de parameters. *Een aantal factoren die naar voren kwamen in het interview op een rij:* - Boogstraal, heeft invloed op de ontsporingskans en op het comfort van de reiziger - Verkanting, soms is een minimumsnelheid ingevoerd bij verkanting en mag niet trager worden gereden. - Stilzetten, is op sommige plaatsen niet toegestaan. - Spanrichting. - Vermogen van de trein, invloed op de capaciteit van de onderstations van de TEV. - Wiel/ rail contact. - Remwegen. - Staat van de trein, bijvoorbeeld de schade en staat van de pantograaf. Mocht een pantograaf helemaal nieuw zijn, is het contact met de bovenleiding draad beter en kan harder worden gereden. - Aantal pantografen en de afstand hiertussen. Tweede pantograaf wordt namelijk veel meer beïnvloed door de golfbeweging van de bovenleiding draad, wat leidt tot een vlamboog.	

<table>
<tr><td colspan="2">- Gewicht trein, groter gewicht wordt de remweg nog langer bij hogere snelheid, waar het misschien gevaarlijk kan worden.
- Versnelling/ vertraging trein, invloed op de mogelijkheid om snel genoeg op te trekken en op tijd weer stil te kunnen staan bij een verlaging van de snelheid.
- Lengte trein, invloed op stopplek perron en remweg.
- Type trein, denk hierbij aan het verschil tussen duw/trek, goederen/passagier en de verdeling van tractie op de assen.
- Passagiers op stations of juist mogelijkheden tot doorrijden. Als je zou kunnen weten of er überhaupt personen op het station staan te wachten (en mensen willen uitstappen), kun je hier variabel mee omgaan (bushalte idee). Overslaan van een halte heeft grote invloed bij het verkorten van de reistijd. Dit is nu het geval tussen Groningen en Zwolle, waar de rijtijd winst voornamelijk gehaald moet worden uit sneller rijden.
Als je een parameter gebaseerd snelheidsprofiel wilt gebruiken, moeten al deze parameters worden meegenomen in het ERTMS-model.</td></tr>
<tr><td>9.</td><td>De factoren die de maximumsnelheid beïnvloeden, zijn deze ook te variëren per trein of rit? Welke andere parameters zijn volgens u variabel per trein of rit?</td></tr>
<tr><td colspan="2">Als we kijken naar de mogelijkheden van variabele snelheidsprofielen, dan zou dit vooral zitten in actieve bijsturing of actieve regelgeving vanuit de VL (Verkeersleiding). Dit kan je doen bij bijvoorbeeld verschillende weersomstandigheden, zoals sneeuwval, droogte en hitte, vorst of harde regenval. Bij droger is er bijvoorbeeld minder geluidsproductie en bij regen juist meer.</td></tr>
<tr><td>10.</td><td>Waar zit volgens u het voordeel/ nadeel van variabele snelheidsprofielen in plaats van statische snelheidsprofiel?</td></tr>
<tr><td colspan="2">Dit is ook belangrijk voor het overtuigen van klanten. Je moet laten zien wat er beter kan
Het is ook nodig om de theorie van variabele profielen te vergelijken met hoe er in de praktijk wordt gereden door de machinisten: hoe rijden de treinen nou echt in de praktijk?</td></tr>
<tr><td>11.</td><td>In hoeverre zou het gebruik van variabele profielen al mogelijk zijn in de huidige ERTMS-software?</td></tr>
<tr><td colspan="2">Verschillende profielen voor personen en goederenvervoer zijn al wel mogelijk. Ook tijdelijke beperkingen of snelheidsrestricties zijn mogelijk om in te voeren vanuit de VL. Volgens mij is er ook een app ontwikkelt die machinisten een adviessnelheid meegeeft voor hun specifieke rit.</td></tr>
</table>

Appendix G – Interview S. Abrahamse

The transcript of this meeting will be in Dutch because the language during the meeting was Dutch. Because of the specific topic of the interview, a new interview setup has been introduced. The interview has been conducted on the 14th of June at Arcadis in Amersfoort. An English summary of the interview can be found below.

English summary
Sander Abrahamse works as a project leader at the bridges group. In the past he worked a lot on sound protection near the rail network. He explained that sound measurements are not done by Arcadis, but by an external company. The largest factor on the production of sound / noise would be the speed of the trains and the condition of the track and underlying basement. The sound barrier (i.e. geluidsplafond), is the legal border for the production of noise. When the noise is more than this barrier, soundproof walls are placed. Variable speed profiles on the topic of noise nuisance would be possible, certainly because it already happens sometimes. You should monitor the winds and pressure on the walls, because driving faster can cause for damage on the soundproof walls. In case of a bridge or tunnel, it is more difficult to, for instance, drive faster due to the legal norms and restrictions.

