Doctoral thesis

Influence of train and traffic control on railway station capacity

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Dissertation

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Preface

I became interested in the railway system at a young age. Since then I have travelled a lot by rail to various countries in Europe. Even though a lot has changed, my interest remains unbroken. The issue of capacity is one that has been with me for a long time, even as a passenger. But this I didn’t notice directly, but rather the consequences and effects on the timetable. Many discussions on the use of new technologies are currently taking place in this railway area. For example, artificial intelligence, automated train operation, cloud or digital interlockings, to name just a few. Within my years of study, I learned a lot and I also gained knowledge about the topic itself. What I have learnt is that it can sometimes be necessary to take a step back in order not to lose sight of the big picture. Particularly in the railway sector, where many specialist areas come together, it can also be important to exchange ideas and discuss them critically at conferences or with colleagues. So, I am very thankful for the input from these conversations, which have brought me closer to finalizing this dissertation. The most important thing for me now is that I have learnt that I am responsible for achieving my targets and that consequent steps forward are a way to achieve goals.

Therefore, I would also like to address a few messages to those people who have supported me. First of all, I would like to thank my mentor Priv.-Doz. Andreas Schöbel for taking the time to supervise my doctoral thesis and for answering my questions so quickly and easily. I would also like to thank Assoc.-Prof. Hrvoje Haramina, who acts as my second mentor. I learnt a lot in numerous discussions with him. Especially during my research stay at the Faculty of Transport and Traffic Sciences in Zagreb. I learnt a lot from both, not only for my doctorate but also for my future academic career. I would also like to thank Prof. Sanjin Milinković and Prof. Stefano Ricci for reviewing my dissertation. Both immediately agreed to do the review. I would also like to thank my colleagues from the St. Pölten University of Applied Sciences, who always had an open ear for me and, were able to provide me with valuable tips for working on my topic. I would particularly like to emphasise FH-Prof. Frank Michelberger, Head of the Carl Ritter von Ghega Institute for Integrated Mobility Research. He supported me at all times and also ensured that I could work on my thesis. Besides him, I would also like to thank Dr. Alexandra Anderluh, who was always available to answer my questions. Additionally, I am thankful for the numerous experts who helped me with my questions and provided good answers. Unfortunately, it is not possible for me to name them all, but I would like to thank each and every one of them.

Of course, I would also like to thank my family and friends. Especially, I would like to thank my love Sabina, who has always supported me in many ways. She understood when I had to spend time working on my thesis. She always had an open ear. And when I had doubts, she has always motivated and encouraged me to finish this doctoral thesis.

Zusammenfassung

Derzeit sind viele Strecken im Eisenbahnwesen hochbelastet und können dem benötigten Verkehrsaufkommen nicht mehr gerecht werden. Da Neubauten sehr hohe Investitionen erfordern und nicht überall möglich sind, stellt sich die Frage, ob man dem Verkehrsaufkommen in anderer Form gerecht werden kann, um eine weitere Verkehrsverlagerung zur Schiene zu ermöglichen. Im Zuge dieser Dissertation soll daher untersucht werden, ob und wie eine Steigerung der Kapazität im Bereich von Bahnhöfen durch die Adaptierung der Zugsicherung möglich ist. Es wird dazu untersucht, wie die Betriebsabwicklung im Bestand durchgeführt wird und welche Zugsicherungssysteme dabei bereits in der Praxis zur Anwendung kommen. Dazu werden PZB, LZB, CBTC und ETCS erörtert. Neben der Erarbeitung dieser Grundlagen ist die Definition von Kapazität ein maßgeblicher Punkt der vorliegenden Dissertation. So werden verschiedene Definitionen für diesen Begriff erörtert und entsprechende Berechnungsmethoden zur Kapazitätsbestimmung präsentiert. Typischerweise lassen sich zur Ermittlung der Leistungsfähigkeit konstruktive Methoden, Optimierungsmethoden, Parametrische Methoden, statistisch- Deterministische Modelle bzw. stochastische Methoden anwenden. Letztere lassen sich in analytische Methoden und Simulationen einteilen, wobei in dieser Arbeit synchrone Simulationsverfahren mit der Software OpenTrack zur Anwendung kommen. Als Vergleichsparameter wird in dieser Arbeit die Zugfolgezeit herangezogen. Dabei werden acht verschiedene Strecken in sechs Simulationen untersucht. Neben einer Ausgangsvariante wird ETCS Level 2, und ETCS Level 3 Moving Block untersucht. Zusätzlich zu diesen Varianten wird auch untersucht, wie sich das Fahren mit Streckengeschwindigkeit bis zum Beginn einer Weiche unter ETCS Level 2 auswirkt. Kombiniert wird dies mit verdichteten Blockabständen. Es zeigt sich dabei, dass die Implementierung von ETCS Level 2 ohne weitere Begleitmaßnahmen nicht zur einer Kapazitätssteigerung führt. Mit den entsprechenden Begleitmaßnahmen können jedoch Verbesserungen erzielt werden. So zeigt sich, dass bei verkürzten Blockabschnitten die Zugfolgezeit Richtung jener des Moving Blocks strebt. Die durchgeführten Untersuchungen zeigen somit wie ETCS Level 3 Hybrid, jener Variante mit den verkürzten Blockabschnitten, zu einer Erhöhung der Kapazität führen kann. Insbesondere zeigt sich, dass das Potential erst voll ausgenutzt werden kann, wenn sämtliche Züge über ein System zur Bestätigung der Zugintegrität verfügen. Die größten Erkenntnisse in dieser Dissertation liegen in der Quantifizierung der Zugfolgezeiten.

Abstract

Existing railway lines, especially in urban areas, are often highly utilized and it is not possible to add additional train routes. Building new railway lines cannot be the solution, because of high construction costs, and the duration of planning and construction. Therefore, for a model shift to the rail, it is necessary to find other solutions. For this purpose, within this dissertation, it should be analysed how the capacity of stations can be increased by train- and traffic control. At the beginning, there will be an analysis of the existing procedures in railway operations, to understand which and how train protection systems are used. In addition, PZB, LZB, CBTC and ETCS are explained. Beneath this background research there will also be research on how capacity is defined and which measures are used to calculate capacity; for these, objective different methods are used, like constructive methods, optimization methods, parametric methods, statistical/deterministic methods, and stochastic models. Stochastic models can be subdivided into analytical methods and simulation methods. In this thesis, synchronous simulations with the software OpenTrack are used. Here, eight different railway lines are simulated in six simulations. Beneath a base variant, variants with ETCS Level 2 and Level 3 Moving Block are investigated. Another ETCS Level 2 scenario is, that at diverging turnouts, with lower speed, the line speed is used up to the beginning of the turnouts. Compared to the situation where the lower turnout speed must be used from the home signal, there can be found a different headway. These measures will be combined with shorter block sections. It can be shown that ETCS Level 2 without additional measures does not result in an increase in capacity. With additional accompanying measures, there can be an increase in capacity. With ETCS Level 2 and the shorter block sections, the headway aims to the headway time of ETCS Level 3 Moving Block. This means, that ETCS Level 2 with shorter blocks, which corresponds to the principle of ETCS Level 3 Hybrid, leads to a higher capacity. The potential is fully used when all trains are equipped with a train integrity monitoring system. The main result of this thesis is the quantification of the change in headway.

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1 Introduction

In addition to the goals of the European Union (EU) Green Deal and Austria's climate neutrality planned by 2040 and a simultaneous increase in traffic volume, especially in urban areas, is leading to new challenges for the transport sector. Beside rising passenger traffic, rail freight transport in Austria is planned to be doubled by 2040 (ÖBB Holding AG, 2021). The Europe-wide target for rail freight transport is to have a 30% modal split share by 2030 (CER on behalf of Rail Freight Forward, 2020, p. 7). In order to successfully accomplish these targets, it is not only necessary to create incentives to choose rail freight transport, but it is also necessary to optimize the existing processes and technical framework conditions. Also, existing railway lines are often at their capacity limit and further increases are not possible (Berger, 2021, p. 67). In the long-term, this can be solved by network expansion, which creates additional capacities for new trains. In the short and medium-term, however, this is not possible or only possible to a limited extent. Therefore, it is necessary to consider how the capacities in the existing railway network can be improved to bring more traffic on the railways. Various technical systems are already available or in discussion, for example automatic route setting and adaptive train control. However, these systems are not used throughout the entire network or are only in the scope of a research. From a closer look at the idea of continuous train control of the train trip, a few parameters can be found sooner or later, such as the overlap, the flank protection, the block length, or others. There can be found statements where Automatic Train Operation over European Train Control System (ATO over ETCS) is propagated as game changer for capacity gain. This raises the question of whether and what effect all these parameters have on capacity. If there is a significant change, these measures could be used to improve the railway operations with minor intervention in the infrastructure to increase the number of trains in a node. This, in turn, would have an impact on the entire system. Smaller intervention in the infrastructure would be easier and faster to achieve and the benefits could be available sooner (Schnieder, 2019, p. 3). That's the reason, why the focus of this work lies on measures in train and traffic control. The work concentrates on the junctions, as this is where most of the disturbances occur (Yuan & Hansen, 2007, pp. 202–204). The main objective is to show the possibilities for increasing capacity at railway stations and to identify approaches for adaptations. For this purpose, this introduction chapter describes the basis the framework conditions and the questions related to this topic.

1.1 Definition of the study area

This thesis deals with railway operations in Europe. Typically, in Europe, a clear differentiation will be made between shunting and train movements. Even if these main processes are comparable, the operational regulations of the individual countries or infrastructure managers differ. Therefore, Austria is used as a basis for this work to explain certain situations and to develop the basis for answering the research questions. Also, comparisons will be made with other European countries to consider the different approaches in different areas such as safety principles. In addition, it should be explicitly mentioned at this point that this is a scientific approach and that for example no possible solutions are excluded, from an economic point of view, or if they are not compatible with the existing operational regulations. Rather, a universally applicable approach is generated, which is tested on selected infrastructure. Bottlenecks in which the methods are tested are used to select the infrastructure. Connected railway lines are used for the simulations and stations with different real track characteristics are simulated. Regarding the infrastructure, only recommendations for adaptations are given, which are, however, not explored in detail. Regarding the time frame for the investigation, current processes and technologies are considered.

1.2 Initial situation and problem definition

As already described in the introduction, a significant increase in rail transport in Europe as well as in Austria is to be expected. In passenger transport, for example, except for the pandemic year 2020, there has been a significant increase in passenger transport. While in 2012 there were still 90.8 million train kilometres in Austria, in 2021 there were already 103 million train kilometres and a further increase can be assumed (ÖBB Holding AG, 2022). Together with the planned doubling of rail freight traffic by 2040, this represents considerable pressure on the existing rail network (ÖBB Holding AG, 2021). New rail infrastructure will not be built within this timeframe, as the average realisation period of a new or rail infrastructure project, for example, at the German infrastructure operator *Deutsche Bahn Netz AG* (DB Netz AG), is currently 20 years (Rompf, 2018, p. 9). It should be mentioned at this point that *DB Netz AG* is now the Track division of DB *InfraGO AG* since 1 January 2024 (DB InfraGO AG, 2024).

The literature shows that infrastructure deconstruction works in the last decades in particular have had a counterproductive effect on capacity. Therefore, on a leaner infrastructure with simultaneously increasing traffic, more bottlenecks and disturbances occur. These then affect all rail traffic, whether local passenger transport, long-distance passenger transport or freight transport. This results for the customers are delays, which can lead to the loss of connecting trains, especially in passenger traffic (Dewilde et al., 2014, p. 276). In order to achieve further increases in traffic, effective short-term measures to increase capacity are required in addition to expansion measures.

Previous considerations are based on different levels of analysis, for example, entire networks, individual lines or only nodes have been considered. In practice, network models are created or only the feasibility of an operational program on a line is examined. However, not only the feasibility of the operational program was part of the previous investigations, but also capacity considerations for the assignment of train paths, which take place far in advance of a train journey. In the following chapter, capacity considerations can already take place in the planning and allocation of train paths. This state of the art will be examined in more detail in the next main chapter.

1.3 Research questions

As already described in the introduction, the problem definition makes it necessary to examine several aspects of optimisation in operational processes in detail. Therefore, one main research question is created, on which several sub-questions are based:

- How station capacity can be increased by using train control methods?

To answer this question, it is necessary to answer the following sub-points:

- Which different approaches for train control are common (methodology / national rules)?
- What different methods exist to increase the performance in railway operations and what effect do they have?
- Is it possible to use these methods in railway stations and what effect do they have?

1.4 Methodical approach

This dissertation is divided into three main parts, whereby the work follows a methodological mix of theoretical and practical approaches. In the first part, the theoretical background is prepared, which is necessary to answer the research questions. Thereby, the processes and technologies of train and traffic control are analysed. Methodically, this is done by literature research in scientific platforms, technical literature, analysis of rulebooks of the infrastructure managers. In this context, the main processes of the formation of train routes are considered. It should be noted, however, that no analyses of all interlocking technologies are carried out, as this is not relevant to answer the research questions. After the state of the art in railway operations has been surveyed, the second part of the thesis deals with the term's capacity, performance, and their determination. In addition, measures are considered that are related to capacity and influence it. Of course, only measures that positively influence capacity will be considered further. In the third part of this thesis, it is examined whether such measures can be applied to railway stations. For this purpose, various lines that have congestion and where bottlenecks are already occurring or may occur in the future due to further increases in traffic will be selected. The aim is to look at lines or stations of different complexity. Based on microsimulations, operational situations with the existing infrastructure and the used technologies will be modelled. Subsequently, the capacity-increasing measures will be implemented, and a gap analysis will be carried out. Based on this, it is verified whether and to what changes are visible. These simulations will be carried out with the software OpenTrack, in which railway operational simulations can be carried out on a microscopic level. The result of the work will be a concept that can be applied to railway stations and contains possibilities for increasing performance.

2 Thematic background

In order to analyse the term capacity, it is necessary to describe the basic framework conditions of railway operations, which will be sketched out in the following part of the chapter. These operations can be classified in most railroad systems as train movements and shunting movements (Pachl, 2021a, pp. 15–16). But there can be also other forms, like in Austria, the secondary traffic (“Nebenfahrt”) (ÖBB Infrastructure AG, 2020b, pp. 76–77). In short, train movements, also known as running movements, are the main transport process and shunting movements are an assistance process for train formation and train disassembly. Train movements typically take place at block headways on the line between two railway stations. These movements are operated according to a fixed timetable (Pachl, 2013a, pp. 409–410, 2021a, p. 15). Shunting movements are used to form or dissemble trains. For example, shunting the order of wagons in a train formation can be changed. Typically shunting takes place in railway stations for example in sidings. In addition, in Austria, trips to the line outside of station areas are done in the form of secondary traffic. This involves the use of locomotives, in some cases special vehicles for secondary traffic, to make movements to industrial sidings, movements into blocked tracks or movements into blocked track sections (Pachl, 2013a, p. 409). In the context of the dissertation, it therefore makes sense to divide the stations into different categories. The Austrian Railway Construction and Operation Ordinance (Eisenbahnbau- und – betriebsverordnung - EisbBBV) defines the term stations as well as branches and junctions. (§11 /1-6 EisbBBV - Eisenbahnbau- und -betriebsverordnung, 2008) According to this classification, industrial sidings are rather to be seen as connecting points. Based on Bendfeldt (2005), not every station where intermediate stops are made is a node. However, every node is a station, as it necessarily connects several railway lines with each other (Bendfeldt, 2005, p. 8).

As already mentioned, the railway environment can be roughly divided into the open line and the station areas. In the station area, the tracks which are primarily used for train movements are called main tracks or more often in England, running lines. Furthermore, there are sidings, which are only used for shunting movements. Mainly, these tracks are equipped only with shunting signals and often without train protection systems. The tracks between two station areas are called open lines. A station area is located between the home signals from each direction. In this area, shunting is allowed to the specific border, which is marked by the limit of shunt boards. But it is also possible to expand this area with the permission of the station dispatcher (Pachl, 2021a, p. 14).

The open line begins at the yard limits; for trains which are leaving, the relevant signal is the exit signal and allows trains to leave the station area. For incoming trains, the home signal gives the permission to enter the railway station. In Austria, for example, intermediate signals or protecting signals separate different parts of tracks from each other. On the open line, block signals are used to divert the line between to stations into several blocks (ÖBB Infrastructure AG, 2017, p. 6). As already described, there are different types of signals. They can not only be divided into home signals, exit signals, etc., but can also be differentiated into categories. Distance and main signals can be used. Other signalling systems with combined signals, which can signalize movement authority and the allowed speed and the aspect of the following signal can be found in different countries (Theeg, 2009, pp. 189–199).

The description visualises that safe rail operations are based on the fact that trains run at a certain distance from each other. Typically, this is realised in fixed block sections or so-called moving blocks (Pachl, 2021a, p. 19). The majority of train movements take place in fixed block sections between two main signals. Because there is only one train allowed in a section at a time, the first train must leave the section before the next train can enter it. This fact shows how the circumstances of the railway environment are essential for the term of capacity. But the occupation time of a block begins much earlier before the train arrives. The blocking time consists of the time for setting the route, a signal sight time, and a time for approaching the block section, in this case, the time between the distance signal and the main signal. This is followed by the travel time through the block and the time for clearing the block section. This is followed by the time for the route release. After that, the block section and a possible overlap are free of trains and the next train journey is possible. Figure 1 shows the process just described (Pachl, 2021a, p. 26).

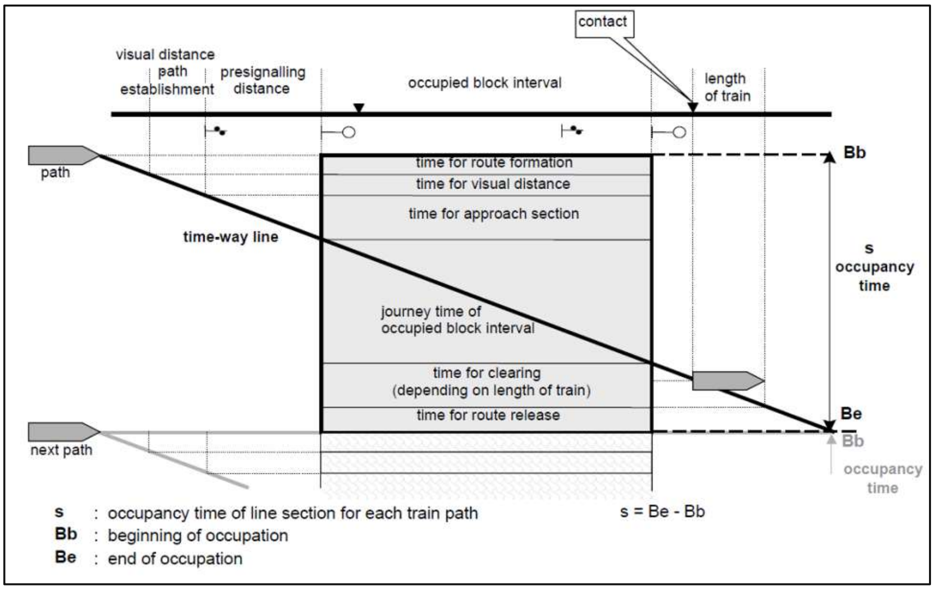

Figure 1: Blocking time of a block section.

Source: Figure taken from International Union of Railways (2013, p. 15)

If a route is set immediately after the first train, then the time between the two trains is called the minimum headway. In practice, however, buffer times are used to prevent delays from being transferred from one train to another (Schwanhäußer, 1974, p. 3).

Figure 2 shows the described components in a time-distance diagram. For this purpose, a simulation from the software OpenTrack of a fictive railway line is used. Out of the timetable data, a time-distance diagram is created. It shows a local express train. In order to show how a minimal headway is revealed, a suburban train is created in such a way that the blocking times touch each other in one line section. The third train shows a long-distance train.

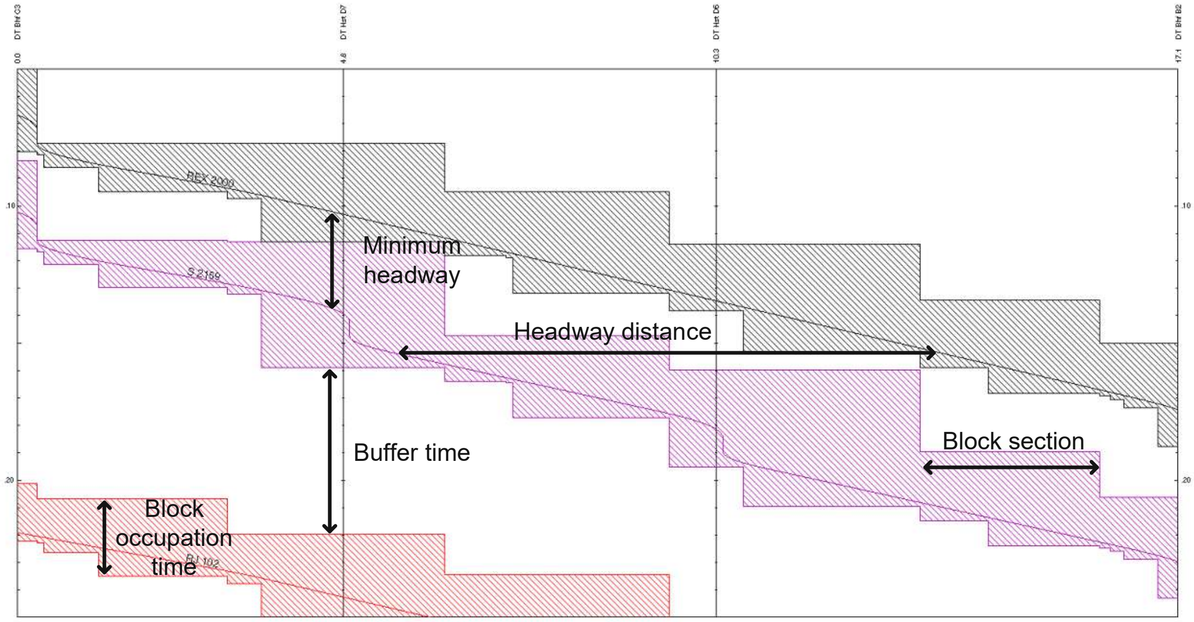

Figure 2: Components of the time-distance diagram

Source: Own visualization in OpenTrack 1.10.3: Time-distance diagram of the NITOB Simulation. Buffer time components based on Palumbo et al. (2015, p. 47)

It can be seen that various factors such as the speed, the used signalling system and the length of the block sections have an effect on the blocking time. The analysis of the blocking time staircases and the minimum headways are accepted methods in the literature to determine the performance of a railway section (Kogel, 2021, p. 14). In general, the definition and the calculation of the blocking time have not changed in the last decades, even though the calculation has been simplified due to a variety of software (Happel, 1959, pp. 79–82). The mentioned factors and others have a direct impact on the capacity of a railway line. Therefore, Chapter 3 (Capacity) will deal with the terms of capacity and the performance of railway lines. Afterwards, in Chapter 3.4 (Capacity assessment), the blocking times will be used again to calculate the capacity itself.

