Delft University of Technology

Thesis

Defining and Evaluating the Comfort Braking Curve in European Train Control System for Operational Efficiency

By:

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Preface

The end of a wonderful research period is in sight. Thanks to the great help of my supervisors and the support of the railroad industry, I managed to finish my thesis within the schedule. This thesis is also the final project of my master's degree in Transportation, Infrastructure and Logistics and marks the end of my time as a student at Delft University of Technology. I am glad that I was able to stick to my plan, thanks in part to the good help. The helpfulness of the rail industry has motivated me even more to continue working in this sector.

I am very grateful to Mott MacDonald for the opportunity to conclude this important phase of my academic career with this research, which touches on all aspects of my studies. This project was not only an assignment for me, but also a valuable learning opportunity to further expand and apply my knowledge in the future.

I would like to thank everyone who contributed in any way to this project; you have made this period unforgettable for me. In particular, I would like to thank:

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My brother, Lieke and Elisa, you provided the distraction and love I needed. Thank you for being my family.

ΜΟΛΩΝ
ΛΑΒΕ

- Leonidas

Julian Nikos Saoulidis
Delft, February 2025

Summary

The Dutch government has decided to fully switch to ERTMS (European Railway Safety System) by 2050, with ETCS (European Train Control System) playing an important role in this. ETCS is currently used on only 10 percent of the Dutch rail network, resulting in limited insights into how train drivers handle brake settings in practice. Train drivers experience differences in braking behavior and speed curves between ATB and ETCS, other research shows that train drivers deviate from the recommended speed curve. This takes inefficiencies in track utilization, unnecessary wear and tear on equipment, and unrealistic expectations regarding capacity.

This research focuses on defining and visualizing a comfort braking curve within the ETCS braking parameters with respect to ETCS Level 2. ETCS Level 2 is gradually replacing the Dutch train protection system in place of ATB-NS'54. This replacement promotes rail safety, capacity and interoperability. Yet these interests cannot be optimally served because train drivers pursue their own comfortable ride under the ETCS Level 2 system. The goal of this research is to define that comfortable ride and design a comfort braking curve that both optimizes ride comfort and meets the performance and safety requirements of ETCS Level 2. Previous research by Pieter van der Beek (van der Beek, 2020) already made it clear that drivers do not follow the recommended speed exactly and that train drivers drive at their own comfort. But giving definition to this degree of comfort and designing the optimal comfort braking curve based on train driver behavior and testing this braking curve operationally is a valuable contribution to science.

The central research question is:

What are the implications of implementing the comfort braking curve on capacity, wear and tear, safety and driver experience?

To answer this main question, the following sub-questions have been developed:

1. What is comfort braking?
2. How does a train driver brake comfortably under ETCS Level 2 , what are the operational characteristics?
3. What are the critical design parameters for modeling the, ETCS Level 2, braking curves (comfort braking curves)?
4. When answers to questions one through three are gathered, what does such a comfort braking curve look like?
5. What are the effects when implementing the comfort braking curve?

These questions were answered using an established research methodology. First, a fundamental foundation of understanding was established using literature research. This foundation provided knowledge about comfortable braking and knowledge about train driver behavior and braking parameters. With this knowledge, further in-depth questions were addressed to experts with semi-structured expert interviews. Through the expert interviews, further insights were gained in terms of practical experiences with ETCS Level 2 and braking behavior. Simulations were then performed, validating the comfort braking curve and testing it under realistic conditions. The results from the simulation were analyzed using the RAMSHE-analysis (Reliability, Availability, Maintainability, Safety, Health and Environment) analysis. This results in knowledge in terms of what the effects are on capacity, wear and safety when the comfort braking curve is implemented.

Main Findings
Comfort braking curves are defined as a curve where the braking deceleration and change in acceleration ('jerk') are within specified acceptable limits to ensure a smooth and comfortable ride. The established comfortable brake deceleration is between 0.5 m/s^2 and 0.6 m/s^2 and the maximum jerk is set at 1.0 m/s^3. In addition to what the literature establishes, practical experience is also important. The train driver behavior was analyzed when driving the train under ETCS Level 2. Train drivers often use rolling out ('coasting') 15 percent of the speed. In addition, train drivers never accelerate toward braking and a margin is maintained over the recommended speed curve to be prepared for unforeseen situations. When halting, train drivers look for a braking mode to achieve braking, this leads to braking steps and braking dips, which is inefficient with respect to energy consumption. These anticipation strategies are responses to discomfort scenarios, outlined in this research, that

are considered uncomfortable.

Now that it is well established what the literature and practice say regarding comfort and what the well-established discomfort scenarios are, design parameters are set out of the ETCS Level 2 braking curves to do a further approximation towards a visualization of the comfort braking curve. For this approximation of the comfort braking curve, we looked at how the current ETCS Level 2 braking curves are constructed and what are the most important design variables related to the current ETCS Level 2 braking curves. This gathered insights into which design variables are important and applicable for further visualization of the comfort braking curve, namely: braking forces ($A_{\text{brake\_safe}}(v)$), velocities (V_{est}), distance and target distance (d_{target}). Analysis of the design of the ETCS Level 2 braking curve also revealed how the safety net is defined. The safety net of the permitted curve is based on the safety net of the emergency braking curve, and this is placed quite at the edge of the warning zone, leading to a steep braking curve close to the warning alarms. With respect to the comfort braking curve, this particular safety net has been softer and placed earlier, in line with how train drivers generally operate.

The information gathered regarding what the literature and practice indicates in terms of comfort leads to a visualization of the comfort braking curve. Figure 1 shows a structural representation, which information was bundled to finally arrive at the visualized comfort braking curve from figure 2.

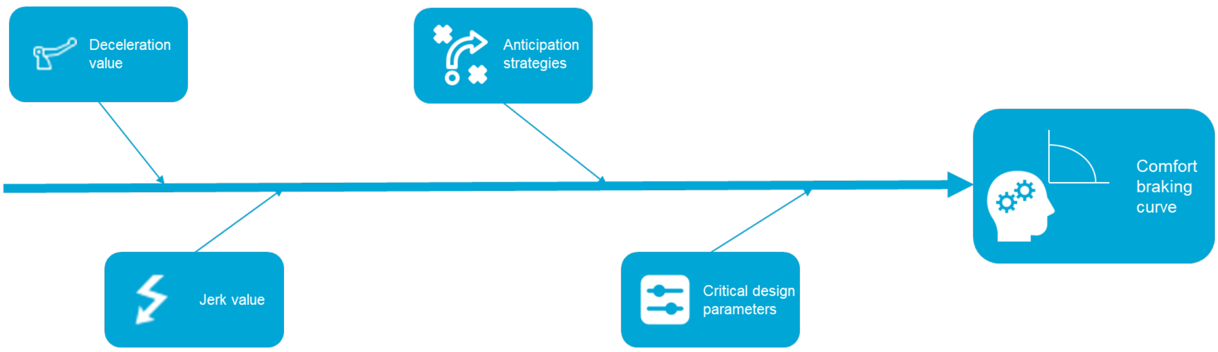

Figure 1: Schematic representation comfort braking curve

This braking curve is a redesigned braking curve that recognizes train driver behavior and takes into account the safety requirements of ETCS Level 2. Or also called the comfort braking curve:

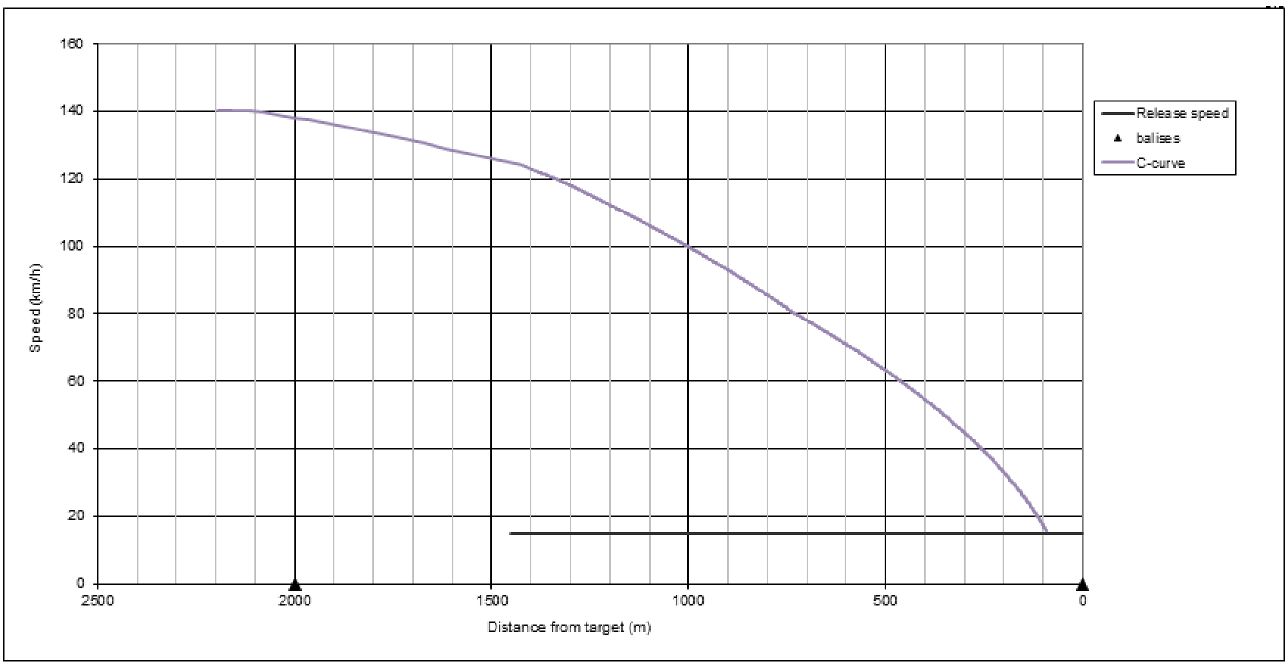

Figure 2: Comfort braking curve

This comfort braking curve is implemented in the simulation FRISO, regarding the VIRM and SNG trains on the Amsterdam-Utrecht route. In this simulation, several tests were performed, from which came various results in terms of the timetable and its robustness, braking distances, energy consumption and power. These results were compared to the results of current driver behavior. First, it followed from the tests that the comfort braking curve fits into the current timetable while maintaining its robustness. Second, due to the decrease in energy consumption and power, compared to current train driver behavior, there is less stress on equipment and infrastructure. Third, there is an improvement in driver experience because their natural behavior is recognized in the comfort braking curve and because the comfort braking curve is a constant deceleration. This constant deceleration and mimicry of train driver behavior leads to a predictable and comfort braking curve. This improves the entire safety of the railroad system compared to the current situation, where train drivers drive at their own comfort. At the same time, the safety standards of the ETCS system remain the same. In conclusion, the comfort braking curve offers a achievable solution to strike a healthy balance with respect to capacity, wear and tear, safety and driver experience within the existing ETCS standards. This will contribute to the full exploitation of the benefits of ERTMS and therefore represents an important scientific contribution. For further research, it is essential to implement the comfort braking curve on a larger scale, for example on multiple routes and with different types of rolling stock. Once the comfort braking curve consistently provides the desired results and it is decided to implement it on a permanent basis, a structured plan of action is recommended. A practical recommendation is to elaborate on this plan using Primavera P6 to ensure a systematic and process-based approach. This research shows that the rail sector is a multifaceted and complex environment, in which a structured approach is essential in order not to overlook crucial steps. An important point of attention in the implementation, for example, is the integration of the comfort braking curve into driver training.

Samenvatting

De Nederlandse overheid heeft besloten om volledig overgeschakeld te zijn op ERTMS (European Railway Traffic Management System) voor 2050, hierbij speelt ETCS een belangrijke rol. Op slechts 10 procent van het Nederlandse spoorwegnet wordt op dit moment ETCS (European Train Control System) gebruikt, dit resulteert in beperkte inzichten hoe machinisten omgaan met de reminstellingen in de praktijk. Machinisten ervaren verschillen in het remgedrag en snelheidscurves tussen ATB en ETCS, ander onderzoek toont aan dat machinisten afwijken van de aanbevolen snelheidscurve. Dit neemt inefficiënties in de baanbezetting, onnodige slijtage van het materieel en onrealistische verwachtingen met betrekking tot capaciteit met zich mee.

Dit onderzoek focust op het definiëren en visualiseren van een comfort braking curve binnen de ETCS-remparameters met betrekking tot ETCS Level 2. ETCS Level 2 vervangt langzaam het Nederlandse treinbeveiligingssysteem in plaats van ATB-NS'54. Deze vervanging bevordert veiligheid, capaciteit en interoperabiliteit op het spoor. Toch kunnen deze belangen niet optimaal behartigd worden omdat de machinist zijn eigen comfortabele rit nastreeft onder het ETCS Level 2 systeem. Het doel van dit onderzoek is om definitie te geven aan deze comfortabele rit en het ontwerpen van de comfort braking curve die zowel rijcomfort optimaliseert als voldoet aan de prestatievereisten en veiligheidsvereisten van ETCS Level 2. Uit eerder onderzoek van Pieter van der Beek (van der Beek, 2020) werd al duidelijk dat de machinist niet de aanbevolen snelheid 1 op 1 volgt en dat de machinist rijdt op zijn eigen comfort. Maar defintie geven aan deze mate van comfort en de optimale comfortremcurve ontwerpen, aan de hand van het machinistengedrag, en deze rem curve operationeel testen, is een waardevolle bijdrage aan de wetenschap.

De centrale onderzoeksvraag luidt:

Wat zijn de implicaties van het implementeren van de comfortremcurve op capaciteit, slijtage, veiligheid en machinistbeleving?

Om deze hoofdvraag te beantwoorden zijn de volgende subvragen opgesteld:

- Wat is comfortabel remmen?
- Wat zijn de kritieke ontwerpparameters voor het modelleren van comfortremcurves?
- Hoe remt een machinist comfortabel onder ETCS Level 2?
- Hoe ziet een comfortremcurve eruit?
- Wat zijn de effecten van het implementeren van de comfortremcurve?

Deze vragen zijn beantwoord met behulp van een vastgestelde onderzoeksmethodologie. Allereerst, werd een begripsfundament gelegd met behulp van literatuuronderzoek. Deze basis leverde kennis op over comfortabel remmen en kennis over het gedrag van machinisten en remparameters. Met deze kennis werden verdere verdiepingsvragen gesteld aan experts met semi-structured expertinterviews. Door de expertinterviews zijn er verdere inzichten verkregen op het gebied van praktijkervaringen met ETCS Level 2 en remgedrag. Vervolgens werden er simulaties uitgevoerd, hiermee wordt de comfortremcurve gevalideerd en onder realistische omstandigheden getest. De resultaten uit de simulatie zijn geanalyseerd met behulp van de RAMSHE-analyse (Reliability, Availability, Maintainability, Safety, Health en Environment). Dit resulteert in kennis op het gebied van wat de effecten zijn op capaciteit, slijtage en veiligheid wanneer de comfort braking curve wordt geïmplementeerd.

Belangrijkste Bevindingen
De comfortremcurve is gedefinieerd als een curve waar de remvertraging en de verandering in versnelling ('jerk') binnen de aangegeven acceptabele grenzen blijven om zo een soepele en comfortabele rit te garanderen. De vastgestelde comfortabele remvertraging is tussen de 0.5 m/s^2 en 0.6 m/s^2 en de maximale jerk is vastgesteld op 1.0 m/s^3. Naast wat de literatuur vaststelt, zijn de praktische ervaringen ook belangrijk. Het gedrag van machinisten is geanalyseerd wanneer zij de trein bestuurden onder ETCS Level 2. Machinisten maken vaak gebruik van het uitrollen van een trein ('coasting'), 15 procent van de snelheid. Hiernaast accelereren machinisten nooit naar een remming toe en wordt er een marge aangehouden ten opzichte van de aanbevolen snelheidscurve om voorbereid te zijn op onvoorziene situaties. Wanneer er gehalteerd wordt, zoeken machinisten een braking

stand om tot een remming te komen, dit leidt tot braking steps en braking dips, wat inefficiënt is ten opzichte van het energieverbruik. Deze anticipatiestrategieën zijn reacties op discomfortscenario's, uiteengezet in dit onderzoek, die als oncomfortabel worden beschouwd.

Nu bekend is wat de literatuur en praktijk zeggen met betrekking tot comfort en wat de welbekende discomfort scenarios zijn, zijn ontwerpparameters uiteengezet van de ETCS Level 2 braking curves om een verdere toenadering te doen naar een visualisatie van de comfortremcurve. Voor deze toenadering van de comfortremcurve is er gekeken naar hoe de huidige ETCS Level 2 braking curves zijn opgebouwd en wat de belangrijkste ontwerpvariabelen zijn. Er zijn hierdoor inzichten vergaard welke ontwerpvariabelen belangrijk en van toepassing zijn voor de verdere toenadering van de comfort braking curve, namelijk: remkrachten ($A_{\text{brake\_safe}}(v)$), snelheden(V_{est}), afstand en doelafstand (d_{target}). Uit de analyse van het ontwerp van de ETCS Level 2 remcurve werd duidelijk hoe het veiligheidsnet gedefinieerd is. Het veiligheidsnet van de permitted curve is op basis van het veiligheidsnet van de noodremcurve gebasseerd en dit is redelijk aan de rand van de warning zone geplaatst. Dit leidt tot een steile remcurve dichtbij de waarschuwings alarmeringen. Met betrekking tot de comfort braking curve is dit specifieke veiligheidsnet zachter gemaakt en eerder geplaatst, in lijn met hoe machinisten over het algemeen handelen.

De verzamelde informatie over wat de literatuur en de praktijk aangeven in termen van comfort leidt tot een visualisatie van de comfortremcurve. Figuur 3 toon een schematische weergave, welke informatie gebundeld is om tot de uiteindelijke comfortremcurve uit figuur 4 te komen.

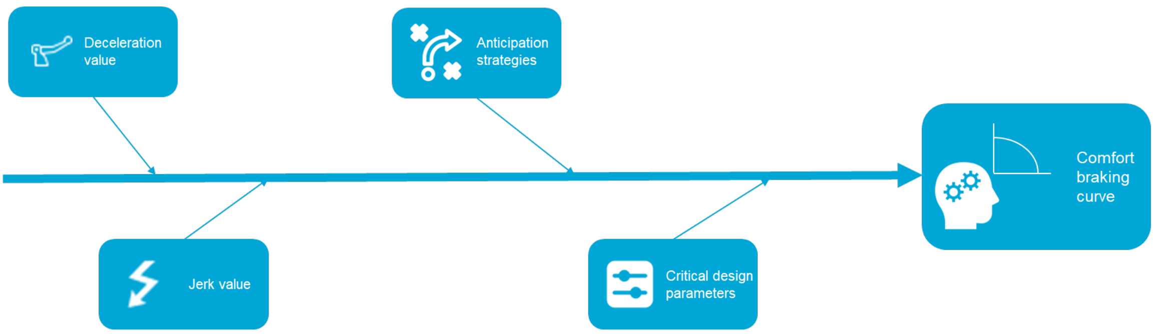

Figure 3: Schematische weergave van de comfortremcurve

Deze remcurve is een opnieuw ontworpen remcurve die rekening houdt met het gedrag van de machinist en met de veiligheidseisen van ETCS Level 2. Deze remcurve wordt ook wel de comfortremcurve genoemd:

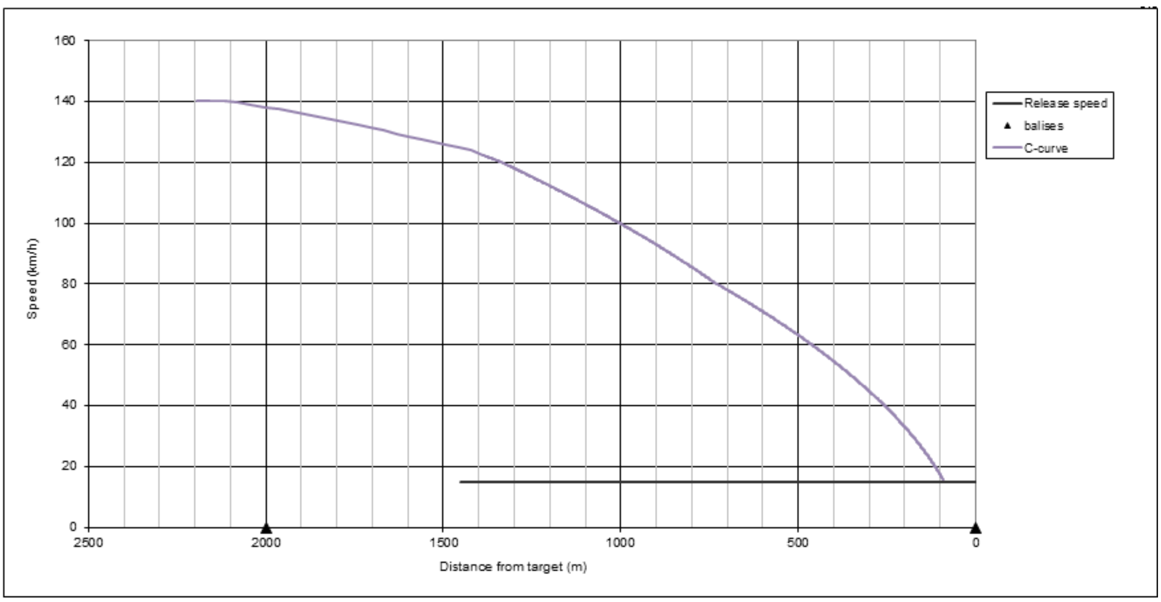

Figure 4: Comfortremcurve

Deze comfortremcurve wordt geimplementeerd in de simulatie FRISO, met betrekking tot de VIRM en SNG treinen op het traject Amsterdam-Utrecht. In deze simulatie zijn verschillende testen uitgevoerd, hieruit kwamen verschillende resultaten op het gebied van de dienstregeling en zijn robuustheid, remafstanden, energieverbruik en vermogen. Deze resultaten zijn vergeleken ten opzichte van het huidige machinistengedrag. Allereerst volgde uit de testen dat de comfortremcurve in de huidige dienstregeling past met behoudt van zijn robuustheid. Ten tweede door de afname in het energieverbruik en vermogen, ten opzichte van het huidige machinistengedrag, wordt het materieel en de infrastructuur minder belast. Ten derde er is een verbetering in driver experience doordat hun natuurlijke gedrag erkend wordt in de comfort braking curve en omdat de comfort braking curve een constante deceleratie is. Deze constante snelheidsafname en nabootsing van het machinistengedrag leidt tot een voorspelbare en comfortabele remcurve. Hierdoor wordt de gehele safety van het spoorsysteem verbeterd ten opzichte van de huidige situatie, waar machinisten op hun eigen comfort rijden. Tegelijkertijd blijven de veiligheidsnormen van het ETCS-systeem hetzelfde. Concluderend biedt de comfortemcurve een haalbare oplossing om binnen de bestaande ETCS-normen een gezonde balans te vinden met betrekking tot de capaciteit, slijtage, veiligheid en machinistenervaringen. Dit zal bijdragen aan het optimaal benutten van de voordelen van ERTMS en vormt dan ook een belangrijke wetenschappelijke bijdrage. Voor verder onderzoek is het essentieel om de comfortremcurve op grotere schaal te implementeren, bijvoorbeeld op meerdere routes en met verschillende soorten materieel. Zodra de comfortremcurve consequent de gewenste resultaten oplevert en besloten wordt deze permanent te implementeren, is een gestructureerd plan van aanpak aanbevolen. Een praktische aanbeveling is om dit plan uit te werken met Primavera P6 om een systematische en meer procesmatige aanpak te verzekeren. Dit onderzoek toont aan dat de spoorwegsector een veelzijdige en complexe omgeving is, waarin een gestructureerde aanpak van groot belang is om geen cruciale stappen over het hoofd te zien. Een belangrijk aandachtspunt bij de implementatie is bijvoorbeeld de inbouw van de comfortremcurve in de rijopleiding.

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1 Introduction

1.1 Current situation and explanation

On May 17, 2019, it was decided that the current train protection system (Automatic Train Protection System (ATB-NS'54) will be replaced by the European Rail Traffic Management System (ERTMS) across the country by 2050 (*21e Voortgangsrapportage van het Programma ERTMS*, 2024). ERTMS introduces a shift in communications and technology, converting analog systems to digital systems, both on the track and on the train. This transformation increases safety by reducing the possibility of human error, increases capacity through more efficient train control and reduced waiting times, and improves interoperability by standardizing signaling systems across countries in Europe (*ERTMS*, n.d.). In order to implement this, fundamental assumptions have been established that determine the method of implementation for ERTMS, namely:

- The ATB of the train protection system will be removed when ERTMS (-only) is implemented.
- It is impossible to transform the whole network, so a focus is placed on by tranches
- ERTMS corridors will be connected together as much as possible
- Further operation should continue as much as possible
- The techniques are tested in combination with the adapted practices and processes before operation

A detailed version of the principles are described in the ERTMS progress report. ERTMS is at the moment in operation on about ten percent of the Dutch railroads, namely the Betuweroute, the Havenspoorlijn, the Hogesnelheidslijn-Zuid, the Hanzelijn and the Amsterdam-Utrecht route (*Waar komt ERTMS? - ERTMS NL*, n.d.). The remaining track is ATB-NS '54, and this will also be switched to ERTMS over the years. ERTMS is technically consists of TMS (Traffic Management System) and ETCS (European Train Control System), with an important component of this research focusing on ETCS braking curves. ETCS in general is a train safety and speed control system that provides safety and interoperability on railroad lines and works with different levels (Ranjbar et al., 2022). ETCS Level 1 provides safety by sending signals on the spot, requiring trackside signals, while ETCS Level 2 uses radio-based communication for continuous signal updates, eliminating the need for trackside signals, and ETCS Level 3 introduces the moving block principle, where trains run over dynamic blocks (Ranjbar et al., 2022). Switching to ERTMS requires operational adjustments from the train driver. This is mainly due to the fact that the speed frames between ATB-NS'54 and ERTMS are different. This is also because in ERTMS there is more digital information in the cab compared to ATB-NS'54. In ATB-NS'54, the train driver obtains information outside the cab, using signals. ERTMS introduces braking curves in addition to different speed profiles. Unlike incremental braking that is based on restrictive trackside signal images in traditional systems, ERTMS relies on continuous information in the cab to control braking. This shift from ATB-NG/NS'54 to ERTMS requires adjustments in train driver operating procedures.

1.2 Problem discription

Because ERTMS is currently in use on only ten percent of the Dutch railroads, there is still limited data available on how train drivers handle these brake settings in practice according to the ETCS Level 2. Another important bottleneck that limits data on train driver braking behavior is that many routes are only partially covered by ERTMS. On the HSL, for example, ERTMS coverage starts at Schiphol Airport, but switches back to ATB when approaching Rotterdam. As a result, most braking operations are still conducted under ATB. This lack of data makes it difficult to get a view of how train drivers act in such situations. A previous study with nine train drivers found that they maintain a certain margin with respect to the recommended target speed (van der Beek, 2020). This certain margin may lead to unrealistic expectations regarding the performance of ERTMS. Other research, such as Groningen's final report, also shows that drivers tend to cruise or coast rather than accelerating directly to an upcoming brake, which improves their ride comfort (van den Band et al., 2020). There is a form of comfort among train drivers who follow the recommended target speed. However, this type of comfort is not without consequences. The different forms of comfortable driving are still unfamiliar, and it leads to different driving patterns and deviations from the recommended target speed. These deviations can lead, first, to inefficiencies in track capacity, for example because train drivers cannot brake and drive optimally within the time limit. Second, it can lead to additional wear and tear because train driver braking patterns are more unpredictable. And thirdly, there are unrealistic expectations of safety due to the unpredictable braking and here it is added that it has different impacts on the train driver experience. Without a solution to the issues mentioned above, the promised benefits (such as a gain in capacity, safety and interoperability) of ERTMS cannot be fully realized. This leaves the potential for optimal use of the Dutch railroad network unused.

1.3 Objective

From the literature review from chapter 2, a knowledge gap has been identified and what this research scientifically contributes to. From the literature review, differences in train driver behavior have been identified and that train drivers drive at their own level of comfort, but it is still unknown what comfort generally means according to the literature and practice and if a braking curve can be specifically implemented to meet both ERTMS requirements and train driver requirements. This knowledge gap creates a barrier to the full utilization of the benefits of ERTMS. The objective of this research is giving definition to this degree of comfort and designing the optimal comfort braking curve based on train driver behavior and testing this braking curve operationally. Given the current situation and the detailed implementation plan established in the progress reports, a structural change in the ERTMS system is not a realistic possibility. The requirements of the research is to find a solution compatible with the existing system. Because of the solution compatibility with the existing system, no fundamental changes are needed within the existing ERTMS and its implementation program. While the comfort braking curve is implemented and the benefits can be realized. This research aims to close the knowledge gap and therefore research questions have been formulated. This will contribute to a practical but also theoretical basis within ETCS Level 2.

1.4 Research question

The purpose of this research is to identify what the literature says about comfort and how it relates to practice. In addition, a structure is developed for the construction of the comfort brake curve, with an analysis of the associated implications. This goal can be achieved using the following main research objective:

Main research question:
What are the implications of implementing the comfort braking curve on capacity, wear and tear, safety and driver experience?

To answer the main research question, sub questions have been developed to split the question in different parts. This sub questions are answered in subsequent sections throughout this report.

Sub-questions:

1. What is comfort braking?
2. How does a train driver brake comfortably under ETCS Level 2 , what are the operational characteristics?
3. What are the critical design parameters for modeling the, ETCS Level 2, braking curves (comfort braking curves)?
4. When answers to questions one through three are gathered, what does such a comfort braking curve look like?
5. What are the effects when implementing the comfort braking curve?

1.5 Methodology

This chapter provides the methods by which the research questions were answered, the methods are indicated in table 1 and are further explained in the following subsections.

What are the implications of implementing the comfort braking curve on capacity, wear and tear, safety and driver experience?	
Sub-question	**Method**
1. What is comfort braking?	literature research
2. How does a train driver brake comfortably under ETCS Level 2 , what are the operational characteristics?	Expert interviews and literature research
3. What are the critical design parameters for modeling the, ETCS Level 2, braking curves (comfort braking curves)?	Expert interviews and Literature research
4. When answers to questions one through three are gathered, what does such a comfort braking curve look like?	Simulation and modeling
5. What are the effects when implementing the comfort braking curve?	RAMSHE-analysis

Table 1: Sub-questions and corresponding method

1.5.1 Literature research

To answer the sub-questions literature research is used. First, it is important to highlight the literature research used for sub-questions one, two and three. Scientific articles and reports are searched on the sources 'Scholar' and 'Scorpus'. The literature research has an important role in the foundation of the research. This is because it provides the basis of knowledge development, creating guidelines for the current system and providing evidence of some consequences (Snyder, 2019). In addition, it provides new perspectives for this research and brings new ideas and further directions (Snyder, 2019). This also provides a fundamental basis for interacting with experts later in this research. The first sub-question is the theoretical part, here we use literature research to define comfort braking. Information regarding the comfort braking curve is searched using the key words 'Comfort braking', 'ETCS Level 2 braking curves', 'Parameters comfort', 'Braking norms' and 'Braking deceleration'. Based on this, more information can be gathered and criteria can be determined. From these findings, the second sub-question follows, the second sub-question is about the operational characteristics of the train driver. To find out more about this, several studies offer further information. With respect to driver behavior, the literature review already provides information on which components are important and unique to the application on their own. Further information can be gathered from the following keywords: 'Train driver behavior', 'Operational behavior train driver' and 'Train driver experience'. Once it is answered, the critical design parameters can be identified (sub-question three). These are the parameters important for modeling the comfort braking curves, useful is to use the source from the European Railway Agency 'Introduction to ETCS braking curves'. This explains the construction of the current ETCS curves. With this information, we can look further and go deeper into the research to specify the answers to sub-questions two and three. This will better prepare the researcher for the next method: expert interviews.

1.5.2 Expert interviews

Expert interviews is the other method used in sub-questions two and three in combination with literature research. Literature research provided the fundamental knowledge, to then go into depth with the experts. Expert interviews are very useful for the sub-questions prepared in this research. The expert interviews provide qualitative but also quantitative results. Selection of the experts are based on experience in the area of expertise. Think about experiences with driving the train under ETCS Level 2, experiences in the field of ETCS Level 2 in general and or working with braking curves. The interviews will be semi structured, focusing lightly on the questions but also leaving it up to the knowledge of the experts. Below are mentioned several advantages why expert interviews are chosen with respect to the sub-questions:

– First, experts can provide this research with knowledge based on micro processes. With these micro processes is meant the detailed level of knowledge, think of individual experience with braking on comfort. Experts blend the general results with context-specific information; this knowledge cannot be found in public domains. In this way, the qualitative and/or quantitative information, gathered from the interview with the expert, can be more easily interpreted and possible correlations become more clear. (Von Soest, 2023). These expert interviews can be used to clarify the operational characteristics of driver behavior. Once these operational characteristics are clear, possible critical design parameters for designing the comfort braking curve can be explored with the expert.

– Second, in the case of ERTMS, as in this research, where practical applicability is low, it is difficult to conduct experimental analyses. However, experts with unique experience and specific knowledge can combine and contrast components, providing valuable insights (Von Soest, 2023).

In appendix A it can be seen, in table 9, which expert was interviewed, their area of expertise and the main takeaways. Further in the appendix is a overview of the completed semi-structured interview. The overview shows how the interview was constructed and which themes were focused on. The data obtained from the interviews is collected and supplemented with the knowledge from the literature research. This provides insights into the train driver operational characteristics and critical design parameters when modeling the comfort braking curve. This information is used to further explore question four.

1.5.3 Simulation and Modeling

The simulation FRISO 'Flexibele Rail Infra Simulatie Omgeving is used in this research once all the information is gathered regarding the comfort braking curve. The research on how these simulation were chosen is outlined in Appendix B. The essential information gathered from subquestions 1 through 3 is combined in subquestion 4 to create a visualization of the comfort braking curve. This visualized curve is then implemented in the simulation. Simulation and/or modeling is a powerful tool for researching new designs, changes to existing rules, and proposed changes to operating rules (Carson, 2004). From this it becomes clear what the implications are when the comfort braking curve is fitted into real-world conditions. In addition, simulations can identify further problems and bottlenecks. This prevents accidents in the real system, because of simulations and modeling (Carson, 2004). The scope described in section 1.6 is implemented in this simulation. In the modeling phase, qualitative and quantitative tests were conducted, namely the palpability test, usability test and the capacity test. These tests determine whether the specified degree of comfort is operationally efficient. The Appendix C describes these tests in detail, but below is a brief explanation of the tests performed in the simulation:

- Palpability test: This test researches from what point the comfort braking curve is felt. This is compared with the moment when the train driver would start braking based on his own experience. This gives insights into braking distances and differences in train driver braking behavior.
- Usability test: During this test, 2 scenarios are simulated; one where the permitted curve is followed in the usual way, i.e. not exactly, and a scenario where the comfort braking curve is applied. This is used to evaluate various performance indicators such as energy consumption, train power and the degree of acceleration and deceleration. This provides insights into the degree of wear and tear on the train and on the track.
- Capacity test: Here we look at 2 scenarios, namely following the permitted curve in the usual way and the scenario where the comfort braking curve is followed. The impact on capacity in both braking curves is examined and the anticipation on this, e.g. how possible blockages occur and how they are solved. In addition, the extent to which the comfort braking curve fits within the current timetable is analyzed. This test provides insights into whether the robustness of the timetable is maintained and whether it is eliminated.