0.	**Kunt u kort iets vertellen over uw functie, achtergrond en werkzaamheden bij Arcadis? Wat zijn uw ervaringen met ERTMS/ bovenleiding projecten? Wat is uw taak/ positie?**
Sander Abrahamse werkt als projectleider bij de afdeling Bruggen/ Kunstwerken. Hij heeft veel ervaring met projecten op het gebied van geluidsschermen en stations, vanaf ontwerp tot beheer en onderhoud. Sander is nu voornamelijk bezig met kunstwerken zoals bruggen, in het algemeen staal en betonconstructies. Geluidsberekeningen worden bij Arcadis niet gedaan, dat doet een extern bedrijf die deze opdracht krijgt vanuit ProRail	
1.	**Hoe ontstaat geluid veroorzaakt door treinen? Welke factoren spelen hierbij de grootste rol?**
Grootste rol speelt denk ik de snelheid gewoon, hoe harder een trein rijdt hoe meer snelheid wordt geproduceerd. Verder zal de conditie van het spoor en de ondergrond een rol spelen. Voor de omgeving speelt voor de overlast de aanwezigheid van geluidsschermen een rol. Vroeger kwam het ook door lassen in het spoor, maar de meeste daarvan zijn ook weggewerkt. De geluidproductie van de trein ontstaat vooral in de spoorstaven en de trillingen in het materieel van de trein, maar ook in de infrastructuur en omgeving.	
2.	**Hoe wordt op dit moment omgegaan met geluidsoverlast door treinen?**
Zoals eerder gezegd, wordt een onafhankelijk onderzoeksbureau ingehuurd om onderzoek te doen naar geluidsoverlast op de gevel van omliggende woningen. Er zijn altijd een aantal eisen waaraan voldaan moet worden, deze staan in het OVS van ProRail.	
3.	**Welke normen bepalen of het geproduceerde geluid te hard is? Verschillende deze normen nog per moment van de dag of per situatie?**
Hierbij wordt gebruik gemaakt van het geluidsplafond. Dit is een fictief door de overheid bedacht plafond. Het is een gemiddelde waarde per etmaal aan geluid wat geproduceerd mag worden. Avonden en de nacht worden zwaarder meegewogen in dit gemiddelde, met een hogere wegingsfactor. Het RMV geeft aan hoe het geluidsplafond is opgebouwd. Hierbij houdt men rekening met de snelheid, maar ook de hoeveelheid en het type treinen. Het plaatsen van bijvoorbeeld geluidsschermen is niet zo zwart wit als deze normen, maar vaak ook gewoon politiek. Als men een scherm wil, terwijl het niet binnen de normen valt, dan komt er vaak gewoon een scherm.	
4.	**Wat voor een soort maatregelen worden getroffen?**
Meestal wordt in Nederland gebruik gemaakt van geluidschermen, eigenlijk altijd absorberende geluidsschermen. Soms wordt er ook gebruik gemaakt van raildempers, die zorgen dat het wiel-rail contact voor minder geluid door de rails zorgt, omdat de spoorstaaf	

zwaarder wordt gemaakt. De reductie door raildempers is 3dB volgens de voorschriften. Bij geluidsschermen maakt de hoogte niet eens zo gek veel uit, meestal is dit 1,5 meter tot 2 meter vanaf BS en staan de schermen op 4,5 meter vanuit hart spoor (als dit mogelijk is en er niets in de weg staat). Op die manier gaat er natuurlijk altijd nog geluid over het scherm heen, maar wordt het meeste geluid opgevangen. De maatregelen die getroffen worden vallen in verschillende categorieën voor verschillende baanvak snelheden. De verschillende categorieën zijn hetzelfde als bij de kunstwerken *(zoals besproken in vraag 6),* maar meestal worden de schermen ontworpen op een snelheid van 160km/h. Een opmerking die nog geplaatst moet worden bij de aanleg van geluidsschermen, is dat deze schermen soms expres hoger worden gemaakt, zodat ze ook als afscherming voor de spoorbaan kunnen gelden. Hierdoor zijn ze dus soms hoger dan eigenlijk volgens de eisen nodig zou zijn.	
5.	**Flexibele omgaan met geluidsnormen door de maximumsnelheid te beïnvloeden, is dit mogelijk en zo ja, hoe?**
Lijkt mij zeker mogelijk om dit te doen, ook omdat dit nu ook al voor een deel gebeurt, misschien eerder onbewust. Dit doordat sommige treinen sowieso al sneller rijden dan sommige anderen – bijvoorbeeld door verschil in materieel – dus dat zou zeker moeten kunnen. Verder zijn geluidsschermen ontworpen op een maximumsnelheid per categorie. Ook de stabiliteit en constructie van de schermen hangt hiervan af. Treinpassages met een hogere snelheid brengen ook een hogere, zwaardere drukgolf met zich mee. De stabiliteit van de schermen zou hierdoor in het geding kunnen komen, dus dit is zeker iets om mee te nemen.	
6.	**Op het gebied van kunstwerken, zoals bruggen en tunnels; wat zouden hier de beperkingen zijn in het flexibel omgaan met snelheden?**
Kunstwerken zijn ontworpen op een maximumsnelheid, misschien wel net als de bovenleiding dat is. Tot die snelheid zou harder rijden in ieder geval moeten kunnen, als er nu een lagere baanvaksnelheid is. De ontwerpsnelheden zijn tot en met 140km/h, 160km/h, 200km/h en 300km/h. Meestal is de ontwerpsnelheid 160km/h, als het kunstwerk na 1980 gebouwd is (ontwerpen daarvoor is geen zicht op de voorschriften). Dit is bij kunstwerken, bijvoorbeeld een stalen brug, voornamelijk gebaseerd op de stabiliteit van de brug. De brug zal zeker niet instorten als iets harder wordt gereden, maar het is erg moeilijk om ergens een grens te leggen. Dit is zeker lastig bij oudere kunstwerken, waarvan we niet precies weten hoe ze eraan toe zijn.	