2.1 Train protection systems

Train protection systems serve to protect train movements, based on the two main errors which can occur. The first would be that the chosen speed is too fast, and the second failure would be not to stop at the End of Authority (red signal) (Fenner, 2020, p. 10). Besides this, train protection systems can also have an impact on the performance of train movements. For example, the systems behave differently with regard to the timing of the braking, or the braking curves themselves (Osburg, 2002, pp. 27–28). Therefore they will be described in their basic functions in this chapter to gain knowledge of how they can be used in terms of capacity. When it is considered that train traffic takes place in fixed or moving block sections, these sections in general have to be free of other train or shunting movements. However, there may also be situations in which two trains are permitted in one block, for example, driving into an occupied section of the station track (Theeg et al., 2009, p. 106). Also, the moveable elements, such as turnouts, must be saved in a certain position, which is ensured by the interlocking. When all conditions for train movement are fulfilled, the driver is informed of the permission for train movement by signals, in the form of trackside signals or, depending on the system, also via cab signalling. To avoid human error, train protection systems are used to ensure that the train drivers respect the relevant movement authority and do not override signals that require them to stop. Also, train protection systems ensure that the restricted speed is respected. In Europe, before the application of the European Train Control System (ETCS), numerous national train control systems were used and are still in use, which represents a corresponding obstacle to interoperability (Rameder, 2011). These train protection systems have different functions, but the main objective is to protect the train traffic.

Therefore, the systems can be categorised into their major functions (Theeg & Vlasenko, 2009, p. 208):

- Cab signalling functions,
- Supervision functions,
- Intervention functions.

Cab signalling functions can be, for example, audio functions that inform the train driver that he is passing a distance signal. It can also be the visual repetition of the signal term in the driver's cab or the display of the permitted speed. The supervision function checks the ability and the attentiveness of the train driver. It also enables braking supervision and train stop function with compliance with speed limits. If the supervision function detects a deviation from the normal behaviour, this function is activated. There are different forms from weak to strong interventions. The weakest is to warn the train driver and the strongest is an emergency brake intervention (Theeg & Vlasenko, 2009, pp. 208–211). In order to be able to go into the processes in more depth, selected train-protection systems are analysed. Common Class B systems in Europe are for example the Indusi/PZB, LZB and the ERTMS/ETCS systems, which are used in Austria and Germany and they were selected for this purpose (European Union Agency for Railways, 2019a, pp. 4–5). Before the various train protection systems are analysed, there should be an overview of the relevance in the practice. Based on the data from Austria in 2021, it can be seen in Figure 3, that the most dominant system is the PZB.

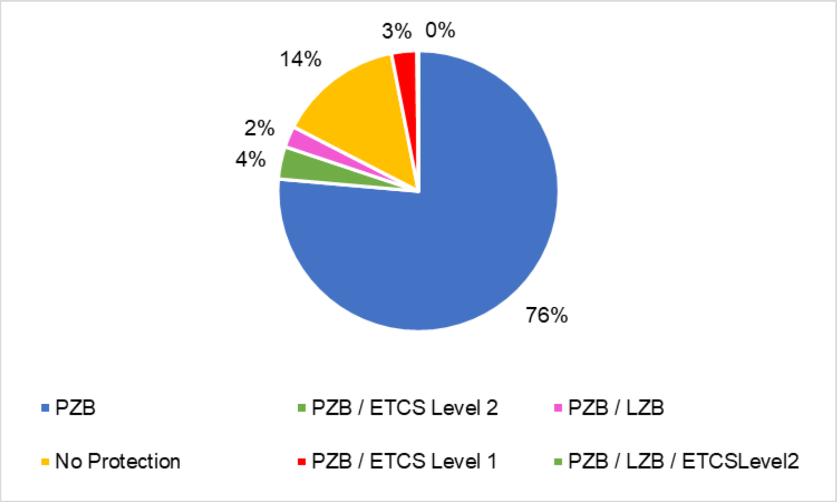

Figure 3: Train protection systems in Austria in the year 2021.
Source: Own diagram based on OpenStreetMap - Author Negjana (2021)

Even though this overview shows that a large part of the lines is equipped with PZB, it does not show how much of the total traffic is handled on these lines. In Austria, about 300 km are currently equipped with ETCS Level 2, of which, a large part falls on the highly frequented western axis (ÖBB Infrastructure AG, 2021a). In addition, the equipping of further planned- but also existing railway lines with ETCS is defined in the strategy paper (Zielnetz 2025+) of the ÖBB infrastructure AG (ÖBB Infrastruktur AG, 2011, p. 10). The company writes that they will expand the ETCS systems to 3700 km of the network, which is in total around 5000 km long (ÖBB Infrastructure AG, 2021a, 2022b).

2.1.1 Inductive train protecting system (Indusi / PZB)

Since the problem of passing signals at danger is not new, first forms of the Indusi were developed in the 1930s. From the first variant, the Indusi I34, there can be found further developments, to the Indusi I60 in the 1960s and the PZB90 in the 1990s. Today, within the European Union, the Indusi I60 and the newer PZB90 are in use in different countries (European Union Agency for Railways, 2019a, pp. 4–6; Mlinarić et al., 2018, p. 2). This chapter is dealing with the PZB90. PZB stands for *Punktuelle Zugbeeinflussung*, which means the system has an intermittent transmission. Within this system, the train driver must respect the line-side signalling and the relevant speed limits of the line. The main purpose is to prevent trains from passing signals at danger or signals with speed restrictions. Besides this, the PZB checks if the maximum speed of the chosen mode (O, M, U) is exceeded. Even if there are major speed changes on the line, these changes can be supervised with the PZB (Pachl, 2013b, p. 76).

For this, the inductive train protection consists out of trackside elements and components on the locomotive. Practically, trackside magnets, which are linked to the trackside signals, are used. If a signal shows a restriction, the magnets are active, and a passing train is influenced. If there is no restriction, the magnets are turned off and have no effect on the train. Therefore, different magnetic fields with 500, 1000 and 2000 Hz are used, depending on the location of the magnet (Theeg & Vlasenko, 2009, p. 233). As mentioned, besides main and distance signals, PZB magnets are also located at speed brakes or at trapezoidal boards. However, the most common application is at the main and distance signals. The distance signal is equipped with a 1000 Hz magnet and at the main signal a 2000 Hz magnet is located. It is also possible that there is an additional 500 Hz magnet 250 – 300 m in front of the main signal (ÖBB Infrastructure AG, 2021b, pp. 9–28).

Figure 4 shows the described location with the 1000 Hz magnet at the distance signal, the 500 Hz magnet and at the main signal the 2000 Hz magnet.

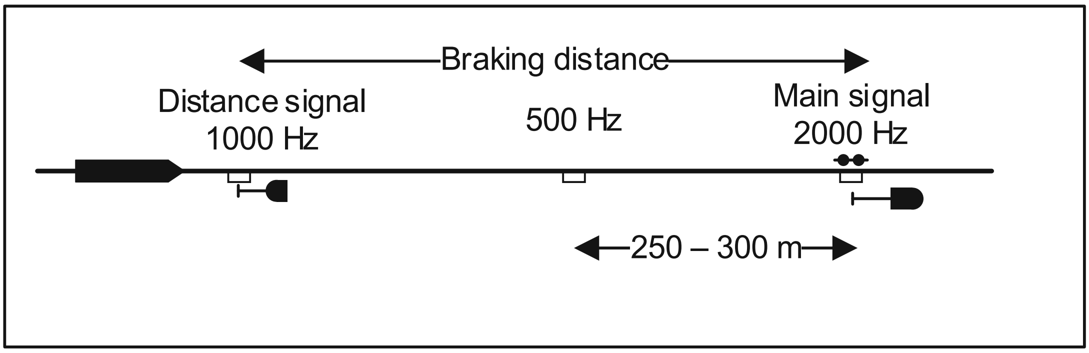

Figure 4: Trackside equipment PZB

Source: Own sketch based on (Diendorfer & Haubenwallner, 2013, pp. 8–11)

Based on the braking performance of the train, a different operating mode which also limits the maximum speed must be used. For train operations, different braking methods are used. Typically, a distinction is made between the braking methods P, R or G. The braking method P is a fast-acting brake that is used for lightweight to medium-weight trains. A comparable method is braking method R. For heavy trains, especially freight trains, braking method G is used, a slow-acting brake with longer braking distances (Bundesamt für Verkehr, 2020, pp. 664–665).

For trains with the brake method G, the Mode U must be used. For trains with brake method R or P, the mode depends on the braked weight percentage. Under 65 braked weight percentage, trains have to use mode U, between and 110 the mode M and above the mode O (DB Netz AG, 2014, pp. 21–22). Typically passenger trains can use the mode O, which allows a maximum speed of 165 km/h (160 km/h plus 5 km/h tolerance). The mode M allows a permitted speed of 125 km/h (120 km/h + 5 km/h tolerance). The third mode U can be used for heavy freight trains and enables a maximum speed of 105 km/h (100 km/h + 5 km/h tolerance). That means that PZB can be used up to a maximum speed of 160 km/h with additional tolerance of 165 km/h (Mlinarić et al., 2018, p. 6). To have a better understanding what happens with the PZB90, two cases will be described. A passenger train with 160 km/h has to stop in front of a main signal. When the train passes the distance signal at danger, the train driver has to confirm that he recognised the signal. Now he has 23 s to slow down the train under the speed limit of 85 km/h, when the passenger train arrives at the 500 Hz magnet, the train has to be under 45 km/h. Now the train has around 250 m left for braking in front of the main signal. The second case would be a freight train in the mode U with a starting speed of 100 km/h. After this train passes the distance signal at danger, the train driver has 38 s to bring the train under the speed of 55 km/h. At the 500 Hz magnet, the train has to be under 25 km/h. If the train driver is over the speed at this point or is overriding the controlled speed, the system will stop the train. It should be mentioned at this point, that in both cases it is possible, that if the train driver stops braking after the 500 Hz magnet, the train can run over the main signal at 45 or 25 km/h. If that happens, the active 2000 Hz magnet will be used to induce a braking and the train will stop after the signal. In the best case, the train will stop within an overlap, if overlaps are foreseen in the used railway system. The overlap aspect will be discussed later in this work. If the signal changes the aspect during the train is between the distance and the main signal, the train driver can release himself 700 m after the distance signal from the surveillance. Also, there are surveillance functions of a restrictive speed limit, if the train stops while he is influenced by the PZB (Diendorfer & Haubenwallner, 2013, pp. 3–8; Maschek, 2013, pp. 539–541). Based on this description, it can be seen that the PZB is a system which supports the train driver, but the responsibility remains by the driver. Despite all these precautions, situations can appear, where the train overrides a stop signal; two such cases, which lead to an accident will be described in the following pages.

In March 2017, a collision took place between suburban train 29795 and freight train 47001 in Wien Süßenbrunn. The freight train had a route which was set by the automatic operation system (Graphic Automatic Light). The suburban train, on the other hand, came from Gerasdorf and had a route up to the exit signal H21, and on the signal H21 was the stop aspect. Figure 5 shows the simplified scenario of the incident.

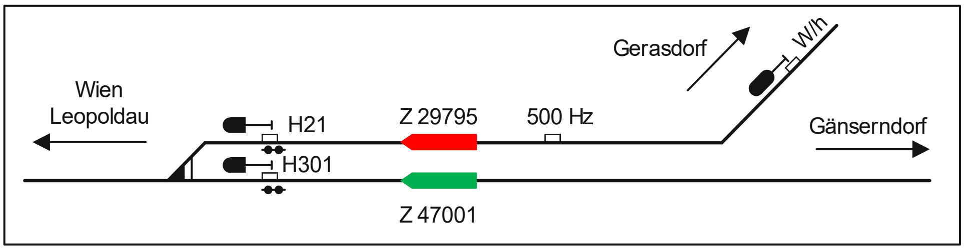

Figure 5: Simplified sketch of the incident in Wien Süßenbrunn.
Source: Figure adapted, taken from Sicherheitsuntersuchungsstelle des Bundes (2021b, p. 12)

The suburban train had a clearance speed of 60 km/h at the home signal, with the distance signal h indicating a stop to be expected. The suburban train was equipped with PZB60, and the driver acknowledged the 1000 Hz interference at the distance signal, showing caution by pressing the confirmation button. His expectation was that signal H21 will change the aspect until he arrived, as it was in most cases (Sicherheitsuntersuchungsstelle des Bundes, 2021b, pp. 11–25). He drove on the line at the permitted 60 km/h, but did not reduce his speed. As both lines are parallel after the curve, the train driver of the freight train noticed that the suburban train was not slowing down, he initiated emergency braking and used the macrophone to give an attention signal two times. The train driver of the suburban train noticed this and initiated braking 30 m before the main signal with the stop aspect. The stop signal was exceeded at 50 km/h and the 2000 Hz interference led to an emergency braking (automatic train stop). However, this was not sufficient to stop within the 50 m overlap and a collision occurred between the two trains. When looking at the situation, several aspects are relevant. On the one hand, the Electrical Multiple Unit 4020 used the PZB60 train protection system which only controls the speed at certain points, in this case, 20 s after the distance signal. In this case, the speed must be below 90 km/h and at the 500 Hz magnet, the speed must be below 65 km/h. As the home signal W showed a speed limit of 60 km/h and the driver kept to this, he was not monitored by PZB60. Looking at this situation under the PZB90 train protection system, after the 500 Hz magnet, the monitoring speed curve would break the train still running at 60 km/h. This would ensure a standstill before the signal showed stop. Furthermore, in a statement on this incident the Labour Inspectorate criticises that the lowering of the overlap distances in the 1980s contributed to a systematic reduction of the safety level. It is emphasized that several such incidents had already taken place, which were only possible because of the short overlaps. It was also claimed that such accidents could be prevented in Austria by applying the German guideline – *Richtlinie 819* (RIL 819) and the overlaps specified in this rule. In summary, it can be said that the causal reason was human error, which in combination with a certain system environment (PZB60, overlap 50 m) led to a collision (Sicherheitsuntersuchungsstelle des Bundes, 2021b, p. 86).

The second example is discussing a similar case from Mannheim in August 2014. In terms of procedure, this situation is comparable to that in Wien Süssenbrunn. Compared with the sketch in Figure 5, the freight train would now be running on the upper track and a Euro City (EC) on the lower track. The main reason for this accident was that the driver of the freight train was looking at the signals to the left of his track, because he had to in a previous station where the signals to the left of the track were valid. However, as the signals on the left side changed in the meantime to clear with speed restriction for the EC, the driver of the freight train assumed that they would be valid for him. Despite an emergency braking caused by the PZB magnet, the driver of the freight train neglected to report this incident to the station dispatcher and continued to drive, which caused the accident (Bundesministerium für Verkehr und digitale Infrastruktur. Eisenbahn-Unfalluntersuchungsstelle des Bundes, 2015, pp. 40–47).

The two cases already show several points. On the one hand, due to the use of older rolling stock with PZB60, there is not the same monitoring possibility as with PZB90. Also, it is shown that due to the speed of 60 km/h, emergency braking is not initiated earlier, as the train was travelling below the test speed of 65 km/h. These incidents also highlight the importance of flank protection and that signals are a weak form of flank protection. Flank protection itself can be categorized by the strength of protection. Based on this categorization, turnouts and derailers are, for example, categorized as a strong flank protection and main signals as weaker protection (Theeg et al., 2009, p. 76). Besides flank protection, the cases also show that overlaps are important, but if there is an additional error (e.g. human failure) that overlaps are only weaken the damage. The topic of overlaps is discussed separately in Chapter 3.6 (Aspects affecting the capacity).

2.1.2 LZB (Continuous train control system)

A prominent representative for continuous train control systems is the *Linienzugbeeinflussung* (LZB). The LZB is a train control system based on the continuous exchange of information between the railway vehicle and the interlocking system. The communication between the train and the interlocking runs via an LZB control centre, where movement commands are transmitted to the train and data from the train to the interlocking. This allows higher speeds compared to line-side signals (Coenraad, 2012a, p. 27). For the transmission a line cable is used, which is in the middle between the two rails and at one rail side at the foot of the rail. Every 100 m, the line cable is crossed. These crossing points serve as a reference point to enable, in combination with the odometry of the train, an exact position detection. Before each speed change, the vehicle computer calculates a braking curve. This results in the supervision curve. The driver has different parameters, such as the current speed, the nominal speed, the target speed, and the target distance as information. It is therefore possible for the driver to control the train manually or to have it guided by the automatic driving and braking system

Automatische Fahr- und Bremssteuerung (AFB) (Pachl, 2000, p. 728). For this purpose, there are different steering variables; the local maximum speed, the distance to the next speed change and the speed at the target. Therefore, with this train protection system, either the conventional block lengths can be used or shorter blocks (Pachl, 2013a, p. 76).

The aspect of the shorter blocks is one of the reasons why the LZB is explained within this work. LZB itself has only limited relevance for this work, as it is to be completely replaced by ETCS over the next few years. In Germany, it is planned to discontinue LZB from 2030 and use ETCS in its place (McKinsey & Company, 2018, p. 9). In the meantime, situations can be found where several train protection systems are used together on a railway line. It is also possible to equip a railway line beside LZB with ETCS to realize that it is necessary to adapt the system to the dual equipment and ensure that basic parameters like the block length are ident. In Germany, dual equipment is feasible from operational-technical system functions *Betrieblich-technische-Systemfunktionen 3 v3.0* (BTSF 3 v3.0) (Pfeifer et al., 2022, p. 11).

With the rollout of the ETCS and the digital interlockings a higher capacity and performance of the railway lines is expected (Verband der Bahnindustrie in Deutschland e.V., 2019, p. 28). A similar goal was already observed in the 1990s, when an attempt was made to increase capacity by further developing the LZB. Therefore, the *Computer Integrated Railroading Erhöhung der Leistungsfähigkeit im Kernnetz* (CIR-ELKE) was created. It was announced that this method should increase performance in the existing network by up to 40% (Geiß, 2002b, p. 39, 2002a, p. 60). A valid reference regarding the achievement of the target could not be found in the research. It is also not possible to draw any conclusions about the capacity gain and the punctuality of long-distance rail transport. This has recently been discussed in the media. To have an understanding of the further work to be able to answer the research questions, the functions that were already feasible under LZB will now be considered. For that reason, not all CIR-ELKE functions are examined, but those that were accompanied by an increase in capacity. Within this examination there will be no distinction between CIR-ELKE I and CIR-ELKE II, a development of the CIR-ELKE I, which allows additional features (Jonas, 2001, p. 199). On the first CIR prototype line between Offenburg and Basel, so-called virtual signals were created, which enabled shorter headway. To ensure a more homogenous speed of all trains, the possibility to have signalization over more blocks was invented. The result was that freight trains with a lesser braked weight percentage could drive with higher speeds. When freight trains are using conventional line-side signalling with only one block, it must be ensured that the braking distance of this train is shorter than the distance between the distance signal and the main signal. Also, shorter blocks in the railway stations were realized, which led to the fact that trains only must reduce the speed in front of the turnout and not in front of the home signal (Geiß, 2002b, p. 39). This is possible when the line-side signals are turned off, which is common when the train is LZB supervised. Then the train can drive the line speed just before the beginning of a turnout. A conventional train would already have to break in front of the home signal (Hain, 2007, p. 4). Beneath the *LZB-Blockkennzeichen* (LBK), which is the physical marker for the virtual signals, a high-performance block, which is used in highly utilized sections with homogenous traffic, can also be found. For example, it is implemented at the suburban railway line in München. With the high-performance block, it is possible to raise the number of trains per direction in one hour from 24 to 30 trains in München. Therefore, in every station between the existing home and exit signals, the blocks are divided in several blocks, which are marked with an LBK. With this solution, it is possible that a following train can drive to the beginning of a platform, while the previous train is still standing at the platform (Hornemann, 2005, pp. 14–20). Which means that the trains can follow each other at around 100 m (Köhn & Fux, 2005, p. 18). With conventional signalling, the first train has to leave the overlap of the related exit signal and after that, the second train can approach the block. The overlap behind the LBKs is 50 m, which means that one virtual block is always empty. To use the advantages of the short blocks it is also important to have the stopping point in front of an LBK as near as possible. In München 5 m distance was established, which is lesser than at lines with higher speeds and LZB. As a fallback level, there are still line-side signals which are only used for trains where LZB is not working. Additionally, it is also necessary to have supplementary rules for the operation when the LZB is not working while a train is between the LBK blocks (Hornemann, 2005, pp. 14–20). Finally, it should be noted that the capacity gain, which is expected from a high-performance block, is also depending on the type of traffic. In München, on the suburban line, there can be found only suburban passenger trains with similar characteristics, and the capacity is increased by 25 %, from 24 to 30 trains. For lines with mixed traffic, it can be expected that the capacity gain is lesser then 10 % (Hornemann, 2005, p. 14; Pachl, 2013b, p. 166).

2.1.3 CBTC

Communications - Based Train Control (CBTC) is a signalling system, which is based on radio communication to enable real-time information for train control. It is an automatic train control system, which enables driving in a moving block (Lindqvist & Jadhav, 2006, pp. 391–393). Compared to the described systems in the previous chapter, where fixed blocks are used, in CBTC, the trains can follow each other in braking distance with an additional buffer. For the Automatic Train Control (ATC) it is necessary to have Automatic Train Protection (ATP) and Automatic Train Operation (ATO) and Automatic Train Supervision (ATS).

Typically, CBTC is used in urban mass transport systems, while the European Rail Traffic Management System (ERTMS) is used for railway lines with longer distances. But considerations about rolling stock combining both systems, like it is done at a railway system in London, can also be found (Farooq & Soler, 2017, p. 1395). The permitted distance to the End of authority is at CBTC called the *Limit of Authority* (LMA) (Farooq & Soler, 2017, p. 1378).

For safe train movements the IEEE Standard for Communications - Based Train Control (CBTC) Performance and Functional Requirements, recommends a braking model which can be seen in Figure 6.

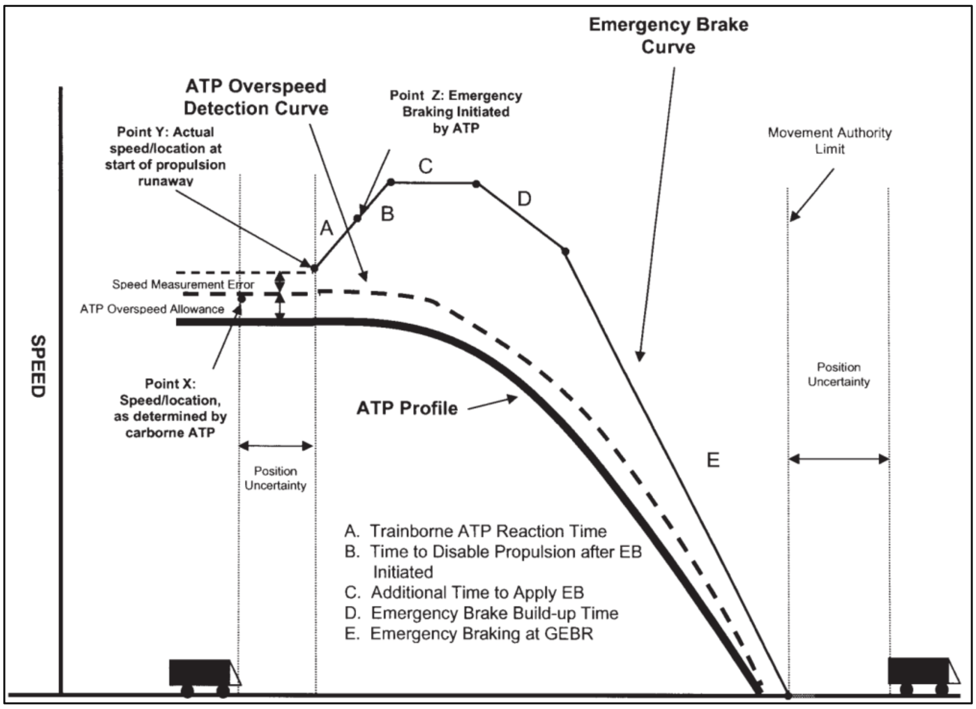

Figure 6: Braking curve surveillance.