1.5.4 RAMSHE-method

Based on the information obtained from the previous sub-questions, it is useful to use a method that creates an overview that summarizes the data collected from the research. This data is important to ultimately answer sub-question five through data analysis. In the RAMSHE method the information is broken down in different domains. Which makes it easier to assess the further effects of implementing the comfort braking curve. RAMSHE stands for 'Reliability', 'Availability', 'Maintainability', 'Safety', 'Health' and 'Environment' (Movares, 2023). The results from the simulation are analyzed based on each domain, this method provides insights into the indicated aspects, what effect does implementing those comfort braking curves, for example, have on the indicated aspects 'Capacity', 'Wear and tear', 'Safety' and 'Environment'. This methods provides a strong analysis and a more specific insight into the results.

1.6 Project scope and limitations

This research is focused on the implementation and optimization of the comfort braking curve within the Netherlands' ERTMS system. This system exclusively uses ETCS Level 2. Adjustments in the settings and braking parameters within this level of ETCS Level 2 have a direct influence on the efficiency and safety of the track. Specifically, this research looks at routes served by VIRM and SNG trains. Using a simulation program, the the routes between Amsterdam and Utrecht are analyzed with respect to the implementation of the comfort braking curve. Amsterdam-Utrecht was selected as the scope because it is the most congested railroad line in the Netherlands by the various train connections, leading to high traffic density. In addition, Amsterdam-Utrecht is also a so-called 'funnel route' with an important junction function. Trains converge in different directions, making this section a critical link in the Dutch rail sector. The Amsterdam-Utrecht section is already equipped with ERTMS and is managed by ETCS Level 2. Freight transport is excluded from the scope, so the analysis focuses specifically on passenger transport. This provides especially more opportunities to define the comfort braking curve for passenger transport, because in freight transport the parameter settings and train driver behavior are very different. Due to these constraints, this research focuses on optimization and efficiency within the clearly formulated scope with the specific train types, leading to consistency in the results. Instead of freight trains, passenger trains have been chosen, namely the VIRM and SNG train types. Specifically these train types were chosen because these two train types are the most widely used in the Dutch railroad network.

The specified scope indicated will lead to a direct application of the findings to passenger transport within ETCS Level 2. However, the results and recommendations of this research will be limited to the above train types and routes, which may lead to potentially less applicability to other train types (freight) and other routes. But this is not to be taken for granted, the braking curve might also be applied to other routes but outside the scope of this research.

1.7 Structure of the report

Chapter 2 - Literature review
This chapter highlights the current state of the art regarding the current systems operating on the Dutch rail network and train driver behavior. This literature review forms the foundation of this research and discusses the differences between ATB-NS'54 and ERTMS and what is known about driver behavior to date. This background information helps to eventually look at broader contexts and refine that context.

Chapter 3 - Modeling Driver Behavior.
Here we specifically analyze train driver behavior under ETCS Level 2 and how train drivers drive under ETCS Level 2 with the driving strategies employed. From literature review and interviews with train drivers, situations are highlighted where train drivers struggle to meet the commanded speed, these are the situations that train drivers perceive as discomforts that cause them to adjust their braking behavior and/or speed.

Chapter 4 - Comfort braking curve
This chapter outlines the norm of comfort braking, based on the literature and what practice says. It looks at the extent to which the theoretical standards match practice, giving a clear picture of how the standards and train drivers' practical experience of comfort can contribute to optimizing the train driver experience.

Chapter 5 - ETCS Brake Curves and the Translation to the comfort braking curve
Chapter 5 provides a detailed explanation of what the ETCS braking curves mean and how the braking curves are constructed. Insights are gained about the construction of the intervention curves within ETCS and how a proposed solution can be integrated into this system and what construction steps it must comply with. This chapter will also translate to the comfort braking curve. Knowing how the original braking curves are constructed and new insights from previous chapters about what comfort braking entails, a visualization of the comfort braking curve is created.

Chapter 6 - Model Construction and Results
This chapter discusses how the simulation model is constructed, including the established boundaries and conditions relevant to this research. Simulation results are presented and provide further insights into its applicability and effectiveness.

Chapter 7 - RAMSHE-analysis
This chapter analyzes the results from the simulation and answers sub-question 5. It also visualizes how the comfort braking curve has an impact on the key performance indicators indicated in the main question: capacity, wear and tear, safety and driver experience.

Chapter 8 - Conclusion
The conclusion summarizes the main results and answers the sub-questions and the main question. In addition, the results are evaluated in terms of train driving comfort and operational efficiency.

Chapter 9 - Discussion
This final chapter discusses the implications and limitations of the research. It reflects on the contribution of the research and its strengths, in addition to identifying possible areas for improvement and suggestions for future research (recommendations).

2 Literature review

The purpose of the literature review is to analyze the information already available within the context of this research. This was done by reviewing scientific literature and determining on what aspects consensus and knowledge gaps existing. Using the web pages 'Scorpus' and 'Scholar', several scientific articles were found that gave body to this research. In addition to the indicated sources, information that may be useful in the process of answering the research question has been forwarded from the guidance of the company Mott Macdonald. This literature review all in all represents the state of the art and clarifies the information currently available within the context of this research.
The first section (Methodology) describes how the information was obtained and further analyzed. The second section (Analysis) contains the analysis, presenting empirical insights, discussing the literature and highlighting further findings. The third part of the literature review presents the state of the art and concludes with a conclusion. This clarifies what research has already been conducted within the context of the objective of this research, and the conclusion substantiates the usefulness of this research using the current state of the art. The final section is the discussion.

2.1 Process of the literature review

Jalali and Wohlin (2012) describes how the literature review was conducted applicable to this research. Namely, the snowballing search method (Jalali & Wohlin, 2012). This method is performed in three main steps:

- Step 1, start the search for leading journals in order to have a start in a set of papers (Jalali & Wohlin, 2012)
- Step 2, go backward by reviewing the reference list of the relevant scientific articles, repeat until no new scientific articles are appropriate (Jalali & Wohlin, 2012)
- Step 3, go forward and continue the literature study where the scientific articles from the previous steps are cited with the specified reference list (Jalali & Wohlin, 2012)

The above 3 steps are further elaborated in this section with respect to this study.

Step 1

The purpose of this research is to give implications of implementing the comfort braking curve. It soon became apparent that an important element is that in the present situation the permitted curve is not followed accurately by the driver. Much research has already been done regarding the behavior of drivers when following the permitted curve and from this, several scientific articles have been selected. The scope of this research is now established.

Step 2

In reviewing the reference list, several specifications emerged in other scientific papers. These relate to monitoring speed and distance in the current situation, influencing factors such as driver anticipation within ERTMS, and the causes of not following the permitted curve, on which many studies have been conducted. It is important to elaborate on these three components to make the search more concrete. To ensure relevance to the purpose of this research, step 2 is a useful tool. The reference list is refined into a list in table 2, where the topic corresponds to the general terms or keywords as shown in table 2.

Table 2: Keywords

Category	ERTMS; ETCS; Braking-curves Train	
Keywords	Train driver behavior:	permitted curve, driver anticipation
	Speed and distance monitoring:	Input: track related, train related, DMI
	ETCS braking curves:	Advantages, Disadvantages
Truncation	(ETCS) OR (Braking Curves) AND (Train Driver Behavior)	

Step 3
After repeating the above two steps, the scientific articles that fit within the context are used for this research. This process is repeated until no new sources are identified. This shows that this analysis of the literature review can be divided into three parts, namely part 1 background information. Which consists of the difference between ATBNS'54 and ERTMS, Automatic Train Operations and the Driver Machine Interface. Part 2, what are the braking parameter settings of the ETCS. And part 3 what are the causes of the deviating behavior from the allowed curve. Followed by the conclusion with the corresponding knowledge gaps and the discussion of the results.

2.2 Background information

2.2.1 Difference ATB and ERTMS

A variety of safety systems are present in the Netherlands. As shown in figure 5 the majority of the rail network is equipped with NS'54 light signal system supplemented on the main network with ATB-EG. On regional lines, ATB-NG is commonly used, while ERTMS has been implemented on a limited number of routes, including the HSL-South and the Betuweroute. What these safety systems specifically entail is described in this section.

Figure 5: Netwerkverklaring 2023 (ProRail, 2023)

NS'54 ATB-EG

NS'54 ATB-EG (ATB- First generaration) is designed to ensure rail safety by ensuring that drivers brake in time for speed restrictions and stop signals (Goverde, 2012). A schematic overview of NS'54 ATB-EG is shown in figure 6. The interlockings control the switches and signals and provide the system with safe setting and locking of routes across track sections and switches. When the setting of the route has taken place, the signal can be released at the beginning of the route. This signal is displayed to the driver and gives permission to proceed. When the signal is red, the route is not released and the train is not allowed to pass. NS'54 ATB-EG ensures that speed commands are transmitted to the train drivers by light signals so that it is always possible to brake in time for a red signal (Tweede Kamer der Staten-Generaal, 2012). The signal images are legally defined by the Rail Traffic Regulations. NS'54 ATB-EG uses fixed blocks where the total length of a block must be equal to at least the maximum braking distance plus an extra for the reaction time of the driver. This maximum braking distance depends on the speed the train is currently entering the block. This maximum braking distance is defined in Article 8 of the Rail Traffic Regulations. Article 8 states that braking distances are based on the worst braking train. For example, in a block, the maximum braking distance is set according to the track section speed. When driving 140km/h the maximum braking distance is 1150 meters, with the additional reaction time implemented it becomes 1370 meters.

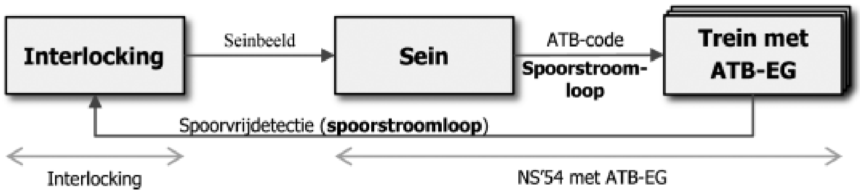


Figure 6: ATB-EG (Tweede Kamer der Staten-Generaal, 2012)

The speed command is shown by a number below the light signal, this represents the allowed speed in tens. Driver errors are caught by the installed ATB. ATB-EG monitors speeds and braking commands for coarse speed steps, such as 40, 60, 80, 130 and 140 km/h (Goverde, 2023a). When a driver does not brake sufficiently after a command, ATB-EG warns the driver. If the driver then fails to react, rapid braking follows, bringing the train to a stop. Figure 6 shows that the interlocking is directly connected to the trackside signals, while the train-bound ATB-EG system constantly receives information from the track via a code based on the track current flow. The information is also displayed in the cab to the train driver. The indicated track circuits provide track clearance detections, thus interlockings know that the track sections (blocks) are cleared.

NS'54 ATB-NG

In the Netherlands, the NS'54 signaling system has been installed with ATB-New Generation (ATB-NG) on most regional lines. This has been implemented on non-electrified railroad lines and lines where light rail is present. Figure 7 shows a schematic representation of ATB-NG.

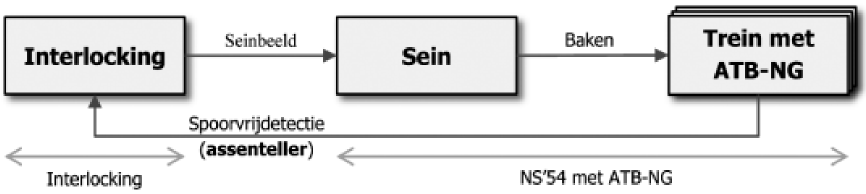


Figure 7: ATB-NG (Tweede Kamer der Staten-Generaal, 2012)

This signaling system corresponds to ATB-EG, but the train protection is different. This train protection monitors all speeds in 10 km/h increments. In addition, it has train-dependent braking curve supervision. Based on the train-specific mass and braking characteristics, the on-board computer of ATB-NG calculates an appropriate braking curve up to the newly specified target speed or red signal the train is approaching. If the train travels above the braking curve, a warning and, if necessary, braking intervention follows, bringing the train to a stop. With ATB-NG the train driver does not have to start braking until just before the braking curve begins, this is called delayed braking, this can be after the yellow signal. Previously this was not allowed, with ATB-EG the train driver had to start braking immediately after passing the signal in question. ATB-NG uses point-by-point data communication via beacons between the rails. These beacons transmit the distance to the train to the next signal at the maximum speed at that point, this intermittent data transmission by beacons, gives the target speed and distance of multiple signals up to 3600m (Goverde, 2023a). Axle counters are present for track-free detection. Trains with ATB-NG on board can operate on tracks where ATB-EG is implemented, but trains installed only with ATB-EG cannot operate on tracks where ATB-NG is implemented.

ERTMS

ERTMS was already briefly mentioned in the introduction. The European Rail Traffic Management System is a European rail safety and management system. The goal is to replace the various national systems for an interoperable standard (*ERTMS*, n.d.). The deployment of ERTMS will enable the creation of a seamless European railway system and increase European railway's competitiveness (Goverde, 2023a). This will lead to international interoperability allowing trains to run seamlessly through different countries on each other's infrastructure. With ERTMS, train drivers continuously receive up-to-date information about speed limits and braking curves via cab signals, based on real-time data (Goverde, 2012). ERTMS is divided into TMS (Traffic Management System) and ETCS (European Train Control System). TMS ensures efficient coordination of trains on the track and improves punctuality through real-time monitoring of train traffic, route planning and automatic route setting, while ETCS ensures interoperability on railroad lines and safety. ETCS in general is a train safety and speed control system that provides safety and interoperability on railroad lines and works with different levels (Ranjbar et al., 2022).

ETCS Level 1 is used in conjunction with the existing systems that regulate the signals along the track, so ETCS Level 1 provides security via spot transmission of signals (Ranjbar et al., 2022). Figure 8 schematically shows the operation of ETCS Level 1. The ERTMS track-side equipment transmits the information given by the signals to the train driver, this is translated into Movement Authority (MA). The Movement Authority is calculated by the LEU (Lineside Electronic Unit) which are transmitted to the train using eurobalises. The speed of the train is continuously monitored by the ETCS on-board based on the received MA. The train only receives ETCS information while passing a balise, this may have the consequence that the information is no longer up-to-date. Therefore, the train driver always pays attention to signals along the track and this way has additional information. The braking curve is calculated from the MA by the ETCS-onboard, it intervenes when the speed is too high. For this the balises are important which are used as location references. The route monitored speed is shown to the train driver through the Driver Machine Interface (DMI). Track-based train detection, with the aid of axle counters, is used to determine whether the track is occupied or not, this allows the decision to be made whether or not to release the track for the next train.

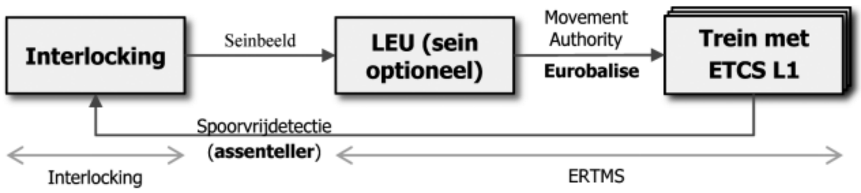


Figure 8: ETCS Level 1 (Tweede Kamer der Staten-Generaal, 2012)

ETCS Level 2 uses radio-based communication for continuous signal updates (Ranjbar et al., 2022). In this section extra attention is paid to the explanation of ETCS Level 2, because it was indicated earlier in this report that the choice has been made to roll out ERTMS in the Netherlands with ETCS Level 2. ETCS Level 2 is therefore also the scope of this research. Figure 9 schematically shows the operation of ETCS Level 2.

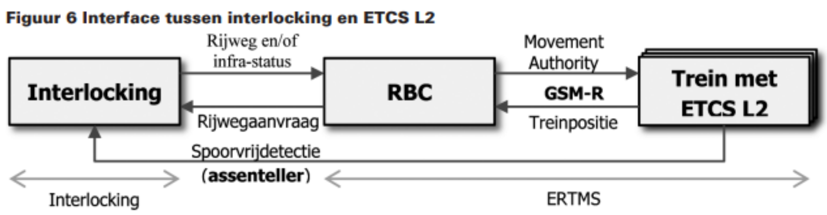


Figure 9: ETCS Level 2 (Tweede Kamer der Staten-Generaal, 2012)

Whereas Level 1 track-train communication is via balises only, Level 2 uses a continuous radio link (GSM-R) for track-train communication. GSM-R becomes in the future FMRCS, GSM-R becomes obsolete. GSM-R is a variant of GSM for rail. Within ETCS Level 2, the balises are used exclusively for the location reference of the train. In addition, the interlocking provides information about the status of infrastructure elements and information about set routes. This location reference from balises and further information from the interlocking is transmitted via the radio link to the Radio Block Center (RBC). The RBC is a system that communicates with trains. The RBC determines the safe route or also known as the MA. This MA is communicated together with the relevant track data by a GSM-R radio link to the on-board computer of the respective train. The MA is thus sent to the train via GSM-R from the RBC. No more signals along and around the track are needed due to the presence of the continuous radio link to the train. Signals have been replaced by stop marker signs, these signs indicate the beginning and end of a block in which the train is running. ETCS Level 2, like ETCS Level 1, provides continuous speed monitoring that intervenes when there is an overshoot of the given driving permission. The ETCS on-board calculates the braking curve with the aid of the MA, which is used to determine when to intervene when the train is travelling too fast. Via the DMI, the train driver is continuously shown the route and monitored speed. Track-bound train detection is used to prove whether the track is occupied or not. In addition to the indicated functionalities of Level 2, there is one more, namely the location information sent periodically to the RBC may be used by the RBC to determine as well whether the track is occupied or not. The condition attached to this is that the train must indicate that it is complete, i.e. that no wagons have been erroneously detached or left behind. This is also known as integrity. Because the RBC uses the location information, the track-based train detection system is redundant. The RBC has the ability to pass, modify or revoke a new Movement Authority at any time. Speed constraints can be accurately implemented right at the start of the switches. This is an important advantage of ETCS Level 2 , as it leads to capacity gains compared to traditional systems. This is because in traditional systems the speed restrictions are set hundreds of meters earlier at the signal. Another advantage is that the physical signals along the track have been converted to virtual signals in the cab signal. This leads to more freedom in designing block boundaries, as the visibility requirements of traditional signals are eliminated.

ETCS Level 3 introduces the moving block principle, where trains run over dynamic blocks (Ranjbar et al., 2022). The situation differs from ETCS Level 2 in that the track-bound track-free detection has been dropped. Trains now fully retain their own integrity and transmit their position (pre- and end position) to the RBC which in turn transmits the information to the interlocking. A discrete fixed block layout is no longer necessary: a train is seen as a moving block which continuously passes its position to the interlocking. The interlocking has the ability to steal the train routes until just before the back of a train. Trains can therefore run at braking distance from each other, to this of course a safety margin is added. ETCS Level 3 is free of signals and track-free detection, this eliminates major cost and construction. There are still Eurobalises on the track that transmit fixed coordinates for calibrating train positions. Monitoring integrity is not a problem for modern trainsets, but monitoring integrity for locomotive cars is, such as freight trains and locomotive-drawn trains.

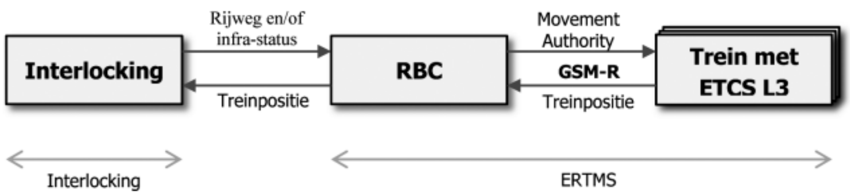


Figure 10: ETCS Level 3 (Tweede Kamer der Staten-Generaal, 2012)

2.2.2 ATO

As described above, European Railways are in the process of implementing ERTMS. A next step is to achieve improved capacity, on-time performance and possibilities to drive energy efficiently. This is where the development of Automatic Train Operation (ATO) would help. (ERA, 2023). ATO adds a wide range of capabilities that replace manual tasks and progress to full automation. The desired degree of automation (GoA) and the level of automation supported are clearly shown in table 3. The definition of GoA stems from the division of responsibilities for certain functions of railroad operations between relevant technical railroad systems and operational personnel.

Table 3: Grades of Automation high level description (ERA, 2023)

GoA	GoA Name	Train Operator	Description
GoA1	Non automated operation	Train driver in the cabin	The train is manually controlled but safeguarded by automatic train protection (ATP). This GoA can also supply advisory information to support manual control.
GoA2	Semi-automated operation	Train driver in the cabin	The train is automatically steered, stopping is automated but a train driver is needed in the cabin to start the automatic steering of the train, the train driver can control the doors (although this can also be automatic), the train driver is still in the cabin to monitor if the track is free and to perform other manual operations. The train driver can take over control in emergency situations or disturbed operation.
GoA3	Driverless operation	Train supervisor on board the train	The train is automatically controlled, which includes automatic departure, a train attendant has a number of operational duties, such as operating the train doors (however this can also be automatic) and can take over control in emergencies or restricted situations.
GoA4	Unattended operation	No train crew authorized to drive the train	Unmanned train operation; all functions of train operation are automatic with no train crew to take over control in emergency or disturbed operation situations. situations.

ATO from the grade of automization GoA2 to GoA4 is useful for various railway operations:

- For regional lines, Intercity lines and High Speed lines, ATO improves timetable compliance, delivers higher performance and provides energy-saving function for train operations managed by ATO (ERA, 2023)
- For freight lines, ATO provides smoother operation. This includes efficient conflict management and minimising unexpected stops of the train (ERA, 2023)

The driving function ATO consists of the following functional features:

- Time Table Speed Management: This determines the optimal speed at which the train can reach the location on time (ERA, 2023)
- Supervised Speed Envelope Management: this system sets the maximum speed, under this the train can run without violating speed limits of the ETCS system (ERA, 2023)
- Automatic Train Stopping Management: This takes care of generating the speed profile, leading to accurate stopping of the train at the scheduled stopping point (ERA, 2023)
- ATO Traction/Brake Control: this system provides output commands for both traction and braking. This helps in the correct control of the train's speed determined by the above three functions (ERA, 2023)

Regarding ATO and its translation to braking curves, it is noted that the functional characteristics mentioned above are supplier specific. (ERA, 2023). This means that certain aspects of the system are not strictly standardized, but depend on supplier choices. When forming braking curves in systems such as ETCS, braking profiles are influenced in the context of how functions are technically implemented. This does not align with the driver perspective from which this report is based.

2.2.3 Driver Machine Interface

The image below shows the Driver Machine Interface of train control systems such as ERTMS. This is the one that a train driver sees in his cab and an essential tool. It provides information about speed, distance and schedule. This provides the train driver with all essential information to operate safely and efficiently.

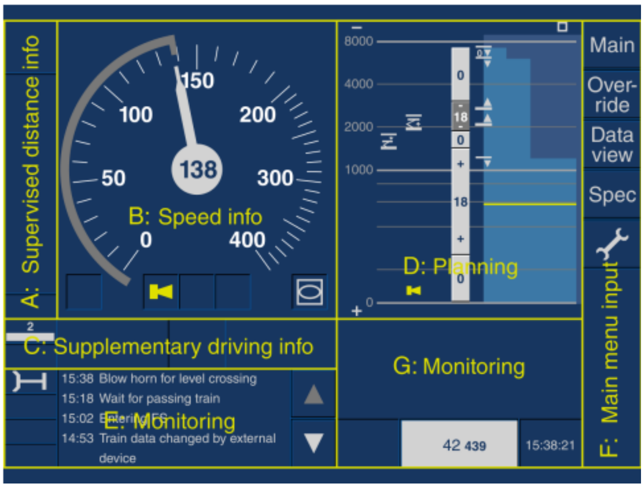


Figure 11: Driver Machine Interface (Goverde, 2023a)

From Figure 11, the components are named from the DMI. First, A, this is the 'Supervised distance info'. This indicates the maximum distance that may be traveled by the train under the current Movement Authority. Second B, this is the 'Speed info'. This shows the current speed and the permitted speed using the gray bar (permitted curve). This gray bar visualizes the braking curve. Third C, the 'Supplementary Driving info'. This bar provides additional information, such as 'Wait for passing train' or 'Blow horn for level crossing'. Fourth D, this is the 'Planning'. This displays a graphical representation of the train's planned driving route with its associated constraints. Fifth E and G, this is the 'Monitoring'. E shows the status update and alerts, think about changes in train parameters and or system errors. This keeps train drivers aware of critical changes. And G show the current time and further train status such as speed and warnings. As the sixth F, this is the 'Main Menu Input'. In the Main Menu Input, control buttons are displayed for system functionalities such as data view, override and specific system options.

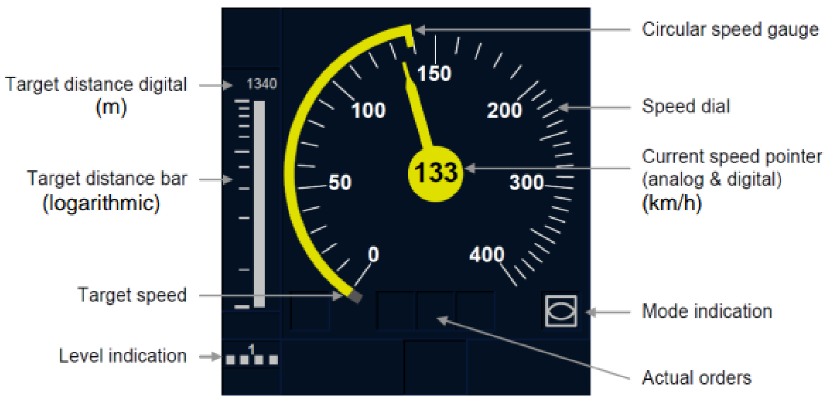


Figure 12: Supervision information (Goverde, 2023a)

Figure 12 shows the detailed speed display. Here, the Circular Speed Gauge provides information about the speed in relation to the permitted speed. In the example, the speed scales from 0 km/h to 400 km/h. The 'Speed Dial' displays the current speed of the train as an analog pointer and as a digital numeric form, in this example the current speed is 133 km/h. The 'Current speed pointer' displays the summary of the above, i.e. the digital speed and the analog speed. The 'Target distance Digital' displays the remaining distance to a key point in meters, think of a stop location or a speed change. The 'Target distance Bar' is the vertical bar that graphically displays the remaining distance from the target distance digital. The 'Target speed' is the white marker on the circle and represents the target speed. In the example, the target speed is 0 km/h. 'Level indication' displays the level in ETCS in which the train is currently operating. 'Mode indication' shows the mode of the train protection system. Think of Full supervision, On sight or Shunting. Finally, the 'Actual Orders', these are the specific driving orders or actions that are important. For example, braking or acceleration.

So, the interface gives real-time information to the train driver to drive safely and efficiently. Speed, distance, and operational status are brought together in one clear screen for the train driver.

2.2.4 Brake parameter settings (ETCS curves)

Figure 13 already shows several braking curves related to ETCS and has already been briefly discussed. Of course, the curves are a lot more detailed than what is shown in that figure. This section looks at the curves and explains which ones all exist and what track- and train-related inputs are needed to calculate the curve. This is the first detailed look at the approach to braking curves.

ERTMS/ETCS, as stated earlier, guards the speed of the train. This ensures that the train remains within the allowed speeds, or Movement Authority. Based on the track and train characteristics shown in figure 14, the onboard European Vital Computer calculates the braking curves over the distance using a mathematical model. All braking curves finish at the same point in the distance, which is the Supervised Location (SvL). Depending on national values, the End of Authority (EoA) is equal to the SvL. The braking curves shown in Figure 13 are divided into two types of braking curves, safety braking curves and advisory braking curves. The safety braking curves are preventive responses of the control system to ensure that a train does not exceed its authorization. The advisory braking curves provide an advisory function to the train driver. The advisory braking curves include the Indication curve, indicated in figure 13 by I, the Permitted curve (P) and the Warning curve (W). These braking curves are calculated in real time by the onboard ETCS system. This calculation requires the speed, location and MA of the train. For positioning the curves relative to each other, figure 13 is useful to use. It is shown there that the Indication curve is ahead of everything else; in fact, this curve indicates the announcement of braking (Goverde, 2023a). Followed by the Permitted curve, which indicates the recommended speed and is displayed to the driver and shall not be exceeded. Following the Permitted curve gives the driver a time buffer to avoid activating the service brake. If this buffer time is exceeded, the system activates the Warning curve to alert the driver. The Warning curve gives a warning sound when it is exceeded (Goverde, 2023a).

In addition to advisory braking curves, there are also safety braking curves. These safety brake curves are used for emergencies and are designed to ensure safe deceleration. Safety brake curves include the Emergency Brake Intervention curve (EBI), Emergency Brake Deceleration curve (EBD), the Service Brake Intervention curve (SBI) and the Service Brake Deceleration curve (SBD). These braking curves are used to activate braking when operator reaction time is insufficient. The EBI curve commands emergency braking, and the SBI curve commands service braking (Goverde, 2023a). In addition, the SBD curve represents the actual deceleration profile of the service brake up to the end of authority (EoA), while the EBD curve represents the actual deceleration profile of the emergency brake up to the supervised location (SvL) at the maximum front of the train. (Goverde, 2023a). The ETCS system provides the ability to deploy safety brake curves. The service brake can be activated to prevent excessive wear of the brake discs and track. This is because when the emergency brake is used, this wear can occur faster. When the service brake option is selected, the SBD curve and the SBI curve are calculated. When the operator cannot brake in time and the SBI curve is exceeded, the SBD curve is activated. In the Netherlands, this option is not selected, and only the EBI curve and the EBD curve are used as intervention curves.

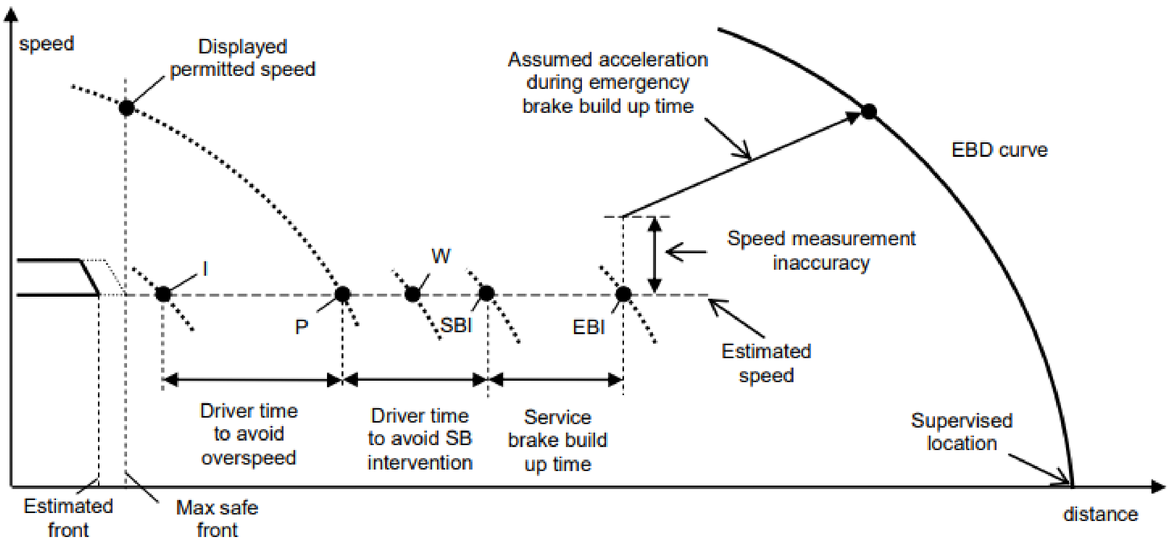


Figure 13: ETCS Braking curves (ERA, 2020)

ETCS continuously monitors the train's position and ensures that it stays within the permitted distances and speed limits. If necessary, the system automatically intervenes to prevent these limits from being exceeded. As indicated earlier, the onboard European Vital Computer uses track and train characteristics to calculate braking curves over the distance. The input for this mathematical model consists of both track- and train-related data. This process is illustrated in Figure 14. The figure shows how various inputs come together in a system that does speed and distance monitoring. When determining braking curves, it is essential to perform accurate speed and distance monitoring of the train. But what exactly are the track- and train-related input data for the current system? For the train-related inputs, factors such as the traction model, brake model, brake position, correction factors, rotation mass factor, train length, and maximum train speed should be considered. As for the track-related inputs, it is important to consider speed restrictions, gradients, track conditions affecting braking or currentless sections, reduced adhesion, and specific speed and distance limits (NS Reizigers - Prestatieregie and Innovatie, 2023). From the input, the dynamic speed profiles can be calculated eventually, the braking curves monitored and the output generated. This generates the TI commands and commands on the train driver's DMI.