Source: Picture taken from American National Standards Institute IEEE (1999, p. 34)

To ensure this, both lineside equipment and vehicle components are needed. Along the track, transponders are placed for the localisation of the trains. These transponders are mainly passive components, which are acting in combination with the odometry on the train. Beneath a CBTC control centre, steering and supervising equipment for turnouts can also be found. Beneath, there can also be used trackside track detection, like axle counters, to ensure simplified train detection in the case of a malfunction. The rolling stock is equipped with a CBTC vehicle computer, which calculates and supervises the speed. There is a Human Machine Interface for the cab signalling and radio equipment for data transmission (Schnieder, 2020a, pp. 10–13).

There are five Grades of Automation (GoA) in railway passenger operation. GoA 0 is driving on sight with the full responsibility of the train driver. GoA 1 is a non-autonomous operation. But compared to GoA 0, here the driver has signalisation and surveillance, whether punctual or continuous. The driver is responsible for departure and stopping, management of doors and monitoring the passenger exchange. In GoA 2, a semi-automatic mode, the driver is responsible for initiating the departure of a train. While the train is running and stopping, the driver only has a monitoring function. GoA 3 is a driverless operation, the train is driving autonomously, but there is still staff on the train which can fulfil additional tasks and steer the train when a malfunction appears. At last, there is GoA 4 where the vehicle is running without staff on board (OVE Österreichischer Verband für Elektrotechnik Austrian Standards Institute, 2015, pp. 17–18).

Especially through the moving block, it is possible to increase the number of trains and reduce the headway between them. Through ATO it is also possible to increase punctuality and to save energy (Schnieder, 2020a, pp. 5–9). What the increase in the number of trains exactly means can be seen in the planned CBTC Project in Frankfurt (DTC - Digital Train Control System Frankfurt). Here it is announced that on B-Line the service frequency in the peak hours will increase from 24 to 30 trains per hour (Rüffer, 2022, p. 14).

As mentioned above, CBTC is mostly used in mass transport systems in urban areas, but there can also be found exceptions. The Waldenburgerbahn in Switzerland was a 750 mm narrow gauge line in the surrounding of Basel. After the Baselland Transport AG (BLT) got responsibility for this line, they rebuilt this line with 1000 mm gauge. Together with this infrastructure realignment, they acquired new rolling stock, Tramlink light rail vehicles from Stadler. With this investment in this branch line also CBTC was taken in place as an Automatic Train Protection. The system architecture of CBTC is modular build and consists of, for example, anti-collision detection and object identification (Radar, lidar and cameras). On the line itself, there is less technical equipment, except the transponders. On the Waldenburgerbahn, the CBTC components are based on the Commercial off-the-shelf (COTS) principle. Every component is redundant, which leads to a higher availability. A relevant aspect is that this branch line is now having an operational concept where the train driver can find on the CBTC Human Machine Interface (HMI) every possible destination. If he chooses a destination, the system will lead him to this destination and is reserving the components of the route. This is also possible for shunting movements. The result is that station dispatchers are not needed in regular operation. At the moment, the line is operated in GoA 1+, where the driver gets a clearance for the line, the optimum speed and the acceleration, but it is planned to adapt the system to GoA 2 to GoA 3 and GoA 4 later (Ronchi et al., 2022, pp. 6–9). In this example it can be seen, that thus CBTC is a system for urban mass transport systems, it could also be useful for local railway lines in suburban or rural areas.

2.1.4 ERTMS / ETCS

ETCS is a train protection system designed to enable interoperability through different countries and to harmonise the various systems (Laumen & Nießen, 2019, p. 1). ETCS is a part of the ERTMS, which consists of the Global System for Mobile Communication – Rail (GSM-R), and ETCS. GSM-R as a communication standard is needed for some Levels of ETCS. In the time this work was being written the actual version is Baseline 3 release 2 (R2) and GSM-R Baseline 1 (European Union Agency for Railways, 2022). The implementation of a new Technical Specification for Interoperability – Command, Control and Signalling (TSI CCS) is ongoing. Also, the ERTMS/ETCS Baseline 4 is planned with the adaptions for ATO and Future Railway Mobile Communication System (FRMCS) (Malfait & Hernández Fernández, 2022, pp. 4–8). ETCS can be implemented in different levels, whereby the different levels describe the technical framework. Beneath the different levels, which will be described later, several operating modes like Full Supervision or Limited Supervision (LS), can also be found (Laumen & Nießen, 2019, p. 2). Based on the specifications and the different national rulebooks, various practical use cases with or without a combination with the National Train Control System (NTC) and a Level of ETCS can be found. Also, there can be scenarios, where within one line there is a section equipped with ETCS and some other parts are not. Here a mixture between modes and levels can be found. Therefore, all common levels will be dealt with in the following pages. No train protecting system or a system which is incompatible with the locomotive is often called as Level 0. Beside this, there is ETCS Level NTC, which was in the past called STM (Specific Transmission Module). Level NTC is the use of a locomotive with ETCS equipment on lines with national train protection systems. But in the true sense ETCS, however, begins with Level 1. There are also provided Level 2, Level 3, and Level 3 hybrid solutions. Level 3 Hybrid in the past sometimes called Level 2 HD (High Density) (DB Netz AG, 2018a, p. 7; Pachl, 2021a, p. 63). This train protection system was developed as a European standard to replace the national automatic train protecting systems, to ensure interoperability in the European railway network. It should be noted that the onboard unit is level-independent, which means a locomotive can use lines from Level 2 and Level 1. The system is therefore backwards compatible. On the vehicle side, the system consists of an ETCS device for the major logical functions, the interface between the train and the ETCS on board system, a Balise Transmission Module, the Loop Transmission Module, a *Euroradio* module, which is an interface to the GSM-R. Also, odometry modules, for estimating the movements, the recording unit, and a Driver Machine Interface (DMI) are part of the system's onboard components (Zoetardt, 2011, pp. 32–33).

In several analyses of the effects of the implementation of ETCS in Austria, it can be shown that this technology is also providing more safety in railway operations. The ÖBB describes that the probability of passing signals at danger is reduced from 85% to 90% with ETCS (ÖBB Infrastruktur AG, 2011, p. 77). As it can be shown that the main precursors of accidents in the EU are broken rails, track buckles and signals passed at dangers (Grossberger et al., 2017, p. 5). So, with ETCS, the prevention of passed signals at danger could prevent accidents.

2.1.4.1 ETCS Levels

ETCS Level 0

Level 0 can be a line without a train control system or a national train control system, which is not compatible with the ETCS Equipment on the locomotive. The main function of this level is to control the speed (Schnieder, 2020b, p. 20). Level 0 can also provide a fallback level in case the vehicle detects a train control system that does not fit the vehicle. The line-side signals must be respected. In addition, there may be operational regulations on the maximum speed when a trip is made without a train protection system. In Germany, the maximum speed for trains without a train protection system is 50 km/h (DB Netz AG, 2018a, p. 7).

ETCS Level NTC

Since Baseline 3, this level is referred to as NTC. Before this, it was called STM (Specific Transmission Module), although the vehicle hardware is still referred to as such. This level is used so that vehicles equipped with ETCS can travel on lines that are only equipped with a national train protection system. The information from the national train protection system is processed by the STM module for ETCS so that the components can use it. The STM module must be adapted accordingly for the respective national train protection systems (DB Netz AG, 2018a, p. 7).

ETCS Level 1

Level 1 is often used as an additional system to the national train protecting system, with remaining line-side signals. So, it is possible that these lines can also be used from trains with a Class B system. Usually, there is no upper limit up to which speed limits ETCS Level 1 can be used. Typically, this signalling system is used on lines up to 160 km/h. The main communication medium between the train and the interlocking are the Eurobalise, which are on the track. The balises can be switchable or fixed. The fixed balises are used to send fixed values, for example, the national values and position data. Via the switchable, Eurobalise can be transmitted the Movement Authority (MA) and additional line date (Theeg & Vlasenko, 2009, p. 242). The MA is the main command in ETCS. It enables the system to supervise the trip to the End of Authority (EoA) and the target speed at the EoA. The location of the danger point after the overlap and a release speed can be also issued (Winter, 2009b, p. 99).

The transmission of the signal aspect from the interlocking to the Eurobalises is accomplished by a Line-side electronic unit (LEU). The LEU is linked with the line-side signals and is converting the aspect into a telegram for the switchable balises. In the ETCS Level 1, these switchable balises are only located at the distance and main signals, which means that a transmission can only take place at these locations. If the signal aspect changes while a train is in between these two signals, it would only be able to drive the prior transmitted speed. To deal with this issue, additional cable loops in in front of the signals or a local GSM-R radio infill were invented. Infill balises, which are placed 250 m in front of the main signal, can also be used. Here the train driver can get a new MA. If the train stops or comes under the release speed, the train driver can only approach the next signal with a maximum of the release speed (Pachl, 2021b, pp. 97–98).

Figure 7 shows a configuration of the ETCS Level 1 with Euroloop or Radio infill function.

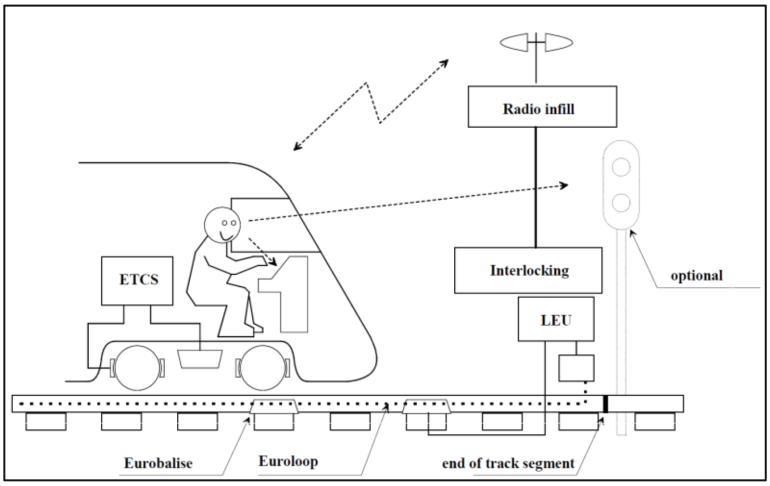

Figure 7: ETCS Level 1 with Euroloop and Radio infill
Source: Picture taken from ERA * UNISIG * EEIG ERTMS USERS GROUP (2016a, p. 19)

If an infrastructure operator decides to remove the signals on the line at this level, it is necessary to have the position where the signals would be a Euroloop or GSM-R Radio Infill. But there is also the possibility to solve this issue without the Euroloop or GSM-R Radio infill. The Société Nationale des Chemins de Fer Luxembourgeois (CFL) has invented ETCS Level 1 Full Supervision (FS) on the whole network. The national train protection system (Class B system) was removed. With ETCS Level 1 FS, the train is continuously controlled and gets the MA at the Eurobalise. For shunting movements or a starting train, it is necessary to bring the train to the first balise. Therefore, the existing signals with various aspects and different types of signals were simplified. One approaching signal remained, the so-called *Signal Fixe d'Autorisation* (SFA). The SFA can only show three aspects. SFA1 means stop for all movements. SFA2 means that train or shunting movements are allowed. SFAC means construction site mode (Morast et al., 2022, p. 62). Under this signal, the ETCS stop marker can also be found. To deal with malfunctions, there is also a distance signal marker, which announces the ETCS stop marker (Feltz, 2022, pp. 9–13). Figure 8 shows the three different aspects of the SFA signal.

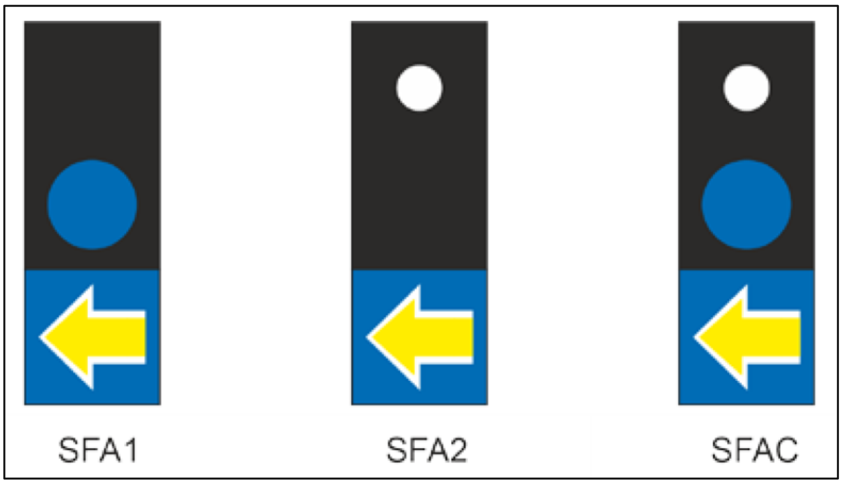

Figure 8: Three aspects of the SFA signal at CFL.
Source: Picture taken from Morast et al. (2022, p. 62)

ETCS Level R

During this work, a modification in the subdivision of the levels is discussed. It seems that the plan is to merge the Levels 2 and 3. They should be merged into a new level R (Radio), as these two levels are based on radio transmission. Since this change is only planned and not finished and it will presumably have little impact on the technical functionalities, it should remain on this side note (Doppelbauer et al., 2023, p. 38).

ETCS Level 2

In ETCS Level 2, the MA are transmitted to the trains via GSM-R. Therefore, it requires a Radio Block Center (RBC) and corresponding radio antenna systems. On the line, fixed balises, which are used for the trains to have a fixed kilometre marking, are placed at every kilometre. Between this fixed balises, the trains are using odometry to determine the actual position. Trackside train detection, for example with axle counters, is still used (Pachl, 2021b, p. 98). The information about the location of the trains is used in the interlocking for setting the routes. The routes which are set in the interlocking are then transferred into an MA via the RBC (Winter, 2009b, p. 95). ETCS Level 2 is typically used in the mode FS. Therefore, radio communication with the train is constantly required. One of the factors, which also affects the capacity is the system runtime of the radio communication. If the first train leaves a section of the Trackside Train Detection (TTD), this information reaches the Interlocking system, from where the next route will be set. This information will be converted from the RBC to a MA. Via the GSM-R, this information will reach the next train. But also within the GSM-R, the information runs over the Mobile Switching Center (MSC), the Basic Station Controller (BSC) and the Base Transceiver Station (BTS) (Büker, 2018, p. 32). Compared with other technologies like Long Term Evolution (LTE) or TETRA, the mutual system GSM-R takes a longer setup time (Mando & Giambene, 2017, pp. 17–19). As mentioned at the beginning of this chapter, in the future there will be FRMCS, which enables other possibilities and other system running times. In Austria, it is planned that FRMCS will be used for ETCS, ATO – ATP. This is now investigated in the project PROGMO+. It is planned to have only a short period of time where GSM-R and FRMCS will be used simultaneously (Grossegger, 2022, p. 5). The influence of ETCS Level 2 on the capacity will be investigated in the next chapters also in combination with the braking curves.

ETCS Level 3

ERTMS/ETCS Level 3 was only very roughly described for a long time since there was not so much existing development for the moving block available. In fact, in the literature, it can be found that ETCS Level 3 is characterized as a signalling system that uses only cab signalling and trains that are localized by odometry and reference balises. The train integrity detection should be realized, instead of axle counters or track circuits, by radio communication from the train to the RBC (Löfstedt, 2011b, pp. 51–53; Mense, 2011, pp. 49–50). Together with the location, it is also necessary to know if the train is complete, which requires a Train Integrity Monitoring System (TIMS). The operation takes place in a moving block or virtual block (Pachl, 2021b, pp. 99–100).

Similar approaches to Level 3, like the French Automation of train spacing in real time (ASTREE), or the Swedish Radio-Block system which was tested at the line between Linköping and Västervik can be found. This system is using radio communication and virtual blocks. Lately, Travikverket started with an examination of ERTMS Regional (Winter, 2009a, pp. 28–29). This application was tested at the Västerdalsbanan (Coenraad, 2012b, p. 47). In addition to this, there is one project in Kazakhstan, which is based on the ETCS Level 3 concept. There, Terrestrial Trunked Radio (TETRA) system is used instead of GSM-R for communication (Wójcik et al., 2020, pp. 129–132). Currently, there are wayside detection elements in use, but it is also planned to use an end of train sensor in the future, especially on secondary- and trunk lines, to avoid trackside detection (Zhanmuratov & Sansyzbay, 2020, p. 69).

Based on the experiences with ETCS Level 1 and 2 and the mentioned other projects, there is research for ETCS Level 3. There could be found papers that claim that the moving block leads only to a marginal reduction by using ETCS Level 3 compared with Level 2. This is argued because junctions cannot be used as a moving block at all (Gill, 2017, p. 8). The approach that can be found in several works suggests that within Level 3, the lines are operated as a moving block and the stations as fixed blocks. The block division of the stations with ETCS will be taken into consideration at the practical part of this work.

Within the X2RAIL-1 project, the definitions and the forms of ETCS Level 3 got more detailed. Based on this there were also worked technical principles for the hybrid Level 3 from the EEIG ERTMS Users Group (EEIG ERTMS Users Group, 2022, pp. 5–22).

The following different system typologies, which could be used in ETCS Level 3 were created in the X2RAIL-1 Project (Siemens, 2019, p. 20):

- Full Moving Block without trackside train detection,
- Full Moving Block with trackside train detection,
- Fixed Virtual Blocks, with trackside train detection,
- Fixed Virtual Blocks, without trackside train detection.

Now, ETCS Level 3 Hybrid, where fixed virtual blocks are used with lesser trackside train detection, is the most developed variant (Furness et al., 2017, p. 2). Therefore, this system will be explained in more detail.

ETCS Level 3 Hybrid

The ERTMS/ETCS Level 3 hybrid is a certain form of the Level 3, where trains are operated in fixed blocks. The physical blocks, which are monitored by train detection equipment, are divided into several Virtual Sub Sections (VSS). This leads to a robust operation and increases the capacity (Barholomeus et al., 2019, pp. 14–16). With regard to this aspect, Level 3 Hybrid is analysed in more detail in this chapter. Basically, it must be mentioned that at this level, it is technically possible that trains without ETCS also use the line and, for example, use a national train protection system. However, this requires that the Trackside Train Detection (TTD) sections are additionally equipped with physical line-side signals. However, the mixed operation with two different train protection systems makes the operation more complex and generates costs for the use of both systems (Furness et al., 2017, p. 7). The idea of increasing performance through block density is not new. Pachl already described in 1999 that an additional signal at half of the regular braking distance or a follow-up signal leads to an increase in performance. However, it is described that the necessary signals and track detection equipment lead to additional complexity, compared to a short reduction of the headway and, therefore, should only be used if other measures to increase performance have already been exhausted (Pachl, 1999, pp. 52–55). In the ETCS Level 3 Hybrid, it is in fact possible to present virtual blocks without having to install signals and TTD on the line. However, Level 3 Hybrid also needs the train integrity of the trains to be reported to make use of the virtual blocks. This is done via the TIMS system. It is easier to achieve train integrity in passenger traffic than in freight traffic, due to the electrical lines between the individual wagons or multiple units. As freight trains are only mechanically coupled by means of UIC screw couplings and brake pipes, it is much more difficult to implement a train integrity system here (Srb & Kampík, 2022, pp. 22–24). However, it should be noted at this point that several research projects are currently working on the implementation of a centre buffer coupling. It is communicated that widespread implementation of the Digital Automatic Coupler (DAC) could be possible by 2030. Projects in this area include, for example, DAC 4 Europe (DAC4EU) (Deutsche Bahn AG, 2021a), the Open European DAC Delivery Programme (EDDP) (Shift 2 Rail, 2021) and Digital Automated Coupling in Infrastructure Operations (DACIO) (Österreichische Forschungsförderungsgesellschaft mbH, 2021). In the DAC4EU project, the DAC is seen as the enabler for train integrity (Deutsche Bahn AG, 2021b). Even if these circumstances will only be relevant in the future, they should not be neglected when considering the advantages of the ETCS Level 3 Hybrid and the use of virtual blocks.

The technical equipment required for this level, does not differ from that for ETCS level 2. Besides the already existing Radio Block Centre (RBC) the approach of Thales is to use a Virtual Block Function (VBF), which behaves like an interlocking. The VBF administers the virtual block function and forwards the status to the RBC. In the RBC itself, the virtual blocks are displayed as if they were physically present. So, the RBC can be used without any modification of the core functionality (Barholomeus et al., 2019, p. 15; Hansen et al., 2018, p. 293). Figure 9 shows the principle of the VBF.

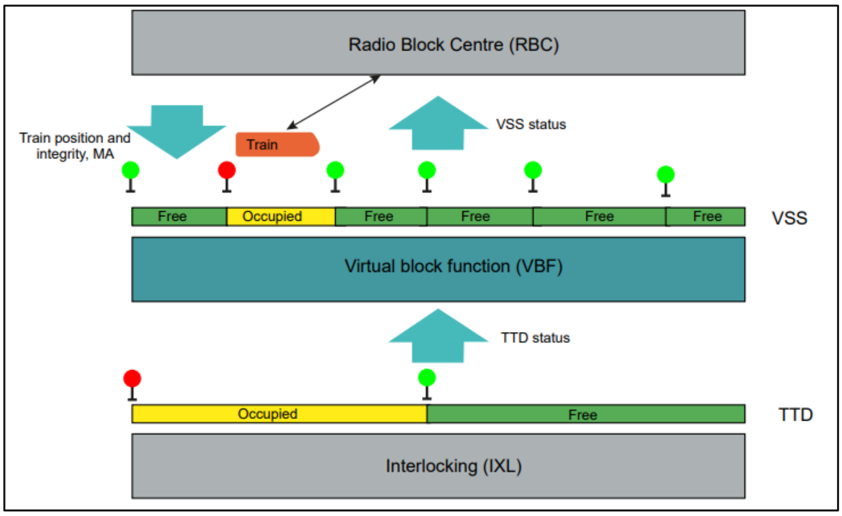

Figure 9: Virtual Block Function in ETCS Level 3 Hybrid
Source: Picture taken from Barholomeus et al. (2019, p. 16)

As a result, when the RBC is restarted, the information about the location of the trains is not lost because it is stored in the VBF (Hennig et al., 2021, p. 48). To ensure that a virtual block is free, the VBF knows four different states. *Free* and *occupied*, these states are also passed on to the RBC, and the terms *ambiguous* and *unknown* are introduced. If a train reports leaving the virtual block, the VSS changes to free. If communication is lost or there are problems in ensuring train integrity, the state changes from *occupied* to *ambiguous*. However, if the train has left the VSS, the section does not become *free*, it changes to *unknown* until the train has left the physical block (Bartholomeus et al., 2018, pp. 17–18).