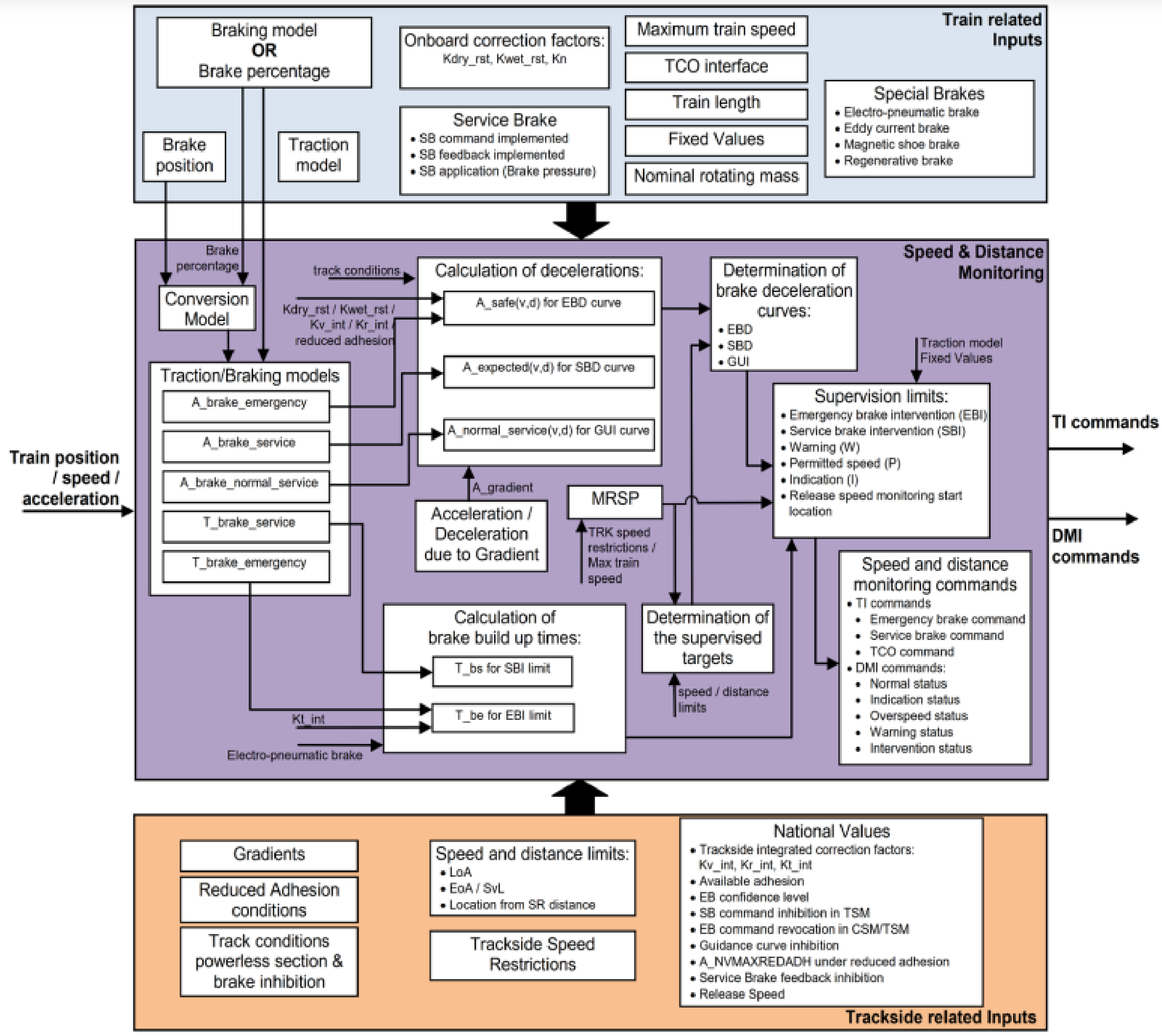


Figure 14: Speed and distance monitoring (Goverde, 2023b)

At first glance, the braking parameter settings of ETCS seems ideal for achieving the future goals of the rail industry, but there are some bottlenecks. Studies and analyses often consider the permitted curve, but they frequently overlook the actual braking behavior of drivers in real-world situations. This leads to a false assumption that train drivers follow the permitted curve perfectly. As a result, it creates unrealistic expectations about braking behavior, its modeling, and the feasibility of planning assumptions and capacity expectations (van der Beek, 2023). In the research by Pieter van Beek, Woudt and Alberts conducted a simulation in which train drivers drove in four different scenarios. In this simulation, drivers had to drive as they normally would in an ERTMS level 2 system. The four scenarios are:

- 'Hard instruction' so following the permitted curve as well as possible as a train driver
- 'Delayed' how would a driver drive in a delayed situation
- 'Soft instruction' the train driver should follow the permitted curve as closely as possible, but still in its own sense of safety
- 'On time' natural behavior drive according to current norms

The results of driving under these scenarios are shown in figure 15.

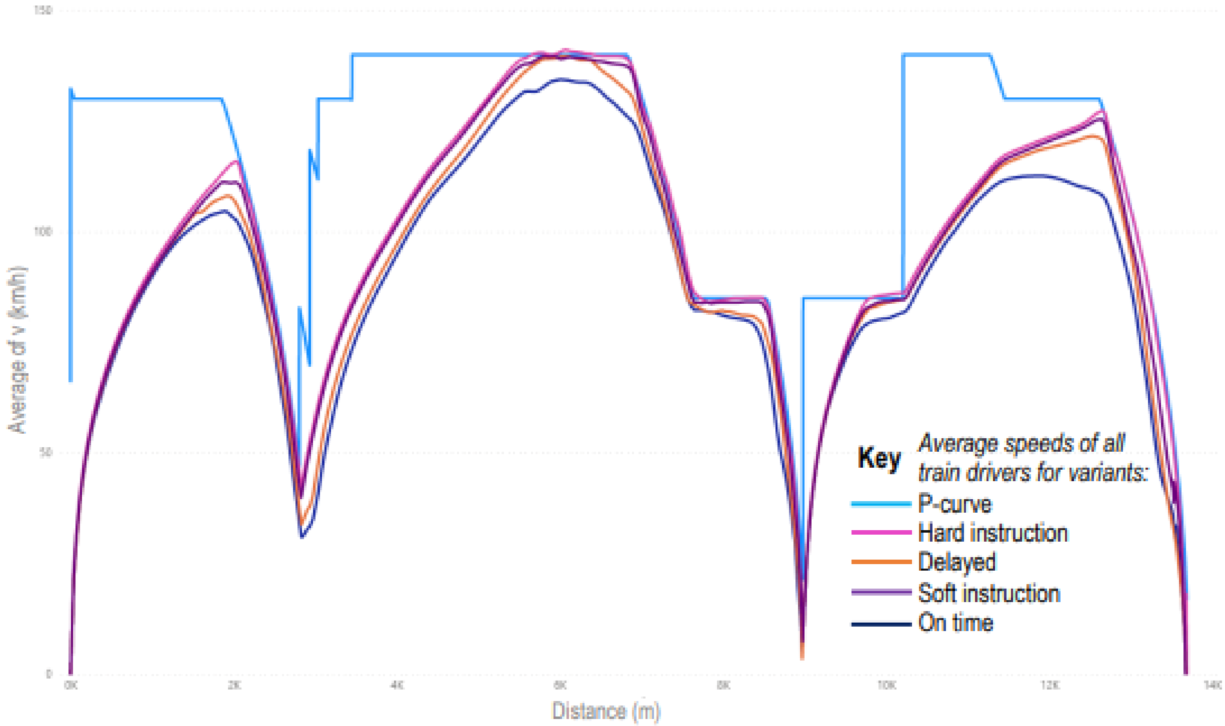


Figure 15: ETCS Braking curves (van der Beek, 2023)

This experiment shows that the driver maintains a margin relative to the permitted curve. This can be assigned to some form of operator comfort or caution. During hard instructions, the train driver is roughly at the recommended speed, but this is not maintainable for the train driver and requires a lot of energy. In the next section, the causes of this margin when running under the ETCS braking curves, and what this means for performance and safety, are discussed in more detail.

2.2.5 Causes of the deviant behavior

The previous section demonstrated that train driver behavior is unique when operating under ETCS brake parameter settings, but what exactly are the causes of this? Pieter van Beek researched the factors that affect driver anticipation. These factors are divided into four categories: driver-related, organizational tasks, train (machine system), and environment (outside the train). Driver-related factors, such as experience and confidence in the system, play a crucial role. These can positively influence braking behavior, leading to more accurate tracking of the permitted curve. As for organizational tasks, time pressure and the nature of the tasks imposed, such as the type of braking task, are important factors. When there is no change in management and the workload remains constant, braking curves become less abrupt, leading to better adherence to the allowable curve. On the train side (machine system), the emphasis is on the uniformity of braking systems and the different characteristics of the train system. In addition, route information provided through the Driver Advisory System (DAS) plays an important role in creating clarity. Uniformity and clarity within the train have a positive impact on comfort during braking. Finally, regarding the environment (trackside), factors such as slippery tracks, track gradients and schedule margin are important. These environmental features can have a influence on comfort and the way the driver brakes (van der Beek, 2023).

An overview of further causes of the deviant behavior is shown in the figure 16 below.

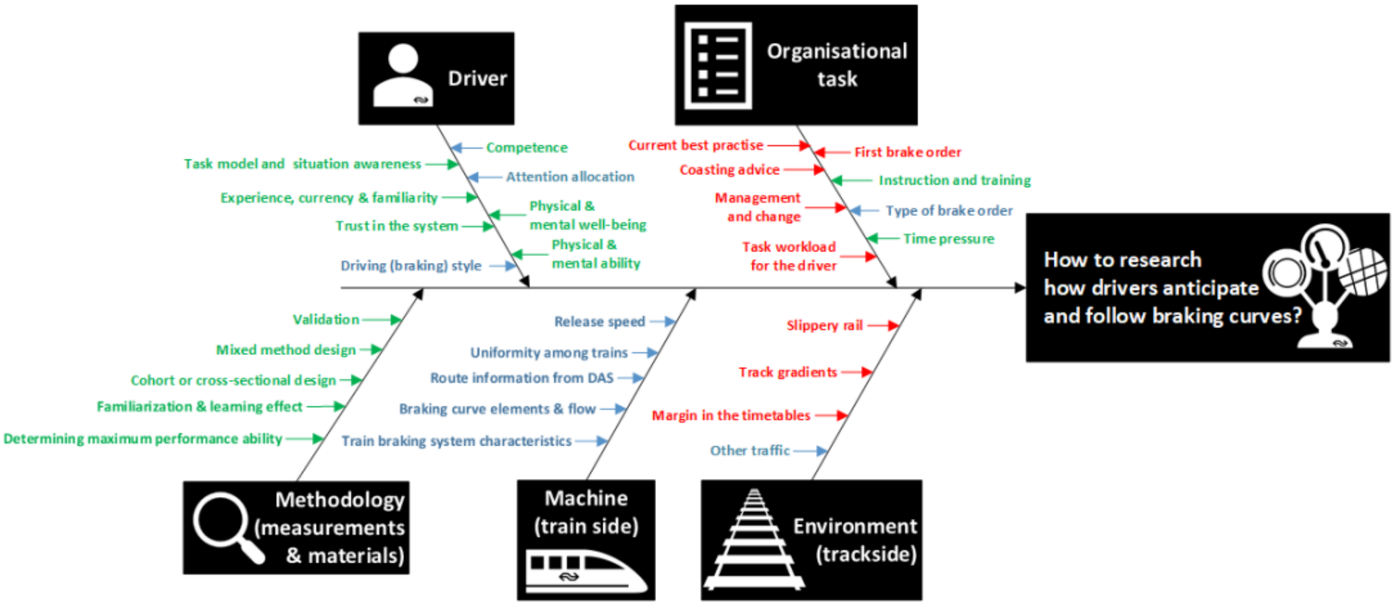


Figure 16: Further causes of the deviant behavior (van der Beek, 2020)

The literature review outlines the existing safety systems in railroads and mainly highlights the operation of ERTMS, specifically ETCS Level 2. ETCS Level 2 is an advanced approach in terms of speed and distance control, supported by virtual on-board computers that generate the braking curves and provide the necessary real-time information to the drivers. The train drivers see this information on their Driver Machine Interface (DMI).

Despite the fact that the theoretical models of ETCS braking curves seem to meet the goals of the rail industry, there are significant deviations in train driver braking behavior. This has been demonstrated in previous research by Pieter van der Beek. These deviations are influenced by several factors, such as experience, confidence in the safety system, working conditions and environmental variables (e.g., slippery track). Train drivers are found to maintain a certain margin with respect to the recommended speed, and this margin is related to a preference for comfort and safety. The findings from the literature review indicate a clear gap between the theoretically designed braking system and its practical application by train drivers. A deeper definition of comfort braking is explored in the following sections. Driver behavior is discussed in more detail: what does the literature say about it, and how do drivers behave in practice? What are the consequences of deviant behavior? In addition, ETCS braking curves are further elaborated to provide an approximation for the formulation of the comfort braking curve.

3 Driver Behavior and experience

This section highlights the driving strategies of train drivers and how they drive under ETCS Level 2. Based on literature review, simulator sessions and interviews with train driver behavior experts, as well as interviews with the train drivers themselves, this research details train driver behavior. This provides valuable insights into the thought processes of drivers while driving and identifies the bottlenecks of driving under ETCS Level 2. This knowledge helps identify what comfort and discomfort mean to the train driver today.

For this research, a day was spent at Railcenter in Amersfoort analyzing how train drivers drive under ETCS Level 2 (baseline 3, release 2) in different scenarios. During this research, the VIRM and SNG were driven. The DMI was clearly displayed on a separate screen so that it could be properly analyzed. After the simulator sessions, the train drivers were interviewed about their experiences. This obviously provided valuable insights for this research. The images below in figure 17 provide a visual representation of what the research at Railcenter looked like.

Figure 1

Figure 2

Figure 3

Figure 17: Railcenter research day (J.N. Saoulidis, 2024)

Besides the investigation at Railcenter, NS' NEO simulator in Utrecht was also utilized, as shown in figure 18. Here, together with an experienced train driver, who is also a researcher, different scenarios were examined while driving under ETCS Level 2, baseline 3, release 2. The results from this simulator were also included in this research.

Figure 18: NEO Simulator NS (J.N. Saoulidis, 2024)

3.1 Train driver behavior

There are four standard driving modes considered by the train driver. These 4 driving modes are shown in figure 19. From interviews with train drivers, these driving modes have also been confirmed, but it is scenario dependent when which mode is used. The modes from figure 19 are outlined below:

- Acceleration, it is determined by the maximum traction effort and passenger comfort acceptance levels
- Cruising, here a constant velocity level is maintained
- Coasting mode, this is movement without active traction or braking on the wheels. This leads to comfortable deceleration
- Braking mode, determined by the maximum braking effort. Here the passenger comfort acceptance level also plays an important role according to train drivers.

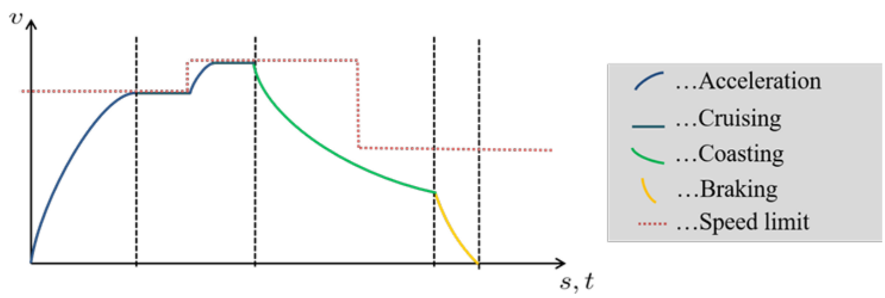


Figure 19: Train Driver techniques (Pröhl et al., 2021)

Braking behavior can be performed in different strategies, this relates to the situation the train driver is operating in, these are also called anticipation strategies. Three anticipation strategies can be distinguished:

- Defensive, a train driver can drive defensively and stay in front of the permitted curve (in seconds or meters) (Prorail, 2014)
- Offensive, here train drivers drive in ways to make up time or at least stay on the permitted curve. Here even a warning is taken for granted (Prorail, 2014)
- On average, this would represent driving on the permitted-curve. This way of driving is logically between defensive and offensive driving (Prorail, 2014)

3.2 Train driver behavior discomfort

Despite the above mentioned train driver techniques and anticipation strategies, train driver behavior is affected. The transition to driving under ETCS Level 2 brings new challenges, especially when it comes to comfort and attention distribution. There are specific occasions when train drivers desire predictability and comfort, this section describes several situations where forms of discomfort are experienced by a train driver.

First, the introduction of ETCS Level 2 changes the shift in attention. It requires a continuous balance between focus on the environment outside and on the DMI inside the cab. Interviews with train drivers revealed that the most important elements outside the cabin are:

- The distance and speed to objects (estimation)
- Explore signs, this is an announcement of a station for instance
- Stations itself, consider a beginning and end of a station
- Train length signs, this sign indicates the stop location regarding the material composition
- General reference points along the track, these reference points are used as road familiarity

In addition to the elements outside the cab are also elements inside the cab, these elements displayed in the DMI are outlined in section 2.2.3. Below is a brief summary of the in-cab elements:

- Speedometer, this meter displays its own speed, permitted speed and the brake curve target speed braking
- Indication marker, this is a yellow line announcing the upcoming inhibition
- Planning area, indicates the Movement Authority, the speed profile and any End of authority
- Distance to target, this displays a visualization of the distance to reach the new target speed

With the implementation of ETCS Level 2, the distribution of attention across the above elements becomes more significant compared to operating under ATB. The effects on visual attention distribution and train driver alertness are challenges in train modernization (van den Band et al., 2020). For example, one of the major differences can be seen between inhibitions toward a halting location as compared to other inhibitions (which is not related to a halting location) (NS Reizigers - Prestatieregie and Innovatie, 2023). When braking toward a halting location, elements outside the cabin are considered much more. This is due to the fact that the ERTMS DMI does not show indications of the halting location. From experience, train drivers look for reference points outside the cab. Train drivers are thus sensitive to a certain instruction to drive closer to the braking curve which causes a change in attention between looking inside and outside. In conclusion, literature and practice converge on this challenge. The speed frames between ATB and ERTMS differ and more information is displayed in the cab in ERTMS. This requires more switching between looking inside and outside the cab, this can make it more difficult to accurately follow the allowable curve (van den Band et al., 2020)(NS Reizigers - Prestatieregie and Innovatie, 2023).

Train drivers and behavior experts regarding train drivers indicate that, apart from the situations explained above, there are also other specific factors that make it more difficult and or undesirable to follow the permitted braking curve. One of the factors is slippery tracks: this is caused by rain, leaves or black ice on the track. This can lead to longer braking distances and cause slipping. This makes it difficult for train drivers to brake accurately and thus also makes it difficult to stay close to the braking curve. This requires train drivers to stay focused in order not to lose control. Another factor that makes it difficult is the type of braking that is active, namely pneumatic braking, these brakes work through air pressure. This type of braking more often has a slower response when compared to other types of braking systems. The pneumatic brake slows down the braking process and results in irregularities in the braking curves. Because the system does not respond quickly enough to adjustments, the train driver struggles to always drive precisely in the braking curve, depending on the type of brake equipped on the train. Another factor is crowded trains. Train drivers automatically adjust their driving behavior as passengers' comfort in the overcrowded train must be preserved. Besides this, when a train is overcrowded, the mass of the train is significantly increased. This directly affects the train's braking distance, this is because heavier trains require more energy to stop. Train drivers have to adjust their braking strategy, this means they have to brake earlier, i.e. they cannot stay tightly on the curve. The overcrowded train combined with the previously mentioned slippery track leads to a worse discomfort situation: train drivers indicate that the VIRM is more slip-sensitive. Added to this is the fact that nowadays the trains have fewer train sets connected to each other and so there is less place for passengers and in many cases passengers are standing in the train. This makes following the allowed curve almost impossible for train drivers to carry passengers in the crowded train when it is slippery, without throwing passengers off balance. Another factor is the braking position of the traction/brake handle. There are different braking positions that allow the train driver to regulate the braking force, but there are systems where the transfer between the action and the actual braking are not linear. This affects precision and, as a result, train drivers deviate from the curve more quickly. The last factor is training oriented. During training, emphasis is placed on energy-efficient driving; for example, this is the technique shown in figure 19, coasting. But little attention is paid to braking strategies that can help with driving on the permitted curve, for example, dosing the braking force and/or making timely adjustments to the braking curve. The mentioned mismatch in training leads train drivers with less experience to focus more on following the braking curve, while this reduces the ability to brake efficiently and safely in complex situations.

These factors are practical barriers for train drivers to drive accurately on the permitted braking curve. This highlights the importance of improved training and technical support (e.g. through forecasting tools in the DMI) to better align driving behavior with the requirements of ETCS and the modern driving environment. Apart from the situations outlined above, there are also other specific scenarios that make it more difficult and or undesirable to drive on the permitted braking curve more closely. These scenarios are outlined below:

The first scenario where train drivers considered the situation as discomfort according to the analysis during the simulator days and subsequent interviews was the staggering of the permitted curve, as shown in figure 20. When a train follows a delayed (freight) train on the same route, this leads to dynamic adjustments in the permitted curve within the ETCS Level 2 block safety system. When the block is occupied directly in front of the other delayed train, the permitted curve indicates that the train should reduce its speed. This can be seen in the first image signal where the train first travels 115 km/h and has to slow down to 30 km/h (figure 1). The permitted curve here indicates that this is necessary to maintain a safe distance. Once the delayed train has cleared the block, the permitted speed is recalculated for the next train. This can be seen in figure 2 from figure 20, while the train has slowed to 56km/h the train can already accelerate again to 120km/h. While the dynamic speed adjustments are essential for track capacity and safety, they still create discomfort for the train driver. This leads to constant deceleration and acceleration. On long routes such as Groningen-Zwolle, this frequent fluctuation in speeds can lead to significant discomfort for the train driver. This discomfort in turn leads to fatigue and increases the risks of human error.

(a) Figure 1 (b) Figure 2

Figure 20: Frequent fluctuation in speeds

This scenario highlights the need for a balance between ride comfort, safety and efficiency. The dynamics between the braking curve and movement authority must be in good balance.

A second scenario where train drivers' experience, and what the NEO simulator also demonstrated, is how the calculations within the ETCS based on Baseline 3 Release 2 affect discomfort. Even though in many cases this leads to accurate calculations, there are situations what can lead to confusion for the train driver. From the moment the train is stopped and wants to accelerate, the DMI shows the permitted curve indicating that 140 km/h is allowed. This seems logical at first, but from the moment the End of Authority (EoA) is only 20 meters away it does not make any logical sense. As soon as the train driver starts accelerating, the permitted curve corrects itself and jumps back to a much lower speed. So while this is correct behavior according to the system, it can lead to uncomfortable and confusing situations in practice. This problem arises from a mismatch between the real-time movement of the train and the calculation of the permitted curve within CSM. CSM stands for Ceiling Speed Monitoring, which is a monitoring mode within ETCS. In CSM the primary focus is on monitoring the maximum speed, so it does not pay attention to dynamic adjustments based on the environment such as EoA.

There is a third scenario which was considered uncomfortable and inconvenient by the train driver and the NEO Simulator confirmed this. In the rail sector, ensuring safety is essential, especially in areas where infrastructure is complex, such as stations with multiple points and intersecting train movements. Points where complex infrastructure exists are characterized as danger points. Danger points is the location beyond the EoA that can be reached by the front of the train without creating a hazardous situation (ERA, n.d.). In order to go absolutely no further than this danger point, the train must approach this danger point at a limited speed to eventually stop safely. This limited speed is known as the release speed, often this release speed is set at 15 km/h. The release speed is a speed at which the train can approach the end of the route, the EoA. This gives the additional ability to proceed to right before the signal or SMB, the release speed is represented by a number in the lower left corner of the DMI (ERTMS NL, n.d.). This leads to train drivers, for example at stations such as Utrecht Centraal, being required to drive in at a low speed over a considerable distance. While this is critical with respect to the Danger Point, it can lead to train driver discomfort and a less efficient flow of train traffic.

To the train driver, it feels like crawling. In contrast to this scenario, when a train driver drives to a SvL (this is a supervised location or also known as a hazard point with additional monitoring on the track) without a danger point, there is no release speed and therefore more freedom for own intuition. This can result in a longer time at higher speed, so the train driver experiences less crawling.

In addition to these practical examples, three more specific cases have been indicated. The three cases are outlined below, that affect train driver braking behavior the most:

- There are sections where train drivers experience the infrastructure as uncomfortable when following the speed of the permitted curve. One of the examples train drivers pointed out were some specific routes. These routes are structured in a way that already makes the ride more likely to be considered omcomfortable. An ironic response was that they better can sell 'Efteling tickets' from the moment when the permitted curve is followed at this specific routes. An example of an uncomfortable ride: A train driver was driving an SNG on a rainy day. The train driver was riding behind a delayed freight train, causing a 15-minute delay. The train driver had to stay in his time path, so he stayed behind the freight train as short as possible. The slippery track and construction of the route made the ride very uncomfortable. The train shook on all sides because of the construction of the route, and the violent force of the SNGs' acceleration and deceleration. As a result, the passengers were not happy with the ride. In addition, this is also not good for the train wheels and because of this the workshops get overcrowded, the train driver at one point decided to ride on his own comfort to ensure the safety of himself and the passengers.
- Following the permitted curve takes no account of whether or not a switch is driven over; driving at 80 km/h over a switch is quickly seen as an inconvenience and increases the risk of wear and tear. It is therefore essential that train drivers take this into account based on experience.
- Other indicated train driver concerns: Train drivers indicate that warning signals, when crossing the permitted curve, are perceived as uncomfortable. Especially because of the impact on passengers. Nowadays, the first class is often positioned directly against the driver's cab, which means that passengers experience a lot of the signals from the cab. Train drivers indicate that they experience this as uncomfortable and that it feels undesirable. When train drivers sit against the brake curve, a continuous bleeping occurs; people do not like this. Not to mention what happens when something does go wrong, when the AERA-check is done and it can be seen that the train driver was continuously on the limit. Train drivers want to avoid this to prevent liability.
  When train drivers constantly have to be on the tip of their seats to meet the schedule, it is not beneficial to their well-being. From the moment the train is delayed, they feel like they are constantly out of the loop. It is indicated that the focus on riding the permitted curve results in a piece of customer friendliness; passengers may make it to the next transfer, but a long focus from Zwolle to Groningen is not comfortable for a train driver.
  Another concern, which is also somewhat related to the upper concern, is that the company doctor is no longer 100 percent enforcing the rules. If they did, there would be a lot more dropouts in the work environment, which is why it is important to monitor the pressure on train drivers.
  Train drivers also emphasize their concern about wear and tear, citing the example of the ICM train. There are three braking modes needed here to meet the braking criterion with only the disc brake. So all the power must be taken away using small brake discs and per axle. This becomes fatal if this is handled inaccurately with respect to acceleration and or deceleration.
  Train drivers have different perspectives towards comparing capacity with customer satisfaction. It is important to have as much capacity as possible on the tracks to transport as many people as possible, and this means following the permitted curve as closely as possible. Yet most of the train drivers indicate that it is all about the seats sold. From the moment people stop boarding trains because of crowding or that it is uncomfortable, then more asphalt than railroads will be needed in the future. Comfort is an essential part of ETCS, and train drivers do it for the passengers not the capacity. So the standard still wants to vary across train drivers, but generally the train driver's priority is to carry passengers as comfortably as possible. 'A train driver has someone else's most precious asset sitting behind his back and wants to make sure it gets home safely.'

From the above analysis, it can be concluded that driving under ETCS Level 2 brings changes. There are 6 factors, 3 scenarios and 3 cases outlined that can put more pressure on train drivers. There is a new balance between focus inside and outside the driver's cab, which influences the distribution of attention. In addition, specific situations have been mentioned that make following the permitted curve more difficult. These situations increase the train driver's discomfort and workload. Yet, comfort is generally a very important value for the train driver to ensure in situations where comfort may be challenged. The remainder of this research looks at how train drivers anticipate the outlined factors, scenarios, and cases, and how these challenges affect their driving behavior. What does the literature say about the degree of comfort and how does the degree of comfort translate into practice? The next section explains this further, with a deeper look at how train drivers deal with situations that are more complex and what strategies are employed to ensure comfort.

4 Comfort braking

In this research, the definition of comfort is addressed in terms of both theory and practice. On the basis of section 3, this section allows a more in-depth discussion of comfort level as we better understand how train drivers act. Besides, it answers how train drivers anticipate the discomfort situations from chapter 3. First, a theoretical description of braking behavior is given, highlighting the standards and principles of the comfort braking curve principle. The question is asked: what is known in the literature or what does the standard tell us? Documents from the ERA (european railway agency) or Baseline 3 release 2 and other sources are used for this purpose. The ERA documents and Baseline 3 release 2 are specifically mentioned because these documents address standards within the rail industry. The ERA deals with technical standards and specifications related to train braking behavior and comes from the International Union of Railways. Baseline 3 release 2 describes the specifications of the ETCS and shows the modifications and improvements related to railroad automation.

After reviewing the mentioned documents and other research, it is possible to answer what the norm says about comfortable braking. From the knowledge of the norm, it is possible to look at practice with an expectation: does the train driver's preference or behavior match what is in the literature? Next, the practical issues are addressed by combining observations from various simulations with insights gained from interviews with train drivers and other experts (see Appendix A). This approach allows for an in-depth exploration of how train drivers behave while operating under ETCS Level 2. For example, the simulation results provide a basis for assessing whether the findings from the literature align with real-world practices, offering valuable insights into the practical applicability of theoretical concepts. This method answers sub-questions 1 and 2.

4.1 Norm based

Comfort is defined as a type of permission and assistance the train driver uses to drive comfortably, a train driver does this to stay within proper limits (ERA, 2020). Driver comfort defines itself, among other things, from the margin below the permitted curve. Train drivers drive under the braking curve in order to avoid alerts from the safety system, but also, for example, to be prepared for unexpected situations and to drive energy efficiently (van der Beek, 2023).

Braking deceleration

Companies like Prorail take into account certain levels of comfort. Prorail works with certain maximum braking delays for ride time calculations that depend on the type of train. In fact, braking must be done with a so-called service brake:

- Intercity: 0.66 m/s^2 (Prorail, 2014)
- Sprinter: 0.8 m/s^2 (Prorail, 2014)
- Freight: 0.31 m/s^2 (Prorail, 2014)

These above braking delays indicate the extent to which the train allows its speed to decrease from Prorail's perspective. Other research often works with an average to approximate comfort braking. Namely, a comfort-based deceleration value of 0.5 m/s^2 based on the 10th percentile of field measurements without including gradients (van der Beek, 2020). Generally, comfort and deceleration are said to be expressed as: A typical and comfortable braking deceleration that is between 0.5 m/s^2 and 0.6 m/s^2 (Prorail, 2014)(van der Beek, 2020). These values ensure that braking deceleration feels smooth and does not result in an abrupt loss of stability for passengers, which is essential for a pleasant travel experience.

Jerk

Jerk is a critical factor in specifying a comfort braking curve because passenger comfort depends heavily on the rate of change in braking force, more even than the deceleration itself. Jerk refers to the rate of change in braking force (Powell & Palacín, 2015) and is measured in m/s^3. Figure 21 shows the change in jerk. Research by Powell and Palacin shows that higher jerk values increase the likelihood of passengers experiencing deceleration as uncomfortable, even at low deceleration. Lower jerk values increase tolerance for higher acceleration or deceleration. Jerk is an important factor in specifying a comfort braking curve (van der Beek, 2020). The level of comfort is strongly related to jerk; research shows that jerk has more impact on comfort than deceleration. The graph in figure 21 shows the jerk change. These standards of jerk were made in the research on passenger stability by Powell and Palacin. The figure shows that there is a higher probability that the train drivers will consider the acceleration unacceptable when higher jerk values occur. This is valid even when braking deceleration is relatively low. Lower jerk values create a higher tolerance for higher accelerations or decelerations.

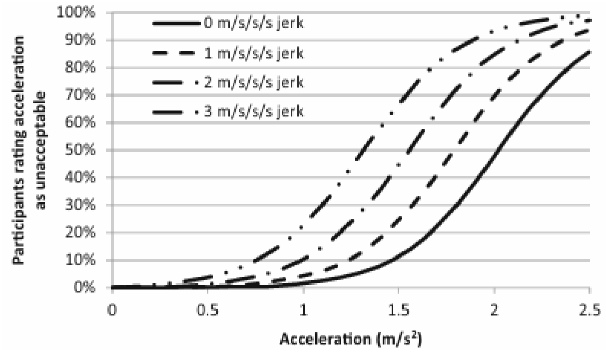


Figure 21: Acceptability jerk level (Powell & Palacín, 2015)

The above illustration works as follows: when a train has a braking delay of the specified 0.5 to 0.6 m/s^2, the experience feels comfortable at a low jerk (up to 1 m/s^3). In this case, the speed decreases gradually, meaning the train does not come to a sudden stop. When the jerk increases to, say, 3m/s^3, the transition will be a lot more abrupt. This gives a greater chance that the train driver and passenger will experience this as unpleasant, this can also be seen in the graph. As the value in jerk increases, the degree of unacceptable also increases among passengers and train drivers. So for ensuring comfort, it is crucial to keep the braking delay and jerk within a certain range. This prevents unexpected changes in train speed and results in a smooth braking experience. This significantly improves comfort on a train. This means that it is very important when modeling the braking curve and designing the braking parameter settings to take into account these two parameters (braking delay and jerk), knowing this can optimize comfort. It is essential in this research when designing the braking curve to seek not only a suitable braking deceleration, but also a proper implementation of the jerk value in order to avoid abrupt movements. This will have the effect of balancing safe stops with maintaining comfort within the train.

In this research, it is chosen to assume a maximum jerk of 1m/s^3. This offers valuable advantages with respect to comfort and control during the braking process. Figure 21 shows that with a jerk of 1m/s^3, the acceleration/deceleration over the entire braking route is well within the acceptable range of the previously established comfortable braking deceleration established previously between 0.5 and 0.6 m/s^2. The jerk related to this braking deceleration is important in this research because this braking deceleration is considered comfortable by train drivers and passengers. In addition, the jerk of 1 m/s^3 gives a smooth transition between different speeds. Compared to a higher jerk, such as 2 m/s^3 or 3 m/s^3, the higher jerk has a more abrupt change in acceleration which passengers and the train driver are more likely to perceive as mostly unpleasant. This is reflected in figure 21, in the increase in unacceptable perception at higher jerks. The lower jerk gives the train driver more control over the train, for example in situations with slippery tracks or approaching halting locations.

In conclusion, comfort braking is a smooth deceleration (0.5 - 0.6 m/s^2) with minimal jerk (max. 1 m/s^3) ensuring smooth speed transitions and a balance between comfort, control, and safety.

4.2 Practice-oriented comfort braking

In addition to what the norm explicitly prescribes, what matters is how this is experienced in practice. What is known about how the train driver reacts and how the train driver actually responds to comfort? That is highlighted in this section.

A train driver obviously cannot drive to the standard: 'I want to brake now at -0.5 m/s^2'; this is something that a driver is going to apply by feeling, road familiarity and training (NS Reizigers - Prestatieregie and Innovatie, 2023). Train driver behavior and braking have an impact on follow-up times and travel times. Specifically, braking to lower speeds and/or accelerating from lower speeds to the recommended speed creates large differences between train driver travel times. Every train driver drives differently with respect to the permitted curve, but research by Stan Albers and Van 't Woudt shows that the average distance to the permitted curve over the different routes is 4 seconds.

From the scenarios from section 3.2, it was already clear that there are different scenarios, what train drivers consider as uncomfortable. Think of the slippery tracks, overcrowded trains, searching for the right handle position or the staggered permitted curve, these are all unexpected situations that train drivers want to be prepared for. So what appears is that train drivers maintain a margin over the permitted curve to avoid exceeding the limit and interventions. When delayed, the margin is smaller, leading to higher mental effort. This is undesirable in the long run. A smaller margin relative to the permitted curve means less time and space to anticipate different situations. So, partly because of unplanned braking, train drivers maintain a wider margin; they stay at a lower speed longer before accelerating again. This has also been confirmed in train driver behavior analyses and from Pieter van der Beek's research. Here it is said that train drivers indicate that they prefer not to drive outside their personal comfort zone because it can affect safety, passenger comfort and energy efficiency (van der Beek, 2023). They will maintain a margin of about 4 to 5 seconds relative to the permitted curve to be able to anticipate unexpected situations (van der Beek, 2023) (van der Beek, 2020). Smaller margins lead to higher workload and stress, while larger margins give room for such things as rolling out the train. The philosophy train drivers have is that it feels less comfortable and energy efficient to be short behind an obstructing train and, as a result, run into braking curves each time. In addition, following the permitted curve when there is a delayed train ahead requires incredible effort.

The previously stated uncomfortable situations from section 3.2 lead to energy inefficiency of the train. Examples are the confusing speed calculations in Baseline 3 release 2 or the staggered permitted curve before the cleared track section. In order to better anticipate braking or unexpected situations train drivers indicate that they prefer not to accelerate just before an upcoming brake, but prefer coasting from the moment a brake is announced in the planning area. This leads to a feeling/certainty that the person is still in control (NS Reizigers - Prestatieregie and Innovatie, 2023). This leads to following their own braking curve as 'Their own comfort', separate from the specified braking curve. Coasting is also more in line with energy efficient driving. In addition, NS (Nederlandse Spoorwegen) aims to promote energy-efficient driving practices by actively encouraging coasting. It became clear from the simulation day at Railcenter that, when the behavior of the train driver was investigated, there was often coasting toward braking beforehand. This was about 10 percent braking in speed relative to current speed, for instance coasting from a speed of 140 km/h is a decrease in speed of 15km/h. When the indication curve receded, the traction was unleashed, resulting in the first 15 km/h coasting. Concluded, train drivers indicate that they prefer not to drive outside their personal comfort zone because it can affect safety, passenger comfort and energy efficiency (van der Beek, 2020). Coasting is an important part of their comfort zone for them. Of course, how big that comfort zone actually is depends on the train driver's circumstances. When the train driver is sick but still decides to drive the train, the train driver is more likely to drive at his own comfort rather than follow the permitted curve as tightly as possible.

Train drivers also have their braking curve related to halting. Halting the train also has an impact on braking for comfort. Research shows that braking is done differently at halts compared to non-halts. For example, more traction brake handle actions are required at halts; train drivers have to search for the "perfect" handle position more often to ensure a comfortable ride and come to a stop at the indicated halt location. This means that, because no comfort braking curve can be followed and the train driver has to find it himself, it will also cost time. The search for that perfect handle position is clearly illustrated in figure 22. Here the speed (y-axis) is plotted in relation to the distance (x-axis), the blue line is the train driver's speed and the orange line is the targeted speed. This figure illustrates how the train driver halts from about 11000 meters. From the moment of halting, the train driver performs 3 unnecessary steps, here the inefficient braking and energy waste is well demonstrated. A similar graph also came from the analysis of train driver behavior in the Railcenter.

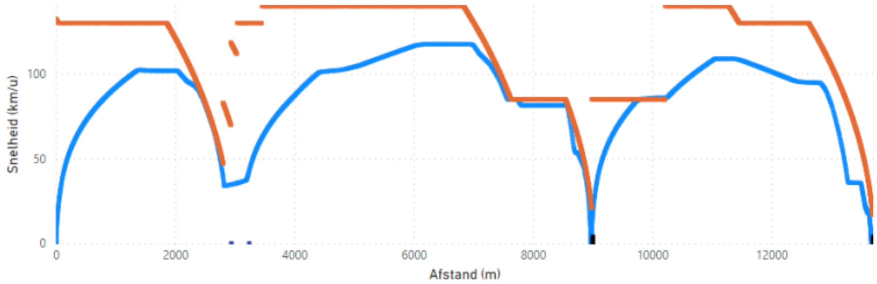


Figure 22: Braking steps to halting (NS Reizigers - Prestatieregie and Innovatie, 2023)

Stopping at the halt location requires frequent shifts of attention between inside and outside the cabin of the train (van den Band et al., 2020). This frequency is higher with a smaller margin relative to the permitted curve. Most train drivers perform stepped braking at halts (Schrik, 2019), which involves first braking at a lower speed (about 40 km/h) and then coasting before applying final braking to come to a stop. So there are different forms how the train is stopped, this is often done using stepped braking. Train drivers find this form of braking a comfortable and convenient way to get to the desired speed. A negative side effect of stepped braking is brake dips, these are illustrated in figure 23.

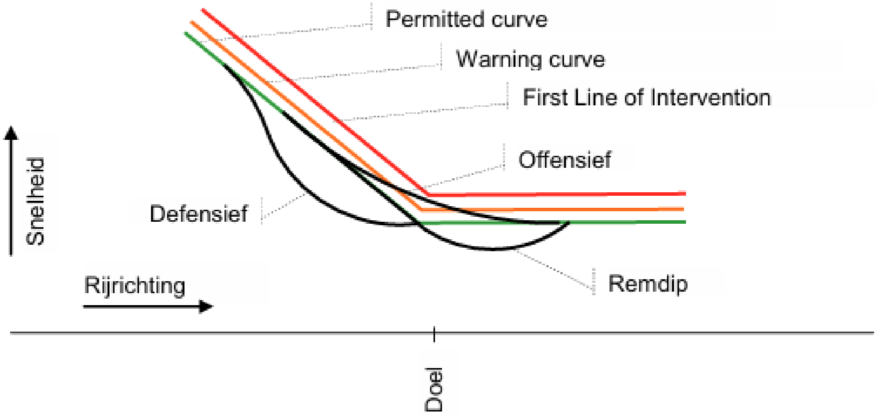


Figure 23: Braking Dip (Prorail, 2014)

The figure shows the different anticipation strategies, but normally the drivers operate on average strategy and this is equivalent to driving with the brake dip (remdip). What can be seen here is that the train driver follows the permitted curve and brakes. The train driver continues braking to slightly beyond what the permitted curve indicates, letting the train coast and then accelerating again. With the brake dip, the train driver gives himself more room to anticipate unexpected situations and reduces the workload by accelerating slowly to the recommended speed. In addition to the brake dip, there is also offensive braking and defensive braking. The offensive braking is constantly insufficient braking, causing the braking curve to cross the warning curve; this results in warning signals of the warning curve. Train drivers indicated that this is undesirable and that the offensive braking form is not used often. There is also the defensive braking strategy, which is used more often. Here the train driver brakes early, based on his own comfort strategy, because the train driver knows that braking is coming. This means braking early, coasting and then accelerating again sufficiently to get to the recommended speed. Research and interviews indicate that defensive braking and the brake dip is a self-created comfort mode for train drivers.

Concluding, train driver braking behavior is influenced by both theoretical and practical conditions. Although comfortable braking is determined by a braking delay of 0.5-0.6 m/s^2 and a jerk of up to 1 m/s^3, the practical experience also shows deviations from the recommended speed. For example, the margins applied and the coasting technique for optimization in the safety and energy efficiency of the train ride. The degree of comfort is a balance between theory and practice. The comfort braking curve should combine the recommended parameters for comfortable braking with the flexibility to anticipate unexpected situations. So what is comfort braking?

Comfort braking is a braking curve that supports the train driver in efficient and well-controlled braking, the comfort braking curve provides an optimal balance between safety, passenger comfort and energy efficiency. The comfort braking curve prevents abrupt speed changes while remaining practical to be applied within operational constraints. The next section presents an investigation of the construction of the original ETCS braking curves. This provides a foundation for filtering essential parameters that are also related to the comfort braking curve and it can be visualized where the comfort braking curve would be integrated.

5 ETCS braking curves, translating to the comfort braking curve

In the literature review, section 2, the standard form of the ETCS brake curves has already been outlined. This section takes a closer look at how these original braking curves (from figure 13) are constructed with respect to ETCS Level 2. The emergency curve is established, and from this curve the other braking curves are approached. The purpose of these other supervision limits is to support the driver to avoid an intervention in the emergency brake intervention by maintaining the speed of the train within the indicated limits of the supervisions. ETCS is a safety system, the system monitors both train position and speed to ensure that trains always stay within the permitted speed and distance limits relative to each other. When necessary, the system intervenes by activating the braking system. This avoids risks and ensures that trains do not exceed the limits. ETCS calculates the braking distance, in real time, based on the braking curve. Braking curves are harmonized and resulted from a clear separation of responsibilities between the infrastructure manager and the railroad undertaking, as required by EU directives. These directives emphasize consistency, predictability and adequate safety margins for train operations.

5.1 ERTMS/ETCS braking curves

Figure 13 presents the braking curves. It is important to know the input parameters of these to form a picture of how the curves are constructed. This way of thinking is necessary in order to eventually make an approximation to the comfort braking curve, based on the construction of the ETCS Level 2 braking curves. There are four main categories of input parameters to feed the ETCS braking curve algorithms and support the real-time monitoring and advisory functions of the ETCS on-board computer:

- Physical parameters, these include instantaneous position, speed and acceleration. These results come from the real time measurements by the ETCS on-board equipment.
- ETCS fixed values, these fixed values are set in the ETCS baseline. They usually involve the ergonomics of the braking curve model itself (for instance driver reaction times).
- ETCS trackside data, this consists of signal data (target speed/locations), infrastructure data (ramps up/down). In addition, it also consists of so-called ETCS national values, which influence the ETCS brake curve model.
- On-board parameters, these parameters are set before the start, this is part of the ETCS train data.

There are required safety standards that the braking curve must meet with respect to infrastructure. The input parameters have an important role in this process. In addition to these input parameters, there are also correction factors. These correction factors ensure accurate brake prediction. The correction factors are discussed in the following sections.

5.1.1 Emergency brake intervention supervision limit

The ETCS system has the responsibility to activate the emergency brake in a timely manner. As a result, the safety of the railroad system depends heavily on the correct operation of this EBD curve, the EBD curve has a crucial role for the safety of a railroad system. To ensure safety, the EBD curve must follow required safety standards defined for the railroad. Once the EBD curve is established, the construction of the other curves can be based from this point. So to do that reasoning properly, it is important to understand how the EBD curve is defined. The EBD curve, is a braking curve that is applied to reduce the speed of the train based on emergency braking. The ETCS system calculates this braking curve based on signal and track characteristics. The EBI is the limit where the ETCS system activates the emergency brake on its own. This without the control of the driver. This functions as a preventive safety measure. Ultimately, the train must brake accurately according to the predicted EBD curve.

The EBD curve is a parabolic curve that predicts train deceleration during emergency braking. This EBD curve depends on two factors, these factors are shown in formula 1. Namely, these are $A_{\text{brake\_safe}}(v)$ and $A_{\text{gradient}}(d)$.

$$A_{\text{safe}}(v, d) = A_{\text{brake\_safe}}(v) + A_{\text{gradient}}(d) \tag{1}$$

First of all $A_{\text{brake\_safe}}(v)$, this variable is affected by the braking force of the emergency braking system. This braking force is represented in a step function, which means that the braking force is constant per speed range. Secondly, there exists the $A_{\text{gradient}}(d)$, this factor demonstrates the influence of gradients in the track on braking deceleration (upward gradients or downward gradients). A gradient affects the speed, when going downhill the train may accelerate extra and when going uphill the train may slow down. Similar to the factor $A_{\text{brake\_safe}}(v)$, the slope is represented by a step function of distance. The combination of the above two factors results in formula 1. Which shows a confluence of interconnected parabolic curves each with a constant deceleration profile for a speed and distance range. This combination of interconnected parabolic curves helps the ETCS system apply the emergency brake (EBD curve) at the right time and in the right way. This curve is shown in figure 24. This figure shows the result of the combination of both factors, namely the braking delay due to the emergency brake combined with the influence of the track. The curve shows how fast the train can decelerate over a given distance, the y-axis here equals speed and the x-axis equals distance. Each parabolic curve shown in the figure represents a speed and distance with a constant braking force. This can be seen when the train travels at a different gradient, resulting in a change in the curve at the point $A_{\text{gradient change}}$ in the graph.

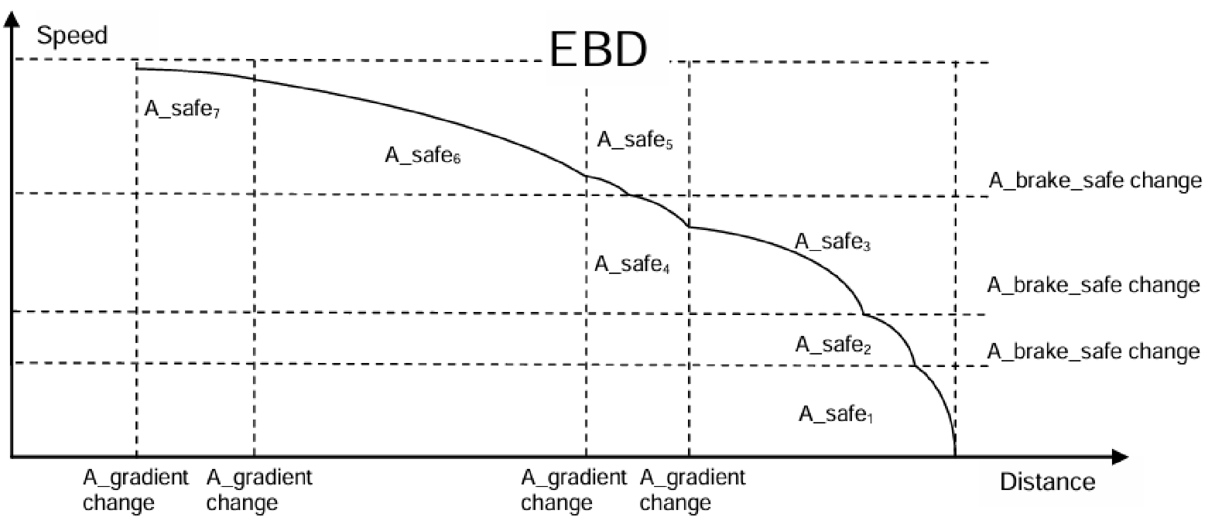


Figure 24: EBD construction (ERA, 2020)

Several countries add safety margins to determine train braking performance. These hidden margins are used to insert additional safety buffers, which can lead to inconsistency. This problem is solved because ETCS has ensured that there are clear reference conditions such as: environmental conditions, track profile, friction elements, wheel wear, all braking systems and driving behavior. Nevertheless, variation in braking performance exists, for example due to weather conditions. In section 2.2.4, correction factors were briefly mentioned. These correction factors are designed to account for the variation in braking performance. The EBD curve must meet the applicable safety standards for the infrastructure on which the trains operate. In the ETCS braking curve model, this is achieved by applying correction factors that optimize the accuracy of the braking curve. The correction factors are:

- $K_{\text{dry\_rst}}$, this correction factor takes into account the variance on dry tracks. It quantifies the confidence that the train is able to brake with a delay at least equal to: $A_{brakeemergency}$ x k_{dry_st}. The value is determined using Monte Carlo analysis combined with a confidence level (N_NVEBCL). This reliability level is set at the national level by the infrastructure manager.
- $K_{\text{wet\_rst}}$, this parameter quantifies the loss in emergency braking performance due to reduced adhesion between wheel and track compared to dry railway conditions. This parameter is determined based on field tests performed to qualify the Wheel Slide Protection (WSP) system, as required by EN15595 standard (EN15595 = 0.893).

As explained above, the main requirement of the ETCS braking curves is to establish the train's emergency braking performance, deceleration profile, and brake application time. Before discussing this further, it is important to understand the distinction between gamma trains and lamda trains. Gamma trains have fixed compositions and a limited number of predefined compositions, with the ETCS system uses these predefined data depending on the train configuration at the start of the journey. Lambda trains have variable compositions, where braking performance is measured by the braked mass percentage. The braked mass percentage is converted via an algorithm to braking performance.

The determination of the emergency braking performance of the gamma train is based on predefined train compositions. With this, all nominal deceleration profiles, the corresponding correction factors and the braking build-up times can be preconfigured in the ETCS system, see figure 25.

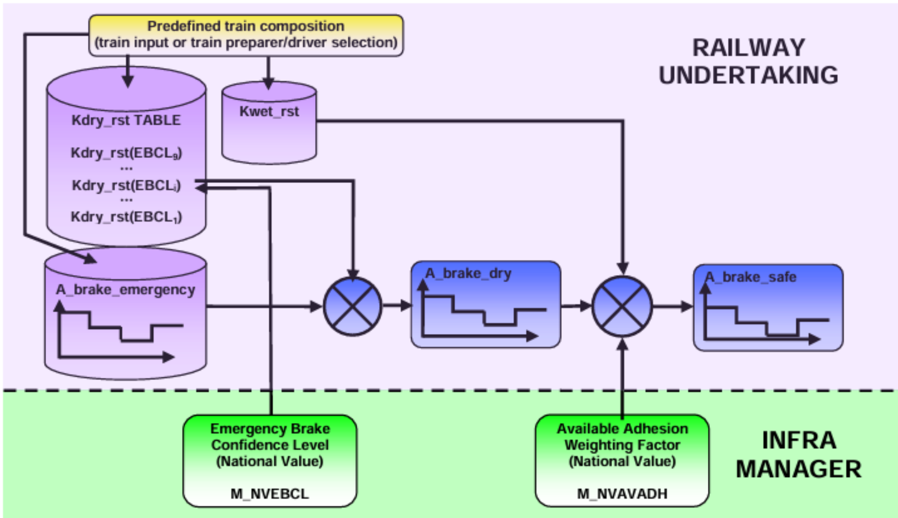


Figure 25: Correction factors for Gamma trains (ERA, 2020)

Below in formula 2 is illustrated how the $A_{\text{brake\_safe}}$ per train was finally determined using figure 25 for gamma trains.

$$A_{\text{brake\_safe}} = A_{\text{brake\_emergency}} \times K_{\text{dry\_rst}}(\text{M\_NVEBCL}) \times (K_{\text{wet\_rst}} + M_{\text{NVAVADH}} \times (1 - K_{\text{wet\_rst}})) \quad (2)$$

For variable composition trains (lambda trains), it is not possible to express braking performance directly or define it in advance from the deceleration data. However, there is an alternative, because even for lambda trains it is important to estimate the emergency braking performance. The alternative is to characterize the braking performance of the train by the percentage of mass braked. This percentage braked mass of the train is calculated by dividing the sum of the braked mass of all vehicles by the total weight of the train. Figure 26 shows a schematic representation.

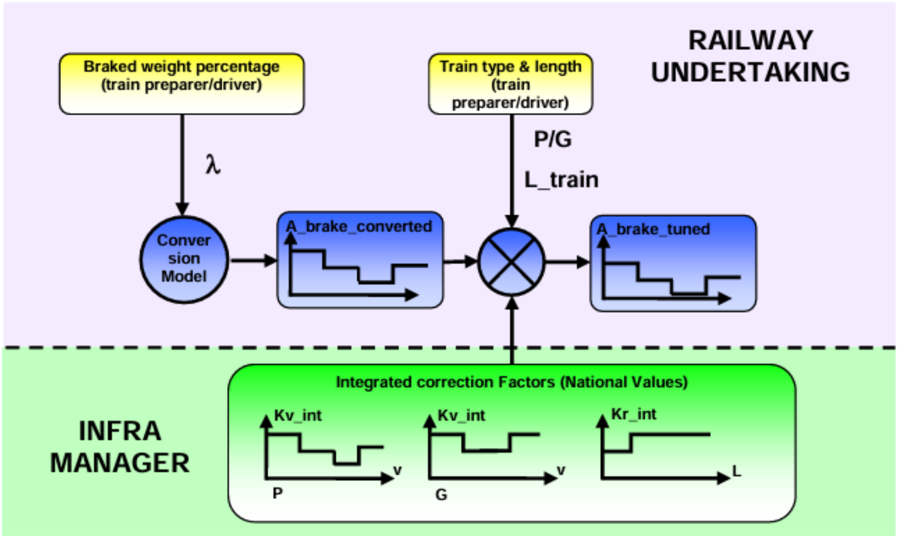


Figure 26: Correction factors for Lambda trains (ERA, 2020)

The resulting deceleration profile and brake build-up time are mathematical approximations with no physical meaning. Nevertheless, they are converted to physical behavior by an algorithm implemented by the UIC (ERA, 2023). There are several integrated correction factors sent by the ETCS trackside. These integrated correction factors are implemented because the driver is not expected to enter explicit correction factors. The correction factors are represented as step functions of speed and train length, which is also shown in figure 26.

The formula below shows the adjusted emergency braking delay in the case of Lambda trains, with the correction factors applied depending on the train length and train type.

$$A_{\text{brake\_tuned}} = A_{\text{brake\_converted}}(\lambda) \times K_{\text{p\_int}}(\text{Train type}) \times K_{\text{r\_int}}(L_{\text{train}}) \tag{3}$$

The tuning factors gives the ability to tweak with the ETCS brake curves. The guaranteed emergency brake deceleration profile is replaced by this tuned deceleration profile. In order to compute the EBD curve, formula 4 is used.

$$A_{\text{safe}}(v, d) = A_{\text{brake\_tuned}}(v) + A_{\text{gradient}}(d) \tag{4}$$

Now that the first approximation of the EBD curve has been established in which the braking force and the influence of the slope have been combined into a theoretical emergency braking curve, a further deepening is possible. Namely, adding real-time conditions, such as corrected speed V_{bec} and the corrected distance D_{bec}. These real-time conditions provide an accurate calculation of emergency braking performance in real-world conditions.

The figure 27 below shows the real-time conditions involved in braking under the EBD curve. Figure 27 shows the supervision limits for braking to a target using the emergency braking curve. The EBD curve demonstrates how the train speed decreases during emergency braking, when to activate the emergency brake depends on the curve. This curve is activated only when the train exceeds the critical speed limits. The figure below often occurs when the train gets close to a Danger point. Think for example close to a switch and when a train is going too fast that may lead to unsafe situations, regarding other trains.

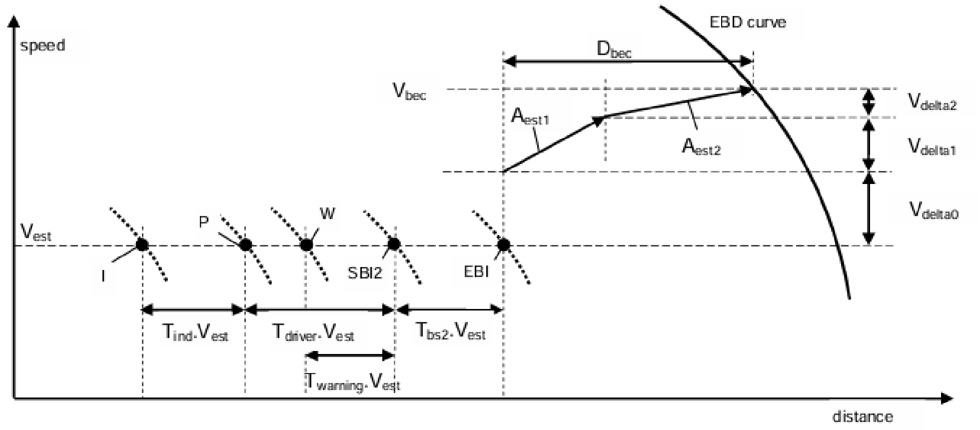


Figure 27: Braking to target supervision limits from EBD curve (ERA, 2020)

The other figure illustrates the supervision limits for braking to a target using the SBD curve. This curve is in place of the emergency braking, the service brake is used to decelerate the train gradually to the EoA. This is a controlled braking with less aggressive actions than the EBD. When the EoA is not close to a danger point, for example, braking to the halting point can be done without too much risk, this in turn also results in more comfortable halting.

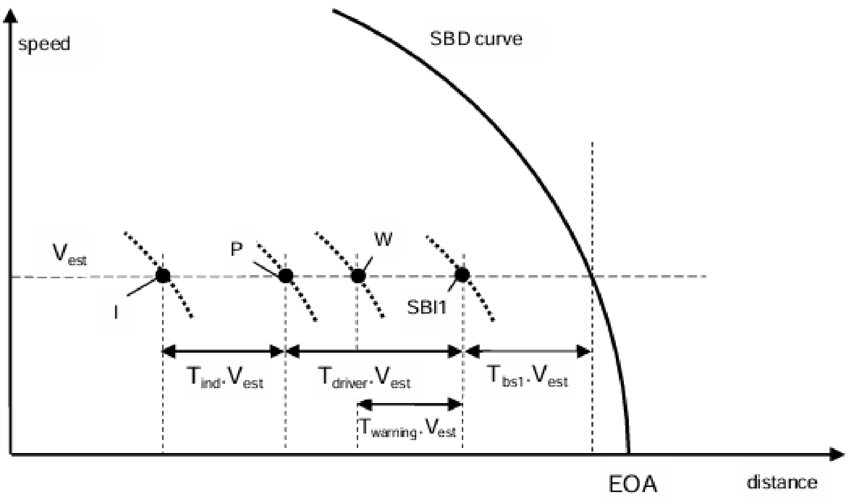


Figure 28: Braking to target supervision limits from SBD curve (ERA, 2020)

First, we look at figure 27. The V_{bec} calculated from the EBD curve there is the corrected speed after the emergency braking is applied. The formula 5 describes how speed and distance are compensated in the time between the emergency braking intervention and the full application of braking force. The corrected speed after emergency braking is calculated by first choosing the maximum value from the sum of the train's estimated speed (V_{est}), the speed uncertainty correction factor (V_{delta0}), the speed increase when traction is active (V_{delta1}), and the V_{target} (also called the target or desired speed). Next, V_{delta2} is added. V_{delta2} is the speed compensation factor used to correct the speed during brake build-up time (T_{berem}).

$$V_{\text{bec}} = \max\left(V_{\text{est}} + V_{\Delta 0} + V_{\Delta 1}, V_{\text{target}}\right) + V_{\Delta 2} \tag{5}$$

In V_{bec}, the variables V_{delta0}, V_{delta1}, and V_{delta2} are addressed, but how are they calculated? In formula 6, V_{delta0} is approximated. The choice here is between whether V_{delta0} equals the uncertainty related to accuracy (V_{ura}), which represents the maximum uncertainty in the measured speed of the train, or whether V_{delta0} equals zero. The latter means that the velocity uncertainties are eliminated, which is often due to national values.

$$V_{\Delta 0} = V_{\text{ura}} \quad \text{or} \quad V_{\Delta 0} = 0 \tag{6}$$

V_{delta1} is calculated from the estimated acceleration during traction time (A_{est1}) multiplied by the time traction is present after emergency braking. This is shown in formula 7.

$$V_{\Delta 1} = A_{\text{est1}} \cdot T_{\text{traction}} \tag{7}$$

In formula 8, V_{delta2} is calculated from the estimated acceleration during the braking time without traction (A_{est2}) multiplied by the remaining time in which traction is not present (T_{berem}).

$$V_{\Delta 2} = A_{\text{est2}} \cdot T_{\text{berem}} \tag{8}$$

Figure 27 shows the D_{bec} is calculated in formula 9 below. D_{bec} is the distance traveled during the time between the emergency braking and full braking. The total distance traveled is divided into two parts in the formula that is applied. Part 1 is the distance traveled during the traction time (T_{traction}), and part 2 is the distance traveled during the time without traction. T_{berem} is the remaining time without traction.

$$D_{\text{bec}} = \max\left(\left(\left(V_{\text{est}} + V_{\Delta 0} + \frac{V_{\Delta 1}}{2}\right) \cdot T_{\text{traction}}\right) + \left(\left(V_{\text{est}} + V_{\Delta 0} + V_{\Delta 1} + \frac{V_{\Delta 2}}{2}\right) \cdot T_{\text{berem}}\right)\right) \tag{9}$$

5.1.2 Service brake intervention supervision limit

It can be seen from figure 27 that after the emergency braking operation follows the boundary of the service braking operation (d_{SBI2}). This is calculated using formula 11. The location of the service brake intervention is calculated for a given speed target, based on the EBD curve. Figure 28 shows that the location of the service intervention is calculated for reaching the EoA (d_{SBI1}). This is calculated using formula 10. From the formulas it can be seen that, these distances are calculated using the current location of the SBD curve (d_{SBD}) or the location of the emergency braking curve (d_{EBI}), minus the estimated speed multiplied by the time intervals during which the train is braking at constant speed before reaching the curves.

$$d_{\text{SBI1}}(V_{\text{est}}) = d_{\text{SBD}}(V_{\text{est}}) - V_{\text{est}} \cdot T_{\text{bs1}} \tag{10}$$

$$d_{\text{SBI2}}(V_{\text{est}}) = d_{\text{EBI}}(V_{\text{est}}) - V_{\text{est}} \cdot T_{\text{bs2}} \tag{11}$$

5.1.3 Warning supervision limit

The service brake limit is followed by the warning limit. This boundary is calculated based on the service braking operation. Based on figure 27 and 28, the warning limit is calculated by calculating the current braking distance, i.e., d_{SBI1} and d_{SBI2}, minus the value where the speed is multiplied by the time the train can remain at speed without braking intervention (T_{warning}, this time is often 2 seconds). Below are the formulas for both situations.

$$d_W(V_{\text{est}}) = d_{\text{SBI1}}(V_{\text{est}}) - V_{\text{est}} \cdot T_{\text{warning}} \tag{12}$$

$$d_W(V_{\text{est}}) = d_{\text{SBI2}}(V_{\text{est}}) - V_{\text{est}} \cdot T_{\text{warning}} \tag{13}$$

5.1.4 Permitted speed supervision limit

The permitted curve follows after the warning curve. This curve is also called the permitted speed limit. The location of the permitted speed limit for the estimated speed for the permitted curve is calculated in the case of EoA (figure 28) by doing the location of the service braking indication minus the driver's reaction time (4 seconds) multiplied by the estimated speed. This is represented in the equation below:

$$d_P(V_{\text{est}}) = d_{\text{SBI1}}(V_{\text{est}}) - V_{\text{est}} \cdot T_{\text{driver}} \tag{14}$$

In the case of a target based on an EBD curve (figure 27), the calculation differs. Here the permitted speed is calculated by choosing the minimum value between the service braking limit, from which the driver's reaction time multiplied by the estimated speed is subtracted, and the target distance (d_{target}). This can be seen in formula 15. This equation prevents late braking and over-speed.

$$d_P(V_{\text{est}}) = \min\left(d_{\text{SBI2}}(V_{\text{est}}) - V_{\text{est}} \cdot T_{\text{driver}}, d_{\text{target}}\right) \tag{15}$$

Formulas 16 and 17 give the allowable speed for the front of the train. formula 16 and formula 17 are both valid when an EoA is known, as shown in Figure 28. Formula 17 shows that $d_{\text{est front}}$ (the location of the front of the train) is added to the current speed, which is multiplied by time (reaction time T_{driver} and time before the service braking curve is reached (T_{bs1})). When the front of the train approaches or crosses the EoA point, it is important to set the allowable speed to 0 because this is where the train must stop. See formula 17.

$$V_P(d_{\text{est front}}) = V_{\text{SBD}}\left(d_{\text{est front}} + V_{\text{est}} \cdot (T_{\text{driver}} + T_{\text{bs1}})\right) \tag{16}$$

$$V_P(d_{\text{est front}}) = 0 \quad \text{if} \quad d_{\text{est front}} + V_{\text{est}} \cdot (T_{\text{driver}} + T_{\text{bs1}}) \geq d_{\text{EOA}} \tag{17}$$

When there is an EBD-based site and the permitted speed must be calculated with respect to the EBD curve (figure 27), the following formulas are important that explicitly establish safety. Formula 18 calculates the maximum allowable speed V_{p}, this is done by comparing two values:

- Value 1: The speed based on the EBD curve, this value is corrected for train location, reaction time, brake application time and distance traveled at brake confirmation. This value is reduced by the speed corrections V_{delta0}, V_{delta1} en V_{delta2}.
- Value 2: The speed goal or target speed V_{target}.

The formula chooses the largest value between the above values as the allowable speed. This ensures safety because the speed cannot be lower than what is safe according to the braking curve.

$$\begin{aligned} V_P(d_{\text{maxsafe front}})_{\text{EBD-Target}} = \max\Bigg(\bigg(V_{\text{EBD}}\Big(&d_{\text{maxsafe front}} + V_{\text{est}} \cdot (T_{\text{driver}} + T_{\text{BS2}}) \\ &+D_{\text{be display}}\Big)\bigg) - (V_{\text{delta0}} + V_{\text{delta1}} + V_{\text{delta2}}), V_{\text{target}}\Bigg) \end{aligned} \tag{18}$$

When the distance from the front of the train corrected by speed, braking and reaction times is greater or equal to the distance given by the EBD curve for V_{target}, the allowed speed is set equal to V_{target}. This can be seen in formula 19 below:

$$V_P(d_{\text{maxsafe front}})_{\text{EBD-Target}} = V_{\text{target}} \quad \text{if} \quad d_{\text{maxsafe front}} + V_{\text{est}} \cdot (T_{\text{driver}} + T_{\text{BS2}}) + D_{\text{be display}} \geq d_{\text{EBD}}(V_{\text{target}}) \tag{19}$$

If the distance from the front of the train, corrected by the estimated speed and driver and brake reaction times, is greater than or equal to the distance according to the EBD curve for the Target or Goal speed V_{target}, then the allowable speed becomes equal to V_{target}. So formula 19 sets the allowable speed equal to V_{target} when the distance correction meets what the EBD curve requirements require.

In summary, formulas 18 and 19 ensure that the train maintains the correct speed with respect to the emergency braking curve and corrects for real-time factors.

5.1.5 Indication supervision limit

The location of the indication limit is calculated by doing the allowed speed limit $d_{\text{p}(V_{\text{est}})}$ minus the estimated speed (V_{est}) multiplied by time (indication time). The indication time is the time during which the driver receives an indication to adjust his speed before reaching the allowed speed. The outline can be seen in formula 20.

$$d_I(V_{\text{est}}) = d_P(V_{\text{est}}) - V_{\text{est}} \cdot T_{\text{indication}} \tag{20}$$

Calculating the indication time is performed in two ways. One way is when the service brake feedback is not available, then formula 21 is applied. In this case, the indication time is adjusted by a safety margin of 0.8 on the reduced service brake time ($T_{\text{bs reduced}}$). Choosing a maximum value of at least 5 seconds ensures that the driver always has enough time to react to the indication.

If service brake feedback does become available, the default time of 5 seconds is used. Outlined in formula 22. This is then added to the driver's reaction time.

$$T_{\text{indication}} = \max\left(0.8 \cdot T_{\text{bs reduced}}, 5\text{s}\right) + T_{\text{driver}} \tag{21}$$

$$T_{\text{indication}} = 5\text{s} + T_{\text{driver}} \tag{22}$$

5.1.6 Release speed supervision limit

In the context of ETCS braking curves, the release speed supervision is a crucial factor to maintain safety when a train approaches the EoA or has to pass a balise. The release speed is defined as the maximum speed that trains can travel safely under a certain speed, even after emergency braking or deceleration events (often 15 km/h).

Two important formulas that are useful here are defined as safe speeds to continue the braking procedure under controlled speeds, are formula 23 and 24. Formula 23 calculates the distance at which an activation has to occur from the service brake. This allows the train to decelerate safely at its release speed. It prevents the train from accelerating too fast or getting too close to the EoA, which leaves not enough time to stop.

$$d_{\text{SBI1}}(V_{\text{release}}) = d_{\text{SBD}}(V_{\text{release}}) - V_{\text{release}} \cdot T_{\text{bs1}} \tag{23}$$

Formula 23 above specifies what is the distance where the service brake should be activated (d_{SBI1}). By calculating the distance of the SBD curve (d_{SBD}) for the release speed, minus the distance traveled by the train with respect to the release speed (V_{release}) multiplied by the time delay (T_{bs1}).