In order to describe the exact functionalities, three different model trains are used here. The first one is a train that is not equipped with ETCS and therefore relies on trackside signalling. The train is only detected via the TTD. It is named non-ETCS train in the following. The second train is assumed to be a train with ETCS and TIMS, i.e. it can use the virtual blocks in front of it and release each one again for the following trains equipped with ETCS. This train is named ETCS-TIMS train in the following. The third possible train in the Level 3 Hybrid is a train that is equipped with ETCS but not with TIMS. Typically, these could be freight trains. This train can use the virtual blocks in front of them and occupy each VSS until it left the TTD. This type of train is named ETCS-non-TIMS train in the following. For visualisation in Figure 10, a route between two stations is created and divided into two physical blocks with axle counters and these are then each divided into three virtual blocks with the same length. The three described model trains are used in this section. The non-ETCS train occupies the entire TTD section and subsequent trains can only follow it once it has left the TTD section. The second train shown in red is an ETCS-TIMS train, and in combination with the third train, an ETCS-non-TIMS train, the advantage of this ETCS level is already visible.

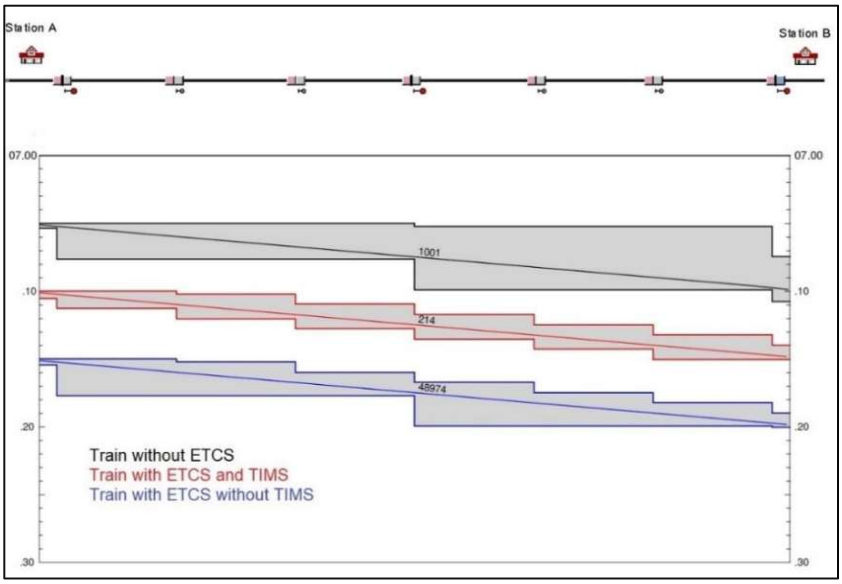

Figure 10: Comparison of blocking time with different equipped trains.
Source: Own illustration in OpenTrack Version 1.10.3.

It can be seen that most limitations occur with mixed traffic, where trains with ETCS and trains with a Class B system are using the line. Trains with ETCS can only follow them when the first train has left the TTD section. The same happens when a train without ETCS follows a train with ETCS and TIMS. The first train must clear the TTD section. This is because the train without ETCS cannot deal with the virtual blocks and is fully addicted of the line-side signals and the TTD.

Considerations concerning the capacity show that ETCS Level 3 Hybrid reduces the headway as expected within this chapter (Jansen et al., 2019, pp. 9–11). This fact will be used in a more in-depth investigation later in this work.

2.1.4.2 ETCS Modes

In the Baseline 3 Release 2–SRS version 3.6.0, there are 17 possible operating modes of ETCS listed. For example, modes like Stand By, Sleeping, Staff Responsible or National System can be found. All modes are created for different purposes and were developed further in the last Baselines updates (ERA * UNISIG * EEIG ERTMS USERS GROUP, 2016b, p. 8). The most important modes for the operation are Full Supervision (FS), Limited Supervision (LS) and Shunting (SH) (Laumen & Nießen, 2019, p. 2). Therefore, especially FS and LS will be described more in detail for this work. Shunting itself has not such a high importance in this work, because train movements are in the focus. For passenger traffic, the model trains will be mostly multiple units, which leads to the fact that at the end of a train trip, there is no shunting needed for changing the direction.

Limited Supervision (LS)

Limited Supervision can be used in the Levels 1, 2 and 3. It enables trains with ETCS to be operated on lines with trackside signals. Therefore, the train driver has to respect the line-side signal aspects (ERA * UNISIG * EEIG ERTMS USERS GROUP, 2016b, p. 35). Whereby LS can be used in all levels, it is mostly common in Level 1, especially in Germany and Switzerland (RailBUSINESS Editorial note, 2011, p. 7; EI- Der Eisenbahningenieur Editorial note, 2018, p. 65; Mense & Feldt, 2010, p. 6). In Germany, the maximum speed which can be used in this mode is 160 km/h. This mode was created in Baseline 3 to enable ETCS on existing railway lines with lower investment costs (Büker, 2017, p. 25).

Full Supervision (FS)

The FS mode enables, that a train is constantly under supervision and not only in front of danger points. The movements of the train are fully supervised. That means the train cannot run over the allowed speed (including tolerance). The used braking behaviour and the braking curves will be described in the next chapter. In FS mode, ETCS is responsible for the train protection, whereby the driver cannot choose the mode manually (European Union Agency for Railways, 2019b, p. 325). This mode is used when all necessary conditions are fulfilled. Therefore, the system needs to have the relevant data of the train and the infrastructure. The infrastructure data must fulfil Safety Integrated Level (SIL) 4 (Winter, 2009c, p. 141).

2.1.4.3 ETCS Braking Curves

One of the key factors of the blocking times is the duration a train needs to run through the block section. Therefore, the speed, the acceleration and the deceleration are the key factors in how long a block is occupied. If a train has a stop in the block section, then the dwell time is also essential. As described, if PZB is used as an ATP the train must stop within the distance from the distance signal to the main signal, from where the restriction or the stop aspect is valid. According to the line speed, the needed braked weight brings a train to a standstill within this distance. If a train has not sufficient braked weight, then it is only allowed to run at a lower speed (§30(5) & §102 EisbBBV - Eisenbahnbau- und -betriebsverordnung, 2008).

If ETCS is used there in contrast with PZB, the fixed point where the braking starts. Rather, the end of the MA is used to calculate when the train must begin to brake to come to a stop in time before reaching EoA (European Union Agency for Railways ERTMS UNIT, 2020, p. 18; Fehlauer & Kahl, 2019, p. 34). So the starting point of the braking curve is at different locations for a heavy freight train and a lightweight multiple unit. This fact and the surveillance of the braking curves lead to a higher safety level. But at the same time, as the braking curves are flatter, the trains are starting to brake earlier. This has the consequence of a capacity loss, and it is necessary to compensate this by adapting the curves or using national values (Eichenberger, 2007, p. 6).

To calculate the different braking supervision curves, the ERA Braking Curves Simulation Tool can be used. Based on this tool, it can be seen, what impact do different changes, like the release speed or overlaps, have. Figure 11 shows a simplified graphic of the ERA Tool.

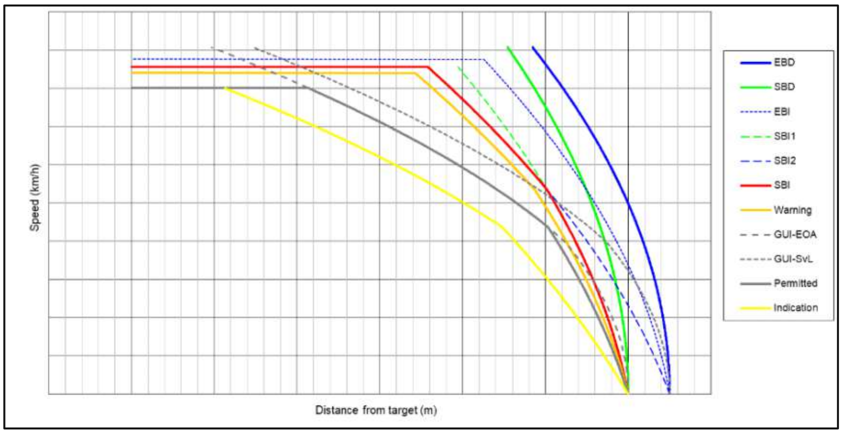

Figure 11: ETCS Braking curves

Source: Own diagram created with ERA braking curves simulation tool (European Agency for Railways, 2020)

The first occurring curve is the Indication (I), which shows the train driver, that he must reduce the speed and start to brake. Then the train driver must follow the Permitted Speed (P) curve. If the train driver does not respect the permitted speed curve, he will reach the Warning Curve

(W), which is starting an acoustic warning. There a Service Brake Intervention (SBI) can be found, which is considering the brake build-up time. If the SBI is not respected, the systems start with a service break. The Service Brake Deceleration (SBD) is calculating the service brake with all available brakes. That is the reason why there can be a difference between the SBD and the Emergency Brake Deceleration (EBD) Curve. The Emergency Brake Intervention (EBI) supervision is considering the brake build-up time and is triggering an emergency braking. The EBD is a calculated emergency braking which takes only a part of the brakes into consideration, which guarantees that the vehicle comes to stillstand before the Supervised Location (SvL) (Busse, 2021, p. 38; Eichenberger, 2007, pp. 7–8; European Union Agency for Railways ERTMS UNIT, 2020, pp. 8–9).

The overlap is a significant factor in the calculation of the braking curves at ETCS. As mentioned, the MA leads to the EoA after this point there is the SvL. This point can be reached by the train without any danger. The distance between the EoA and SvL is the overlap. But the SvL can also be at the same position as the EoA. This implies that, in this situation, the overlap is zero and then all braking curves must be calculated to this point. That means that also the permitted speed curve will be more restrictive. Therefore, the braking curves will be flatter, or in other words, the train starts earlier to brake (Eichenberger, 2007, p. 14; Löfstedt, 2011a, p. 207).

To give a better overview of the described content, Figure 12 shows the EBD curve with the different surveillance curves.

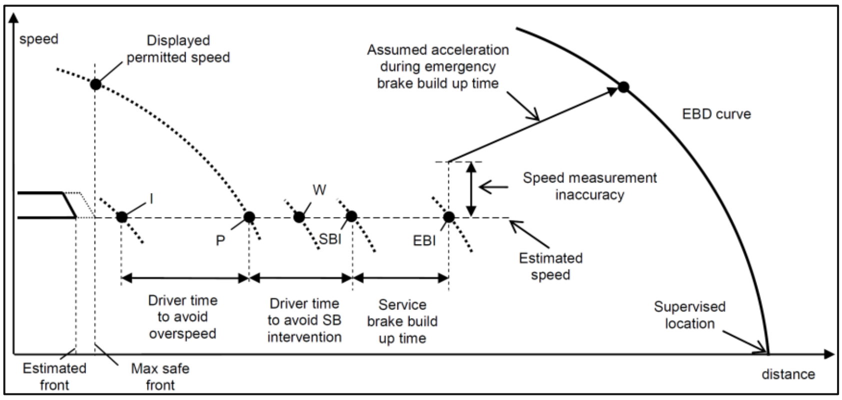

Figure 12: EBD braking curve and related supervision

Source: Picture taken from European Union Agency for Railways ERTMS UNIT (2020, p. 9)

Two different braking models are used in ETCS. These models are also offering the possibility for the infrastructure manager and the railway undertaking to implement national values or correction factors (European Union Agency for Railways ERTMS UNIT, 2020, pp. 12–16). The lambda and the gamma model are more common.

Lambda Model

The basis for this model is the braked weight percentage, which is also known as lambda. Lamba depends on the braked weight and the mass of the train. This value must be entered into the ETCS computer by the train driver. From there the system calculates an emergency brake deceleration and brake build-up time model. Typically, this model is used for trains which are changing their composition more often. Therefore, it is not possible to make specific examinations of the behaviour for every possible locomotive and wagon composition, since there is a wide variety of freight wagon types (Fehlauer, 2018, pp. 13–15).

Formula 1 shows the braked weight percentage.

$$Braked\ weight\ percentage\ [\%] = \frac{braked\ weight\ \ [t]}{vehicle\ mass\ [t]} \times 100$$

Formula 1: Braked weight percentage

Source: Formula taken from Austria Standards International Standardization and Innovation (2019., p. 7)

Gamma Model

The second possibility is the gamma model, this model can be used for all trains with a fixed composition or a finite number of defined compositions. Typically, there are multiple units whether in the suburban area or high-speed traffic. Here, the braking force is proven by tests. Therefore, a more accurate picture of the braking behaviour can be presented (European Union Agency for Railways ERTMS UNIT, 2020, p. 15; Fehlauer, 2018, pp. 13–15).

2.2 Driver Advisory Systems (DAS)

The behaviour of the train driver has a direct influence on punctuality and energy consumption during the train journey. This journey can be divided into four different sections: Acceleration, Cruising, Coasting and Breaking. If a train is, for example, delayed an appropriate driving behaviour can reduce this delay. But also, if a train is on time, an efficient behaviour can save energy (Albrecht, 2014b, p. 131). Therefore, since the 1970s driver support systems were developed. Static systems offer only offline information, which is based on timetable data. It gives the train driver information on when he should start behaviours, such as coasting. Because of this, dynamic train-related systems and dynamic network-related systems were developed. There are two main differences between them. Driver support systems can be only informative advisory or assistance systems. These systems can be standalone or integrated systems, which are partly or fully integrated into the ATP (Albrecht, 2014a, pp. 106–107).

Nowadays there are different DAS which have different functions, some of them are integrated solutions with a Traffic Management System (TMS). The next four presented systems are a non-comprehensive list of DAS:

Computer-Aided Train Operation (CATO)

This system was primarily developed for freight trains. It is a dynamic network-related standalone system, which was used especially on single-track lines to optimise the crossings of two freight trains.(Albrecht, 2014a, pp. 110–111) CATO is the first DAS which enabled the interaction with a centralised TMS (Tschirner et al., 2014, p. 131).

***Elektronischer Buchfahrplan und Verzeichnis der Langsamfahrstellen - Energiesparende Fahrweise* (EBuLa)**

The EbuLa ESF is an electronic timetable for train drivers and includes zones with speed restrictions and offers the possibility for an energy saving mode. This DAS is used in Germany and was invented for passenger trains of the DB. A future DAS the train control regulation so called *Zuglaufregelung* (ZLR), is planned (Albrecht, 2014a, pp. 110–111).

Adaptive Train Routing (ATR) / Traffic Management System (TMS)

In Austria, the ÖBB uses the ATR, which is integrated in the TMS. It is used to give the driver recommendations to prevent conflicts in the traffic and save energy based on homogeneous driving behaviour. The system is connected to the Advanced Railway Automation Management Information System (ARAMIS), which enables ATR to react on different situations, like route conflicts occupied tracks in stations, conflicts in the blocking times, etc. (Schuh-Säbelkampf & Schlapfer, 2020, pp. 31–36).

3 Capacity

In the railway system, different disciplines come together, and in this context, terminology is sometimes used in different ways in several fields. For example, the term capacity can be used not only for a railway line but also for the capacity of passenger trains to express the passenger capability. The market (customers), the infrastructure managers, the timetable planners and the operators have a different view of the term. However, they all describe it as quantity in a certain period, be it people, freight, train paths or trains (Roberts et al., 2010, p. 3). In the present work, the term is used to consider the railway lines. But even after this first definition, there are still different ways of looking at the term capacity. In the context of a traffic analysis of a railway line or a junction not only capacity is a relevant term. Likewise, performance is a more comprehensive parameter. Therefore, in this chapter, the terms, needed to answer the research question, will be explained.

3.1 Definition of capacity

In the literature, the capacity in the field of railway operations is not exactly defined. On one hand, there are detailed approaches that represent the concept differently. On another hand, very simple approaches are used, such as only trains per hour, but this appears inadequate to represent reality (Barter, 2008, p. 215). However, it was noticeable that the definition of capacity according to Krüger (1999) was often found in publications (Abril et al., 2008, p. 776; Lai & Barkan, 2009, p. 33; Landex, 2008, p. 7). This definition describes capacity precisely but not too extensively:

> *„Capacity is a measure of the ability to move a specific amount of traffic over a defined rail line with a given set of resources under a specific service plan.“* (Krueger, 1999, p. 1194)

Is should also be mentioned that the focus on capacity is not the same worldwide. For example, in the USA, railway operations, especially in freight transport, are improvised. That means that a freight train does not have a planned timetable in advance, but it will be sent when there is a demand. In Europe there is a fixed timetable and planned path for each train, whether freight or passenger train (White, 2005, p. 35). That leads to the fact, that the capacity is oriented to the amount of possible train paths in Europe. Compared to that in the USA, the main performance metric is the delay of trains (Pouryousef et al., 2015, p. 33). This work considers the European Railway network, therefore; though the American approaches are checked to look for potential applications, something can be applicable, but the focus is on the European approaches. For this purpose, the codes of the International Union of Railways (UIC) are used for the research of the definition of capacity.

According to UIC Code 406 capacity means the possible total number of trains in a defined period, considering the characteristics of the existing train paths (e.g. different speeds or stopping patterns) (International Union of Railways, 2013, p. 13).

Also, a definition of capacity usage can be found in the UIC 406, from 2004. This definition is not only consisting of the infrastructure occupation, but it is also including a certain buffer time and a reserve time for single-track lines and a reserve for maintenance. This definition (k=A+B+C+D) is explained in Formula 2.(International Union of Railways, 2004, p. 17) That means, in general, that capacity consumption can be expressed as a factor of occupancy time and buffer times in a considered time period. The calculation formulas from the UIC 406 (2nd Edition) will be explained in Chapter 3.4.2 (Optimization methods).

$$k = A + B + C + D$$

$$K = \frac{k * 100}{U}$$

k…………….total consumption time [min],
A……………infrastructure occupation [min],
B……………Buffer time [min],
C……………Reserve time for single-track lines [min],
D……………Reserve time for maintenance [min],
K……………Capacity consumption [%],
U……………Selected time frame [min].

Formula 2: Total consumption time and capacity consumption based on UIC 406 (2004)

Source: Formula taken from International Union of Railways (2004, p. 17)

$$Capacity\ consumption\ [\%] = \frac{Occupancy\ Time\ [min] + Additional\ Times\ [min]}{Defined\ Time\ Period\ [min]} \times 100$$

Formula 3: Capacity consumption according to UIC 406

Source: Formula taken from International Union of Railways (2004, p. 13)

This UIC code also illustrates the different capacity parts, which can be seen in Figure 13.

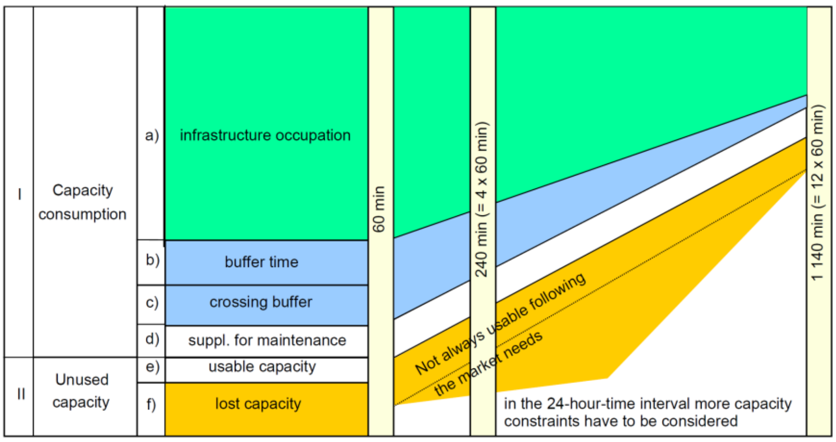

Figure 13: Capacity consumption according to the UIC 406 method
Source: Picture taken from International Union of Railways (2004, p. 16)

It can be seen that in an examined timeframe, there are two main parts: the consumed and the unused capacity. The unused capacity is divided into the usable capacity and the lost capacity, whereby the unused capacity is the difference between the total time and the used capacity, where additional train routes could be possible. If train routes are for example not required, then there can be word of lost capacity (International Union of Railways, 2004, p. 16).

The capacity consumption is the sum of infrastructure occupation, the buffers and additional time for maintenance. Buffer times are a relevant parameter to ensure a robust timetable. Especially to avoid that other trains are not so heavily influenced if one train has a delay from any reason (Happel, 1959, p. 89). That means there is a minimal headway, where trains have a so-called technical running time and an additional buffer between the trains. Based on the RIL 405, the rulebook for railway capacity of the DB InfraGO AG(former DB Netz AG), the buffer time is one minute in normal cases and two minutes if there is a higher speed difference between two trains or the trains are running into the opposite direction (DB Netz AG, 2007a, p. 5; Kaminsky, 2001, p. 119). At this point, it should be mentioned that in timetable planning, there should also be recovery margins to ensure the punctuality of the trains. For this purpose, the UIC 451-1 describes time supplements for timetable planning. They can depend on distance, running time or be constant for different train categories (freight trains, multiple units or locomotives and passenger coaches) (International Union of Railways, 2000, pp. 4–7).

For the capacity definition, there are also other descriptions, which are defining these parts. Besides the UIC subdivision of capacity components, Krueger (1999) defined a division into four different types for a parametric capacity model (Krueger, 1999, p. 1194):

- Theoretical (physical) capacity: the upper limit of traffic considering trains with the same train consist, priority and no disruptions,
- Practical capacity: the upper limit of traffic, with a defined quality level, with a 10% buffer in addition to the minimum running time,
- Used capacity: the actual traffic volume that is operated on a line,
- Available capacity: the difference between used and practical capacity within a timeframe.

It can be seen in this description that in contrast to the UIC 406, Krueger also describes the theoretical capacity, which cannot be reached in praxis. Therefore, the practical capacity, which respects real conditions is much lower. On a single-track line, the practical capacity is estimated at around 60-70 % of the theoretical capacity (Kraft, 1982, p. 465). Other estimations claim practical capacity at around 75 % of the theoretical capacity (Roberts et al., 2010, p. 4). That shows that more detailed investigations are necessary, considering the dependencies and influences of several trains.

From this it becomes clear, that capacity is not a static term, which can be calculated only once. It is a dynamic value, which is calculated for a selected track section and for a specific time range with a defined timetable. It can be concluded that single or bidirectional traffic on a line creates another capacity output. Moreover, different signalling systems and the block division, with specific route options (e.g. entering speed) can change this parameter (Abril et al., 2008, pp. 777–778). These aspects will be described more in detail, when practical examinations are carried out in this work. In general, in the research world and in the UIC 406, the capacity depends on the number of trains, average speed, heterogeneity and stability (Sameni, 2012, pp. 11–15). In addition, the train headway has a direct influence on the capacity. The smaller the minimum train headway of the investigated area, the higher the capacity. For example, if a freight train with 90 km/h and a long-distance train with 200 km/h are considered, the difference in speed and acceleration results in a longer train headway than in the case of two trains with the same speed. If a line is only used for high-speed trains or only metro trains, then the capacity is also changed. These factors can be made visible in the capacity balance, which is shown exemplarily in Figure 14.

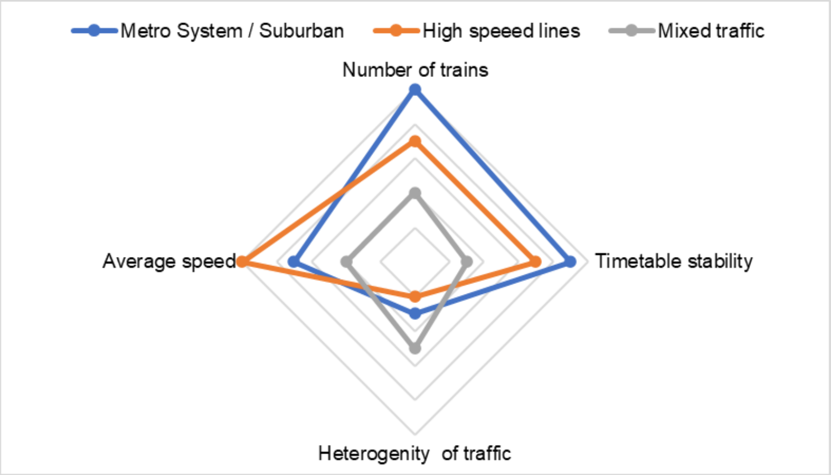

Figure 14 Capacity balance according to UIC 2009

Source: Own diagram based on International Union of Railways (2004, p. 3)

The capacity balance allows also a first argumentation as to why the capacity of a certain line can be higher, for example in homogeneous systems, like a metro where all trains have the same speed and stopping pattern, in which, in the end, results in a better practical capacity (Landex, 2008, p. 77).

As described above, the term practical capacity, frequently used, can be also compared with fundamental capacity. The practical capacity is also described as fundamental capacity, which can be used for operations (Landex, 2008, p. 78). Additionally the capacity on a certain day is named as available capacity which can be equal or smaller than fundamental capacity, due to maintenance or a lack of staff (Landex, 2008, p. 78). A similar subcategory can be found, it is called the commercial capacity. It is described that not the whole practical capacity is attractive for the market. This can occur in two reasons, one is, for example, a certain path that leads to longer travelling time, due to needed crossings. A second reason for this could be that, for example, the need for passenger traffic is in a certain time frame and out of this time frame there is no need for further trains (Roberts et al., 2010, p. 5).

From this description, it can be concluded that there are different main categorizations, but these categorizations cannot be compared exactly with each other:

- International Union of Railways (2004, p. 16) UIC 406: Capacity consumption (Used capacity) - Unused capacity (Usable capacity - Lost capacity),
- Krueger (1999, pp. 1195–1196): Theoretical capacity – Practical capacity (Used capacity, Available capacity),
- Landex (2008, pp. 77–78): Maximum capacity – Fundamental capacity – Available Capacity,

- Roberts et al. (2010, p. 5): Theoretical capacity – Practical capacity – Commercial capacity.

There can be made also a capacity calculation in different ways, to identify which time part is usable for the train path or not. For this purpose, different methods are used, which will be described in Chapter 3.4 (Capacity assessment). Before this is done, there will be a comparison with the performance, which is not so often used in English literature, but more often in German literature.

3.2 Performance / Efficiency (Leistung / Leistungsfähigkeit)

To get a full picture of capacity, it should be sketched out that there is also the term *performance* or *efficiency*. Performance is the ability of a railway system to process a certain amount of train routes in a defined area with a planned quality level (Vakhtel, 2002, p. 19). In Germany, the infrastructure operator DB InfraGO AG (former DB Netz AG) describes the performance as the number of trains processed or to be processed per unit of time. Performance is the feasible number of journeys (DB Netz AG, 2007b, p. 3).

Performance is the upper limit of a possible number of trains. With more trains the waiting times rise to theoreticallyinfinite waiting time, whichmeans that the timetable is not usable in the practice, also the opposite side, with zero waiting time, it is not suitable in practice. When there are zero trains or only a few trains, the waiting time is tending to zero, but the traffic is not adequate to the need (Vakhtel, 2002, p. 19). The performance is also categorized into theoretical and practical performance. The theoretical value cannot be achieved, and this value has no reference to quality. It is only a limit for considerations, which is calculated to make comparisons with the practical performance value (DB Netz AG, 2007b, p. 9). For the calculation of the performance, there can be a separation in track groups and turnout areas (Nießen, 2008, pp. 25–26).

Considerations about performance are comparable to the capacity according to UIC 406. Therefore, due to the equivalence to the term capacity, the term capacity is furtherly used.

3.3 Level of Service

If the level of service is considered, it becomes obvious that the operational quality is also a question of economic efficiency. With fewer trains on a line, delays are less likely to be transmitted and waiting times are shorter. At the same time, however, railway lines are built and operated at a very high investment cost and therefore need to be utilized to their full potential. The higher the capacity utilization, the more operational difficulties arise.

Therefore, the aim is to have an economical optimal operational quality. Where there is a balanced infrastructure occupation and an appropriate quality. Typically, there can be found different quality levels (premium, optimal, risk-bearing, inadequate) (Meirich, 2017, pp. 24–27; Vakhtel, 2002, p. 22). Figure 15 shows the illustration of the Level of Service.

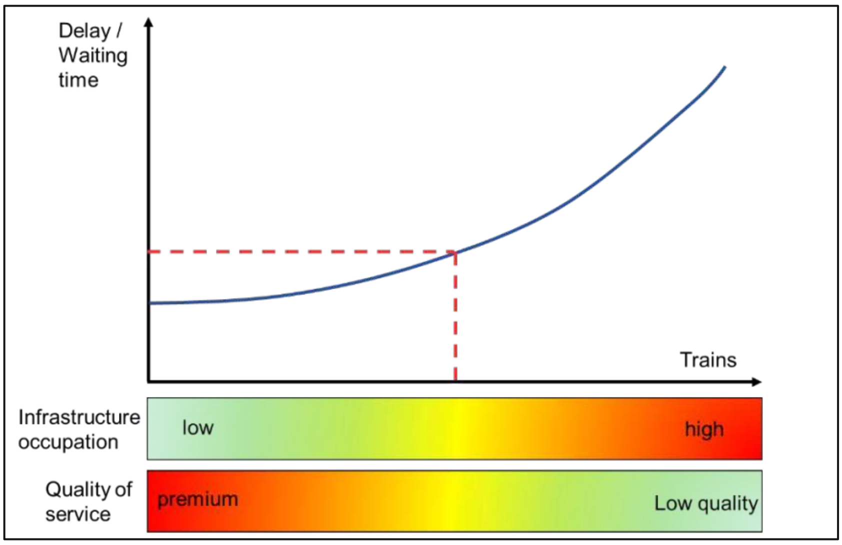

Figure 15: Illustration of the Level of Service

Source: Own sketch based on Jänsch et al. (2021, p. 302)

Based on the German RIL 405, the quality factor, which is the quotient of the calculated waiting time and the permitted waiting time, can be found in the literature. If this factor below 0.5, the line offers many unused train paths. If the factor ranges between 0.5 and 1.2, it is economically optimal, because there are remaining routes, but the infrastructure is efficiently utilized. Between 1.3 and 1.5, the operation starts to get risky, and restrictions occur. Above 1.5 ,the system is congested (Kogel, 2021, pp. 16–17).

These quality factors can be used also as a basis for further measures. For example, the quality factor is used in Germany to assess railway lines. That means, in practice, if a line is over 1.5 the section has to be declared as congested and the operator must develop solutions against this congestion. If the section has a factor under 0.5, it can be a basis for infrastructure removal (Kogel, 2021, p. 17) (§55 ERegG - Eisenbahnregulierungsgesetz, 2016).

3.4 Capacity assessment

For the calculation of capacity, different methods can be used. As input, the infrastructure parameters are used as a basis. Several infrastructure variants with the capacity as an indicator for investigation can also be compared. Depending on the focus of the research, railway nodes, line sections or networks can be investigated. Therefore, besides the selection of the research environment, there must be a determination of time. Investigations can be made in existing systems or in the near future. But it is also possible to investigate scenarios in the wider future as a basis for infrastructure investments or long-term procurement of rolling stock. The goal is to determine a factor for the selection of the method (Meirich, 2017, p. 30). For short-term investigations, a constructive timetable analysis can be the method of choice. Simulation methods can be used for short and midterm investigations and sometimes for long-term investigations. In simulations, operational scenarios are simulated with stochastically delayed trains, and for this purpose, it is necessary to have a timetable, so that it is possible to have a detailed illustration of the reality that shows the dependencies of trains and infrastructure on each other. For long-term investigations, when there is no timetable available, it is possible to use analytical methods, which can also be used for mid-term investigations or sometimes for short-term investigations, with some limitations (Warninghoff & Ferchland, 2004, p. 491). In the literature, several categorizations of the methods, with different levels of complexity can be found. To solve the research questions, it must be defined which method will be used. For this purpose, it is important to get a better overview of the different methods. So, a categorization will be presented and based on that categorization there will be a more detailed explanation of them. As described, there are several detailed categorizations. For this research, graphical methods, optimization methods, parametric methods, analytical models, simulations, and statistical / deterministic methods will be discussed. Graphical methods are often assigned to constructive methods, for this work they are described more in detail (Mikulčić & Mlinarić, 2021, pp. 142–143). In addition to this category, the stochastic method is subdivided into analytical and simulation methods according to Vakthel (2002). The choice of the generic term stochastic models is used, as there is a stochastic approach within the analytical method and stochastic simulations. However, due to consistency with the literature this division will be retained (Vakhtel, 2002, p. 24). For investigations of scenarios from the past, deterministic methods will be used (Weingand, 2021, p. 303). Figure 16 shows an overview of the different methods for capacity assessment.

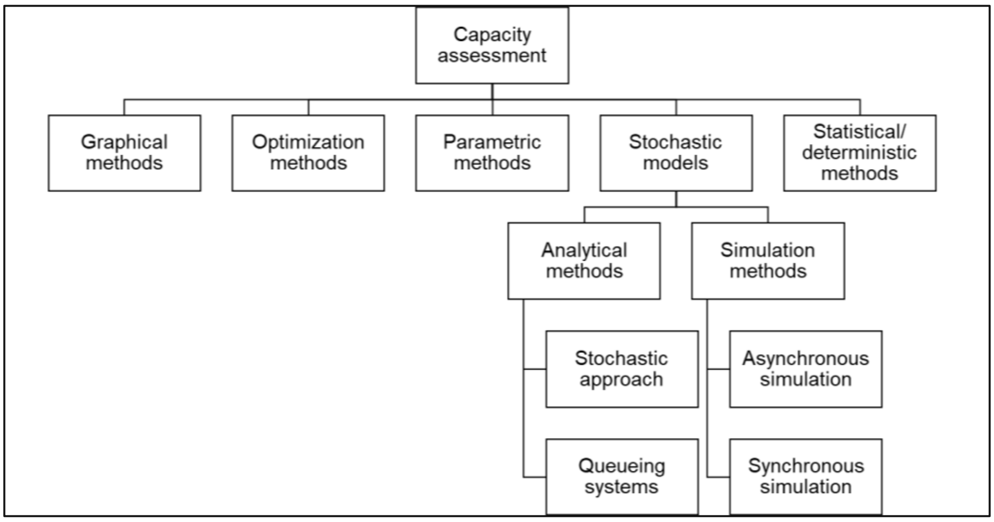

Figure 16: Classification of the methods for capacity determination

Source: Own illustration based on Vakthel (2002, p.24)

3.4.1 Constructive methods

In the constructive method, a timetable is designed over a certain period on a certain section of the line. Based on the time spent on the trip, it can be seen how long the infrastructure elements are occupied. The constructive method allows only conclusions to be made about scheduled operation, but not about deviations that occur with a certain probability are considered (Wieczorek, 2006, p. 17).

Typically, this method is represented by the graphical representation of the blocking times (Gille, 2013, p. 24). This approach will be described in the next paragraphs.

Graphical methods

For simple railway lines which are not highly crowded, the graphical method can be a possibility to calculate the capacity of a certain section with lower complexity. This method is carried out from the Department of Railway Transport at the University in Žilina. It is based on the UIC 406 methodology, but it also uses elements of the certain analytical method which is used at the Železničná Spoločnosť Slovensko (ŽSR), the Slovakian railway. The graphical approach gained attention as it multiplies time and distance. The result of this multiplication, i.e. the area of occupancy, is the starting point for further approaches and further development of this method (Gašparík et al., 2015, pp. 283–285).

The occupation squares are drawn to fit to the track safety devices and the train control system. These requirements for drawing the squares are taken from the Slovakian regulation ŽSR D24. Formula 4 shows the practical track capacity (Gašparík & Zitrický, 2010, p. 389):

$$n_{prakt} = \frac{T - (T_{vyl} + T_{stal})}{t_{obs} + t_{dod} + t_{rus}}$$

n_{prakt}……..……..Practical Capacity [trains per commuting time],
T……………….Time Window [min],
T_{vyl}…………..…Time for Inspection, Maintenance, … [min],
T_{stal}…………….Total Time of permanent manipulation [min],
t_{obs}……………..Occupation Time for Train movement [min],
t_{dod}……………..Additional Buffer Time to solve disorders [min],
t_{rus}……………..Average Time of train interferences[min].

Formula 4: Occupation rate based on ŽSR D24

Source: Formula taken from Gašparík & Zitrický (2010, p. 389)

For the ŽSR D24, average trains are used and considered in certain areas of a line. If there are bottlenecks, the possible capacity in this is assumed to be the practical capacity for the entire line. Regarding to fact that between two trains must be a buffer time, the ŽSR D24 summarizes t_{dod} and t_{rus} and offers values for t_{medz} (the time factor between two trains) (Ľupták et al., 2018, p. 214).

The approach from the University Žilina calculates the occupation rate with three main components, the selected time period and the occupation squares of every block section and the additional station time intervals. The calculation can be seen in Formula 5.

$$S_V = \frac{\sum_{i=1}^{n} S_{obsi} + \sum_{j=1}^{m} S_{PVj}}{S_T} \times 100 \quad [\%]$$

SV………………..Occupation rate [%],
ΣSObsi……………Sum of occupation squares for each block section [m * min],
ΣSPVj…………….Sum of track and station time intervals [m * min],
ST………………..Square of the selected time period (length of the examination room * total time selected) [m*min].

Formula 5: Occupation rate

Source: Formula taken from Gašparík & Zitrický (2010, p. 389)

The occupation rate is thus an expression of the utilisation of the infrastructure. This allows conclusions to be drawn about the capacity. The method can therefore be applied as follows: the occupation rate is determined with a desired timetable. This is then compared with the corresponding recommendations of UIC 406. If the route is not yet fully utilised, then further trains can be inserted, and a new calculation can be carried out. This can be done until the recommended occupation rate is reached (Gašparík & Zitrický, 2010, p. 391).

The described graphical approach can be used manually or by using any software which has graphical support. This means that the blocking times are visible, and the time components can be calculated out of this. It would certainly be possible to develop a tool for this purpose (Gašparík & Zitrický, 2010, p. 391).

3.4.2 Optimization methods

As already mentioned at the beginning of Chapter 3.4 (Capacity assessment), there are different classifications of methods for determining capacity in the literature. In some sources, optimisation methods are seen as a separate category, but in other works, they are subcategorized under analytical methods. The presentation as a separate method, as chosen in this work, allows the most exact separation of the different approaches (Mikulčić & Mlinarić, 2021, p. 143).

The optimization method is using a more strategic approach than purely analytical methods. The approach in this method is to saturate the timetable as much as possible. This is done by starting with either an empty timetable or one with real train data and filling it with trains until saturation occurs. At this point, saturation expresses the state in which the timetable is being presented with the maximum possible number of train courses. Some methods try to do this with a graph theoretical approach. In the other approaches, however, the focus is collecting two values. A maximum value is the highest possible number of trains, and a minimum value, the lowest costs per timetable variant. It is also possible to search for the best solution with the lowest costs (Abril et al., 2008, pp. 780–781).

To realise this, a mathematical formulation is created for optimisation methods. Depending on the approach, different procedures can be chosen. That can be for example integer programming, linear programming, multi-objective, heuristic and metaheuristic methods or mixed integer programming (Sameni & Moradi, 2022, p. 5).

This category also includes the graphical compression of frequent train paths, as used in UIC 406. UIC 406 is therefore not only an important set of rules in which the definition of capacity is explained, see Chapter 3.1 (Definition of capacity), but also offers a corresponding methodology for calculating this capacity (Abril et al., 2008, p. 781). In the literature and practice, this method has received a great deal of attention and is also used by railway companies, whether the method is applied manually or implemented in software solutions (Landex, 2011, p. 2). For this reason, the UIC 406 method will be discussed in more detail below.

UIC 406 method

The UIC 406 method for capacity determination is a calculation method that is carried out using a compression method. Due to the complexity and interconnections of different train runs, it is necessary to divide the route into the smallest possible sections to apply this variant. This creates subsections that can be evaluated. For this purpose, the existing timetable or a desired timetable is displayed graphically. This is done by means of blocking times. The actual occupancy of the respective infrastructure results from these blocking times. In a selected period, it is calculated how long this section is occupied. For this purpose, the blocking time staircases are moved as close to each other as possible. However, the sequence of the trains and possible dependencies (e.g. transfer connections or train crossings) are considered. In this case, the minimal technical headway time should be between the trains. Now it is determined when the first occupancy has taken place and when the release time is for the last train. In this way, an occupancy time is received in addition to the defined period (Landex, 2008, pp. 12–13). The calculation in Formula 6 shows the calculation of the capacity consumption, the occupancy time and the additional time rate.

$$C_C = \frac{t_O + t_A}{t_D} \times 100$$

$$O_R = \frac{t_O}{t_D} \times 100$$

$$A_R = \left[\frac{100}{O_R} - 1\right] \times 100$$

$$C_C = \frac{t_O \times (1 + A_R)}{t_D} \times 100$$

C_C……………Capacity consumption [%],
t_O……………Occupancy Time [min],
t_A……………Additional Times [min],
t_D……………Defined Time Period [min],
O_R…………..Occupancy Time Rate [%],
A_R…………..Additional Time Rate [%].

Formula 6: Capacity calculation according to UIC 406
Source: Formula taken from International Union of Railways (2013, pp. 29–30)

For the appropriate application of the method, the relevant recommendations for the occupancy time rates and the additional time rates are given in UIC 406. There are also further recommended values for nodes. The limit values should be selected for the traffic. A distinction is made between suburban lines, high-speed lines, and mixed-traffic lines. In addition to this, higher values can be tolerated in the peak hour than in the entire daytime range. Table 1, 2 and 3 are showing these limit values.

Table 1: Proposed Occupancy time rates

Source: Table taken from International Union of Railways (2013, p. 29)

Type of line	Peak hour [%]	Daily period [%]
Dedicated suburban passenger traffic	85	70
Dedicated high-speed line	75	60
Mixed-traffic lines	75	60

Table 2: Proposed additional time rates for line

Source: Table taken from International Union of Railways (2013, p. 30)

Type of line	Peak hour [%]	Daily period [%]
Dedicated suburban passenger traffic	18	43
Dedicated high-speed line	33	67
Mixed-traffic lines	33	67

Table 3: Proposed occupancy rates and additional time rates for nodes

Source: Table taken from International Union of Railways (2013, p. 30)

Type of line	Concatenated Occupancy Rate [%]	Additional Time Rate [%]
Switch area	60…..80	67…..25
Track area	40…..50	150…..100

- Calculation of capacity in railway nodes

The revision of the UIC 406 method in 2012 has made an accurate assessment of nodes possible. This was achieved by specifying the calculation methods in the track groups and route nodes. These changes can therefore be found in the 2nd Edition of the UIC Code. With the new approach, the infrastructure is divided into nodes in track areas and switch areas, which are analysed separately from the line. This makes it possible to take into account train movements that do not run on the examined line, but only terminate in this node. Additionally, the fact that tracks are occupied by longer stops, for example, is also taken into account (Warninghoff & Huber, 2012, pp. 48–49).

A track occupancy plan is created for each track group, then a compression is carried out individually for each track. Based on this, the occupancy rate of the entire track group is determined (Warninghoff & Huber, 2012, p. 50). In the switch areas, the respective journeys are considered in such a way that only the technically minimum headway is present between the individual train journeys. Now a calculation sheet is created with the corresponding times (Warninghoff & Huber, 2012, p. 50).

Figure 17 shows a concatenations table, which enables the calculation of the Occupancy Time Rate and the Concatenations Rate.

Trip/ Route	Begin of Occupation	End of Occupation/Exclusion							
		pA	pB	aP	aF	fB	fA	bF	bP
pB	0,0	1,4	1,7	1,4	1,4	1,7	1,4	*	*
pA	1,4	3,1	2,8	*		*	3,1	*	*
fB	1,7	*	4,1	*	3,7	4,1	3,7	*	3,7
pA	3,1	4,8	4,5	*	*	*	4,8	*	*
fB	4,1	*	6,5	*	6,1	6,5	6,1		6,1
pA	4,8	6,5	(6,2)	*	*	*	6,5	*	*
bP	6,1	*	*	7,9	7,6	7,6	7,6	7,6	7,9
aP	7,9	*	9,4	9,7	9,2	*	9,2	*	9,7
fA	9,2	11,6	11,2	11,3	11,3	11,2		*	11,2
fB	11,2	*	13,6	*	13,2	13,6	13,2	*	13,2
aP	11,3	*	(12,8)	13,1	(12,6)	*	(12,6)	*	(13,1)
fB	13,6	*	16,0	*	15,6	16,0	15,6	*	15,6
pA	11,6	13,3	(13,0)	*	*	*	(13,3)	*	*
bF	7,6	*	*	*	(9,9)	*	*	9,9	(9,3)
bF	9,9	*	*	*	(12,2)	*	*	12,2	(11,6)
aF	15,6	*	18,0	17,8	18,5	18,0	18,0	18,5	18,0
pA	13,3	15,0	(14,7)	*	*	*	(15,0)	*	*
pB	18,0	19,4	[illegible]	19,4	19,4	19,4	19,4	*	*
aP	19,4	*	[illegible]	21,2	20,7	*	20,7	*	21,2
aP	21,2	*	22,7	23,0	22,5	*	22,5	*	23,0
bF	18,5	*	*	*	(20,6)	*	*	20,8	(20,2)
aP	23,0	*	24,5	24,8	24,3	*	24,3		24,8
bF	20,8	*	*	*	(23,1)	*	*	23,1	(22,5)
bP	24,8	*	*	26,6	26,3	26,3	26,3	26,3	26,6
(pB)	24,5	25,7	26,2	(25,9)	[illegible]	(26,2)	(25,9)	*	*
(pA)	19,4	27,6	[illegible]	*	*	*	27,6	*	*
(fB)	26,3	*	28,7	*	28,3	28,7	28,3	*	28,3

Figure 17: Example of a concatenations table

Source: Figure taken from International Union of Railways (2013, p. 46)

$$O_R = \frac{t_C}{t_D} \times 100$$

OR………………..Occupancy Time Rate [%],
tC…………………Concatenations Time [min],
tD…………………Defined Time Period [min].

Formula 7: Occupancy Time Rate

Source: Formula taken from International Union of Railways (2013, p. 45)

$$\varphi = \frac{K}{Z} \times 100$$

φ…………………Concatenations Rate [%],
K…………………Excluding trips[1],
Z…………………Total trips in Time Period [2].