Formula 24 below calculates the distance of emergency braking at release speed, if the service brake is proven to be insufficient and speed uncertainties and time for emergency brake activation are included. The formula states that the emergency brake activation distance is determined by the distance of the EBD curve (d_{EBD}) for the release speed minus the speed. With the speed compensation factor taken into account (V_{delta0rs}) during the time the brakes are activated (T_{berem}) and the time the traction is disengaged (T_{traction}). This causes the train to stop in time before the situation becomes critical.

$$d_{EBI}(V_{\text{release}})_{\text{Target}} = [d_{EBD}(V_{\text{release}} + V_{\text{delta0rs}})]_{\text{Target}} - (V_{\text{release}} + V_{\text{delta0rs}}) \cdot (T_{\text{berem}} + T_{\text{traction}}) \tag{24}$$

So there are safety braking curves, think of the emergency braking curve, which are deployed in emergency situations and ensure safe deceleration of the train even when conditions are disadvantageous. This takes into account various factors such as the build-up time of braking force and the possible uncertainties of speed. These braking curves are a solid safety net and provide safety assurance.

On the other hand, there are advisory braking curves, consider the permitted curve, these braking curves provide real-time support and guidance. However, the permitted curve is so sharp and steep that it is much like the emergency braking curve. This is because from the Emergency braking curve, the other braking curves are structured. Thus, the safety net of the permitted braking curves is designed based on the safety net of the emergency braking curve and is placed pretty much on the edge. Nevertheless, the safety net of the permitted curve allows train drivers to drive within the safe limits of the system. The focus of this research is to make this particular safety net softer and positioned earlier, in line with how train drivers generally act. The permitted curve is modified to promote smoother speed adjustments, but still remains compatible with the philosophy what has been described in this section. In the next section 5.2, the knowledge gained from the previous chapters is gathered into a visualization of the comfort braking curve, bringing together the theoretical and practical insights.

5.2 Translating to comfort braking curve

In chapter 5.1, the original ETCS braking curves are detailed. In this section, those braking curves are translated into the comfort braking curve. This involves consideration of what needs to be adjusted under the existing ETCS braking curves to stay within the comfort level. With the knowledge so far, it is important to consider:

- Braking deceleration adjustments, section 4.1
- Minimizing the Jerk, section 4.1
- Adapted anticipation strategies, section 4.2, regarding the indicated discomfort of the train driver in section 3.2.
- Adjusted speed margins, section 4.2
- Taking into account the main variables in the applied calculations of the ETCS Level 2 braking curves, namely: braking forces, speeds, distance and target distance. Presented in section 5.1

The above information is applied to the design of the comfort braking curve. Using the ERA Braking curve Tool, the comfort braking curve is visualized with the specific characteristics implemented. The comfort braking curve can be seen in figure 29 (c-curve). The proposed comfort braking curve has its specific characteristics compared to the other existing ETCS curves. Figure 29 shows the proposed comfort braking curve compared to the original braking curves. In the first perspective, it can be seen that the comfort braking curve is below the permitted curve. The comfort braking curve is close to the indication curve and even exceeds the indication curve until the comfort baking curve reaches the permitted curve in the end point. On what acquired knowledge is this comfort braking curve based and what are its specific characteristics? This is explained in the remaining part of this section.

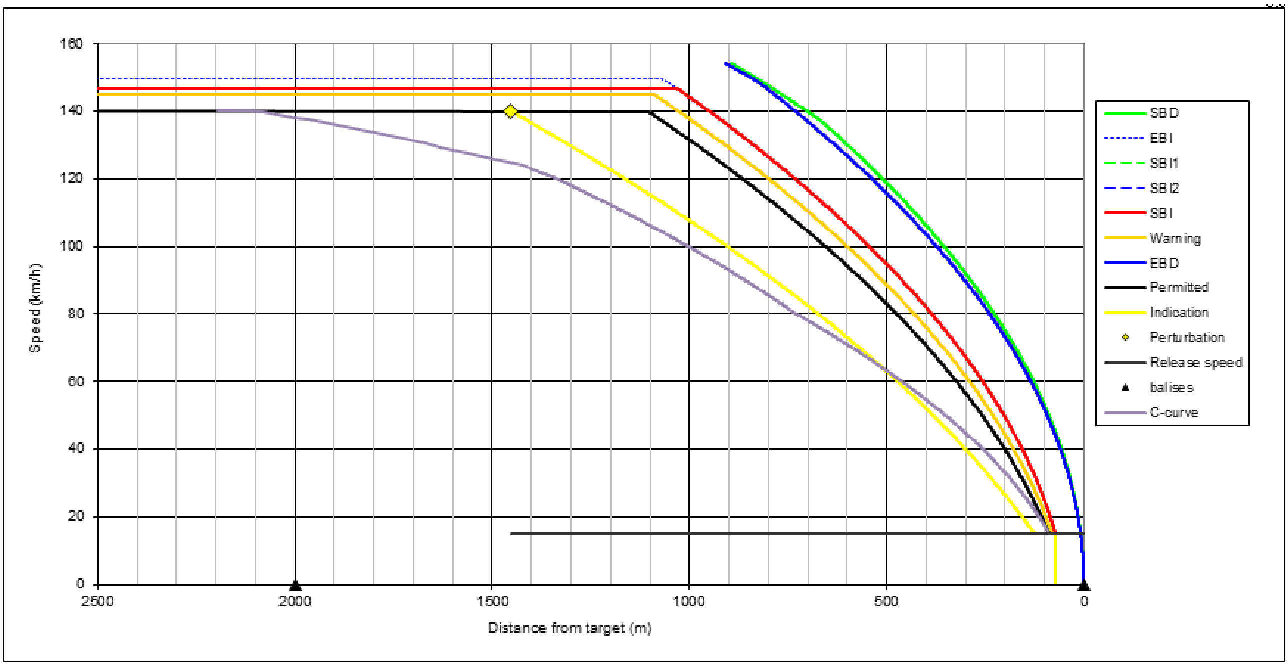


Figure 29: ERA braking curves, comfort braking curve

It was explained earlier in chapter 5 that ETCS Level 2 braking curves are built from the EBD. The variables and formulas from chapter 5 are important to visualize a reasoning and placement of the comfort braking curve. The comfort braking curve is derived from the permitted curve. From the calculations of the permitted curve explained, there are several variables that are important to the comfort braking curve. First, V_{est}, or actual speed. This variable is important for determining the braking distance and when and how the train should decelerate. This deceleration should occur in a consistent and smooth manner, without abrupt changes. For this reason, the V_{est} will also be temperate in the comfort braking curve. Another variable is T_{driver}, which is essential because it is, precisely in the comfort braking curve, that train driver perception must be taken into account. These reaction times take into account additional buffers that the train driver would also normally adopt to escape stressful situations. In reality brakes are applied earlier in order to depend less on the original reaction time and leave space for unexpected situations. The comfort braking curve adjusts to this. Another variable is the D_{p}, permitted distance. This variable is the upper limit of the permitted curve that indicates the limit within which the train can safely travel. The comfort braking curve could be either ahead or behind this limit. This depends on the start of braking, jerk and braking deceleration when they are applied. However, a hypothesis can already be formed: namely, additional margin must be built in for the train driver to ensure a smooth transition. Most likely, the comfort braking curve would be below or on the permitted curve.

Knowing from which reasoning the comfort braking curve is based, it is important now to address the specific characteristics of the braking curve visualized in figure 29.

First of all, it can be observed that braking is started earlier. The comfort braking curve is initiated by a deceleration of 0.01 m/s^2 to 0.25 m/s^2. This is included based on findings that train drivers prefer to let the train roll out (coasting, a technique explained in section 3.1) before a braking moment, rather than still accelerating as soon as they know braking is coming. This behavior is integrated into the comfort braking curve. Depending on rolling resistance and aerodynamic drag, some additional braking must be applied at the initial braking deceleration to achieve a comfortable jerk, later in the braking process, and moving into constant and comfortable braking deceleration. This involves maintaining a constant braking deceleration until the end point of the train. After coasting follows the second part of the comfort braking curve. This braking deceleration starts from the moment the braking deceleration of 0.5 m/s^2 is applied. It was previously determined that the comfortable deceleration can be between 0.5 m/s^2 and 0.6 m/s^2, but for the approximation of the first comfort braking curve, we first considered 0.5 m/s^2. The constant braking deceleration of 0.5 m/s^2 gives train drivers more predictability and control during braking. The braking curve has a continuous decrease in speed, making the braking process gradual and comfortable. This characteristic is consistent with the natural behavior of train drivers discussed earlier. In line with ETCS Level 2 requirements, the steady decrease in braking deceleration prevents abrupt shocks and abrupt changes in speed.

In the figure 30 below, the visualized comfort braking curve has been filtered out from figure 29 which shows the original ETCS braking curves. Here the comfort braking curve is expressed by itself and from here it is easier to derive the jerk values.

Figure 30: ERA braking curves, comfort braking curve

There are 2 points on the comfort braking curve that indicate some form of abruption in figure 30. Circled as point 1 and point 2. In point 1 is when the deceleration is initiated and point 2 is when the coast braking is completed and switches to a higher braking deceleration. These switching of braking decelerations must meet the standard to maintain the degree of comfort.

At the first circled point 1, the train enters from its original speed and proceeds to coasting movement with a braking deceleration of 0.1 m/s^2, gradually increasing to 0.2 m/s^2. The realization of the braking is associated with a jerk value of 0.201045809 m/s^3. When looking at the jerk standard (figure 21), this value does not appear to cause any possibility of discomfort to passengers and train drivers. And could even increase to 1 m/s^3, the established comfortable jerk for this research.

In the second circled point 2, the second part of the braking is initiated, whereby a braking deceleration of 0.2 m/s^2 is switched to 0.5 m/s^2. The switch in lever position results in a jerk of 0.248614981 m/s^3. Looking at the standard in figure 21, this jerk also has no consequence for reduced comfort and could even increase to 1 m/s^3 as well.

In addition to the established comfort braking curve in figure 29, it is also important to define the range within which comfortable braking can be achieved. Earlier in this research, it was determined that comfortable braking occurs at a deceleration between 0.5 and 0.6 m/s^2. For the range of comfortable braking, the comfort braking curve is the lower limit and a constant deceleration of 0.6 m/s^2 is the upper limit, in compliance with current safety regulations. This results in an area within which comfortable braking is possible, as shown in figure 31. This results in a bandwidth between which the train driver can ride comfortably.

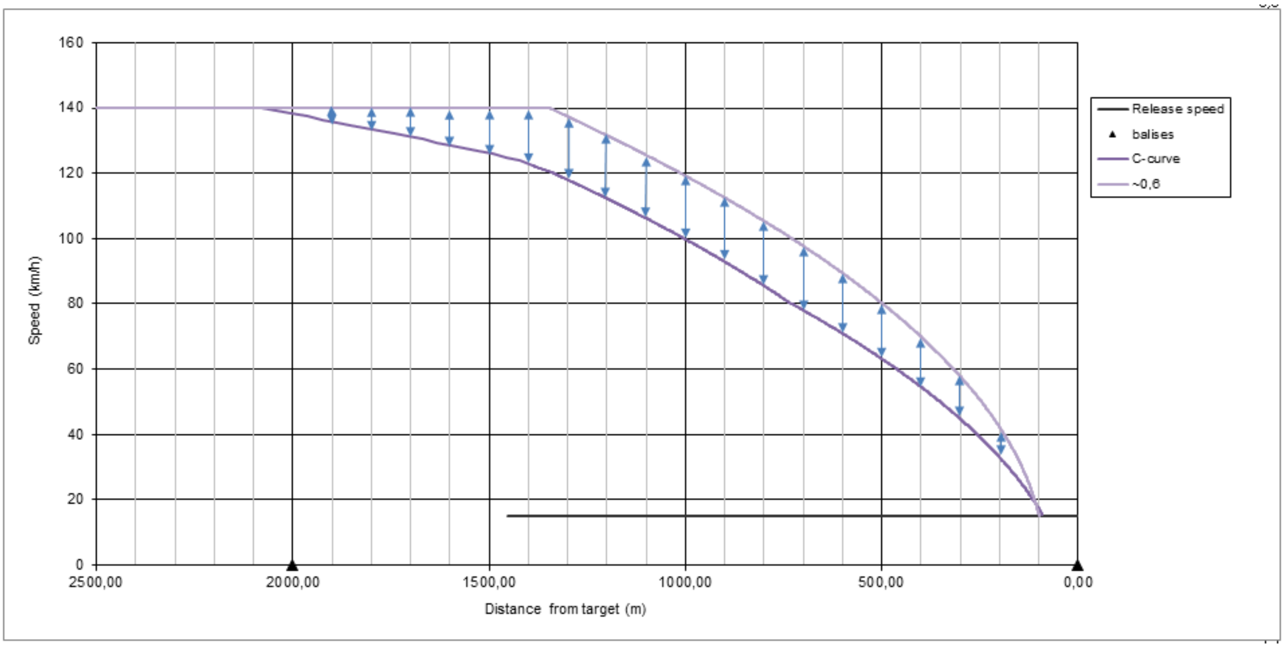


Figure 31: Bandwidth of comfortable deceleration

In chapter 3.1 different driving strategies like defensive and offensive driving were already addressed, an offensive variant is also defined for comfort driving which is discussed in appendix E, but which is not relevant to this research. In this research, the comfort braking curve is defined in its ideal form as illustrated in figure 30.

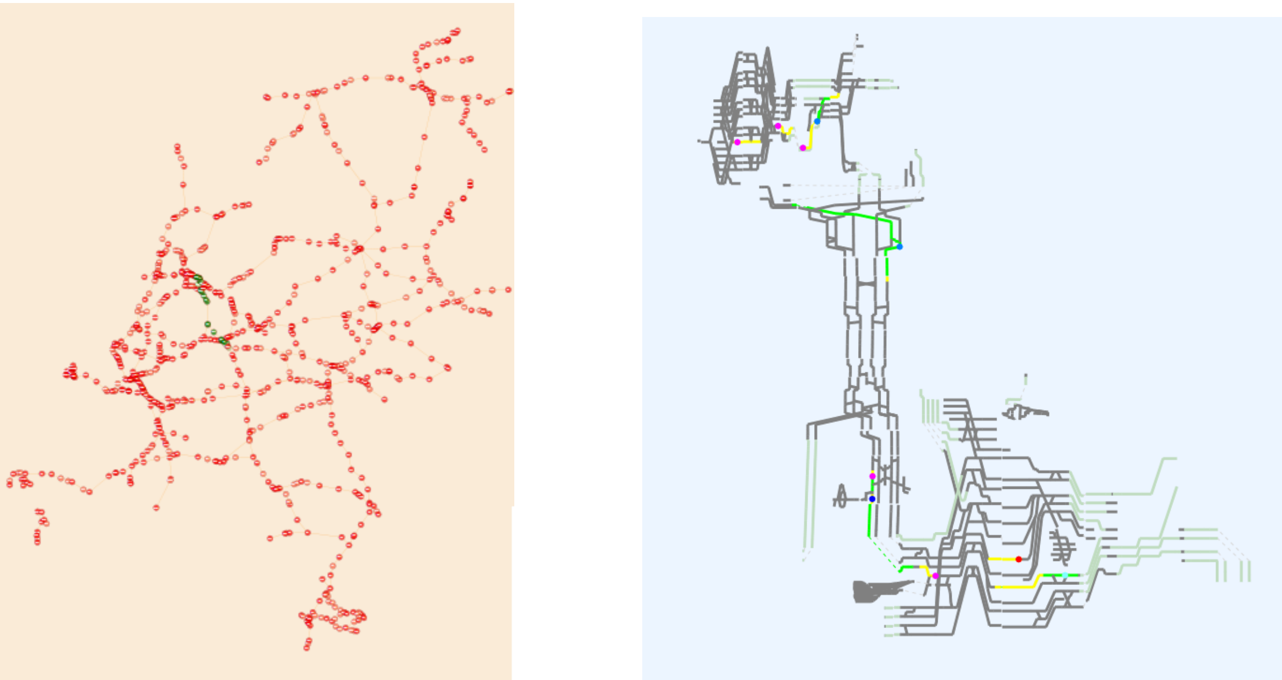
In conclusion; apart from the indicated range of comfort braking and the offensive form of the comfort braking curve, the focus is on the comfort braking curve from figure 29. This comfort brake curve is visualized from the knowledge gained from the different chapters and is implemented in the simulation. The comfort brake curve achieves a reduction in workload and usability from the perspective of train drivers. The comfort braking curve provides, with the established properties, a predictable profile that is consistent with the natural driving style of train drivers. The comfort braking curve remains within the safety margins of the safety braking curves and the advisory braking curves, therefore the integration of the comfort braking curve is without any degradation in safety. In the following of this research, the comfort braking curve will be implemented and tested in the simulation FRISO. FRISO fits seamlessly with the requirements of this research, this is particularly related to the possibility of implementing and editing train driver behavior. Simulation research, including the rationale for its selection and consideration of alternative simulations, is described in Appendix B.

6 Model construction

In this chapter, the assessment described in appendix C is implemented in the simulation FRISO. First the model setup is outlined, how is the scope implemented in this simulation and how is it visualized. Next, the boundaries are shown, these will be the braking curves that are important in this research and that the train drivers will follow in the simulation. One of the boundaries is the comfort braking curve from figure 30. In addition, the conditions of the simulation are specified; these are the National values and Fixed values. Following this, the results will be outlined that identify what the impact of the implementation of the comfort braking curve has in reality (or also known as the implications), measured by the palpability test, usability test and the capacity test.

6.1 Model setup

In section 1.6 the scope was already explained. This has been mimicked in the simulation. The figure below shows the map of the Netherlands, but in train stations. In the figure you can see that the route between Amsterdam Central Station and Utrecht Central Station is selected, these are the green dots in figure 32a. The timetable is filtered with regard to this route.



(a) (b)

Figure 32: Model setup

The route that is tested is represented thus as the green dots in the figure, the red dots represent the remaining stations that are not included in the simulation (as seen in figure 32a). The VIRM and SNG are specifically tested on the comfort braking curve. The filtered timetable on this route will run on ETCS Level 2 and the timetable outside this route is removed from the simulation. Figure 32b shows the visualization of the route from the simulation, the trains are shown as colored dots.

The model setup also includes specific national values and fixed values, these values are shown in table 4.

National values	Value
Correction factor Passengers (Kv_int <= 160 km/u)	0.90
Correction factor Passengers (Kv_int > 160 km/u)	0.76
Correction factor Goods (Kv_int <= 160 km/u)	0.90
Correction factor Goods (Kv_int > 160 km/u)	0.76
Release Snelheid (km/u)	15
Wheel/track adhesion factor	1.00
Maximum decelerations under reduced adhesion (Passengers)	1.0
Maximum decelerations under reduced adhesion (Goods in P)	0.7
Maximum decelerations under reduced adhesion (Goods in G)	0.7

Fixed values	Value
Train driver response time (s)	4
Warning time (s)	2

Table 4: Overview of national values and fixed values in two tables

The table above includes correction factors and values related to adhesion in the model. These National values are taken from the ERA braking curves tool. The other table shows the fixed values. It is shown from section 5 that the average reaction time of train drivers is 4 seconds and the time to warn the train driver is 2 seconds. All these values, from both tables, were included in the running of the simulation.

6.2 Model boundaries

Two different braking curves, or also called the model boundaries, were established in the simulations. These braking curves consist of specific parameters established earlier in this research by researching what the literature and practice say about comfort. One of the braking curves represent the current behavior of the train driver in the braking curve, or also called 'train driver behavior'. The braking curve regarding to the train driver behavior, is based on the characteristics how the train driver would normally drive in practice under the permitted curve. The other braking curve represents the extra additions indicating the comfort braking curve, which is visualized and explained in section 5.2 (focused on a deceleration of 0.5 m/s^2). The comfort braking curve has the same characteristics as the train driver behavior, but it includes some additional characteristics or other translations that train drivers generally consider comfortable that define the comfort braking curve. This includes, for example, coasting toward braking and the average margin of 4 seconds below the permitted speed. In addition, other factors are also built into or eliminated from the comfort braking curve that are explained further in this section. This section explains and compares the two braking curves with respect to the VIRM train and the SNG train. The timetable will integrate the train driver behavior curve, while the comfort braking curve will be implemented for the VIRM train and SNG train.

6.2.1 Train driver behavior curve & comfort braking curve

For both the VIRM and SNG, the train driver behavior curve and comfort braking curve are implemented. The same characteristics are taken into account for each rolling stock type, the only thing taken into account is that the SNG train has stronger braking power and therefore less coasting time. Below the braking curves are explained how they are implemented in the simulation and what are de adjusted parameters in the simulation.

Braking curve, train driver behavior

First, the braking curve is defined with respect to train driver behavior. Here the original train driver behavior is simulated how the train driver would drive when the permitted curve is followed. The parameters included in this braking curve were observed from results of this research. A time margin of four seconds is built into this braking curve compared to the ERTMS curve. In addition to this, the braking curve is characterized that the braking deceleration is between 0.0 and 0.5 m/s^2, with the maximum speed limited to 140 km/h. The braking deceleration is set from 0.0 m/s^2, because interviews with train drivers revealed that train drivers prefer to drive on a smooth braking curve without abrupt jerk values. This bandwidth allows the curve to break down consistently.

The target speed is calculated based on the planning time, where a deviation from the planning time is acceptable up to 3 seconds before and after the planning time. The option is enabled that train drivers have the possibility to 'Start braking earlier' than indicated, this characterizes the train driver behavior to brake early and gradually. The braking that the train driver makes is being averaged, this means that the train driver is braking with minimum force as necessary so that it is sufficient to achieve the recommended speed. In other words, technically minimal braking is used. As noted earlier, the train driver also uses 'brake dips' (explained in section 4.2), this is also implemented in this braking curve when approaching an EoA.

Comfort braking curve
The comfort braking curve corresponds in settings to the train driver behavior curve, yet there are some changes and additions highlighted here. The comfort braking curve also assumes constant and simultaneous deceleration. And is separate from the ERTMS curve, the already previously discussed safety net is softened here. Therefore, the built-in time margin of 4 seconds is omitted. Because with the comfort braking curve, it is assumed that it is easy to follow 1 to 1 because of this braking curve is smooth and easy to follow with constant braking delay.So the 4 second margin here is unnecessary. The comfort braking curve does not depend on the other ETCS curves. The maximum speed here is also limited to 140 km/h. The option 'Start braking earlier' is defined differently in the comfort braking curve, namely as coasting. Before starting braking with a braking delay of 0.5 m/s^2, the first 15 km/h will be coasted. This is also outlined in figure 30 section 5.2. Coasting is based on the planing time, the distance at which the train starts coasting depends on the type of train itself. But a coast delay of 10 percent is assumed against current train speed. Added to this, the braking dip is eliminated, the braking dip does not occur because step braking is not used in a comfortable situation (which is illustrated in figure 22).

So, there are two types of braking curves defined in the simulation modeled as model boundaries, the train driver behavior curve and the comfort braking curve, with respect to the two trains defined in the scope (VIRM and SNG). The simulation is performed with these boundaries. The comfort braking curve is tested by comparing the effects of driving under these two braking curves. The results follow from the three tests mentioned in the method and described in detail in Appendix C, namely: The Palpability test, The Usability test and The Capacity test. In section 6.3 only the results are compared against each other, an analysis on this and what the effects are is outlined in section 7.

6.3 Model Results

6.3.1 Capacity test

In this section the capacity test is performed, the Appendix D shows the timetable for both VIRM and SNG under the train driver behavior curve and the comfort braking curve on the route between Amsterdam Central and Utrecht Central This illustrates how the trains perform under the specific conditions. The timetable for each train is divided into different shifts on the same route, for example, the VIRM and SNG occur in different shifts of (A, B, C, D, F, G, H, I, L) and each shift is divided over 10 hours. The tables are shown based on shift D, this is a shift in the middle of the timetable which allows the incorporation of the comfort braking curve to be checked optimally. First, the simulation results of the VIRM will be explained, followed by the presentation of the simulation results of the SNG.

First, tables 10, 11 and 12 regarding the VIRM and the implemented train driver behavior curve are highlighted here. What this shows is that the timetable is achievable when the standard train driver behavior is implemented. In general, the train enters the station on time except for a few moments, namely the 4th, 8th, 9th and 10th hour. This is due to the fact that there is another VIRM train on the same route in a different shift, shift L. Shift L is earlier than it should be on some moments in the timetable, so shift D has to wait for it. One solution to this is a simple displacement of shift L in the timetable. In general, following the behavior of the train driver in a timetable leads to a time gain of up to 92 seconds. The interesting part now is to see what the schedule looks like when the comfort braking curve is applied for the VIRM compared to the train driver behavior; for this, we look to the Appendix D tables 13, 14 and 15. What the timetables show is that no delays occur when the comfort braking curve is implemented, only in the previously specific hours are delays here as well. Shift L is also earlier on parts of the route, shift D has to wait for this. Because the VIRM uses the comfort braking curve in its entirety, so also shift L, the delay increases slightly. This is because the train is still earlier on the spots but the braking takes longer. So shift D has to wait slightly longer, compared to the timetabling of the train driver behavior curve, until the VIRM of shift L is gone. Nevertheless, this delay with respect to the comfort braking curve of the VIRM is not much larger comparing to the train driver behavior curve, at most 229 seconds or also known as 3 min and 48 seconds. Apart from this, it is important to note that the comfort braking curve generally achieves the timetable with respect to the VIRM and the timetable maintains robustness because the VIRM is still even earlier at most points in the timetable. The time gain relative to the train driver behavior curve decreased slightly to a maximum of 88 seconds compared to the original timetable, this change in time gains is mainly in the end of the timetable/route. Because the braking from the comfort braking curve is initiated earlier, resulting in slightly reduced time gains later in the timetable compared to the train driver behavior curve. Therefore, the rest of the time gain is the same as the train driver behavior curve.

Second, the SNG timetable, tables 16 to 18 show the standard train driver behavior curve. Here it can be seen that in every hour the original timetable can be met, only at some points it is driven exactly on the timetable and thus there is no slack. For example in Maarssen (MAS) the second hour with exactly 0 delay or time gain. The time gain when driving under the train driver behavior is up to 57 seconds. From the moment the comfort braking curve is applied in tables 19 to 21 in Appendix D, there is remarkably little difference. The time gain decreases slightly but not much, the reduced time gain is now 38 seconds compared to the SNG with the driver behavior curve. In the places where time gain occurred during the train driver behavior curve, there is still time gain now. A little more time gain is taken away because braking occurs earlier in the comfort braking curve, but these differences are small. The reason why the time gains have decreased so little is further highlighted in this section when looking at the speed-way diagram in the usability test, figure 39. But first the palpability test is elaborated below.

6.3.2 Palpability test

The palpability test is presented below. In the tables below, the braking distances of the implemented braking curves are clearly presented. For the train driver behavior curve in tables 5 and 7, the columns are divided into where the braking curve is felt; or also called 'Where in the route' and what the total braking distance is. The comfort braking curve is divided into two parts - coasting and comfort braking (approximately -0.5 m/s^2) - therefore tables 6 and 8 are split into these two columns as well. The other columns in the tables indicate after how many meters the braking is felt 'Where in the route' and what the total braking distance actually is.

First, the palpability test for the VIRM: during the train driver behavior curve, the VIRM starts braking after 27780 meters and this braking process has a total braking distance of 1507 meters. The comfort braking curve related to the VIRM, starts the braking process earlier, namely after 25187.5 meters coasting is initiated. As a result, the comfort braking curve is felt 2592.5 meters earlier. The total braking distance of the comfort braking curve is 4099.5 meters. This results in a shorter braking phase in a higher braking deceleration of 345 meters. This is explained by the coasting part, which is part of the overall braking process.

VIRM, Train driver behavior	
Where in the route (m)	**Total braking distance (m)**
27780 - 29287	1507

Table 5: Train driver behavior VIRM

VIRM, Comfort braking curve			
Where in the route (m)	**Coasting (m)**	**Comfort deceleration (m)**	**Total braking distance (m)**
25187.5 - 29287	2937.5	1162	4099.5

Table 6: Comfort braking curve VIRM

The SNG has several braking processes in its route, below these braking processes are explained under the different braking curves in the tables 7 en 8:

- Braking process 1: The train driver behavior curve is deployed after 3600 meters of driving, with a total braking distance of 1500 meters (shown in table 7). Compared to the comfort braking curve, this braking is deployed after just 2500 meters, resulting in braking being felt 1100 meters earlier. The comfort braking curve includes 700 meters of coasting, resulting in a longer braking distance of 2600 meters (shown in table 8).
- Braking process 2: In this braking process, the train driver behavior curve starts braking after 8820 meters, with a total braking distance of 1440 meters. The comfort braking curve is felt earlier at a distance of 7950 meters, which is 870 meters earlier. The comfort braking curve has a total braking distance of 2310 meters.
- Braking process 3: This braking process starts with the train driver behavior curve after 11380 meters and has a total braking distance of 1089 meters. Compared to the comfort braking curve, the braking process is initiated after 11300 meters, which means that braking is felt 80 meters earlier. The total braking distance of this braking process is 1169 meters.
- Braking process 4: Under the train driver behavior curve, the braking process begins at 13245 meters with a total braking distance of 765 meters. Under the comfort braking curve, braking occurs after 12875.5 meters, therefore the comfort braking curve is felt 369.5 meters earlier. The total braking distance of the comfort braking curve is 1124.5 meters.

SNG, Train driver behavior	
Where in the route (m)	**Total braking distance (m)**
3600 - 5100	1500
8820 - 10260	1440
11380 - 12469	1089
13235 - 14000	765

Table 7: Train driver behavior SNG

SNG, Comfort braking curve			
Where in the route (m)	**Coasting (m)**	**Comfort deceleration (m)**	**Total braking distance (m)**
2500 - 5100	700	1900	2600
7950 - 10260	737.5	1572.5	2310
11300 - 12469	860	309	1169
12875.5 - 14000	674.5	450	1124.5

Table 8: Comfort braking curve SNG

A visualization of these braking curves are presented in the usability test, here the braking distances from the palpability test can be used to see at which speeds the braking curves are deployed and how that relates to the other stops in the route.

6.3.3 Usability test

Here the usability test is performed, first the results of the train driver behavior curve of the VIRM will be highlighted and the results of the comfort braking curve of the VIRM will be compared with it. Next, exactly the same is done for the SNG.

VIRM, train driver behavior curve

First of all, figure 33 shows the speed-way diagram related to the VIRM and its train driver behavior curve. At the end of this diagram, the train driver behavior curve is visualized with a standard braking delay of 0.5 m/s^2. The dark blue line is the braking curve/current speed and the light blue line represents the target speed. The yellow line represents the acceleration and is logically positive at the beginning, when accelerating to 140km/h. At Abcoude station (AC), there is a slope which causes some acceleration this can also be seen in the graph. After the slope the braking takes place and it can be observed that the constant deceleration is applied of 0.5

m/s^2. For this train driver behavior curve, the properties specified in section 6.2 are included.

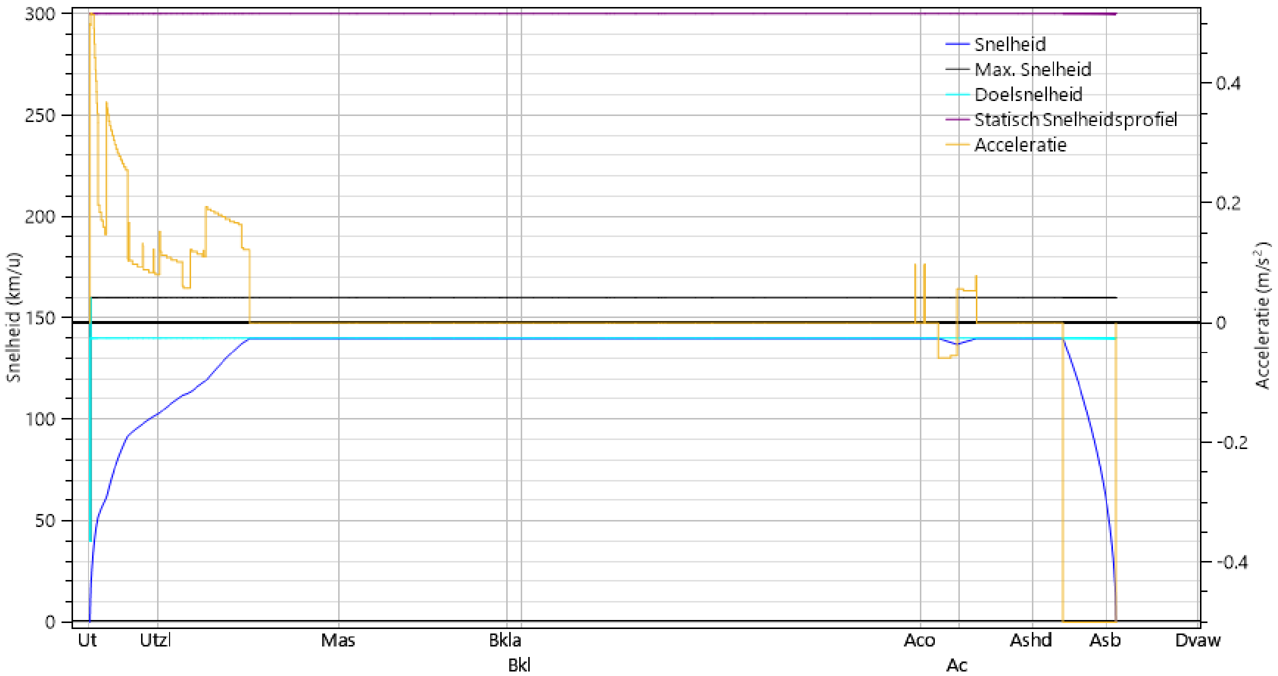


Figure 33: VIRM speed-way diagram, train driver behavior curve

Figure 34 below shows the energy consumption (kWh, black line) and power (kW, blue line) with respect to the VIRM and the train driver behavior curve. First of all, the energy consumption increases throughout the route to 372.37 kWh per trip. From the moment of constant driving at 140 km/h, the energy consumption does not increase much. Where energy consumption does increase is logically, especially at the moments of acceleration and deployment of acceleration at Abcoude. With respect to power, there are 3 major peaks. The first peak extends from Utrecht Central Station (Ut) to Maarssen (MAS) and has a power of 3480.490 to 3415 kW. The second peak gives a value of 3120.25 kW and does not extend far along the route. The third peak is surrounding Abcoude station and has a value of 3403.74 kW.