Formula 8: Concatenations Rate

Source: Formula taken from International Union of Railways (2013, p. 46)

Despite the adaptation of the UIC 406 method, there are still some points to consider when looking at nodes. For example, the length of the tracks is also decisive, as they can be used for overtaking, which must be considered. In addition, an excessively long dwell time on a track must be considered (e.g. loading and unloading of wagons) (Warninghoff & Huber, 2012, p. 50).

A practical example of line capacity

The timetable compression on the line sections will be explained in a practical example. Figure 18 shows a time-distance diagram of the section from Zagreb Glavni Kolodvor / Zagreb Main Station (CLN) to Sesvete (SSV). This is a double-track line section, therefore the trains run on each track in only one direction. A detailed description of the line can be found later in Chapter 4.3 (Railway node Sesvete) of this thesis, where the simulations are carried out. Therefore, the corresponding conditions of the simulation will not be discussed further in this chapter.

A 10 min interval with suburban trains is introduced. This is considered in a three-hour (180 min) time window. The possible headway time is 2.28 min. If the timetable is compressed, an occupancy time of 46 min can be calculated.

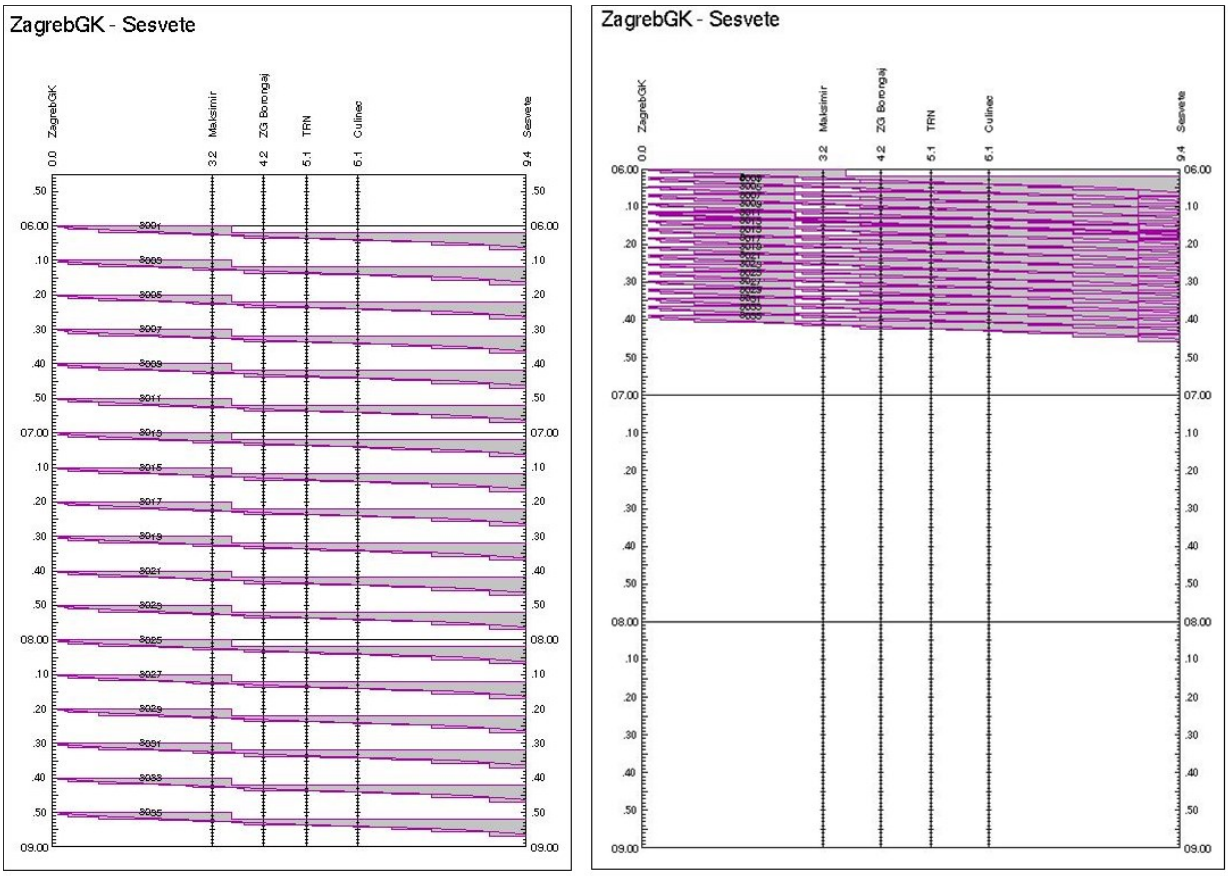

Figure 18: Ten minutes tact timetable and compressed timetable

Source: Own illustration in OpenTrack Version 1.10.3.

As occupancy time rate from Table 1, the 85 % value for the peak hour is chosen. As an additional time, factor from Table 2, 18 % value is chosen.

$$O_R = \frac{t_O}{t_D} \times 100 = \frac{46\ min}{180\ min} \times 100 = 25.56\ \%$$

$$A_R = \left[\frac{100}{O_R} - 1\right] \times 100 = \left[\frac{100}{85} - 1\right] \times 100 = 17.64\ \%$$

$$C_C = \frac{t_O \times (1 + A_R)}{t_D} \times 100 = \frac{46\ min \times (1 + 0.1764)}{180\ min} \times 100 = 30.07\ \%$$

Formula 9: Capacity calculation of the example Zagreb – Sesvete

Source: Calculation based on Formula 6 Capacity calculation according to UIC 406 (Capacity calculation according to UIC 406)

It can be seen in this simple example how the calculation of the capacity can be done with this method. In this example, the capacity consumption for the chosen time frame is 30.07 %. The calculation can be done manually, but it can also be carried out with software support. A requirement for this is that the corresponding software offers conflict detection, which is already the case with various programmes for timetable creation (Landex, 2008, p. 13).

3.4.3 Parametric methods

This method is mainly used in the United States of America. It uses parametric models developed to show relationships between different factors. More concretely, these parameters are operating data, traffic data and infrastructure parameters.

Compared to the other variants, here the focus is on delay and the development of the delay, which becomes clear when the types of capacity in the parametric capacity model are considered. A distinction can be made between a theoretical capacity and a practical capacity. The practical capacity is divided into used and unused capacity. These relationships have already been explained in Chapter 3.1 (Definition of capacity). At this point, a relevant aspect is that the practical capacity is made up of the minimum run time, operating delays, traffic delays and plant delays (Krueger, 1999, p. 1195).

As a basis for this process, it is necessary to use the infrastructure parameters, and the timetable/operating data. These can then be used to determine the capacity of a particular section, with the output being theoretical, practical, and used capacity (Krueger, 1999, p. 1200).

If a parametric model is used with appropriate software, the capacity can be evaluated dynamically. Therefore, this method is also suitable as decision support to evaluate possible changes in the timetable (Krueger, 1999, p. 1200).

Detailed explanations of this approach and the usage of the parametric method can be found in Krueger (1999). The development of the method and the calculation of capacity is explained in detail in Prokopy & Rubin (1975) and Krueger (1999, pp. 1194–1200).

3.4.4 Statistical / deterministic methods

Statistical / deterministic methods are a technique for evaluating operational situations from the past. This means that the data found in practice is evaluated, as it is more of a preparation for the application of further methods. In other words, this method can also be seen as an analytical preparation (Weingand, 2021, p. 303).

The most important parts of this method are the collection of data and the evaluation of the actual condition. A forecast for the future can only be achieved indirectly by this method. For example, in the case of infrastructure elements which were already overloaded in the past, it can be assumed that the operational constraint will increase even in the case of an increase in traffic or the deconstruction or failure of an element. Relevant for the evaluation are the break-in delay and the unscheduled waiting times, as well as extensions of stopping or journey times.

An important component of this method is the quality of the data. The data can be collected via corresponding traffic management systems. In Germany, for example, information on train movements can be accessed for the last 90 days (DB Netz AG, 2020, p. 3).

3.4.5 Stochastic models

The methods described before are based on an estimation of actual arriving conditions, where it is assumed that they will arrive as planned. However, since the railway system is a dynamic system where unexpected disruptions or dwell time extensions occur, this leads to deviations, or more simply, to delays. Therefore, a corresponding assessment of the randomly occurring events is required. This is made possible by stochastic methods. Potthoff (1962) and Schwanhäußer (1974) provided significant developments in this field. Over the last decades, this has led to the current STRELE approach, which is used in DB RIL 405 principles for capacity determination (Schultze, 2015, p. 69). In addition to analytical methods, simulation methods that also deal with probabilities will also be discussed in the following.

Analytical methods

Beneath the queueing system and the stochastic approach, there are also commonly used analytic methods, which will be described before. Typically, that is the UIC 405 method and the Capacity Utilization Index (CUI) (Mikulčić & Mlinarić, 2021, p. 143).

The analytical approach of the UIC 405 method was replaced by UIC 406 in 2004 (Kianinejadoshah & Ricci, 2022, p. 2). Therefore, the UIC 405 is used today mainly to describe the relationship between infrastructure capacity and the quality of operations (International Union of Railways, 1996, p. 5). The former calculation of this method itself is explained in Rotoli et al. (2016, pp. 17–19).

For the CUI there has to be a timetable, which is the basis for the analysis. In this process, the trains are compressed, comparable to the UIC 406. This means that the train journeys are lined up according to the technically minimum possible headway. With UIC 406, however, all occupancies of the blocking times are considered. With CUI, only a complete section between the stops is considered. This leads to less accurate results (Rotoli et al., 2016, p. 20).

Another weak point of the CUI is that, for example, two trains with different speeds generate the same capacity utilisation as several trains with a homogeneous speed. Therefore, although the same CUI is determined, the capacity utilisation of the trains is different since it is only considered if the line is blocked or not. But not the operating programme behind it. Therefore, it becomes even more important to establish a connection between the delay and the utilisation of a line (Roberts et al., 2010, p. 13). Formula 10 shows the calculation of the CUI:

$$CUI\ [\%] = \frac{(a+b+c)}{(a+b+c+d)} \times 100$$

CUI………..Capacity Utilisation Index [%],
a……………Occupied time [min],
b……………Unusable time [min],
c……………Recovery allowance [min],
d……………Unused [min].

Formula 10: Capacity Utilisation Index

Source: Formula taken from Roberts et al. (2010, p. 13)

An important factor in this method is the relationship between capacity utilisation and the delay. For this purpose, the Britian railway network was examined and for every strategical railway line the needed route specific constants were determined (Gibson et al., 2002, p. 347).

Formula 11 shows the calculation of the Congestion-Related Reactionary Delay (CRRD) on the track section in in the period t.

$$D_{it} = A_i \times e^{\beta * C_{it}}$$

D_{it}…….…...Reactionary delay [CRRD/train/distance],
A_i……….…..Route specific constant [1],
β……………Route specific constant [1],
C_{it}………….. Capacity Utilisation Index [%].

Formula 11: Capacity Utilisation Index

Source: Formula taken from Rotoli et al. (2016, p. 20)

The relationship between the CUI and the CRRD can also be shown graphically, as is the case in Figure 19. It shows how an increase in the number of trains also leads to an increase in the CRRD and thus to waiting times. If other route-specific constants are used in the calculation of the CRRD, a corresponding shift of the curve *d* occurs.

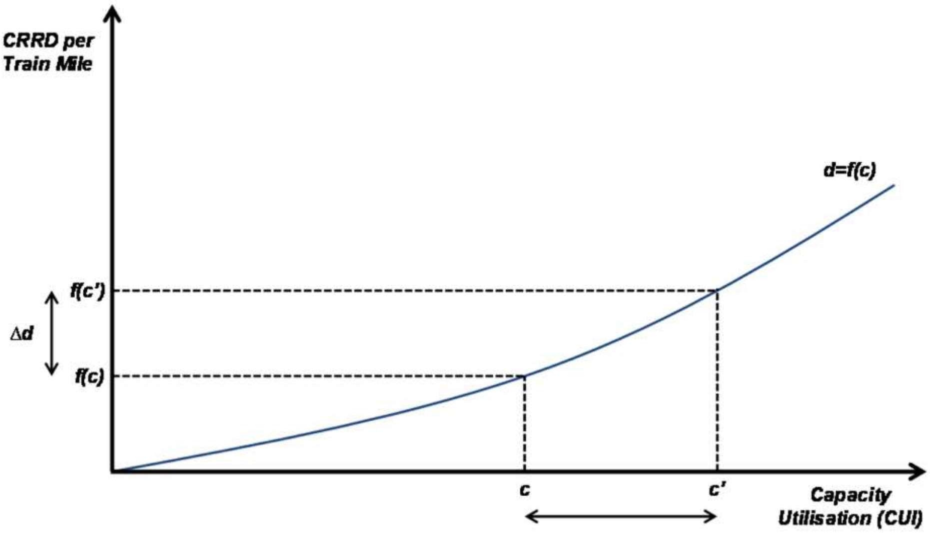

Figure 19: Relationship between CUI and CRRD
Source: Figure taken from Ove Arup & Partners Ltd (2013, p. 26)

Analytical methods with queueing system and the stochastic approach

As described at the beginning, the queuing theory is a procedure that is based on fundamental considerations by Potthoff and was further developed by Schwanhäußer and thus largely incorporated into today's RIL 405 (former DS 405) of the DB (Kaminsky, 2001, p. 119; Schultze, 2015, p. 69). Since then, however, various considerations have been made for improvement and corresponding extensions have been developed. Due to the variety of this approach, this method cannot be fully explained within this document. For this reason, the relevant literature has already been referred to and the basic approach to the application and the benefits of this method will be dealt with in the following.

In terms of procedure, this method can be carried out by including the infrastructure data and the data of the model trains in a journey time calculation. In this way, the headway can be determined. In combination with the relative frequency of the train sequence cases, it is possible to determine an average train sequence time. If a service theory model is not available, the chained occupancy rate can be calculated. If this model is available, the expected value for the delays can be determined with the initial delays (Pachl, 2021b, p. 168).

This methodology uses a model, the model can consist of one or more different operating variants, and it is based on the service-theoretical approach. This model diverts railway networks, as already seen with UIC 406, in nodes and line sections. The nodes and the line sections are analysed separately. For the elements, the minimal headway is calculated. The nodes are thereby broken down into so-called partial route nodes, so that these can be represented as a single-channel operating system in each case. These must roughly correspond to the routes, as the corresponding elements must exclude each other, just as in reality. Therefore, one element cannot be used by two routes at the same time (Pachl, 2021b, p. 178).

The procedure can be described as follows. At the beginning, corresponding model journeys are created. These can either be abstracted from an existing timetable or sketched from requirements for a future unknown timetable. For this reason, this method is also called a timetable-free method (Yuan & Hansen, 2007, p. 203).

The train type, vehicle data and train sequences are selected, and they should be as similar as possible to the future traffic. Then, priority rules are set. Priority, equal priority, secondary priority or partial priority or partial secondary priority. A route exclusion table is created for the nodes and each part of the nodes. The blocking times of the routes are determined according to the infrastructure and the occupancy time is calculated. In this way, the concatenation φ can be calculated, which describes the probability with which the trips in the node exclude each other. From this, the blocking time of the concatenation journeys can be calculated and the occupancy rate in the chosen time window can be calculated. This results in the sum of the obstruction time. Using this data, the main results for the performance of a node can now be determined (Kaminsky, 2001, pp. 119–122).

With this basis, it is possible to determine the quality factor, which has been explained in Chapter 3.3 (Level of Service). For this determination it is necessary to have information about the mean delay and the occurrence probability of delays. Also, it is necessary to know how long the waiting queue and the knock-on delay is. As a next step, it is possible to calculate the performance, whereby there can be calculated different forms of performance, for example, the hourly performance. In the determinative performance the mean buffer time is the most important factor. If this buffer time is respected, then the delays can be compensated (Kaminsky, 2001, p. 10).

Formula 12 shows the calculation of the average buffer time, for a given number of trains, with which a certain level of service is to be achieved. By considering the boundary and primary delays, the distribution of knock-on delays, arrival delays and departure delays can be determined (Yuan & Hansen, 2007, p. 203). Formula 12 also shows an example of the calculation of the unplanned waiting time in line sections.

$$t_{\_p} = \frac{z_{\_} \times (1-\rho)}{\rho} = \frac{A}{N} \times \frac{(1-\rho)}{\rho}$$

$$ET_W = \left(p_{ve} - \frac{p^2{}_{ve}}{2}\right) \times \frac{t_{\_}{}^2{}_{ve}}{t_{\_p} + t_{\_ve} \times \left(1 - e^{\frac{-z_{\_}}{t_{\_ve}}}\right)}$$
$$\times \left[p_g \times \left(1 - e^{\frac{-z_g}{t_{\_ve}}}\right)^2 + (1-p_g) \times \frac{z_{\_v}}{t_{\_ve}} \times \left(1 - e^{\frac{-2z_v}{t_{\_ve}}}\right)\right.$$
$$\left. + \frac{z_{\_}}{t_{\_p}} \times \left(1 - e^{\frac{-z_{\_}}{t_{\_ve}}}\right)^2\right]$$

ETW…….…..Expected unscheduled waiting time per train [min],
tp……………..Average buffer time [min],
ρ……….…….Recommended value for infrastructure occupation [1],
A……….…….Minimum infrastructure occupation [min],
N……….…….Actual number of running trains [1],
pve……….…..Probability of entry delay [min],
tve…………....Average entry delay [min],
z…….….…....Average minimum headway time of all trains [min],
zg…………….Average minimum headway tome of equal ranking successions of trains[min],
zv…….….…..Average determinative minimum headway of different ranking successions of trains [min],
pg……………Probability of occurrence of equal ranking succession of trains [1].

Formula 12: Schwanhäußer's STRELE approach
Source: Formula taken from Rotoli et al. (2016, p. 20)

The disadvantage of the presented method is that only a simplified train pattern is analysed and therefore this method reaches its limits when a systematic or tact timetable is used (Weingand & Heppe, 2013, p. 485). Simulations are more suitable for such complex questions. This fact also explains why the software tool SLS (Streckenleistungsfähigkeit und -simulation / Line performance and -simulation) also contains STRESI I (Streckensimulation / Linesimulation) in addition to the STRELE formula (Schultze, 2015, pp. 69–72). In addition, there are also different approaches to consider special cases with STRELE, such as the so-called *Zacken-Lücken-Problem* (spike gap problem), in which a train that only travels a partial section of a considered route is taken into account (Niebel & Nießen, 2014, p. 36).

Besides this procedure and the simulation method, presented in the next paragraph there is also a simplified procedure for the operational investigation of nodes using the degree of exclusion. This is described by Pachl (2021b, pp. 179–192). Furthermore, this approach is applied in this work at the model of the railway station Sesvete in Chapter 4.3 (Railway node Sesvete).

Simulation-methods

Railway simulations create an operational model from the real environment. For this purpose, the infrastructure is modelled in a software tool as detailed as possible and the actual or planned operation processes (timetable, rolling stock) are inserted and simulated according to different start parameters. In this way, it is possible to generate different operating variants or analyse, which impact a changed track layout has. In other words, simulations act like an experimental approach. This means, that the result depends on the accuracy of the input data (Pachl, 2021b, pp. 162–163). That means, if the complexity of the underlying data is higher, then the quality of the simulation results is better. According to the available data and the degree of abstraction the modelling software can be selected. For example, rough long-term planning requires less data than a short-term timetable study. Different levels of abstraction have therefore been established for the investigation tasks. A distinction is made between macroscopic and microscopic levels. In addition, a variant in between has been formed from the above-mentioned levels, the mesoscopic level (Gille, 2013, pp. 18–21).

Macroscopic models provide an overview of the nodes and edges, but they only use rough average values for the respective nodes or route elements. For instance, the edge between two nodes is considered as one whole element. The nodes show the number of tracks, but the use length, for example, is not considered (Gille, 2013, p. 19). Software tools for macroscopic simulation are for example NEMO, SIMONE or STRESI (Botte & D’Acierno, 2018, p. 171).

Microscopic models offer a detailed picture of the infrastructure. This means, that the track elements are visualized with their real parameters (e.g. speed, gradient, radius) and the track layouts are respected. Also, the chosen signals, with the appropriate signal type, are placed at the correct positions. With all this information, it is possible to calculate the blocking times for the trains for each block section (Gille, 2013, pp. 18–19). Software tools for microscopic simulations are for example RailSys, OpenTrack or EGTRAIN (Botte & D’Acierno, 2018, p. 171).

Mesoscopic models are a mixture of both types. They represent the line as an edge, but not with track accuracy. The nodes, on the other hand, are considered in such a way that, besides the number of tracks, the connection to the track and the use length is considered. This means that it can be excluded that trains in the stations use the same track (Gille, 2013, p. 19). Software tools for mesoscopic simulations are for example multi-train simulator, decomposition approach or TTPSW (Botte & D’Acierno, 2018, p. 171).

Figure 20 shows how the different levels visualize the nodes and the line sections in-between.

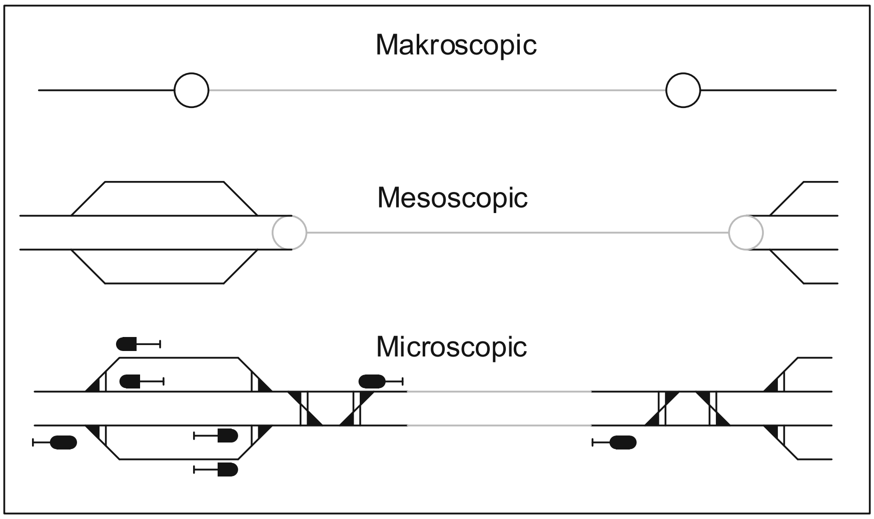

Figure 20: Levels of Abstraction in simulations

Source: Own sketch in MS Visio based on Gille (2013, p. 20)

In addition to this classification, there is also an essential differentiation in how the simulation is carried out. A simulation can be done synchronously or asynchronously. In asynchronous simulations, the trains are simulated according to their priority (Radtke & Hauptmann, 2004, p. 617). This priority is determined by the user and can, for example, include train categories. Therefore, one and the same situation may generate different results if the priority has been chosen differently in both cases. If a conflict occurs the train with the lower priority is postponed. In addition, in asynchronous simulation, the train paths are not bent. The terminology bend originates from the consideration of two train movements in the time-distance diagram. To avoid a conflict between the two following trains, the second train must either minimize its speed or even make an additional stop. These measures lead to the fact that in the time-distance diagram, the blocking times are bent (Dicembre & Ricci, 2011, p. 61; Weingand & Heppe, 2013, p. 517).