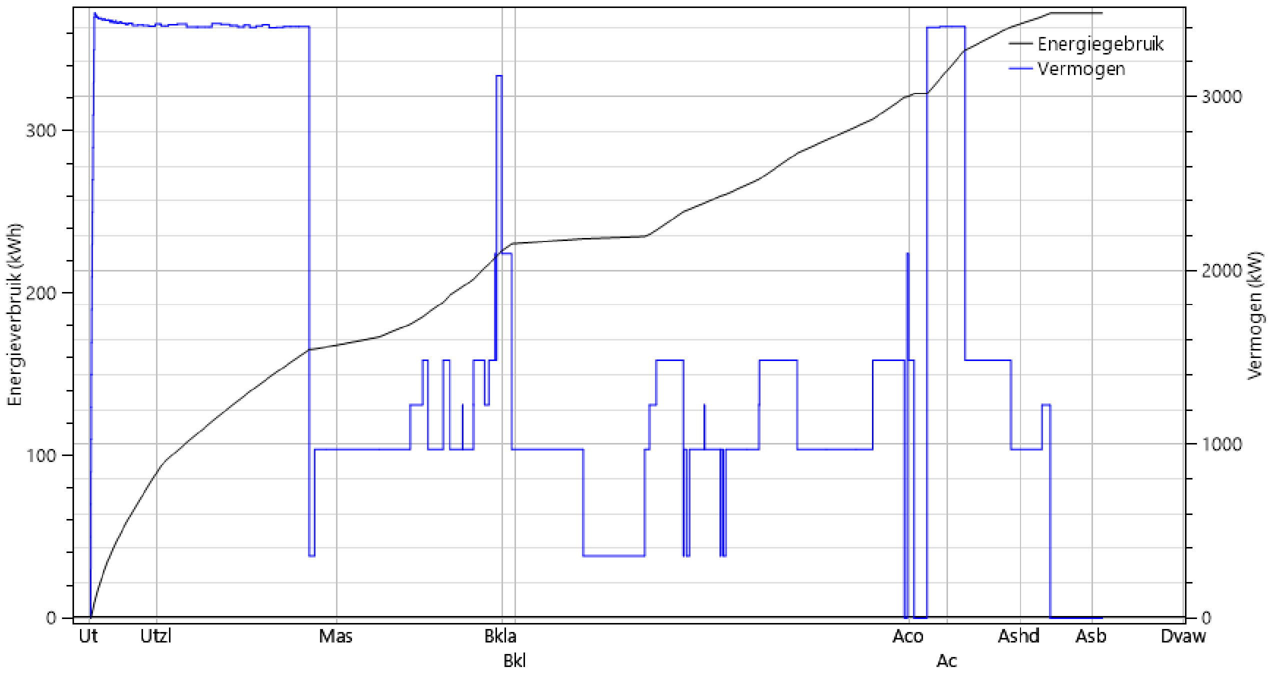


Figure 34: VIRM energy consumption diagram, train driver behavior

VIRM, comfort braking curve

The figure 35 below shows a visualization of the comfort braking curve in the speed-way diagram. As can be seen, this braking curve is similar to the comfort braking curve illustrated earlier in this research (figure 30). From the point of departure, acceleration increases until the target speed of 140 km/h is reached, after Abcoude the coasting is initiated and rolls out 15 km/h (10% of the current speed). The coasting is deployed with a braking deceleration around 0.08 to 0.1 m/s^2 which is shown in figure 35. After this, the coasting is converted to a comfort braking deceleration of 0.5 m/s^2 which can also be seen in the speed-way diagram. For the comfort braking curve, the properties specified in section 6.2 are included.

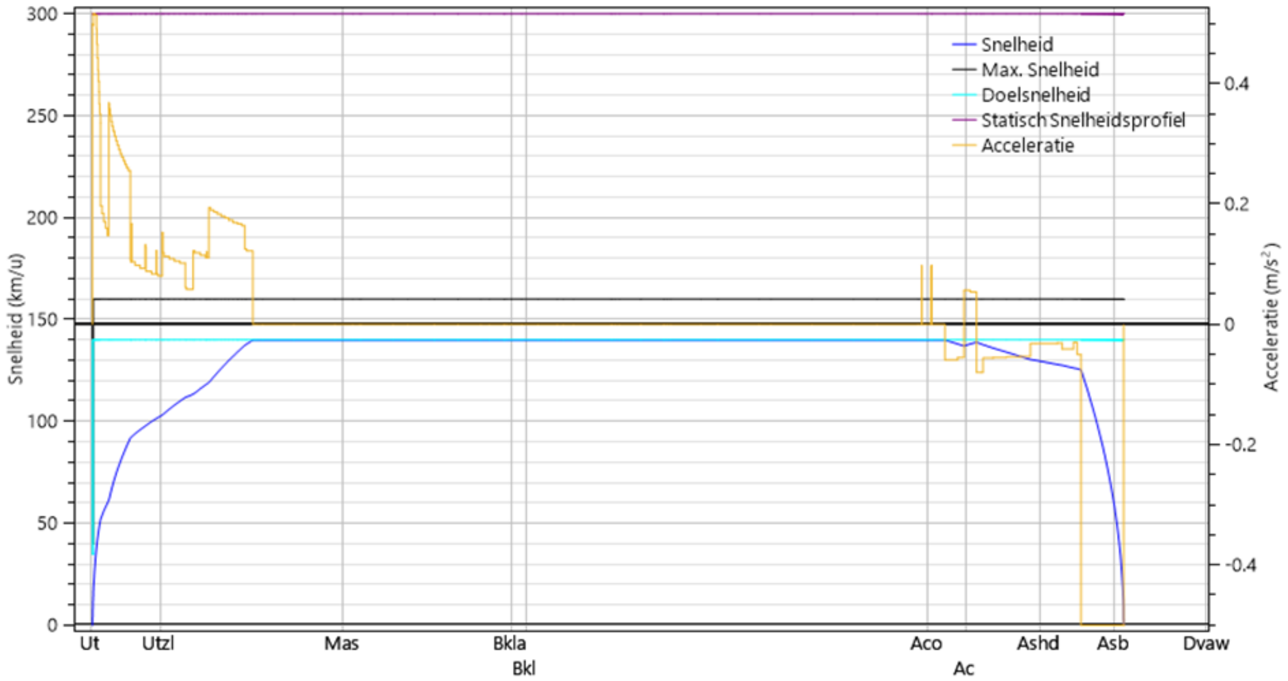


Figure 35: VIRM speed-way diagram, comfort braking curve

The figure below shows the energy consumption when implementing the comfort braking curve with respect to the VIRM. It shows the energy consumption reduced to 345.02 kWh per trip compared to train driver behavior. This amounts to a decrease in energy consumption 27.35 kWh. The power peaks are the same, except at the time when the comfort braking curve is deployed, because there is less acceleration to braking and coasting is deployed. At the moment of coasting no more power is needed while in figure 34 it can be seen that prior to braking, power is still being supplied. This is because, for example, power still needs to be provided to drive 140 km/h. This power is saved in the comfort braking curve. For both the train driver braking curve and the comfort braking curve, when driving at 140 km/h relatively little power is delivered.

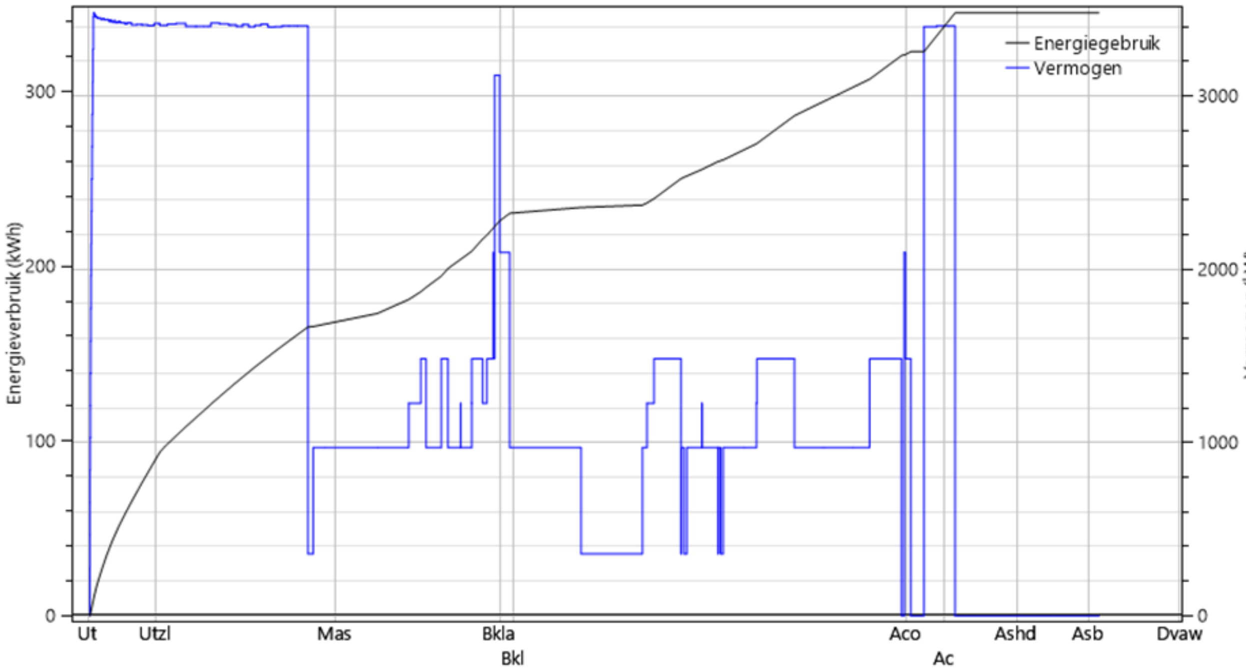


Figure 36: VIRM energy consumption, comfort braking curve

SNG, train driver behavior curve

The graph below relates to the SNG trains included in the simulation. First of all, in figure 37 the train driver behavior braking curve is visualized. The diagram shows how the sprinter accelerates to a speed of up to 140 km/h and what decelerations it requires to do so in order to come to a stop with a braking delay of 0.5 m/s^2. First, it accelerates from Breukelen (BKL) and the train is stopped at Maarssen (MAS), then it accelerates again and the train is stopped again at Utrecht Zuid (UTZL). At both stations the train is stopped with a deceleration of 0.5 m/s^2 which is reflected in the graph (the yellow line, to be read from right vertical axis). The train then travels two small distances where it must be brought to a stop towards Utrecht Central Station, here the train cannot accelerate to the maximum speed (110 km/h and 95km/h) and it is slowed down with a deceleration of 0.4 m/s^2 which subsequently changes to a deceleration of 0.5 m/s^2.

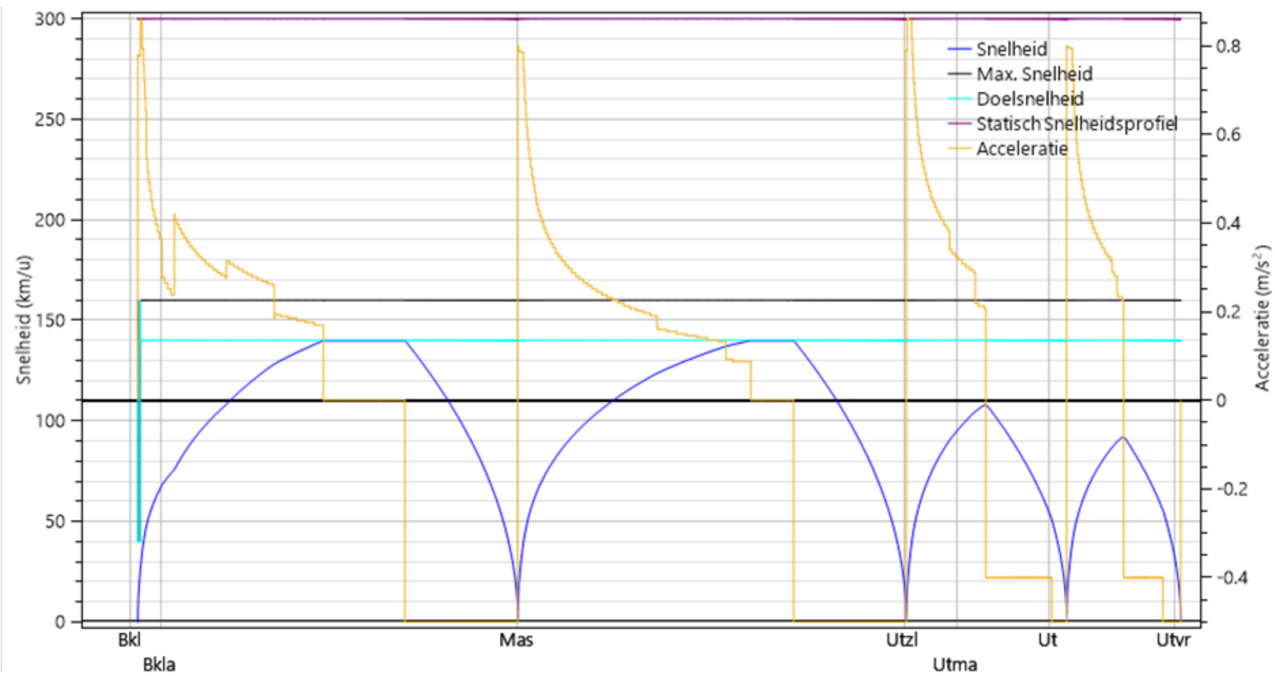


Figure 37: SNG speed-way diagram, train driver behavior

Regarding the above speed-way diagram, figure 38 shows the energy consumption required to perform this route under train driver behavior. This route gives an energy consumption of 206.28 kWh per trip and it can be seen from the figure that there are 4 acceleration peaks that initiate acceleration to reach speed after halting. The first peak gives a power of 2368.43 kW. The second peak gives a power of 61.56 kW and the third and fourth peaks give values of 2367.75 kW and 2360.43 kW. So this is the power the SNG has to deliver to get up to speed. Altogether, a energy consumption of 206.26 kWh.

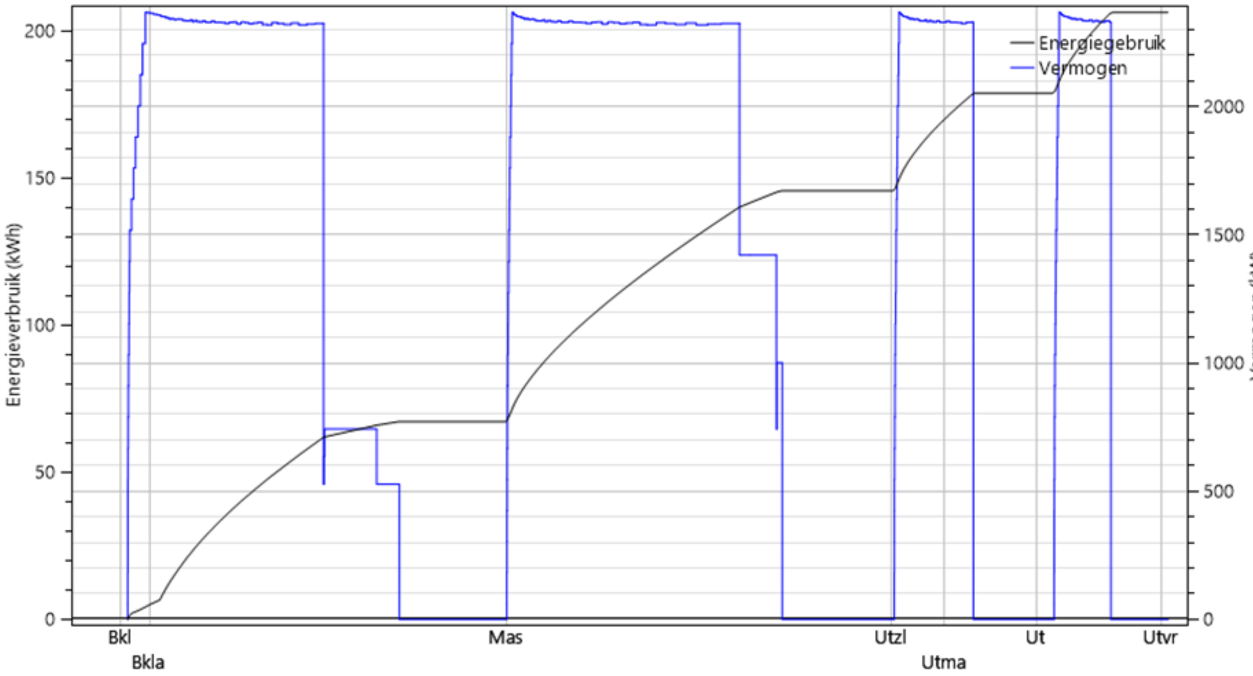


Figure 38: SNG energy consumption, train driver behavior

SNG, comfort braking curve

From the moment the comfort braking curve is applied to this route with respect to the SNG, the visualization of the comfort braking curve looks as shown in figure 39. These braking curves look similar to the comfort braking curve illustrated in figure 30. Here it can be seen that in the first halting the train accelerates up to the maximum speed and then rolls out with a deceleration of 0.067 m/s^2 and changes to a deceleration of 0.4 m/s^2. The deceleration 0.4 m/s^2 is necessary, rather than 0.5 m/s^2, because after coasting it is no longer necessary to brake with a deceleration of 0.5 m/s^2 to stop. In the second halting, something remarkable happens that the comfort braking curve involves and spreads to the 3rd and 4th halting. The train no longer accelerates to its maximum speed (namely, 136km/h second acceleration, 60 km/h 3rd acceleration and 75 km/h 4th acceleration) and gives room to coast until a braking deceleration of 0.4 m/s^2 can be employed. So acceleration is interrupted even earlier to coast toward braking compared to the comfort braking curve regarding to VIRM. At the second stop, the speed increases to 136 km/h and then braking with a deceleration of 0.1 m/s^2 after which the braking deceleration is shifted to 0.4 m/s^2. The routes to the 3rd and 4th stops are relatively short. As a result, the speed increases to 60 km/h at the 3rd stop before transitioning to coasting with a braking deceleration of 0.05 m/s^2, followed by further deceleration at 0.4 m/s^2. At the 4th stop, the speed increases to 75 km/h before coasting with a braking deceleration of 0.094 m/s^2. After this coasting phase, the second part of the comfort braking curve begins, applying a deceleration of 0.4 m/s^2.

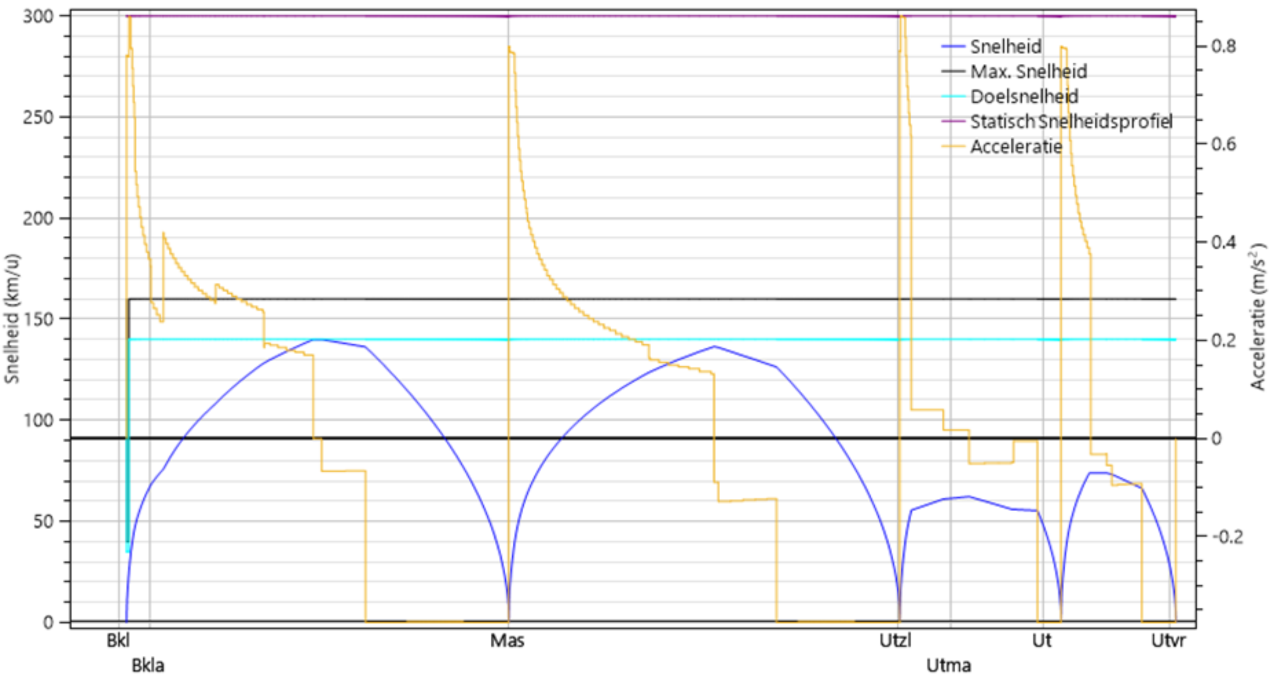


Figure 39: SNG speed-way diagram, comfort braking curve

With respect to the speed-way diagram, the power consumption required is shown in figure 40. the power to be delivered has a much shorter time span because the speed to be delivered is lower and shortened at high speed. The peaks that represent the power have the same values due to the standard acceleration to start the train, namely: 2368.43 kW, 2361.56 kW, 2367.75 kW and 2360.43 kW only these peaks are much shorter because the acceleration shortened. Also, the powered to drive the longer time at the target speed is takespeed is taken away,, this is because coasting is employed. Altogether, results to a decrease in energy consumption of 154.56 kWh. This is a difference compared to train driver behavior of 51.72 kWh per trip.

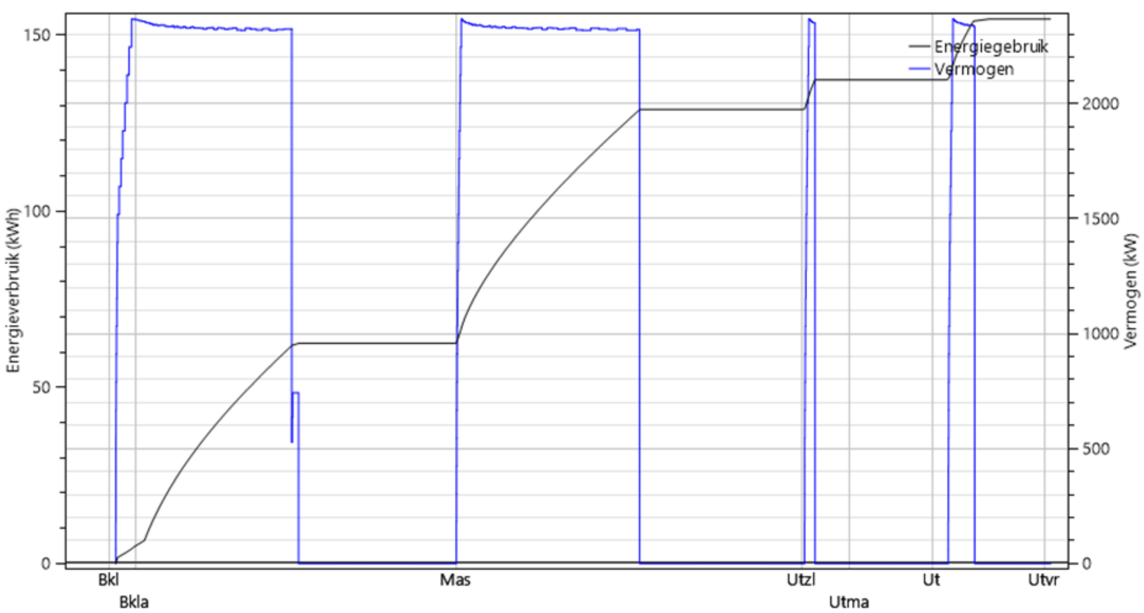


Figure 40: SNG energy consumption, comfort braking curve

Now that the results have been outlined using the performed tests, in the next section these results are analyzed using the RAMSHE analysis. This provides an explanation of why and how it impacts the key performance indicators of this research.

7 RAMSHE-analysis

In this chapter, the results of the tests are analyzed using the RAMSHE analysis. In the figure 41, the tested and implemented comfort braking curve and train driver behavior curve are scored on the research question, What are the implications of implementing the comfort braking curve on capacity, wear and tear, safety and driver experience?.

The figure shows a general picture of the implications of implementing the comfort braking curve. The line is scaled to, improvement in capacity, safety and driver experience and a reduction in wear and tear compared to the train driver behavior curve. On the basis of the RAMSHE analysis, the analysis is discussed. The focus of the analysis is obviously on the comfort braking curve. The train driver behavior braking curve was used in the results as a comparison which better captured the impacts of the comfort braking curve. As an example, with regard to the scaling on improvement in capacity it is analyzed in terms of Reliability, Availability, Maintainability, Safety and Health and Environment.

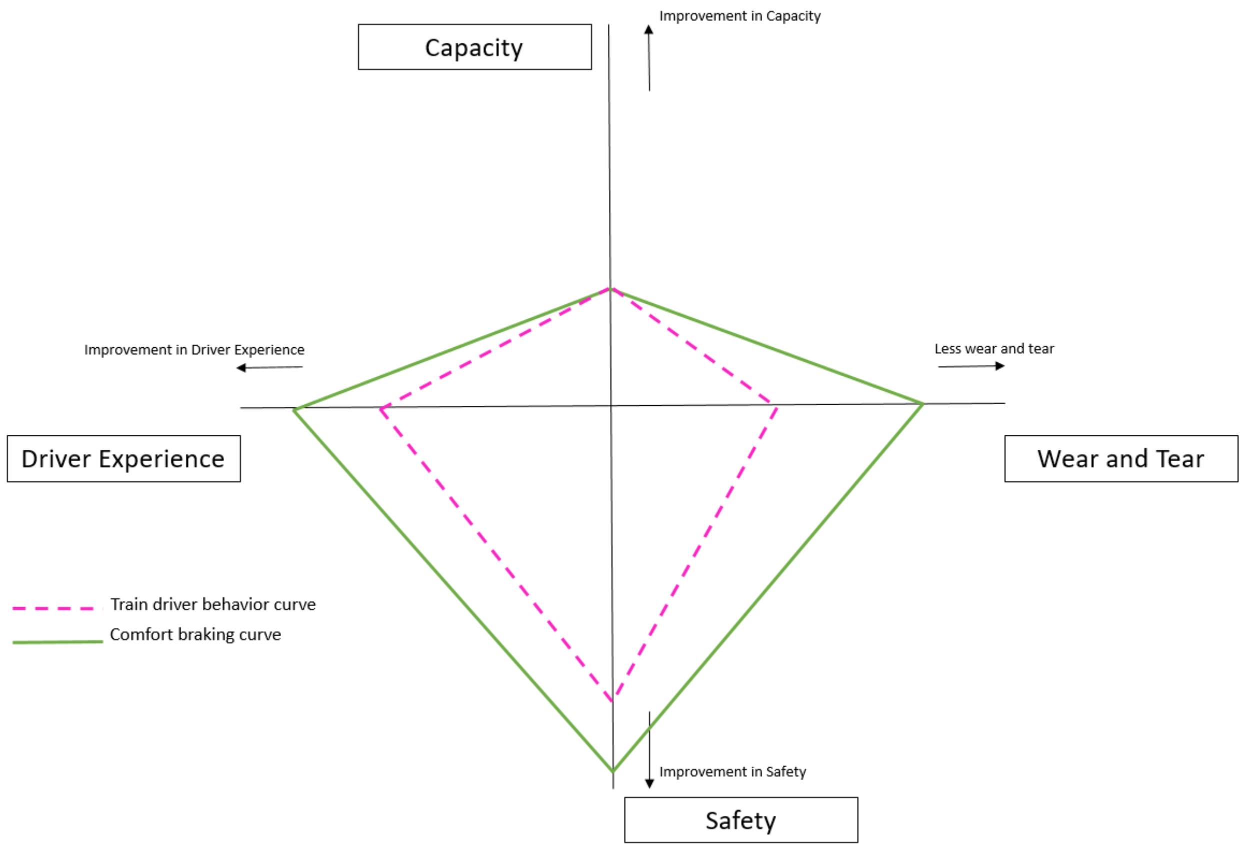


Figure 41: Scaling comfort braking curve relative to train driver behavior curve

7.1 Reliability

The introduction of the comfort braking curve provides clear benefits in terms of reliability compared to the train driver behvior curve, there are important implications in terms of wear and tear, driver experience and safety (as shown in figure 41). The SNG in particular benefits from the improved acceleration capabilities, as can be seen from the results and from figure 39. The maximum speed is broken off at an early stage due to coasting towards braking, this creates significant energy savings and less pressure on the train driver to reach a high speed. This benefits both the driving experience and sustainability.
The comfort braking curve provides a improvement, compared to the train driver behavior curve, in safety and a reduction in wear and tear because train drivers are less likely to accelerate abruptly or brake more sharply (consider, for example, the braking example in figure 22). This removes the more extreme braking risks that the permitted curve does, since this braking curve is almost as intense as the emergency brake (elaborated in

section 5). The comfort braking curve contributes to a smoother ride, because of the braking delay of 0.5 m/s^2 and a low jerk value, which is beneficial not only for the train driver but also for the passenger experience. All these advantages have positive effects on the discomfort scenarios from section 3.2, for example, the staggered permitted curve (figure 20). The traditional permitted curve calculations of the allowed speed sometimes lead to staggered recommendations because the train can first accelerate maximally, but then has to brake abruptly as soon as the block of the delayed train before it is still occupied. When this is cleared, acceleration can resume. The comfort braking curve maintains smooth driving behavior and improves stability, driving experience and energy efficiency. Because by not accelerating to maximum speed and coasting to braking deceleration, it gives the train driver room to anticipate this situation by moderating the speed in advance. These benefits lead to an improvement in reliability and a more efficient train operation, because the improvement in driver experience results in fewer human errors and the reduction in wear and tear.

Implementing the comfort braking curve eliminates the concern around crossing the warning curve (also an indicated discomfort of train drivers). The comfort braking curve is further away from the warning curve, which means that any overshoot does not lead directly to dangerous situations. For the train drivers, this removes some of the stress. Should braking be deployed slightly later than the comfort braking curve advice, this has no negative impact on safety. As a result, the system becomes more reliable, less stressful and the train driver can follow the comfort braking curve without hesitation. An important factor in this is the relaxation and softening of the safety net with respect to the comfort braking curve. Relaxation and softening of the safety net means that the steep braking characteristics of the permitted curve have been removed. The warning curve is a lot further away from the comfort braking curve and this allows for more flexibility when braking, while still ensuring safety. The warnings and alarms were close to the permitted curve, overshooting already resulted in almost immediate alarms, this creates stress and pressure. The emphasis of the comfort braking curve is on a smooth and controlled braking process, which not only increases reliability but also impacts the driver experience.

The earlier mentioned mismatch in training from section 3.2, where some examples were mentioned regarding discomfort and need for additional support, results in train drivers with less experience focusing more on following the permitted curve. This leads to a reduction in the ability to anticipate efficiently and safely in complex situations.The comfort braking curve provides more support for the group of less experienced train drivers. The comfort braking curve is in line with the current shift pattern and gives the train driver more room to react adequately to unexpected situations. This eliminates the feeling of constantly being behind the times. When the comfort braking curve is implemented, attention can be better distributed over the various aspects of train operation. Think of the focus on the incab or outside the cabin. This increases driver experience and increases safety on the track comparing with the train driver behavior curve, as shown in figure 41. All in all, the ride becomes more reliable.

The comfort braking curve fits into the current timetable, with minimal shifts involving only the VIRM. Overall, the robustness of the timetable is maintained, meaning that there is sufficient flexibility to anticipate unexpected situations. The analysis shows that it is not necessary to accelerate to maximum speed in order to meet the timetable.The SNG travels 138 km/h in the first section, 136 km/h in the second section, 60 km/h in the third section and 75 km/h in the fourth section. This can be seen in figure 39. By not accelerating each time to the maximum speed, the train operations become much more stable and efficient. The results show that the implementation of the comfort braking curve does not cause significant delays. With regard to the VIRM, there is only a delay of only 4 seconds compared to the train driver behavior braking curve, this difference is negligible because the train still stays within the planned schedule. Regarding the SNG, the biggest delay compared to the train driver behavior curve is 38 seconds. But this delay is negligible as well, by the fact that the train still arrives 19 seconds earlier than the latest planning time. The overall conclusion here is that the comfort braking curve fits well with the existing timetable and that it maintains robustness alongside this. But no additional trains can be fitted into the timetable with respect to the comfort braking curve, this is therefore also included in the scoring of capacity. Capacity does benefit from other perspectives, which is discussed further in this section.

Explained earlier in this research, it was shown that train drivers maintain a margin from the permitted curve in order to be prepared for unforeseen braking moments. Train drivers stay on average 4 km/h below the target speed. This margin is eliminated by the more defensive approach of the comfort braking curve. The curve itself integrates earlier braking, ensuring the train remains below the permitted speed. As the train enters coasting mode, a gradual speed reduction begins, followed by a constant braking deceleration of 0.5 m/s^2, as shown in figure 39. This ensures that train drivers have room to anticipate unforeseen braking moments. All in all, the result is smoother driving with enough room to react appropriately to the situation. This approach not only provides promotion in the comfort ride, but contributes to a safer and more reliable track operation by eliminating the train driver's perception of being 4 km/h below the target speed.

Earlier in this research it is found that train drivers do not want to accelerate unnecessarily towards a braking, this would be energy-inefficient despite the permitted curve indicating this. The behavior of the comfort braking curve recognizes this unnecessary acceleration and therefore the curve is adjusted to accommodate this, this contributes to reliability and consistency in train operation. The comfort braking curve has gradual and build-up braking with coasting toward deceleration, keeping the jerk below 1 m/s^3. This train driver behavior implemented in the comfort braking curve leads to recognition of train driver behavior in the braking curve. Which is not only positive for the driver experience, but also increases safety. In addition, avoiding unnecessary acceleration and braking reduces the number of human errors, but it also leads to a reduction in equipment wear. Avoiding abrupt changes in speed leads to reduced stress on the train's braking and propulsion systems, which in turn reduces maintenance costs and extends the lifespan of the rolling stock. These benefits, combined with the improvement in driver experience and safety, make the comfort braking curve a valuable addition in this area of reliability.

Besides the positive effects regarding reliability, there is also a negative point. The comfort braking curve is a completely new strategy that has been defined, it already existed among train operators but it has never been visualized in its totality. So this is still in its infancy. The comfort braking curve has only been tested on the VIRM and the SNG, other trains have not been looked at. So how reliable this braking curve will be in reality when implemented in the DMI remains to be proven.

Overall, the comfort braking curve performs better than the train driver behavior curve in terms of reliability. The comfort braking curve provides train drivers with a predictable and stable braking strategy, this stagnates human error and increases reliability in train operations. These results are included in the overall performance score, as shown in figure 41.

7.2 Availability

In the rail industry, customer satisfaction and capacity are often contrasted as two conflicting goals. On the one hand, it is essential to maximize capacity to carry as many passengers as possible, but on the other hand, train drivers indicate that customer satisfaction is key, with passenger comfort considered to be most important. It is also about the seats sold and not on purely maximizing the possible passengers. The comfort braking curve is an elegant middle path between these two conflicting goals. The braking and acceleration patterns are drawn more gradually, which not only improves passenger comfort but also maintains adequate on-track capacity. Abrupt speed changes have been avoided, without compromising the robustness of existing service arrangements. This creates a healthy balance between rail efficiency and customer satisfaction. This balance is an important part of availability, which contributes to an efficient train operation.