In contrast in synchronous simulations, all trains are simulated according to a predefined timetable like in a real environment. In this way, dependencies or interactions between different trains can be simulated realistically (Watson & Medeossi, 2014, p. 194).

It can therefore be summarised that simulations represent an individual approach and must be adapted to the specific situation. This is also the case with the optimization methods, for example (Mikulčić & Mlinarić, 2021, p. 144). This individual approach also leads to the fact that several variants are always required to be able to draw a comparison between them. In contrast, a dimensionless calculation is possible with analytical methods (Weingand & Heppe, 2013, p. 517).

However, there are various combinations of different methods, such as analytical, simulative, and constructive methods. For example, one software that combines different methods is *Leistungsfähigkeitsuntersuchung von Knoten und Strecken* (LUKS) (Janecek et al., 2010, p. 26).

Deterministic and stochastic simulations

A simulation can already be carried out with a single train. This is done for example to check if the infrastructure and train parameters are correct. But the primary objective would be to determine the running time of a specific train. Then, a nominal deterministic timetable without delays could be simulated. The purpose would be to find out if there are double occupations, headway conflicts or other conflicts. As soon as these restrictions or conflicts have been removed, the deterministic simulation can be used to calculate running times, headways, or deterministic capacity. Like in analytical methods, it is also possible to use this method with stochastic inputs. Therefore, different types of delays are inserted as input parameters. One possibility for that is to use the calculation tools, which are already implemented in several simulation software. The software then chooses randomly the delay with the calculated probability, which means that the delay is calculated artificially. These kinds of simulations can be used to prove timetable's robustness and find out systematic conflicts. It is also possible to deal with capacity analyses, where a certain level of saturation is needed. Besides these three types, there is also the category of advanced stochastic simulations, where the delay is not calculated artificially, but real data is available. Therefore, it is possible to use delays from the real environment as input parameters. Advanced stochastic simulations can be used in cases where a railway line already exists and where very detailed results are needed (Watson & Medeossi, 2014, pp. 202–203).

Besides these described techniques, a simulation multiple times, with changed timetables can also be run. This means that there is no fixed timetable, but there are train sequences (Pachl, 2021b, p. 164).

Regarding delays, it should be noted here that, in addition to delays, there are also early arrivals. Typical delays are break-in delays, which are delays caused by trains that have already entered the network under consideration. In addition, there are typically departure time delays or stop-time extensions. In addition to these, travel time extensions can also occur. The various delays can be primary delays or delays transferred to other trains (Büker, 2017, p. 28; Fink et al., 2023, p. 21).

Additionally, it should be mentioned that a higher capacity utilisation of a line leads to lower buffers between trains and thus it is easier for delays to be transferred between two trains. This occurs when the delay of the train ahead is greater than the planned buffer time. This type of delay is called *consecutive delay* (Landex, 2008, p. 92).

Usually, delays can be determined statistically, and various methods are suitable for this purpose. Schwanhäußer, for example, showed that a negative exponential distribution with a limited function range, which limits the function above a certain threshold value, is suitable for determining the delay distribution. A predefined maximum delay serves as the limit value. In addition to this, Conte developed a model of graph theory that uses the nominal distribution. A third method is the calculation using a logarithmic nominal distribution. More details about the delay distribution can be found in Friedrich (2021, pp. 13–18).

After the stochastic parameters are defined, it must be decided how many simulation runs should be done. The number of simulations must be as high that the result is no longer random. In the literature, there can be found values in between 30 and 300 runs (Landex, 2008, p. 102). For example, in the framework of the investigations for Stuttgart 21, in total 200 disturbed timetables were simulated to prove the robustness of timetable’s structure (Martin et al., 2008, p. 26). The decision on how many simulations are needed is individual for each project. It must be defined how detailed the results should be and how much time for the simulation runs is available (Lademann, 2001, pp. 133–134).

Input and Output of Simulations

As mentioned before, the quality of simulations depends on the used data. Therefore, this subsection deals with typical data, which is inserted in simulations. For this explanation, the software OpenTrack is used.

Figure 21 shows the data flow in the simulation software OpenTrack. In the left side of the figure, the input data is visualized. This data consists of the infrastructure, the rolling stock, and the timetable. Based on the simulation, the output data is generated. For example, that can be train graphs or speed-distance diagrams. The software OpenTrack also creates an animation of the simulation for the user. This animation is visualized in a Graphical user interface (GUI) (Botte & D’Acierno, 2018, pp. 166–167).

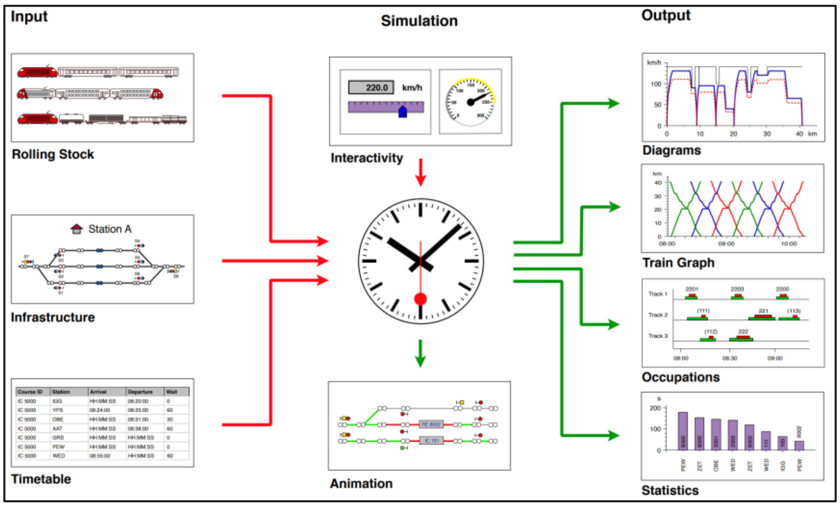

Figure 21: OpenTrack Dataflow with Input and Output data

Source: Picture taken from Open Track Railway Technology (2022)

To create an infrastructure in a simulation, it is necessary to have track parameters of the network. Typically, these are the layout of the tracks, the speed, as well as the gradient and the position of the signals (Hürlimann & Nash, 2017, pp. 3–17). In addition to the infrastructure data, the used trains are also created in the software to be able to carry out the corresponding rolling stock dynamics calculation. This is described in more detail in Chapter 3.5.1 (OpenTrack Simulation) (Nash & Huerlimann, 2004, pp. 51–53).

Besides the rolling stock and the infrastructure, it is necessary to define a timetable, which is included in the simulation. This can be a fictitious or real timetable (Schöbel & Schöbel, 2018, pp. 269–276).

Different parameters can be generated as output. These vary depending on the software. Typically, however, the travel times of trains are determined. These can be displayed accordingly, for example in the form of a time-distance diagram or a speed-distance diagram. However, many other conclusions are also possible. For example, occupancy diagrams of stations can also be generated (Nash & Huerlimann, 2004, pp. 51–53). The outputs from the simulations will be seen later in this dissertation, as they will be used for comparing different variants.

Regarding the software solutions used for railway operations, it should be also mentioned that interfaces between different software are available. These interfaces enable the exchange of infrastructure, rolling stock and timetable data between the different software solutions. A prominent example of these interfaces is the open-source data RailML (Nash et al., 2004, pp. 233–239).

3.5 Selection of method

For the further approach in the work, it is necessary to choose a method with which the impact on capacity can be assessed. Since the focus is on train and traffic control, this means that the selected measures are discussed in detail, and it is therefore necessary to choose a method that fulfils this requirement. Furthermore, realistic study areas should be selected where the measures can be investigated. Due to this aspect, it is necessary to choose a method that can deal with railway operations in detail and deliver meaningful results. At the same time, however, a corresponding complexity should be represented in the investigations. Since the interactions between different train movements and general effects on railway operations are also considered, synchronous simulation is chosen as the concrete method.

This has the advantage that several variants can be compared with each other, and the effects of the individual technologies can also be considered. The commercial simulation software for this purpose includes for example *Trenissimo*, *LUKS*, *RailSys*, *Rail Traffic Controller* and OpenTrack, which enable microscopic simulation (Coviello et al., 2023, p. 721). The literature research shows that OpenTrack can be an adequate tool for simulations and also the corresponding signalling system can be included in the analysis (Abril et al., 2008, p. 781). OpenTrack is a solution that delivers exact results for timetable simulations and it is usable to calculate the performance of a railway network (Uzgidim et al., 2023, p. 323). Because it is a commercial software the programming code is not known (Botte & D'Acierno, 2018, pp. 166–167). But the calculation methods and some details about the software architecture can be found in the manual (Hürlimann & Nash, 2017).

Therefore, in the following section of this thesis, the calculation of the driving dynamics is described. After that with the preliminary results of this first part of the work, further measures are defined, which can influence the capacity. Then, synchronous microsimulations are carried out with OpenTrack to verify which measures influence the capacity.

3.5.1 OpenTrack Simulation

As described in Chapter 3.4.5 (Stochastic models), OpenTrack is a synchronous simulation software that can be used to model railway operations. The underlying systematic and the used formulas to calculate the train movements are analysed in this section The infrastructure of the railway lines is sketched in a worksheet by vertices and edges, with different attributes. Typical attributes for the edges can be the length of the section, the speed profile, or the gradient. Vertices are used everywhere where something changes or an infrastructure element, like a signal, is placed. Turnouts are visualized with a vertex and three connected edges. To realize that turnouts are only used in real operation, not from the through route to the divergent route or vice versa, OpenTrack is using the double vertex graph technique. That means, that every vertex is literally two vertices. This enables also the direction from which the train enters the vertex to be clear. From the attributes of the infrastructure and the rolling stock, the train movements can be calculated (Hürlimann & Nash, 2017).

Figure 22 shows a tractive effort / speed diagram from a locomotive of the series 1116, as used in OpenTrack. For each point of the speed, it is possible to calculate the possible tractive effort (Hürlimann, 2002, p. 51).

Here, the upper horizontal line shows the limitation by the maximum possible tractive force (See Formula 13), and the following hyperbola is the limitation by the power (See Formula 15). The horizontal line represents the limitation of the maximum speed of the locomotive. In addition, the possible adhesion values are shown in grey. The adhesion curves limit the maximum tractive force, which can be used. If the normal adhesion is used, the power is limited by this line; above this speed, skidding occurs (Filipović, 2015, pp. 36–37).

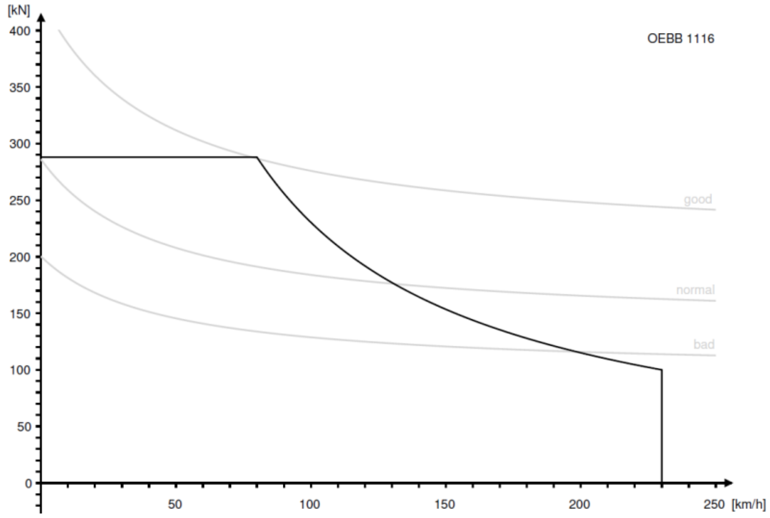

Figure 22: Tractive effort / speed diagram

Source: Diagram created with OpenTrack Version 1.10.3 – With rolling stock input data

So, the tractive force can be calculated as seen in Formula 13.

$$F = m \times g \times \mu$$

F…...………..Tractive force [kN],
m……………Train weight (mass) [kg],
g……………..…Acceleration due to gravity [m/s²],
µ……………. Friction coefficient [1].

Formula 13: Maximum possible tractive force

Source: Formula taken from Pachl (2021b, p. 24)

Several influencing factors, such as weather conditions or the condition of the contact surfaces of the wheel, change the friction coefficient. On dry rails and at 40 km/h the coefficient is 0.25 or in extremely poor conditions it can be as low as 0.05, which makes it more difficult to accelerate a train. Along the measured adhesion, values according to Curtius and Kniffler, the calculation described in Formula 14 results for dry rails (Filipović, 2015, pp. 36–37).

$$\mu = \frac{7.5\ km/h}{v + 44\ km/h} + 0.161$$

µ…...………..Friction coefficient [1],
v……………Speed [km/h].

Formula 14: Friction coefficient

Source: Formula taken from Filipović (2015, p. 40)

As described, the second limiting value is determined by the power of the engine. This limitation depends on the speed and has the form of a hyperbola:

$$F = \frac{P}{v}$$

F…...………..Tractive Power [N],
P……………Motor Power [W],
v…………….Speed [m/s].

Formula 15: Maximum possible tractive power

Source: Formula taken from Filipović (2015, p. 24)

To accelerate or start a train, it is necessary that there is an excess of train force. Therefore, there must be more tractive force than the sum of all resistances affecting the train. In the case of normal running, the sum of the resistances must be equal to the tractive force, therefore only the travelling resistances are relevant. If a braking process is induced, the braking force and the total of all resistances are relevant (Pachl, 2021b, p. 24). Formula 16 shows the traction power surplus as it is also calculated in OpenTrack:

$$F_Z = Z(v) - R_F(v,s)$$

F_Z…..…….....Tractive effort surplus [N],
Z……………..Tractive effort [N],
R_F…..………..Friction Resistance [N],
v..…..……..….Speed [m/s],
s……………..Distance covered [m].

Formula 16: Traction power surplus

Source: Formula taken from Hürlimann & Nash (2017, p. 114)

To calculate the total resistance, it is necessary to consider the trackside resistance and the vehicle resistance. Typically, these are, air resistance, tunnel resistance, acceleration resistance, curve resistance and rolling (or friction) resistance. At this point, only the calculation of the total resistance of the rolling resistance is described. More detailed consideration on the calculation of resistance calculation can be found in Filipović (2015, pp. 27–36) or Pachl (2021b, pp. 23–32). Formula 17 shows the way, the total resistance is calculated in OpenTrack.

$$\sum R = R_L + R_S + R_B + R_W + R_A$$

ΣR…..………..Total Resistance [N],
R_L…………….Rolling Resistance (or train resistance) [N],
R_S……………Gradient Resistance [N],
R_B……………Curve Resistance [N],
R_W……………Switch Resistance [N],
R_A…………….Acceleration Resistance [N].

Formula 17: Total Resistance

Source: Formula summarized, taken from Hürlimann & Nash (2017, pp. 75–83)

The train resistance, which includes air resistance, bearing friction, rolling resistance is often including the tunnel resistance, like in OpenTrack. To calculate this resistance there can be used different calculation formulas, like the UIC, the SBB or SNCF methods (Filipović, 2015, pp. 273–274). In OpenTrack and in the simulations in the next chapters for locomotives and passenger wagons the Strahl's formula is used.

$$R_{LT} = g \times \left\{\left[f_L \times \frac{m}{1000}\right] + \left[k_{St1} \times \left((v + \Delta v) \times 3{,}6\right)^2\right]\right\}$$

$$R_{LP} = g \times \left\{\left[1{,}9 \times \frac{m}{1000}\right] + \left[k_{Sa1} \times 3{,}6 \times \frac{m}{1000}\right] + \left[k_{Sa2} \times (n + 2{,}7) \times \left((v + \Delta v) \times 3{,}6\right)^2\right]\right\}$$

$$R_{LG} = g \times \frac{m}{1000} \times \left[2{,}2 - \frac{k_{St2}}{v \times 3{,}6 + k_{St3}} + k_{St4} \times (v \times 3{,}6)^2\right]$$

$$R_T = f_T \times v^2$$

Passenger trains:

$$R_L = R_{LT} + R_{LP} + R_T$$

Freight trains:

$$R_L = R_{LT} + R_{LG} + R_T$$

RL…..…………Total Rolling Resistance [N],
RLT……………Locomotive Resistance [N],
RLP……………Resistance for Passenger Wagons [N],
RLG…..…………Resistance of Freight Wagons [N],
RT…..…………..Tunnel Air Resistance [N],
g……………..Acceleration due to gravity (Value 9.81) [m/s²],
fL…………..….Resistance Factor (In OpenTrack 3.3) [1],
fL…………..….Tunnel factor [1],
kSa1…………..Resistance Coefficient (In OpenTrack 0.0025) [s/m],
kSa2…………..Resistance Coefficient (In OpenTrack 0.00696) [kg*s²/m²],
kSt1……………Resistance Coefficient (In OpenTrack 0.03) [kg*s²/m²],
kSt2……………Resistance Coefficient (In OpenTrack 80) [m/s],
kSt3……………Resistance Coefficient (In OpenTrack 38) [m/s],
kSt4…………… Resistance Coefficient (In OpenTrack 0.00032) [s²/m²],
n………………Number of passenger wagons [1],
m……………..weight of locomotive / passenger wagons / freight wagons [kg],
v……………..Train speed [m/s],
Δv…………..Wind resistance (In OpenTrack 4.17) [m/s].

Formula 18: Rolling resistance according Strahl/Sauthoff
Source: Formula taken from Hürlimann & Nash (2017, pp. 76–77)

A relevant factor is also the acceleration resistance, which acts during the breaking and acceleration processes. To determine this, the kinetic energy must be considered in the form of a mass factor for translational and rotating masses (Pachl, 2021b, p. 34).

The maximum acceleration can also be derived from the acceleration resistance formula. It is reached when the maximum traction power surplus is invested in the acceleration process. This means that the acceleration resistance corresponds to the traction power surplus. From this fact, the acceleration can be determined as shown in Formula 19 (Hürlimann, 2002, pp. 58 & 63).

$$R_a = m \times a(1 + 0.01 \times \rho)$$

$$a = \frac{F_Z}{m \times (1 + 0.01 * \rho)}$$

R_a..............Acceleration resistance [N],
a..................Acceleration [m/²],
F_Z..............Traction power surplus [N],
m.................train weight (mass) [kg],
ρ.................Mass factor for rotating masses [1].

Formula 19: Acceleration resistance and maximum technical acceleration

Source: Formula taken from Hürlimann (2002, pp. 58 & 63)

OpenTrack uses the Euler's method to determine the different function values. Starting from a known initial value, a desired value of the function is calculated by the differentiation of the function with a fixed time step. This means that with the help of numerical integration, the speed of a specific point within time can be determined by means of an initial speed. In addition to the current speed, the distance travelled can also be determined by integrating the formula again. This procedure is described in Formula 20.

$$v(t) = v(t - \Delta t) + \Delta t * \frac{dv}{dt} \times (t - \Delta t); v(t0) = v0$$

$$v = v0 + \int_{t1}^{t2} a * dt \quad or \quad a = \frac{dv}{dt}$$

$$s = s0 + \int_{t1}^{t2} v * dt \quad or \quad v = \frac{ds}{dt}$$

v..................Speed [m/s],
v0...............Initial speed [m/s],
t..................Time [s].
Δt...............Time difference [s]
a..................Acceleration [m/²]

Formula 20: Calculation of speed, distance with Euler’s method

Source: Formula taken from Hürlimann & Nash (2017, pp. 114–115)

3.6 Aspects affecting the capacity

Comparing the capacity of a single-track with a double-track line shows that the capacity on the double-track line can be expected four times higher. If a double-track line is compared with a four-track lines, such as the Westbahn line (Vienna to Linz (ÖBB Infrastructure AG, 2023c)) or the planned Südbahn line (Vienna to Mödling (ÖBB Infrastructure AG, 2023b)), only a 50 % increase in capacity can be achieved. This is because on double-track lines where, in contrast to single-track lines, directional operation is already possible (Abril et al., 2008, p. 777). This fact also shows that capacity on single-track lines is influenced more by the speed of the individual trains than by heterogeneity. On double-track lines, on the other hand, it shows that capacity can be influenced more by heterogeneity than by speed (Zhang et al., 2011, p. 69). Besides these two aspects there can be found more capacity-affecting factors. They can be divided into infrastructure factors (e.g. block length), traffic parameters (e.g. train mix) and operating factors (e.g. track interruptions for maintenance) (Abril et al., 2008, pp. 777–778). Several aspects will be investigated more in detail in the next subsections to develop a model with different approaches for the simulations.

Determination of affecting aspects

In addition to the categorisation into infrastructure factors, traffic parameters and operating factors described above, there are further finer divisions. Schnieder (2020a) divides these into six categories: vehicle, track topology, station structures, operating programme, train protection and automation (Schnieder, 2020a, p. 2). Regarding train protection, ETCS performance enhancement factors are also described in studies on improvements in the Stuttgart junction (Inegnierugemeinschaft 'Machbarkeitsstudie ETCS S-Bahn Stuttgart', 2019, p. 39). These include the braking model, ATO/TMS, block division, system running times, optimised driving dynamics and the breaking model.

In consideration of the ETCS implementation, the higher capacity is often mentioned as an outcome. But there are also doubts about these expectations, which can be found in the literature. It is criticized, that these increases are often based only on theoretical headway calculations in an isolated network (Coenraad, 2012b, p. 48). However, there are also studies in which the differences between a national train protection system and ETCS Level 1 or Level 2 were almost non-existent, as the braking curves were similar even before the introduction of ETCS (Landex et al., 2019, pp. 59–60). Therefore, it is necessary to consider a whole line or even a network where more factors of the real rail environment are respected.

Even though it is known that capacity can be influenced by various areas, like dwell time, the focus of this paper will be on train and traffic control. Therefore, infrastructure measures, for example, are shown but are not in the focus. In addition to the train control system, overlaps and speed restrictions also have an impact on capacity. These components will be discussed in more detail below.

3.6.1 Overlaps

This chapter of the dissertation focuses on overlaps, more specifically how they are defined and why they are used in railway operations. Also, the different approaches of railway operators in Europe are analysed regarding to this issue. Furthermore, the influence of overlaps on capacity will be discussed. In railway operations, the word overlap is defined as a part of the train route. It is located after the signal at the end of the route, which signals the stop aspect. Their purpose is to avoid train collisions if a train overrides a stop signal (Pachl, 2021a, p. 51). The Transport Authority of the New South Wales describes in their principles about signalling systems (T HR SC 1003 ST) an overlap as follows:

„An overlap is the section of track immediately in advance of a stop signal, which is required to be unoccupied, have all points in the overlap lined up and no conflicting movements authorised, before the stop signal in the rear is permitted to show a proceed indication. Where required for operational purposes in closing up trains, the overlap may be reduced or omitted entirely as long as mitigations are in place to control the approach speed of the train approaching the signal at stop.“ (New South Wales (NSW) Government – Transport Asset Standards Authority, 2018, p. 9)

Based on this definition, an overlap can be sketched like in Figure 23, where the overlap is a part of the route.