The comfort braking curve aligns seamlessly with train drivers' natural behavior, including the implementation of coasting prior to braking. This is not only a recognized approach, but is actively encouraged by NS. This integration into the comfort braking curve not only improves the driver experience, but also accommodates stakeholders such as NS or Prorail. For example, through reduced track and equipment maintenance.

Another analysis in the area of Availability is the elimination of brake dip. Train drivers look for the correct handle position when halting to ensure a comfortable halting and coming to a stop exactly at the stopping location. This often gives braking dips as a result which is illustrated in figure 23. With the implementation of the comfort braking curve, the braking dips are eliminated, in fact there is no need for searching braking behavior which ensures comfort. The uniform braking deceleration of the comfort braking curve has the consequence that a consistent handle position can be applied and adjusted in a controlled manner as well, without using step braking. This is because the speed gradually decreases with a comfort deceleration and this makes braking behavior more predictable and reliable. The brake dip also causes the unnecessary extra energy and wear an tear, when the brake dip is eliminated the energy consumption also decreases. This can be seen in the figures 36 and 40. So all in all a saving of energy for the train driver by eliminating the need to search for comfort braking modes. The comfort halting leads to improvement in wear and tear, driver experience and consequently safety on the track.

The factors described above, which perform well in terms of availability, such as the application of coasting and the gradual reduction of braking force, contribute to improvements in train operation in several areas. For example, the driver experience improves, because the driving behavior better matches the train driver's natural behavior. In addition, there is a stagnation in wear and tear, because the coasting and gradual braking process prevents the braking dips. Finally, the created balance between comfort and capacity, because of the comfort braking curve, improves passenger comfort through consistent braking and acceleration patterns, while maintaining capacity on the track. These improvements, compared to the train behavior curve, are incorporated into the scale in figure 7.

7.3 Maintainability

When the comfort braking curve is implemented there is a significant reduction in energy consumption and power, this can be seen in the figures 40 and 36. With respect to the VIRM, the energy consumption with the train driver behavior curve is 372.73 kWh. When the comfort braking curve is implemented the energy consumption drops to 345.02 kWh, this is a saving of 27.35 kWh per trip. Regarding the SNG, the implementation of the comfort braking curve shows a greater stagnation in energy consumption: a decrease of 51.72 kWh compared to the train driver behavior curve, this is almost double reduction compared to the VIRM. This reduction in energy consumption has a direct impact on maintainability: the reduction in energy consumption reduces the stress on the equipment, which has a positive influence on both the wear and tear and the safety. In addition, the lower energy consumption also means less need for maintenance on the track. Resulting in less work on the track, preventing the track from being put into operation. Less maintenance also means more tracks open for use, which has a positive influence on the capacity on the track but also in the workshop. Because the rolling stock is under less stress, there is less need for trains to go to the workplace. This leaves more capacity available as operational deployment on the track. All in all, due to the combination of energy efficiency, safety and lower maintenance requirements, the comfort braking curve is a valuable improvement in both the technical aspect and the operational aspect regarding the rail system.

This report highlights an action in Baseline 3 release 2 that can distract train drivers, this is explained in section 3.2 and is about the speed calculations that can lead train drivers astray. This creates unnecessary accelerations and decelerations which in turn leads to direct wear and tear on the train and on the track. The implementation of the comfort braking curve reduces the use of brake discs. Because of the coasting and controlled braking delay used, the train uses less of the abrupt braking. This compensates for the wear and tear caused by the ambiguity on acceleration of Baseline 3 release 2, but also results in less confusion. The speed also does not increase to the maximum again because, when the train is close to the EoA, it must be in calculated that the train will coast and brake with a braking delay of 0.5 m/s^2. Because of this, which will happen during the permitted curve, the speed when implementing the comfort braking curve will never suddenly indicate 140 km/h.

There are certain routes on which train drivers, out of experience, slow down, the main reason being to ensure passenger comfort. The implementation of the comfort braking curve helps those drivers who are inexperienced. Because of this curve that starts coasting earlier, in many cases it is not necessary to reach the maximum speed, especially in the SNG, to decelerate still with a braking delay of 0.5 m/s^2. This results in the train automatically having a lower speed, this reduces the feeling of shaking and shocking on routes that are uncomfortable to ride. This provides a more comfortable ride and so the passengers do not feel as if they have entered an attraction park. Apart from the routes that can quickly be considered uncomfortable as a passenger in a train, there are also switches around the station that are uncomfortable when driven at high speed (+- 80 km/h). The comfort braking curve causes the train to move slower because braking is started earlier, which not only makes the driving experience better but also reduces the wear of the switches. This maintenance analysis leads to a better driver experience and a reduction in wear and tear.

From the palpability test it became clear that the overall stopping distances became longer from the moment the comfort braking curve was implemented, this is due to the coasting being initiated earlier. In general, the coasting results in a shorter braking period. It is precisely in the hard braking period of the train that a lot of wear and tear occurs, so this is partially eliminated by the coasting process.

All in all in the area of maintenance, the comfort braking curve scores better than the train driver behavior, this can be seen in figure 41. In terms of maintenance, there is an improvement in capacity, due to the extra space in the workshop and less maintenance on the track itself. In addition, wear and tear decreases significantly in the case of comfort braking and there is an improvement in driver experience and safety through the safe support of non-experienced train drivers. This prevents unnecessary acceleration and deceleration.

7.4 Safety and Health

The implementation of the comfort braking curve simplifies the role of the DMI. Redundant elements could be eliminated, as the comfort braking curve allows for a simplified and streamlined process. This ensures there is not too much information and notifications in the cabin; as a result, there is not a constant switch of attention between outside and inside the cabin. For example, TIMTIM is no longer needed with respect to the comfort braking curve, the roll out is already implemented in the comfort braking curve. The DMI is needed for only essential advice at the right times, for the comfort braking curve this would only be the coasting and even deceleration. This minimizes the task load, which also contributes to driver health. Earlier in this research, it has been indicated that drivers say that the company doctor has a lot of work to do with the drivers who experience high pressure, the comfort braking curve would be a benefit for this.

In terms of safety, it has already been indicated in section 3.2 that slippery track is an important aspect for drivers to consider. In situations such as these slippery tracks, the comfort braking curve provides a more restrained braking profile compared to the permitted curve. This supports drivers in performing comfortable and controlled braking in the case of slippery track. From experience, drivers indicate that driving under slippery track conditions can be challenging, but an indicated gradual braking delay of comfort braking has reduced this sensitivity of slippery tracks. With respect to health, the comfort braking curve plays an important role in crowded trains. Especially these days because the trains are smaller and thus overcrowded. In order not to throw passengers off balance, a braking delay of 0.5 m/s^2 and a minimum jerk value is crucial. This not only increases comfort but also ensures passenger safety. Abrupt braking in a crowded train can create dangerous situations for passengers. Nevertheless, if once in a crowded train the passengers experience such a dangerous situation due to abrupt braking, they lose confidence and choose another mode of transportation. So a comfort braking curve also creates more reliability from the passengers which in turn leads more to sold seats. So in the context of safety and health, complex situations and acting afterwards are already implemented in the comfort braking curve.

Train drivers often exhibit more defensive braking behavior when braking to a stop to avoid overshooting hazards, this defensive behavior is eliminated when implementing the comfort braking curve. The curve approximates the EoA with a consistent braking deceleration, reducing the danger of overshooting. For both the VIRM and the SNG, this leads to a significant improvement in the driver experience.

But on the other hand, train drivers do not want to be restricted in their freedom of movement, and the comfort brake curve can sometimes be perceived as restraining. With comfort brake curve advice, train drivers may experience some restriction in their freedom of movement, leading to the feeling of always being able to accelerate faster than indicated. And therefore more quickly not listening to the advice. Nevertheless, the comfort braking curve offers great advantages, as the smooth roll-out and consistent deceleration lead to calmness and flexibility that compensate for the limited freedom of movement. This flexibility is beneficial on days when operators are less feeling well. On these days, they do not feel the need to follow a permitted curve as closely as possible and automatically drive at their own comfort. The comfort braking curve provides a good middle path in these situations, the driver is supported on comfort without causing further delays in the timetable. The operation continues to run smoothly despite the driver's situation.

All in all, implementation in the area of Safety and Health is leading to less cognitive load. In more complex situations, such as a slippery track or crowded trains, less of the train driver's experience is required. In addition, the comfort braking curve provides support on days when the train driver feels a bit sick, the driver experience improves. There is also an improvement in safety, both for the passenger and the train driver. Train drivers have an improved focus distribution and in overcrowded trains the brakes are applied with a comfortable deceleration and jerk value.

7.5 Environment

As explained as a scenario in section 3.2, train drivers perceive discomfort from the moment they enter the station with the train almost crawling. By implementing the comfort braking curve, the braking process is initiated earlier, this also has the consequence that the speed has to be lower also for the haltings to maintain the constant braking deceleration of 0.5m/s^2. Due to the uniform decrease in speed and the already lower speed, the crawling effect in the stations is instinctively less prominent. This not only has a positive impact on the driver experience, but also makes the environment (e.g. passengers) feel more positive.

From the moment train drivers drive against the permitted curve, an alarm sounds continuously after exceeding already 1km/h extra, this is disturbing for the driver and for the passengers. From the moment something goes wrong and AERA control starts looking back at the driving behavior, the offensive driving behavior is not desired. Train drivers worry about this and therefore often choose to drive under the curve. The comfort braking curve offers a significant improvement here for its environment. The comfort braking curve is designed so that operators can drive confidently against the curve without the consequence of alarms or the feeling of being on the limit. This not only enhances the driving experience, but also removes the concern highlighted in section 3.2 about this situation regarding passengers hearing the alarms.

From the moment the train driver receives an indication notification, a natural shock reaction occurs, this can affect the timetable. When an emergency braking is applied anyway, this completely affects the capacity at that moment what passes over that route. With the comfort braking curve there is a constant deceleration and the braking curve is deployed earlier, making it far from the emergency braking. This lowers the chance of natural shocks when getting an indication and the chance of emergency braking is significantly reduced. This positively affects the entire environment on that same route, there is a lower chance of abrupt changes occurring on the route.

So in the context of environment, the comfort braking curve scores better than the train driver behavior curve. There are less abrupt changes on the route which has a positive effect on driver experience, safety and wear and tear.

All in all, the RAMSHE-analysis provided a clear understanding of the results from the simulation tests and the implemented comfort braking curve takes significant advantages. Nevertheless, there are also so indicated concerns about the comfort braking curve in the RAMSHE-analysis. The conclusion provides a summary answer to the research questions raised in chapter 1.4.

8 Conclusion

This section contains the conclusion of this research. First, each sub-question is answered individually, the main research question is answered through the synthesis of this information. The next sections will elaborate the discussion and address further recommendations as a result of this research.

8.1 Answering sub-questions and research questions

Sub-question 1: What is comfort braking?
In other words, what does the literature say about comfort braking? The comfort braking curve, as defined in this research, is a braking method that focuses on improving train driver comfort. These improvements are made without sacrificing safety or ETCS Level 2 performance. The comfort braking curve is characterized by a braking delay between 0.5 m/s^2-0.6 m/s^2 and a maximum jerk value of 1 m/s^3. This combination ensures a controlled and smooth braking curve and abrupt changes in speed are avoided. So, the comfort braking curve is a smooth deceleration (0.5 m/s^2-0.6 m/s^2) with minimal jerk (max. 1 m/s^3) ensuring smooth speed transitions, well-controlled braking and a balance between comfort, control, and safety.

Subquestion 2: How does a train driver brake comfortably under ETCS Level 2, what are the operational characteristics?
Besides what the literature says, it is also important to look at how the train driver acts in practice with respect to his own comfortable driving. Under ETCS Level 2, the driver has defined his own comfort braking curve based on anticipation strategies and operational characteristics. In addition to the classic driver modes (acceleration, cruising, coasting and braking) and the well-known anticipation strategies (Defensive driving, offensive driving and average driving), there are also many anticipation strategies from practice that are commonly repeated in driver behavior. These actions are based on the discomfort scenarios described in this research:

- Defensive braking style: early braking and anticipating to avoid unforeseen situations (overcrowded trains or slippery tracks). Train drivers do not accelerate towards a braking advice.
- Maintain margin of 4 seconds under the permitted curve and are generally 5 km/h under the recommended speed.
- Coasting: 10 percent of the speed
- Step braking: braking in stages at lower speeds, brake dips are common consequences here.
- Braking by instinct: based on experience, road knowledge and training, driving over difficult sections and over switches requires more experience.

So taking into account these anticipation strategies and operational characteristics, it is important that the comfort braking curve functions under these operational constraints. So a comfort braking curve is: A smooth deceleration (0.5 m/s^2-0.6 m/s^2) with a minimal jerk (max. 1 m/s^3) that provides smooth speed transitions, well-controlled braking and a balance between comfort, control and safety. The comfort braking curve prevents abrupt speed changes and remains practical within operational constraints.

Subquestion 3: What are the critical design parameters for modeling the, ETCS Level 2, comfort braking curve?
In this research, the safety net of the original braking curves from ETCS Level 2, is made softer and more flexible. This safety net is also placed earlier. This goes in line with how train drivers generally act. The allowable curve is modified to promote smoother speed adjustments, but still remains compatible with ETCS Level 2 norms. The identified critical design variables for the comfort braking curve are listed below:

- Braking deceleration adjustments: 0.5 m/s^2
- Minimizing the Jerk, max. 1 m/s^3
- Adapted anticipation strategies, regarding the indicated discomfort of the train driver in; coasting (from -0.01 m/s^2 to -0.25m/s^2)

- Adjusted speed margins
- Taking into account the main variables in the applied calculations of the ETCS Level 2 braking curves, namely: braking forces ($A_{\text{brake\_safe}}(v)$), speeds (V_{est}), distance and target distance (d_{target})

Subquestion 4: What does such a comfort braking curve look like?

Below is a visualization of the comfort brake curve. Where the anticipation strategies and critical design parameters are implemented.

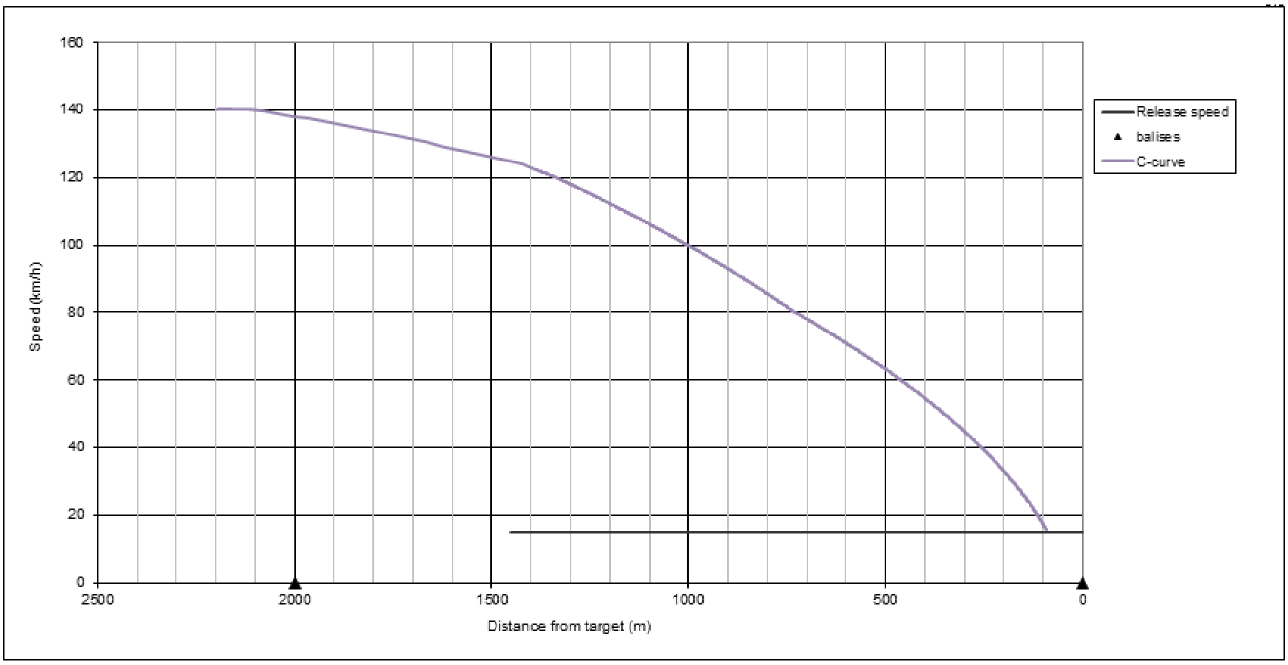


Figure 42: The visualization of the comfort braking curve

The developed comfort braking curve, is a relaxation of the current safety net of the permitted curve with gradual speed reduction. The comfort braking curve is introduced with coasting and is followed by a stable braking deceleration with a maximum jerk value. This braking curve ends with gradual reduction to a stop and has been successfully tested on the VIRM and SNG trainsets.

Subquestion 5: What are the effects when implementing the comfort braking curve?

This question has been answered using the RAMSHE-analysis:

In terms of reliability and safety, the predictable and consistent braking strategy leads to a stagnation in human errors and operational disruptions. Increased distance from the warning curve and constant speed reduction gives train drivers room to anticipate unexpected situations, thus reducing potential emergency braking and stress. Resulting in driving stability and overall safety. The availability of the balance between comfort and capacity optimizes operational efficiency. Smoother braking and acceleration patterns support the train driver in (complex) situations. This results in a better driving experience and a reduction of disruptions in the timetable, increasing efficiency on the route environment so that other trains do not have to wait for abrupt interventions. In terms of maintenance, the controlled braking delay leads to the avoidance of abrupt speed changes. This results in less wear on the rolling stock and infrastructure. In addition, there are longer maintenance intervals, which results in more capacity in the workshop and more availability of track and rolling stock. With regard to health and safety, the simplification of the driving task reduces the cognitive load on train drivers. This improves their well-being and concentration in the long run. In addition, the consistent braking delay contributes to stability for passengers by reducing the risk of loss of balance and discomfort on crowded trains.

All in all, the comfort braking curve leads to a more reliable and safer rail system, with both train drivers and passengers benefiting from a more stable and efficient train operation. Still, the comfort braking curve is in its infancy and has yet to be tested on a wide range of equipment.

Research Question: What are the implications of implementing the comfort braking curve on capacity, wear and tear, safety and driver experience?

1. Capacity:

The comfort braking curve maintains capacity on the track for both the VIRM and SNG. While not directly fitting more trains into the timetable, the robustness of the timetable is maintained. The capacity of the rolling stock and at the workshop does increase, due to the consistent braking profile and relaxation of the braking curve, the level of maintenance decreases.

2. Wear and tear:

The comfort braking curve reduces wear and tear on both the rolling stock (VIRM & SNG), but also on the infrastructure. The reduction in energy consumption and power causes a stagnation in stress on the train's braking and propulsion systems. This results in fewer maintenance intervals and longer life of train components and rail infrastructure.

3. Safety:

The comfort braking curve provides an improvement in safety, this is due to the predictable and controlled braking process. In unexpected conditions, such as slippery tracks, the comfort braking curve supports operators with a defensive braking curve and gradual braking deceleration. As a result, emergency braking and overshootings are minimized. Abrupt speed changes in trains are avoided, contributing to passenger safety on crowded trains. One negative point regarding the comfort braking curve is that this braking curve is completely new. It is still in its infancy and has also only been tested for 2 types of trains.

4. Train driver experience:

The comfort braking curve improves the train driver experience. The possibility of simplifying the DMI due to alarm avoidance reduces cognitive load and work stress. The comfort braking curve matches train drivers' natural driving behavior, such as gradual coasting. Because the comfort braking curve recognizes train drivers' driving behavior, it reinforces their confidence in recommended speeds. The curve also provides additional support from when the train driver is unwell, the comfort braking curve provides comfortable braking without sacrificing capacity. The comfort braking curve is not entirely beneficial with respect to the train driver experience. Due to the restraint of the braking curve, the driver may still seek the edge and or feel that there is less freedom in their driving.

In conclusion, the comfort braking curve offers a balanced improvement with respect to capacity, wear and tear, safety and driver experience. The implementation results in an increase in the reliability of track operations, less maintenance and safer and more comfortable rides.

9 Discussion

This research resulted in both strengths and areas for improvement. The results show that the comfort braking curve is an innovative and realizable solution for improving driving comfort without sacrificing operational efficiency and safety. Nevertheless, limitations and challenges have been identified regarding this research. This section highlights the strengths and contribution of this research and the areas of improvement.

9.1 Strengths and contribution of this research

The first strength is that this research is multidisciplinary in terms of relevance. Namely, it is a combination of technical modeling and behavioral science insights. This results in an integrated approach in the field of train driver behavior and train control under ETCS Level 2.

Second, this research focuses on an innovative topic related to train protection systems that has not been studied in detail, namely: implementing the comfort braking curve without making concessions with respect to operational efficiency and safety. This contributes to an important knowledge gap and provides a theoretical basis for possible developments of the comfort braking curve.

Third, the comfort braking curve is designed such that no fundamental changes to the existing infrastructure or ETCS system need to be made, so the comfort braking curve is compatible with the current system. This results in the eventual implementation being practically feasible and also cost effective. The compatibility of the comfort braking curve contributes to the interoperability of the rail network.

Fourth, this research resulted in fundamental adjustments being made to the simulation program FRISO. According to controllers, these fundamental modifications are an improvement to the simulation program. The adjustability of the time shifts will be modified so that the EBD/SBD curves can be misused to shape the comfort braking curve. In addition, there will be an option to define the comfort braking curve in FRISO as part of the train driver behavior. The comfort braking curve can be added to the safety curves according to specifications. An additional option will be a check mark that turns off the security curves, this allows the impact of the security to be analyzed and the relevance of the security curves to be demonstrated. These modifications provide the maximum flexibility to analyze the comfort braking curve in FRISO.

Fifth, the comfort braking curve has its own specific braking characteristics. The design and visualization do include parameters of the ETCS braking curves. However, the comfort braking curve functions independently and is independent of the other ETCS Level 2 braking curves.

Sixth, it is often said that ETCS is a safety system and not an advisory system. Yet ETCS is mandatory in nature: train drivers are trained to continuously follow the boundary of ETCS. As a result, in practice it functions as more than just a safety system. Although ETCS is not specifically focused on comfortable braking in terms of terminology, train drivers try to comply with the advice as best they can. They see the advice not as optional, but as a mandatory task. This is precisely why the implementation of the comfort braking curve could be a valuable addition. Currently, conclusions are drawn based on the ETCS braking curves that do not fully reflect reality. This is because train drivers in practice do not drive exactly on the permitted curve, leading to the wrong conclusion. The comfort braking curve based on train driver behavior would be a good addition for this reason. So even though ETCS is not a safety system and would have nothing to do with comfort, the comfort braking curve is a good implementation because ETCS braking curves are driven differently than assumed.

And last, given the future developments regarding ATO, future research could also focus on the integration of the comfort braking curve within these automated systems. The comfort braking curve would be a strong addition as a suitable braking curve for ATO, since the current braking curves according to ERA regarding ATO are supplier-specific, just from train driver-specific is a more useful approach.

9.2 Areas for improvement of this research

Unfortunately, the fundamental improvements in FRISO came just too late. A fundamental adjustment in a simulation still took longer than thought, the FRISO controllers need more time for it. For this reason, the comfort braking curve visualized in figure 29 is not simulated 1 to 1 but certainly has the same characteristics regarding the smooth and constant braking delay. Therefore, the effects correspond as the proposed comfort braking curve. In fact, follow-up research is also going to be conducted when the fundamental adjustments are made in FRISO.

At the moment, there is relatively minimal driving under ERTMS in the Netherlands, as the system is mostly limited to routes such as the HSL and the Hanzelijn. On the HSL, for example, a train at Schiphol enters the ERTMS area, but before Rotterdam already enters an ATB area. This results in a braking process under ATB and not under ERTMS. The comfort braking curve is visualized based on available literature, interviews and data from simulations in which train drivers demonstrate their driving behavior. Some data from train drivers who have already driven under ETCS has been included, but this dataset remains limited. Therefore, an important improvement point for the future is to collect more data as more sections of track are equipped with ERTMS ETCS Level 2. This additional data can help to further refine and specify the comfort braking curve. But for now, the limited data is an area of improvement.

The research was conducted under a limited scope. Namely, the scope is only for passenger trains (VIRM and SNG) and on a specific route (Amsterdam-Utrecht). Unfortunately, this means that the results cannot be generalized to other trains or routes. A research into whether the comfort braking curve is material specific is already indicated in the recommendations.

Although the simulation and models provide good insights into the application and implications of the comfort braking curve, the comfort braking curve is untested in real situations. A field experiment would add a strong contribution to the validation and would further confirm the results.

This research has limited analysis of negative impacts, this research focuses on specific key performance indicators such as energy consumption, power, time and braking distances. But impacts on other parts of the rail network (e.g., nodes), have not been examined as in depth. An area of improvement would be a widening in the research scope.

9.3 Recommendations

Outlined below are four recommendations of interest for follow-up research:

- The first recommendation relates to the equipment. Does the comfort braking curve depend on equipment-specific applicability. The comfort braking curve is currently tested on the VIRM and SNG. A recommendation is to do further research on other rolling stock, think of other regional trains or freight transport. This can help further optimize the comfort braking curve and its wider applicability.
- In addition, it is also valuable to look at further scope broadening of comfort. In this research, we have focused on the comfort braking curve from figure 29 (i.e., with a deceleration of 0.5m/s^2), but the implementation of the bandwidth from figure 31 and the resulting effects is also an important aspect of comfortable braking.
- Another recommendation relates to release speed. The release speed does not necessarily contribute to train operator comfort due to the crawling effect. Since the speed of the comfort braking curve is already lower, and braking is constant, it is interesting to see if release speed can be omitted. This in turn could lead to additional simplification of the braking curve and possibly higher acceptance by train drivers.
- Another recommendation is to do further research on simplifying the DMI. The comfort braking curve is independent of the other braking curves from ETCS Level 2 and no longer needs those notifications and advisories displayed on the DMI. For instance a DMI, without the warning curve. What does the DMI look like with only the comfort braking curve? There are a lot of possibilities to simplify the DMI with the implementation of the comfort braking curve.

- The next recommendation deals with the integration of ATO systems. ATO is based on standard braking curves, for visualization of the standard braking curve the comfort braking curve can be a valuable addition. The ERA indicates that the braking curve for ATO is supplier specific, but it is interesting to consider making this train driver specific. So based on driver behavior, like the comfort braking curve.

- A practical recommendation for Mott Macdonald and/or other rail stakeholders: A pilot will have to be carried out on a test track with ETCS Level 2, integrating the comfort braking curve. Within 6 months the comfort braking curve can be implemented in the software of 5 VIRM trains, 6 months because it is compatible with the current system. After this, these 5 trains can be tested on the test track. After successful completion of the tests, the software can be implemented in a wider scope of trains. If the comfort braking curve continues to provide positive results and it is decided to implement it officially. It is important to immediately plan how this can be implemented over the years, think of planning programs like Primavera P6 that can help with this. This gives better insights and risks for the future and how the implementation should be done step by step. For example, the urgency of implementing the comfort braking curve directly in the training of train drivers should not be overlooked. This leads to the optimal use of the comfort braking curve.

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Appendix A Expert meetings and stakeholder interviews

During the course of this project multiple meetings and interviews have been held, which will be summarised in this appendix.

A.1 Expert meetings and Interviews

Table 9: Main takeaways from every meeting and interview

When	Who	Subject	Main takeaways
26-09	Pieter van der Beek	Train Driver Behavior	Train driver behavior deviation; Causes and Consequences
27-09	Melcher Zeilstra	ETCS Level 2 braking parameter settings	Explanation about the ETCS braking curves and possibilities for comfort
04-10	Stan Albers	Data	ATB vs ETCS Level 2; Train driver behavior and comfort; Technological support (DAS and TIM-TIM); Capacity vs comfort
09-10	Cornelis Kleibeuker	Train Driver/Researcher	Answer how a train driver drives under ETCS Level 2 NEO simulator scenarios related to ETCS Level 2 B3R2
14-10	Maarten Bartholomeus	Expert ERTMS/ETCS	ATO; ERA braking curve tool; Feedback comfort braking curve
01-11	Cor Van 't Woudt	Senior research leader NS	FRISO opportunities
13-11	Rafael Mendes Borges	Simulation Researcher	FRISO opportunities
14-10	Jelle van Luipen	Simulation expert	Collaborate research Railcenter; access to FRISO; Stormtrooper inventory
08-11	Dick Middelkoop	Manager Model development	Developments FRISO research-related
Every Wednesday	Eelco Schrik	Catch up meeting	Eelco Schrik knows a lot about the rail industry, I speak to him every Wednesday to ask him questions about my subject and we keep track of my progression
Once every two weeks	Eelco Schrik, Bjorn Schutte and Ruben Vergroesen	Catch up meeting	Eelco Schrik knows a lot about the rail industry, I speak to him every Wednesday to ask him questions about my subject and we keep track of my progression

A.2 Interview setup

The persons from table 9 were interviewed in their natural language: dutch. The interview is a semi-structured interview. The questions were translated into english.

A.2.1 Questions and setup

Introduction

- Introductory round, exposition project
- Ask permission to record the interview

Train driver Perception and Behavior

1. In your opinion, what is the biggest difference in driver perception in driving under NS'54/ATB and under ETCS Level 2?
2. In your opinion, should the forward view function be in the train protection system? What are the train driver's preferences in terms of incab focus and out-of-cab focus?
3. What are the main differences between passenger and freight transportation behavior? Do they underpin decisions on the same information and take the same steps when braking?
4. Keep a train driver in mind when driving under other conditions: take, for example, driving a VIRM (Verlengd InterRegio Materieel) or an SLT (Sprinter Lighttrain)?
5. Is it possible to establish a braking curve regardless of the equipment? So some kind of general comfort braking curve.
6. Is the train driver aware of these differences of handling in running other trains?
7. Do you think ATO is the solution to solve the behavioral deviation?
8. From the moment the indication is given to the train driver, the train driver reacts and there is a shock reaction. This also has its influences on the train driver, what is your opinion about this?

Timetable and Comfort

1. From the moment the train driver is behind schedule and they approach a station, do they emphasize comfort or meeting the schedule?
2. The train driver relies on his own feeling while driving and not on specific braking parameters, for this reason is an accurate braking curve even necessary or is a comfort braking curve in the train a better option?
3. How do you envision abandoning the permitted curve and implementing a different braking curve?
4. From the moment there is hard intervention, or also called an intervention of the emergency brake , a lot of capacity is lost. So isn't capacity actually gained generally when the comfort braking curve is implemented so that less emergency braking is applied generally?

Technical Parameters and Simulations

1. Reaction times are included in the calculations of the permitted curve, but train drivers are also aware of this. Doesn't this automatically make them feel less pressure to follow the permitted curve?
2. These are important parameters related to a braking curve:
   - *Brake Deceleration: 0.5-0.6* m/s^2
   - *Sprinter: 0.66* m/s^2
   - *IC: 0.8* m/s^2
   - *Freight: 0.31* m/s^2

- *Jerk: between 0.7 3* m/s^3
- *Processing time, Driver response, Brake build-up time*

In your opinion, am I missing essential parameters for modeling the comfort braking curve? What are for you important aspects related to comfort, besides brake delay and jerk?

3. Do train drivers pursue the same comfort braking curve under different conditions?
4. Restructuring of braking parameter settings/design: Based on this sheet (braking curve model ETCS Level 2), how would you place the warning and indication curve? Where does the comfort braking curve take place? Should target speed monitoring be included here as well? Do you have ideas on how the warning, indication and target speed monitoring would be assigned to a comfort braking curve? Are these curves then still useful if the comfort braking curve positions underneath these braking curves?
5. Which simulation is useful with respect to implementing a new braking curve?
6. Are anticipation strategies considered in training of train drivers?
7. What is the difference between baseline 2 release 3 and baseline 3 release 2?

Appendix B Modelling tool selection

To model the impact of the curve, a simulation is needed, in order to do a validation and verification of the implementation. For that purpose, an applicable simulation program must be chosen. This section highlights the three simulations that were considered and which simulation program was finally used to proceed.

B.1 Opentrack

In the mid-1990s, OpenTrack began a research project at ETH (Swiss Federal Institute of Technology). This project aimed to develop a catalyst for practical and economic solutions to challenges in the rail sector. Today, Opentrack has become an established software tool within railroad simulation and planning. This tool is used worldwide. With opentrack, various railroad systems can be modeled and analyzed, for example:

- Intercity and regional trains
- Freight trains
- High-speed lines
- Light rail and streetcar systems

And many more, in addition, Opentrack supports a range of functions. For example, capacity analysis of tracks and stations, calculation of minimum follow-up times between trains, driving time calculations and timetable construction, design and evaluation of signaling and safety systems such as ETCS. On top of this, Opentrack also provides ability to perform calculations of the energy and power consumption of train's trips. When the trains are simulated, the timetable is observed and the movements of the train are calculated based on differential equations for distance and speed. During the simulation, data related to speed, acceleration/deceleration, position and energy consumption are stored. This data can be analyzed after the simulation. An additional functionality of Opentrack is the animation mode, which allows users to follow the simulation in real time.

All in all, Opentrack is a multifaceted intstrument for optimizing, analyzing and planning railroad systems. Figure 43 shows a schematic representation of this simulation. It briefly visualizes what the input to the simulation is and what output it generates. When the rolling stock, infrastructure and timetable are specified as inputs, this eventually leads to outputs such as: diagrams, occupations, train graphs and statistics. This output is very useful for various research and analysis.

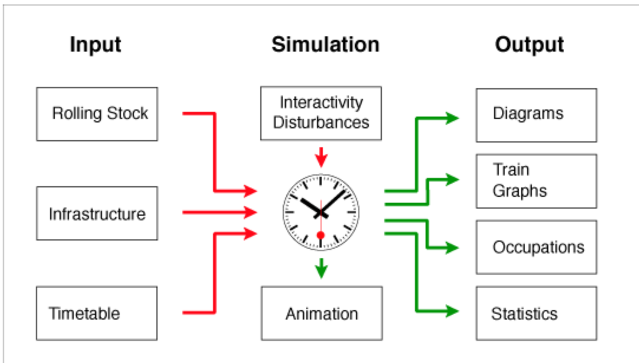

Figure 43: Schematic representation Opentrack, (OpenTrack Railway Technology, n.d.)

B.2 Railsys

Railsys is a commercial software used for railroad operations and planning. This simulation includes programs such as infrastructure manager, schedule manager, simulation manager and evaluation manager. Each module provides input to the next step. A schematic representation of the steps is shown in figure 44.

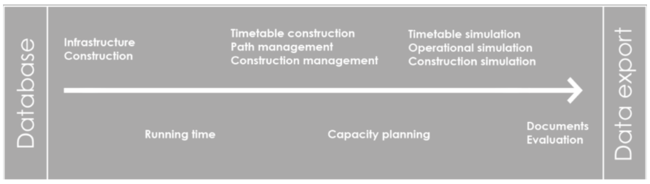

Figure 44: Schematic representation RailSys, (Rail Management Consultants International GmbH, 2024)

The simulation consists of different modules. First, the infrastructure module. This module is the first step and is used to modify the infrastructure and block sections. Multiple signaling systems are supported in the simulation, for example ETCS Level 2. Routes are created in the infrastructure module and later used in the next step to determine train paths and driving times, this step is the timetabling module.
Second, the timetable module. In the timetable module, timetable data is entered. This data consists of arrival and departure times, and is linked to vehicle profiles to calculate driving times. Importing other timetables from other RailSys projects is possible.
Third, the simulation functions. The simulation function provides various outputs. These include time-distance graphs and where conflicts are in the schedule. When a simulation is run, the graphs are updated with delays. In addition, the simulation also has a compression function to identify infrastructure and schedule bottlenecks.
Fourth is System Configurations. RailSys supports adjustments to ERTMS/ETCS settings to simulate driving behavior. But it has no option to adjust the driver's own driving behavior.

So railsys is a scheduling-related tool that offers many possibilities in the field of timetabling and infrastructure. Railsys performs timetable and operational simulations to determine the required infrastructure, schedule robustness and punctuality of the planned infrastructure. It also contributes to capacity management and monitoring of capacity utilization.

B.3 FRISO

The 'Flexibele Rail Infra Simulatie Omgeving', or also known as FRISO. This tool is an advanced simulation environment with which train movements can be simulated at a detailed level. This simulation environment features unique functionalities and extensive capabilities related to simulation studies, analysis and testing. Figure 45, below, shows a schematic representation of FRISO.

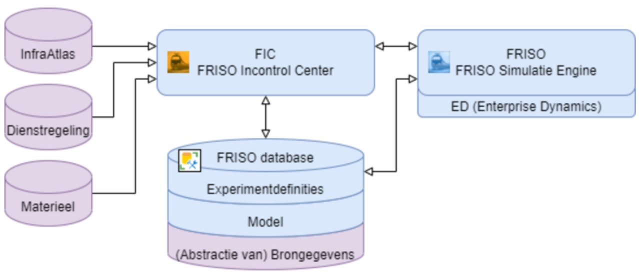

Figure 45: Schematic representation FRISO, (Friso Documentation, n.d.)

From this representation it becomes clear what the inputs are (Infrastructure, Timetable and Rolling stock) to finally arrive at the outputs in the FIC (Friso Incontrol Center).

The main components of FRISO are:

- FRISO Database: contains all data related to the simulation study. This includes infrastructure data, timetables, rolling stock specifications and simulation settings.
- FRISO Simulation Engine: this engine is used to perform the specified simulation
- FRISO Incontrol Center (FIC): This provides the interface of the simulation, it controls the simulation and in this interface the settings are managed.

The main component related to the FRISO database consists of several functionalities, the functionalities are:

- Infrastructure data: this includes signal images and the routes
- Timetables and equipment specifications: gives more space for detailed simulation
- Simulation settings: this includes route settings, disruptions and also the number of experiments.

Using the main components and associated functionalities, changes can be made to the existing infrastructures using the FRISO Infra Editor. This allows routes to be modified in the context of signal images or new infrastructure. The editor features a section generator and a data check tool, with this inconsistency errors are detected and corrected. The modifications can be automatically saved to the database.

When the simulation is specified on the appropriate scope, the FRISO engine is used to run the simulation. The settings are managed in the FIC. The output of the simulation is analyzed using graphs and files that provide further insights into the performance and effects of the simulation.

Additional functionality of FRISO is the link with the Traffic Management System (TMS), this gives the possibility to test and compare the TMS systems. In addition, it is also possible to investigate what the TMS contributes to optimizing the railroad system. Another special feature is the integration into the Trinity chain simulator. FRISO can be used as part of this chain simulator, this offers refinement and validation possibilities and this results in valuable applications in the rail sector. Think of training for users or testing influences on the new systems and train driver behavior. Another functionality of FRISO is an additional option for the validation of ETCS brake curves. The tool checks the calculations of the braking curves and this configuration can easily be read into the validator.

So FRISO is a versatile and detailed simulation tool. This tool is essential for analyzing and improving projects in the rail sector. Its extensive capabilities make FRISO a powerful simulation tool for research, training and innovative projects in the rail sector.

B.4 Comparison

The above simulations are briefly reviewed in this section on the advantages and disadvantages, from this it is concluded which simulation is suitable for this research. In this research braking is approached from the perspective of the train driver, for this reason it is a must to be able to adjust train driver behavior in the simulation.

OpenTrack
This simulation is a versatile simulation software that provides capabilities for modeling, simulation and analysis of the railroad system. Railroad systems such as high-speed trains, subways and streetcar networks. In addition, it offers evaluation of driving times, timetables, railroad infrastructure and energy consumption. This can be done with respect to ETCS Level 2, which is useful in this research. It offers an animation mode that allows users to visualize and analyze the simulations.

Advantages:

- The simulation can replicate a wide range of railroad systems
- Features advanced analytics such as minimum follow-up time and energy consumption
- Good visualizations

Disadvantages:

- Not focused on the in-depth adjustments related to train driver behavior
- The simulation focuses on general system analysis and is less focused on individual driving styles or driver-specific behavioral simulations

RailSys
This is a powerful planning and simulation software specializing in railroad operations and timetables. It has modules related to infrastructure management, schedule management, simulation and evaluation. This provides the ability to specify and evaluate infrastructure and schedule bottlenecks. In addition, RailSys provides a comprehensive analytical option to analyze capacity management, schedule robustness and punctuality. However, specifying train driver behavior is not possible here either.

Advantages:

- Strong in the areas of schedule analysis and infrastructure analysis
- Supporting the ETCS settings
- Ability to identify infrastructure and schedule bottlenecks

Disadvantages:

- Again, no option in adjusting driver behavior
- Railsys focuses more on planning and operational simulations and this is something not specifically required in this research

FRISO
FRISO is a simulation developed to simulate train running at a detailed level. It offers extensive capabilities, such as connecting to the Traffic Management System, providing training simulators and testing new systems. The unique advantage of FRISO is the ability to modify and simulate the train driver behavior. This makes this simulation suitable for validating ETCS braking curves and measuring the impact of train driver behavior on the railroad system. In addition, the braking curves can be adjusted to simulate the comfort braking curve.

Advantages:

- Ability to adapt in the train driver behavior
- Support in the extensive infrastructure modifications and validation of ETCS brake curves
- Detailed simulation of train driver behavior

Disadvantages:

- No possibility of specific modifications on sections where driving is specifically different. Consider, for example, driving over switches. This is because train drivers do not go through switches at full speed, but this is also not possible in Opentrack and Railsys.

In conclusion, despite OpenTrack and RailSys being advanced tools for general system analysis and timetable management, FRISO is chosen in this research. This is because FRISO has the unique ability to modify and simulate train driver behavior. As mentioned earlier, this is an essential component for defining, designing and assessing the comfort braking curve; in fact, this braking curve is defined and designed from the train drivers' perspective. With the ability to model driving behavior, this provides the opportunity to gain accurate insights into how the train driver brakes in certain situations and what influences this has on comfort and safety. FRISO fits seamlessly with the requirements of this research, and in this simulation, the comfort braking curve will be implemented and tested.

Appendix C Braking curve assessment

When the comfort braking curve has been defined and visualized, it is important to verify that the curve actually has the desired effects. So there is a need to test whether the degree of comfort is operationally efficient. This is done with the scope defined earlier: the ERTMS track section Amsterdam-Utrecht is selected, and the simulations are carried out with the train equipment VIRM and SNG. The hypothesis is that the proposed comfort braking curve eliminates the previously mentioned discomfort scenarios and the raised concerns from section 3.1 of the train driver and the proposed comfort braking curve represents train driver's course of action in general indicated in section 4.2. This hypothesis is tested both qualitatively and quantitatively. In addition, several measurement tests are conducted:

- Palpability test: from the moment the comfort braking curve is implemented, it is checked when the braking becomes palpable when the comfort braking curve is followed compared to the moment when the train driver, from his own experience, starts to apply the braking. This gives a view of the differences in train driver behavior.
- Usability test: this involves simulating a scenario the permitted curve is followed as it is normally followed (i.e., not exactly). And a scenario is simulated with the comfort braking curve. Here we look at the differences in the key performance indicators related to the normally followed situation and the comfort braking curve situation, think of the energy consumption, think of the power of the train, and the degree of acceleration/deceleration. Using this data, it is possible to address the wear and tear related to the train and track. Because, for example, the more power the train requires, the more deceleration and acceleration, the more energy is required of the equipment.
- Capacity test: in this test 2 situations are compared. Namely, in one situation the permitted curve is followed as it is normally followed (i.e., not exactly) and in the second situation the comfort braking curve is followed, but exactly (because the comfort braking curve mimics train driver behavior itself). In both situations we look at what the capacity implications are, from the moment congestion occurs, how it is resolved in both situations. To answer these questions about capacity, schedule fit plays an important role. It looks at whether the comfort braking curve fits the schedule and how much time a train has left or is short in the schedule to anticipate unexpected situations. In this capacity test, it can be tested whether the properties of the comfort braking curve are feasible as a braking curve without excessive delay, compared to the original train driver behavior. Both timetables, i.e. in both situations (normally and in the comfort braking curve situation) , are compared with each other.

These qualitative and quantitative tests answer the research question, What are the implications of implementing the comfort braking curve on capacity, wear and tear, safety, and driver experience? The implications for capacity are more strongly supported by the Palpability test and Capacity test. Because these tests give a picture of the start of braking and integration into the timetable. The implications for wear and tear emerge from the Usability and Capacity tests, because less braking power during train operations or less congestion on the railroad track contributes directly to the minimization of wear and tear on both track infrastructure and train equipment. The safety and driver experience implications are related to the recognition of driver behavior in the comfort braking curve, this is supported by the Palpability test and Usability test. Namely, these tests provide recognition of train driver behavior. Once the train driver recognizes the braking curve as corresponding to his natural behavior, driver experience will improve, stress during the mentioned discomfort scenarios will decrease and thus overall safety will increase. Safety will also increase when the equipment is saved, this is based on the Usability test.

Appendix D Timetable

Tmtbl. pt	Planting time	Realization time	Delay
	1st Hour		
Ut	00:42:00	00:42:00	0
Utzl	00:44:00	00:43:47	-12
Mas	00:46:48	00:46:13	-35
Bkla	00:49:06	00:48:16	-50
Bkl	00:49:18	00:48:26	-52
Aco	00:54:36	00:53:19	-77
Ac	00:55:06	00:53:48	-78
Ashd	00:56:06	00:54:42	-84
Asb	00:57:54	00:56:22	-92
Asb	00:58:48	...	...
	2nd Hour		
Ut	01:42:00	01:42:00	0
Utzl	01:44:00	01:43:47	-12
Mas	01:46:48	01:46:13	-35
Bkla	01:49:06	01:48:16	-50
Bkl	01:49:18	01:48:26	-52
Aco	01:54:36	01:53:19	-77
Ac	01:55:06	01:53:48	-78
Ashd	01:56:06	01:54:42	-84
Asb	01:57:54	01:56:22	-92
Asb	01:58:48	...	...
	3rd Hour		
Ut	02:42:00	02:42:00	0
Utzl	02:44:00	02:43:47	-12
Mas	02:46:48	02:46:13	-35
Bkla	02:49:06	02:48:16	-50
Bkl	02:49:18	02:48:26	-52
Aco	02:54:36	02:53:19	-77
Ac	02:55:06	02:53:48	-78
Ashd	02:56:06	02:54:42	-84
Asb	02:57:54	02:56:22	-92
Asb	02:58:48	...	...
	4th Hour		
Ut	03:42:00	03:43:26	86
Utzl	03:44:00	03:45:14	74
Mas	03:46:48	03:47:41	54
Bkla	03:49:06	03:49:44	39
Bkl	03:49:18	03:49:55	38
Aco	03:54:36	03:54:56	20
Ac	03:55:06	03:55:21	19
Ashd	03:56:06	03:56:21	15
Asb	03:57:54	04:00:43	169
Asb	03:58:48	...	...

Table 10: Schedule overview of train VIRM: 1st to 4th hour, standard train driver behavior

Tmtbl. pt	Planning time	Realization time	Delay
	5th Hour		
Ut	04:42:00	04:42:00	0
Utzl	04:44:00	04:43:47	-12
Mas	04:46:48	04:46:13	-35
Bkla	04:49:06	04:48:16	-50
Bkl	04:49:18	04:48:26	-52
Aco	04:54:36	04:53:19	-77
Ac	04:55:06	04:53:48	-78
Ashd	04:56:06	04:54:42	-84
Asb	04:57:54	04:56:22	-92
Asb	04:58:48	...	...
	6th Hour		
Ut	05:42:00	05:42:00	0
Utzl	05:44:00	05:43:47	-12
Mas	05:46:48	05:46:13	-35
Bkla	05:49:06	05:48:16	-50
Bkl	05:49:18	05:48:26	-52
Aco	05:54:36	05:53:19	-77
Ac	05:55:06	05:53:48	-78
Ashd	05:56:06	05:54:42	-84
Asb	05:57:54	05:56:22	-92
Asb	05:58:48	...	...
	7th Hour		
Ut	06:42:00	06:42:00	0
Utzl	06:44:00	06:43:47	-12
Mas	06:46:48	06:46:13	-35
Bkla	06:49:06	06:48:16	-50
Bkl	06:49:18	06:48:26	-52
Aco	06:54:36	06:53:19	-77
Ac	06:55:06	06:53:48	-78
Ashd	06:56:06	06:54:42	-84
Asb	06:57:54	06:56:22	-92
Asb	06:58:48	...	...
	8th Hour		
Ut	07:42:00	07:43:26	86
Utzl	07:44:00	07:45:14	74
Mas	07:46:48	07:47:41	54
Bkla	07:49:06	07:49:44	39
Bkl	07:49:18	07:49:55	38
Aco	07:54:36	07:54:56	20
Ac	07:55:06	07:55:21	19
Ashd	07:56:06	07:56:24	15
Asb	07:57:54	08:00:43	169
Asb	07:58:48	...	...

Table 11: Schedule overview of train VIRM: 5th to 8th hour, standard train driver behavior

Tmtbl. pt	Planning time	Realization time	Delay
	9th Hour		
Ut	08:42:00	08:43:26	86
Utzl	08:44:00	08:45:14	74
Mas	08:46:48	08:47:41	54
Bkla	08:49:06	08:49:44	39
Bkl	08:49:18	08:49:55	38
Aco	08:54:36	08:54:56	20
Ac	08:55:06	08:55:24	19
Ashd	08:56:06	08:56:21	15
Asb	08:57:54	09:00:43	169
Asb	08:58:48	...	...
	10th Hour		
Ut	09:42:00	09:43:26	86
Utzl	09:44:00	09:45:14	74
Mas	09:46:48	09:47:41	54
Bkla	09:49:06	09:49:44	39
Bkl	09:49:18	09:49:55	38
Aco	09:54:36	09:54:56	20
Ac	09:55:06	09:55:24	19
Ashd	09:56:06	09:56:21	15
Asb	09:57:54	10:00:43	169
Asb	09:58:48	...	...

Table 12: Schedule overview of train VIRM: 9th and 10th hour, standard train driver behavior

Tmtbl. pt	Planning time	Realization time	Delay
1st Hour			
Ut	00:42:00	00:42:00	0
Utzl	00:44:00	00:43:47	-12
Mas	00:46:48	00:46:13	-35
Bkla	00:49:06	00:48:16	-50
Bkl	00:49:18	00:48:26	-52
Aco	00:54:36	00:53:19	-77
Ac	00:55:06	00:53:48	-78
Ashd	00:56:06	00:54:44	-82
Asb	00:57:54	00:56:26	-88
Asb	00:58:48	...	...
2nd Hour			
Ut	01:42:00	01:42:00	0
Utzl	01:44:00	01:43:47	-12
Mas	01:46:48	01:46:13	-35
Bkla	01:49:06	01:48:16	-50
Bkl	01:49:18	01:48:26	-52
Aco	01:54:36	01:53:19	-77
Ac	01:55:06	01:53:48	-78
Ashd	01:56:06	01:54:44	-82
Asb	01:57:54	01:56:22	-88
Asb	01:58:48	...	...
3rd Hour			
Ut	02:42:00	02:42:00	0
Utzl	02:44:00	02:43:47	-12
Mas	02:46:48	02:46:13	-35
Bkla	02:49:06	02:48:16	-50
Bkl	02:49:18	02:48:26	-52
Aco	02:54:36	02:53:19	-77
Ac	02:55:06	02:53:48	-78
Ashd	02:56:06	02:54:44	-82
Asb	02:57:54	02:56:22	-88
Asb	02:58:48	...	...
4th Hour			
Ut	03:42:00	03:44:26	146
Utzl	03:44:00	03:46:14	134
Mas	03:46:48	03:48:39	111
Bkla	03:49:06	03:50:42	96
Bkl	03:49:18	03:50:52	95
Aco	03:54:36	03:55:47	71
Ac	03:55:06	03:56:16	70
Ashd	03:56:06	03:57:11	65
Asb	03:57:54	04:01:43	229
Asb	03:58:48	...	...

Table 13: Schedule overview of train VIRM: 1st to 4th hour, comfort braking curve

Tmtbl. pt	Planning time	Realization time	Delay
	5th Hour		
Ut	04:42:00	04:42:00	0
Utzl	04:44:00	04:43:47	-12
Mas	04:46:48	04:46:13	-35
Bkla	04:49:06	04:48:16	-50
Bkl	04:49:18	04:48:26	-52
Aco	04:54:36	04:53:19	-77
Ac	04:55:06	04:53:48	-78
Ashd	04:56:06	04:54:44	-82
Asb	04:57:54	04:56:26	-88
Asb	04:58:48	...	...
	6th Hour		
Ut	05:42:00	05:42:00	0
Utzl	05:44:00	05:43:47	-12
Mas	05:46:48	05:46:13	-35
Bkla	05:49:06	05:48:16	-50
Bkl	05:49:18	05:48:26	-52
Aco	05:54:36	05:53:19	-77
Ac	05:55:06	05:53:48	-78
Ashd	05:56:06	05:54:44	-82
Asb	05:57:54	05:56:26	-88
Asb	05:58:48	...	...
	7th Hour		
Ut	06:42:00	06:42:00	0
Utzl	06:44:00	06:43:47	-12
Mas	06:46:48	06:46:13	-35
Bkla	06:49:06	06:48:16	-50
Bkl	06:49:18	06:48:26	-52
Aco	06:54:36	06:53:19	-77
Ac	06:55:06	06:53:48	-78
Ashd	06:56:06	06:54:44	-82
Asb	06:57:54	06:56:26	-88
Asb	06:58:48	...	...
	8th Hour		
Ut	07:42:00	07:44:26	146
Utzl	07:44:00	07:46:14	134
Mas	07:46:48	07:48:39	111
Bkla	07:49:06	07:50:42	96
Bkl	07:49:18	07:50:52	95
Aco	07:54:36	07:55:47	71
Ac	07:55:06	07:56:16	70
Ashd	07:56:06	07:57:11	65
Asb	07:57:54	08:01:43	229
Asb	07:58:48	...	...

Table 14: Schedule overview of train VIRM: 5th to 8th hour, comfort braking curve

Tmtbl. pt	Planting time	Realization time	Delay
	9th Hour		
Ut	08:42:00	08:44:26	146
Utzl	08:44:00	08:46:14	134
Mas	08:46:48	08:48:39	111
Bkla	08:49:06	08:50:42	96
Bkl	08:49:18	08:50:52	95
Aco	08:54:36	08:55:47	71
Ac	08:55:06	08:56:16	70
Ashd	08:56:06	08:57:11	65
Asb	08:57:54	09:01:43	229
Asb	08:58:48	...	...
	10th Hour		
Ut	09:42:00	09:44:26	146
Utzl	09:44:00	09:46:14	134
Mas	09:46:48	09:48:39	111
Bkla	09:49:06	09:50:42	96
Bkl	09:49:18	09:50:52	95
Aco	09:54:36	09:55:47	71
Ac	09:55:06	09:56:16	70
Ashd	09:56:06	09:57:11	65
Asb	09:57:54	10:01:43	229
Asb	09:58:48	...	...

Table 15: Schedule overview of train VIRM: 9th and 10th hour, comfort braking curve

Tmtbl. pt	Planning time	Realization time	Delay
	1st Hour		
Bkl	00:28:00	00:28:00	0
Bkla	00:28:42	00:28:31	-10
Mas	00:32:18	00:31:31	-47
Mas	00:33:00	00:33:00	0
Utzl	00:37:12	00:36:34	-37
Utzl	00:37:54	00:37:54	0
Utma	00:38:48	00:38:40	-7
Ut	00:41:00	00:40:02	-57
Ut	00:44:30	00:44:30	0
Utvr	00:46:30	00:46:18	-12
Utvr	00:47:12	...	...
	2nd Hour		
Bkl	01:28:00	01:28:00	0
Bkla	01:28:42	01:28:31	-10
Mas	01:32:18	01:31:31	-47
Mas	01:33:00	01:33:00	0
Utzl	01:37:12	01:36:34	-37
Utzl	01:37:54	01:37:54	0
Utma	01:38:48	01:38:40	-7
Ut	01:41:00	01:40:02	-57
Ut	01:44:30	01:44:30	0
Utvr	01:46:30	01:46:18	-12
Utvr	01:47:12	...	...
	3rd Hour		
Bkl	02:28:00	02:28:00	0
Bkla	02:28:42	02:28:31	-10
Mas	02:32:18	02:31:31	-47
Mas	02:33:00	02:33:00	0
Utzl	02:37:12	02:36:34	-37
Utzl	02:37:54	02:37:54	0
Utma	02:38:48	02:38:40	-7
Ut	02:41:00	02:40:02	-57
Ut	02:44:30	02:44:30	0
Utvr	02:46:30	02:46:18	-12
Utvr	02:47:12	...	...
	4th Hour		
Bkl	03:28:00	03:28:00	0
Bkla	03:28:42	03:28:31	-10
Mas	03:32:18	03:31:31	-47
Mas	03:33:00	03:33:00	0
Utzl	03:37:12	03:36:34	-37
Utzl	03:37:54	03:37:54	0
Utma	03:38:48	03:38:40	-7
Ut	03:41:00	03:40:02	-57
Ut	03:44:30	03:44:30	0
Utvr	03:46:30	03:46:18	-12
Utvr	03:47:12	...	...

Table 16: Schedule overview of train SNG: 1st to 4th hour, standard train driver behavior

Tmtbl. pt	Planting time	Realization time	Delay
	5th Hour		
Bkl	04:28:00	04:28:00	0
Bkla	04:28:42	04:28:31	-10
Mas	04:32:18	04:31:31	-47
Mas	04:33:00	04:33:00	0
Utzl	04:37:12	04:36:34	-37
Utzl	04:37:54	04:37:54	0
Utma	04:38:48	04:38:40	-7
Ut	04:41:00	04:40:02	-57
Ut	04:44:30	04:44:30	0
Utvr	04:46:30	04:46:18	-12
Utvr	04:47:12	...	...
	6th Hour		
Bkl	05:28:00	05:28:00	0
Bkla	05:28:42	05:28:31	-10
Mas	05:32:18	05:31:31	-47
Mas	05:33:00	05:33:00	0
Utzl	05:37:12	05:36:34	-37
Utzl	05:37:54	05:37:54	0
Utma	05:38:48	05:38:40	-7
Ut	05:41:00	05:40:02	-57
Ut	05:44:30	05:44:30	0
Utvr	05:46:30	05:46:18	-12
Utvr	05:47:12	...	...
	7th Hour		
Bkl	06:28:00	06:28:00	0
Bkla	06:28:42	06:28:31	-10
Mas	06:32:18	06:31:31	-47
Mas	06:33:00	06:33:00	0
Utzl	06:37:12	06:36:34	-37
Utzl	06:37:54	06:37:54	0
Utma	06:38:48	06:38:40	-7
Ut	06:41:00	06:40:02	-57
Ut	06:44:30	06:44:30	0
Utvr	06:46:30	06:46:18	-12
Utvr	06:47:12	...	...
	8th Hour		
Bkl	07:28:00	07:28:00	0
Bkla	07:28:42	07:28:31	-10
Mas	07:32:18	07:31:31	-47
Mas	07:33:00	07:33:00	0
Utzl	07:37:12	07:36:34	-37
Utzl	07:37:54	07:37:54	0
Utma	07:38:48	07:38:40	-7
Ut	07:41:00	07:40:02	-57
Ut	07:44:30	07:44:30	0
Utvr	07:46:30	07:46:18	-12
Utvr	07:47:12	...	...

Table 17: Schedule overview of train SNG: 5th to 8th hour, standard train driver behavior

Tmtbl. pt	Planning time	Realization time	Delay
	9th Hour		
Bkl	08:28:00	08:28:00	0
Bkla	08:28:42	08:28:31	-10
Mas	08:32:18	08:31:31	-47
Mas	08:33:00	08:33:00	0
Utzl	08:37:12	08:36:34	-37
Utzl	08:37:54	08:37:54	0
Utma	08:38:48	08:38:40	-7
Ut	08:41:00	08:40:02	-57
Ut	08:44:30	08:44:30	0
Utvr	08:46:30	08:46:18	-12
Utvr	08:47:12	...	...
	10th Hour		
Bkl	09:28:00	09:28:00	0
Bkla	09:28:42	09:28:31	-10
Mas	09:32:18	09:31:31	-47
Mas	09:33:00	09:33:00	0
Utzl	09:37:12	09:36:34	-37
Utzl	09:37:54	09:37:54	0
Utma	09:38:48	09:38:40	-7
Ut	09:41:00	09:40:02	-57
Ut	09:44:30	09:44:30	0
Utvr	09:46:30	09:46:18	-12
Utvr	09:47:12	...	...

Table 18: Schedule overview of train SNG: 9th and 10th hour, standard train driver behavior

Tmtbl. pt	Planting time	Realization time	Delay
	1st hour		
Bkl	00:28:00	00:28:00	0
Bkla	00:28:42	00:28:31	-10
Mas	00:32:18	00:31:44	-34
Mas	00:33:00	00:33:00	0
Utzl	00:37:12	00:36:48	-23
Utzl	00:37:54	00:37:54	0
Utma	00:38:48	00:38:48	0
Ut	00:41:00	00:40:40	-19
Ut	00:44:30	00:44:30	0
Utvr	00:46:30	00:46:29	-1
Utvr	00:47:12	00:47:12	0
	2nd hour		
Bkl	01:28:00	01:28:00	0
Bkla	01:28:42	01:28:31	-10
Mas	01:32:18	01:31:44	-34
Mas	01:33:00	01:33:00	0
Utzl	01:37:12	01:36:48	-23
Utzl	01:37:54	01:37:54	0
Utma	01:38:48	01:38:48	0
Ut	01:41:00	01:40:40	-19
Ut	01:44:30	01:44:30	0
Utvr	01:46:30	01:46:29	-1
Utvr	01:47:12	01:47:12	0
	3rd hour		
Bkl	02:28:00	02:28:00	0
Bkla	02:28:42	02:28:31	-10
Mas	02:32:18	02:31:44	-34
Mas	02:33:00	02:33:00	0
Utzl	02:37:12	02:36:48	-23
Utzl	02:37:54	02:37:54	0
Utma	02:38:48	02:38:48	0
Ut	02:41:00	02:40:41	-19
Ut	02:44:00	02:44:00	0
Utvr	02:46:30	02:46:30	0
Utvr	02:47:12	02:47:12	0
	4th hour		
Bkl	03:28:00	03:28:00	0
Bkla	03:28:42	03:28:31	-10
Mas	03:32:18	03:31:44	-34
Mas	03:33:00	03:33:00	0
Utzl	03:37:12	03:36:48	-23
Utzl	03:37:54	03:37:54	0
Utma	03:38:48	03:38:48	0
Ut	03:41:00	03:40:40	-19
Ut	03:44:00	03:44:00	0
Utvr	03:46:30	03:46:29	-1
Utvr	03:47:12	03:47:12	0

Table 19: Schedule overview of train SNG, 1st and 4th hours, comfort braking curve

Tmtbl. pt	Planting time	Realization time	Delay
	5th hour		
Bkl	04:28:00	04:28:00	0
Bkla	04:28:42	04:28:31	-10
Mas	04:32:18	04:31:44	-34
Mas	04:33:00	04:33:00	0
Utzl	04:37:12	04:36:48	-23
Utzl	04:37:54	04:37:54	0
Utma	04:38:48	04:38:48	0
Ut	04:41:00	04:40:40	-19
Ut	04:44:30	04:44:30	0
Utvr	04:46:30	04:46:29	-1
Utvr	04:47:12	04:47:12	0
	6th hour		
Bkl	05:28:00	05:28:00	0
Bkla	05:28:42	05:28:31	-10
Mas	05:32:18	05:31:44	-34
Mas	05:33:00	05:33:00	0
Utzl	05:37:12	05:36:48	-23
Utzl	05:37:54	05:37:54	0
Utma	05:38:48	05:38:48	0
Ut	05:41:00	05:40:40	-19
Ut	05:44:30	05:44:30	0
Utvr	05:46:30	05:46:29	-1
Utvr	05:47:12	05:47:12	0
	7th hour		
Bkl	06:28:00	06:28:00	0
Bkla	06:28:42	06:28:31	-10
Mas	06:32:18	06:31:44	-34
Mas	06:33:00	06:33:00	0
Utzl	06:37:12	06:36:48	-23
Utzl	06:37:54	06:37:54	0
Utma	06:38:48	06:38:48	0
Ut	06:41:00	06:40:40	-19
Ut	06:44:30	06:44:30	0
Utvr	06:46:30	06:46:30	0
Utvr	06:47:12	06:47:12	0
	8th hour		
Bkl	07:28:00	07:28:00	0
Bkla	07:28:42	07:28:31	-10
Mas	07:32:18	07:31:44	-34
Mas	07:33:00	07:33:00	0
Utzl	07:37:12	07:36:48	-23
Utzl	07:37:54	07:37:54	0
Utma	07:38:48	07:38:48	0
Ut	07:41:00	07:40:40	-19
Ut	07:44:30	07:44:30	0
Utvr	07:46:30	07:46:29	-1
Utvr	07:47:12	07:47:12	0

Table 20: Schedule overview of train SNG, 5th and 8th hour, comfort braking curve

Tmtbl. pt	Planning time	Realization time	Delay
	9th hour		
Bkl	08:28:00	08:28:00	0
Bkla	08:28:42	08:28:31	-10
Mas	08:32:18	08:31:44	-34
Mas	08:33:00	08:33:00	0
Utzl	08:37:12	08:36:48	-23
Utzl	08:37:54	08:37:54	0
Utma	08:38:48	08:38:48	0
Ut	08:41:00	08:40:41	-19
Ut	08:44:30	08:44:30	0
Utvr	08:46:30	08:46:29	-1
Utvr	08:47:12	08:47:12	0
	10th hour		
Bkl	09:28:00	09:28:00	0
Bkla	09:28:42	09:28:31	-10
Mas	09:32:18	09:31:44	-34
Mas	09:33:00	09:33:00	0
Utzl	09:37:12	09:36:48	-23
Utzl	09:37:54	09:37:54	0
Utma	09:38:48	09:38:48	0
Ut	09:41:00	09:40:40	-20
Ut	09:44:30	09:44:30	0
Utvr	09:46:30	09:46:29	-1
Utvr	09:47:12	09:47:12	0

Table 21: SNG schedule overview, 9th and 10th hour, comfort braking curve

Appendix E Offensive comfort braking curve

A more offensive form of comfort braking is shown below. This offensive form is partly consistent with the comfort standard from literature and practice. First, this braking curve is introduced with coasting, as shown in figure refComfort curve braking offensive, the light blue line. After this, a braking deceleration of 0.5 m/s^2 is introduced and then connects to the permitted curve, resulting in higher braking deceleration. Harder braking deceleration is not necessarily a negative thing, but it is important to build up gradually. This offensive braking curve offers the advantage that it gives the train driver a little more room to act offensively, so the train driver is not advised to brake at an earlier stage which happens with the comfort braking curve. This may be perceived as obstructive, potentially leading train drivers to disregard it. This offensive form was not explored further in this research, but it remains an interesting perspective to compare with.

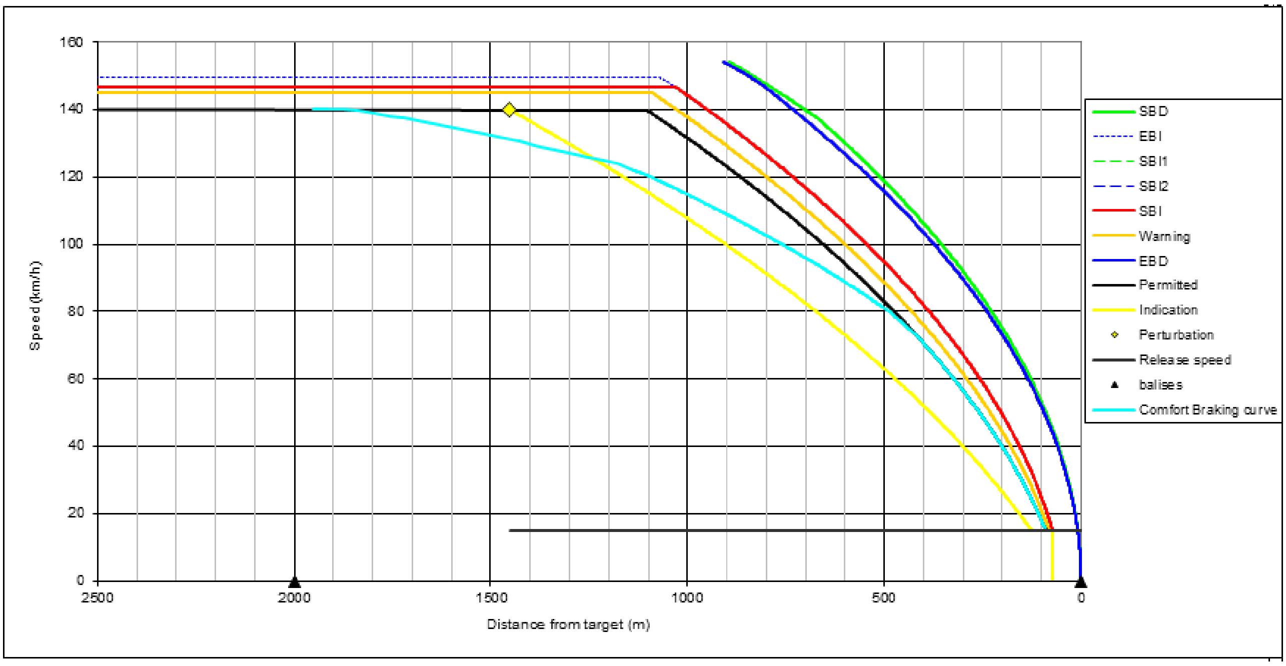

Figure 46: Offensive comfort braking curve