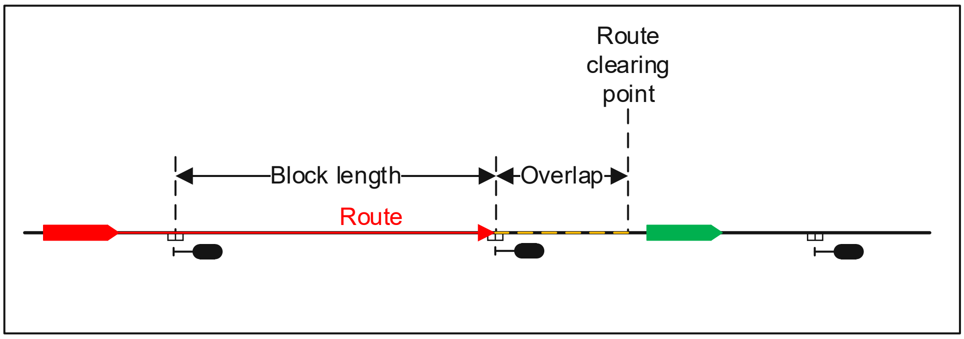

Figure 23: Overlap as a part of the train route
Source: Own sketch in MS Visio based on Pachl (2005, p. 7)

Another aspect of overlaps is that several railway operators require flank protection for overlaps. But there are also railway systems where it is mandatory to lock the turnouts in the overlap itself and other operators deal in a different way with that. That means, if a double-track line with a turnout area is considered and turnouts are situated in the overlap, there can be different solutions, for the use of the tracks. One solution could be that the turnouts on the unused track must be locked in the straight position to ensure flank protection for the route to the home signal or especially for the overlap. Also, the turnout in the overlap must be locked. Another solution would be, that there is no need for locking the elements and providing flank protection, but only the requirement that the area must be free of vehicles (Theeg et al., 2009, p. 79).

As described in the previous paragraph, different safety philosophies can lead to a significant difference in the degree of overlap. These are sometimes due to the historical planning of infrastructure. For example, railway stations in Austria are designed in such a way that the danger point is located relatively close behind the exit signals. A longer overlap would lead far into other routes and so a reduction of the overlaps was initiated in the 1980s (Sicherheitsuntersuchungsstelle des Bundes, 2021b, p. 84). Therefore, in the following chapter the different approaches in Europe will be sketched.

But there is also the possibility to use shared overlaps, so that two different train routes can use the same overlap area after their stop signal. It is argued that the risk of overrunning of two trains at the same time is very low. More precisely the probability of overriding a signal is rated at 10^{-5}, so the probability that two trains are assumed to overrun a stop signal at the same time, would be 10^{-10}, which corresponds to one incident in 10 billion journeys (Maschek, 2015, p. 137). There is also the possibility to use selective overlaps, which means that in some cases the dispatcher can choose the overlap he wants to use for the route. That means he can choose not only the used track for the overlap, for example when there is a turnout in the overlap, but rather also the length. Beneath that, there can be a different length for one route. For example, it may be possible to select a longer overlap to enable a higher speed to enter the station. If, however, the overlap would extend into a route that is to be used at the same time, a shorter overlap could be selected. If the shorter overlap is selected, the speed will be reduced. In practice, three variants can be found (Theeg et al., 2009, p. 82):

- Static overlaps: this overlap can’t be changed after the route is set.
- Extendable overlaps: this variant enables that, after the route is set, the overlap can be extended later; this would also allow an increase in the permissible speed.
- Swinging overlaps: they are applied for example in Great Britain and are used to change the overlap to another track. Therefore, it is necessary that the train is still far away so that the elements in the overlap can reach the new position in time before the train approaches.

Need for overlaps

As already mentioned in the introduction of this chapter, overlaps serve to ensure that in the case of passing a signal with a stop aspect, no collision happens. If the overlap is long enough, it ensures the danger point (DP) is at a wider distance from the exit signal. So, there will be no collision if the train overruns the signal. In Austria, the overlap must be 50 m, in most cases, which will be exactly mentioned in the comparison of overlaps in Europe. But for example, the overlap in Germany is longer and from this, the result is, that the danger point is correspondingly further away from the signal (Maschek, 2011, p. 31). Overrunning signals is also understood to mean slipping through or intentionally passing over a signal. Looking at the 2020 safety report, 72 signal crossings with a danger point and 180 signal crossings without reaching the danger point can be found in Austria (Sicherheitsuntersuchungsstelle des Bundes, 2021a, p. 42). So after the overlap the danger point is located. Since this incident report does not differentiate between train and shunting movements, an older safety report from 2016 was used, in which the signal overriding was still differentiated according to train and shunting movements. It shows that in 2016 there were 60 signal overrides for train journeys and 55 signal overriding's for shunting/secondary traffic (Sicherheitsuntersuchungsstelle des Bundes, 2017, p. 29). In Germany, in contrast, the 2020 safety report only specifies signal overrides in terms of millions of train kilometres travelled. In this context, 87 times signals were passed to reach the danger point and 455 times signals were passed without reaching the danger point (Eisenbahn-Bundesamt, 2021, p. 33).

If it is desired to compare whether there is a difference between the reaching of the danger point between Germany and Austria a proportional comparison has been made. The results can be seen in Table 4.

Table 4: Comparison, reaching the danger point
Source: Table based on mentioned data above

Country	Without DP	[%]	With DP	[%]	Amount	[%]
Austria	180	71	72	29	252	100
Germany	455	84	87	16	542	100
Difference				**13**		

This comparison suggests that the significantly higher reaching of the danger point has a connection with the shorter overlaps in Austria. However, there can be different reasons for this. For example, it would be also possible that if 500 Hz magnets are used more widely, the brake intervention starts earlier so the danger point is also not reached so often but this cannot be shown from this observation. However, it does show the necessity of an overlap.

It should also be noted here that the turnouts must be set during the overlap in Austria, but do not have to be locked. In addition, if required, turnouts can even be secured for a crossing train route, but they cannot be used by another train if they serve as an overlap for the first train (ÖBB Infrastructure AG, 2020b, pp. 47–50).

Based on the various safety philosophies of the infrastructure managers and the legal requirements different overlap lengths are used in Europe. To illustrate the practical situation two examples of signal overriding are discussed in Chapter 2.1.1 (Inductive train protecting system (Indusi / PZB)). The recommendations of the safety investigation authorities show that an longer overlap would have led to the avoidance of the incidence or reduction of the damage.

As it can be seen in these two incidents, there are two countries with different overlap lengths. Therefore, it is investigated how overlaps are used in different countries of Europe. The chosen countries have a connected railway network and at least in the EU countries, there is comparability through the application of the Technical Specifications for Interoperability (TSI). In each country, the largest infrastructure managers or the legal requirements are considered for the comparison. The standard gauge of 1435 mm is considered, which is the main gauge in Europe (Forschungsinformationssystem. Mobilität und Verkehr, 2021). Although Spain has a high-speed standard-gauge network and most of its lines are of Iberian gauge, it has been included for the purpose of this study (Cruz-Villalón, 2017, p. 591). For countries in grey, no data is available. Furthermore, the railway network of the Holy See and Monaco is not considered due to the size of the network. Lichtenstein is included. In Figure 24 typical length can be seen. Detailed results of the investigation can be seen in Appendix E (Comparison of Overlaps).

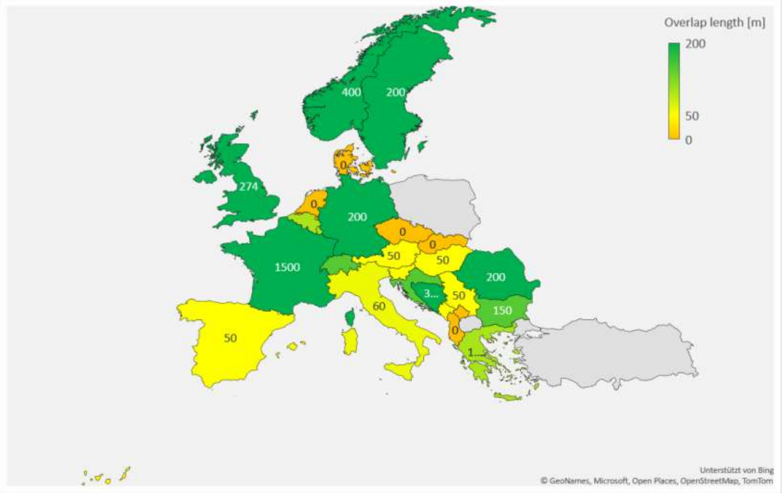

Figure 24: European overview of overlap-lengths

Source: Diagram created with Excel based on Appendix E (Comparison of Overlaps)

Infrastructure adaptions with overlaps

If a station at a single-track line is considered in a layout with two station tracks and a corresponding overlap, different approaches can be chosen, as previously mentioned to increase the capacity. These will be described in the following. For this purpose, the initial situation is explained. In this case, a station on a single-track line is used for crossings. The usage length of both station tracks is 500 m to allow crossings with freight trains. If it is assumed here that the overlap would be 150 m long and would extend over the corresponding turnout area of the turnouts, only one entry from one direction is possible at a time. A second train would have to enter with a time delay and in the worst case stop in front of the home signal. Assuming that it is a freight train with a high tonnage, the acceleration after the standstill could cause a loss of time and energy in the operational process. Figure 25 illustrates the described situation.

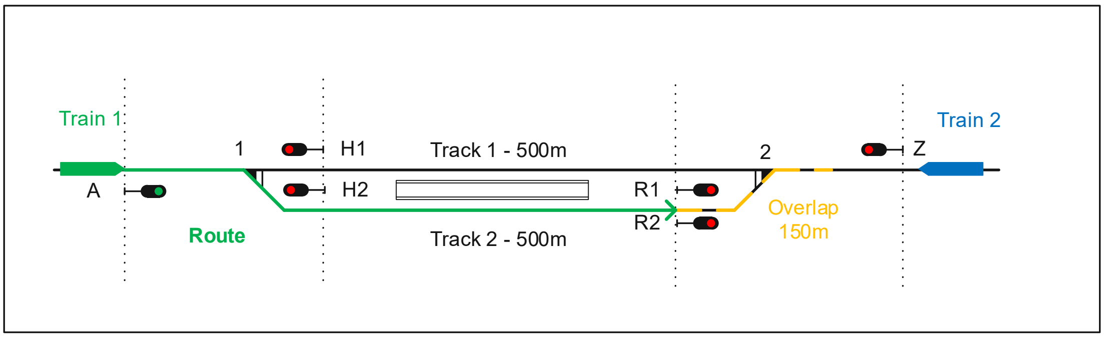

Figure 25: Railway station area with overlap

Source: Own sketch in MS Visio

Assuming that the length of the overlap cannot be changed, various infrastructure measures can be considered for increase, in which the use of flank protection points cannot bring any improvement in the concrete example. This would require the station to be designed in the form of an axle jump. This would require more infrastructure reconstruction and, in addition, a train route on the straight train without speed restriction would no longer be possible. The alternatives are to divide the entry track, move back the exit signal and extend the track between the signal and the danger point. The described variant holding the using length of 500 m makes it necessary to increase the distance between the exit signal and the danger point. That means that in existing railway stations it is a cost-intensive variant, which is also may not be possible if the space is around the tracks is not available. Also possible would be that the using length of 500 m will be shortened. This has the consequence that crossings of longer freight trains are not possible if they are longer than the new using length of the track. So, in this case the capacity is also decreased. This means this adaption could be effective only on a line where the traffic consists of short multiple units of passenger traffic, and there will no reason for freight traffic in the future. For passenger traffic, it is also necessary to have one long island platform or two platforms for each track, which are built in a displaced manner. Figure 26 shows the variant with the shorter using length.

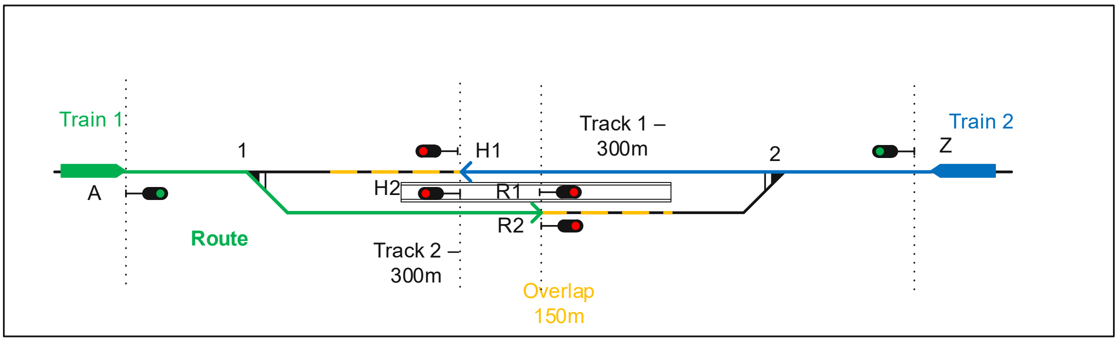

Figure 26: Railway station area with shorter using track length

Source: Own sketch in MS Visio

A common solution for increasing capacity would be the implementation of protecting signals to divide the area between the home signal and the exit signal into two parts. If the protecting signal is in the middle of the using length, as in the example, there are then two parts of the track with each 250 m. That offers the possibility to use short and long home routes. The short routes which are set only to the protecting signal can be used for passenger trains to cross in this railway station and enter the station at the same time because the overlap doesn't reach the danger point. If it is necessary that longer trains cross each other, for example, freight trains, then they must enter the station time-shifted, because they must use the longer home route from the home signal to the exit signal, with the overlap reaching the danger point. Figure 27 shows the described situation with two trains shorter than 250 m.

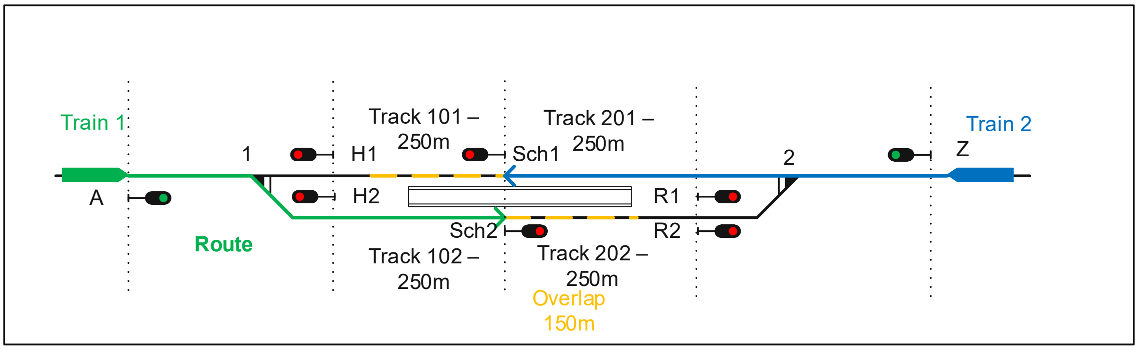

Figure 27: Railway station area with protection signals

Source: Own sketch in MS Visio

Location of overlap

There is also a possibility to change the position of the overlap, but not the length of it. As described in the Croatian rulebook, there is the possibility to start the overlap directly at the stopping point of a train. For example, if a passenger train has a stop at the platform 150 m before the exit signal, then the overlap would start directly at the train's stopping point and sometimes, depending on the country and speed, only up to the exit signal (Članak 110 Pravilnik o načinu i uvjetima za sigurno odvijanje i upravljanje željezničkim prometom, 2022). Therefore, there would be no restriction with other routes. Figure 28 illustrates this situation, which allows two trains to enter a station with two tracks at the same time with a 150 m overlap length.

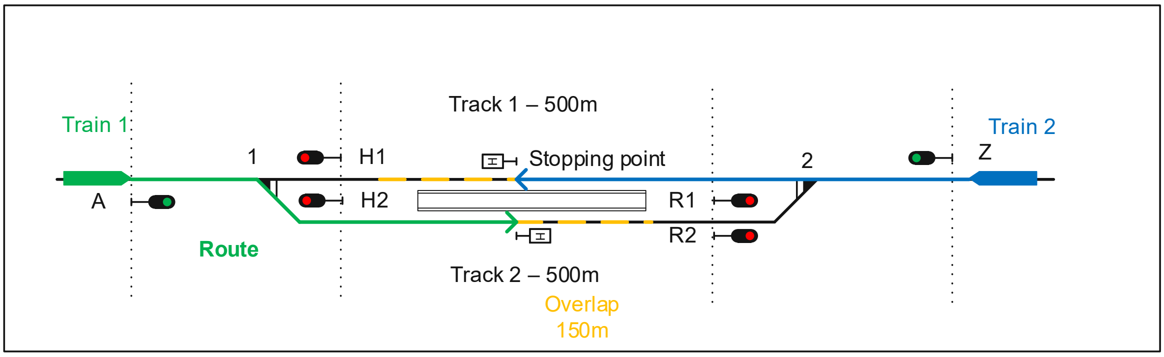

Figure 28: Location of the overlap on stopping point on platform

Source: Own sketch in MS Visio

Overlap investigation

As mentioned in the previous chapter, the respective using length and the overlap are two parameters that can influence the capacity. To give a better overview of the practical application, the extensions and the overlap lengths of different routes are considered in this chapter. For this purpose, four railway lines are considered, which will be used for simulation in Chapter 4 (Verification of the approach at Railway junctions), where also more details about the lines will be described. These are the line from Zagreb to Dugo Selo including the station Zagreb Resnik; the Salzburger Lokalbahn; the Südbahn from Wien Meidling to Wiener Neustadt; the Main suburban railway line from Wien Meidling to Floridsdorf, also called Stammstrecke.

For the analysis, all stations with more tracks are taken into consideration. Thereby, the using length is measured. This is done by calculating the length from the exit signal to the end of the track circuit or the axle counter on the opposite side. The distance between the exit signal and the nearest turnout is used for the distance to the danger point. In this way, two data points can be generated for a track, in each direction. In some cases, however, only stations with one direction are mapped in the simulations at the beginning and end of the created infrastructure.

For example, the station Wien Meidling is mapped once in the Südbahn simulation only with the direction to Wiener Neustadt, and a second time only in the direction to Wien Floridsdorf in the model of the Stammstrecke. The using lengths at Wien Meidling station are also different for each direction in both simulations. However, this is not problematic for further consideration, as the aim of this analysis is to assess whether there is a correlation between the distance to the danger point and the using length.

The length of the distance to the danger point can be considered as the maximum length an overlap could have without creating restrictions to other routes. Whereby the term start of the turnout is equivalent to the point where the border sign of the turnout is located or where the track detection of the turnout area begins. To visualize the using length and the distance to the danger point Figure 29 shows them on a simple sketch of a railway station.

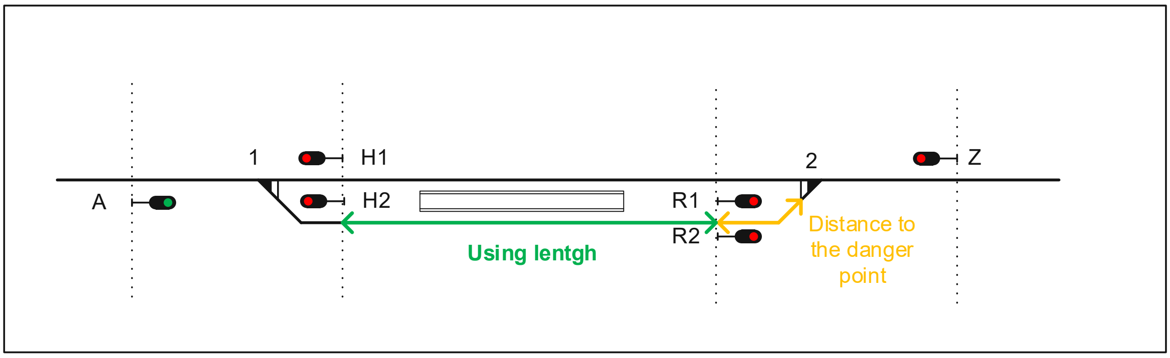

Figure 29: Using length and Distance to the danger point in a railway station

Source: Own sketch in MS Visio

The data of the four lines result in 168 data points, which are listed in Appendix F (Analysis of the distance to danger point). The datapoints are processed in IBM SPSS and categorised according to the railway line. In the first step, a scatterplot is created from this data. This plot is shown in Figure 30.

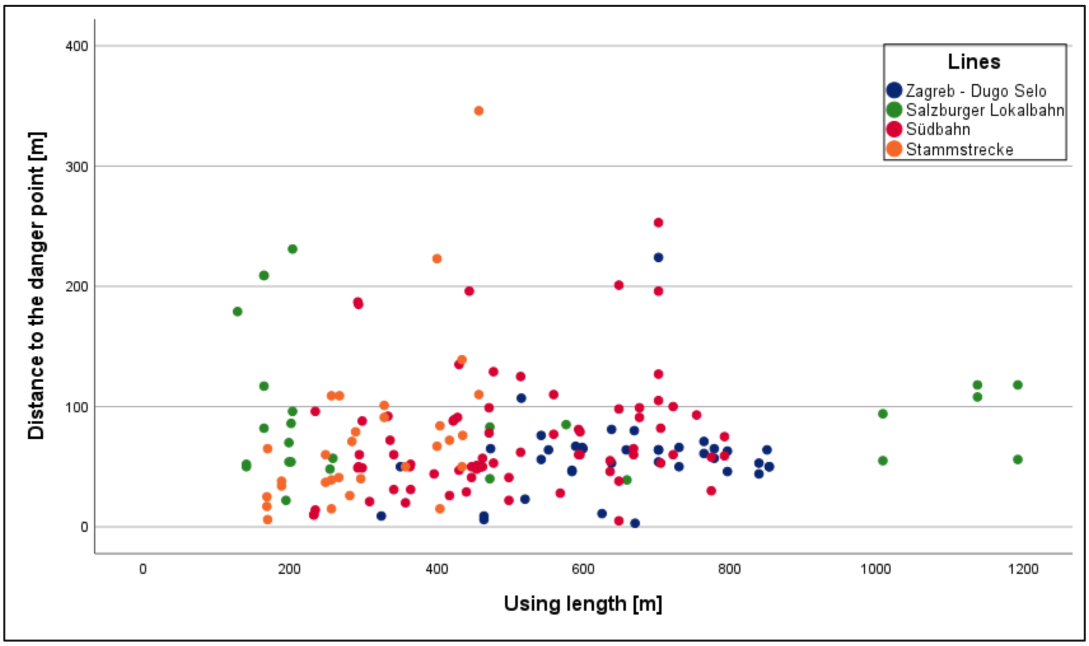

Figure 30: Correlation between Distance to the danger point and Using length in the simulations
Source: Own illustration in IBM SPSS Statistics Version 29.0.0.0. based on data from Appendix F (Analysis of the distance to danger point)

The distance to the danger point, respective the overlap, is mainly in the range of 0-50 m. However, a purely visual observation shows no correlation between the overlap and the using length. For this purpose, a regression curve is placed in the diagram and the correlation is determined, but there was no significant result. This can be explained by the fact that the track topography is probably defined by other framework conditions. This could be, for example, the type of traffic, the requirements at the time of construction or, more simply, the available space.

To create further information from this data, the results for the individual lines are presented in the description of the lines. The results can be found in Chapter 4 (Verification of the approach at Railway junctions). It could be also interesting how the using length is distributed. As it can be seen in Figure 31, the average using length is 464.36 m long with a standard deviation of 228.95 m. No consistent distribution is recognisable, but the using lengths in the range of about 400 m and 700 m are clearly overrepresented.

This consideration is relevant for the dissertation, as it provides information on whether a division of track sections makes sense, as shown in Figure 27.

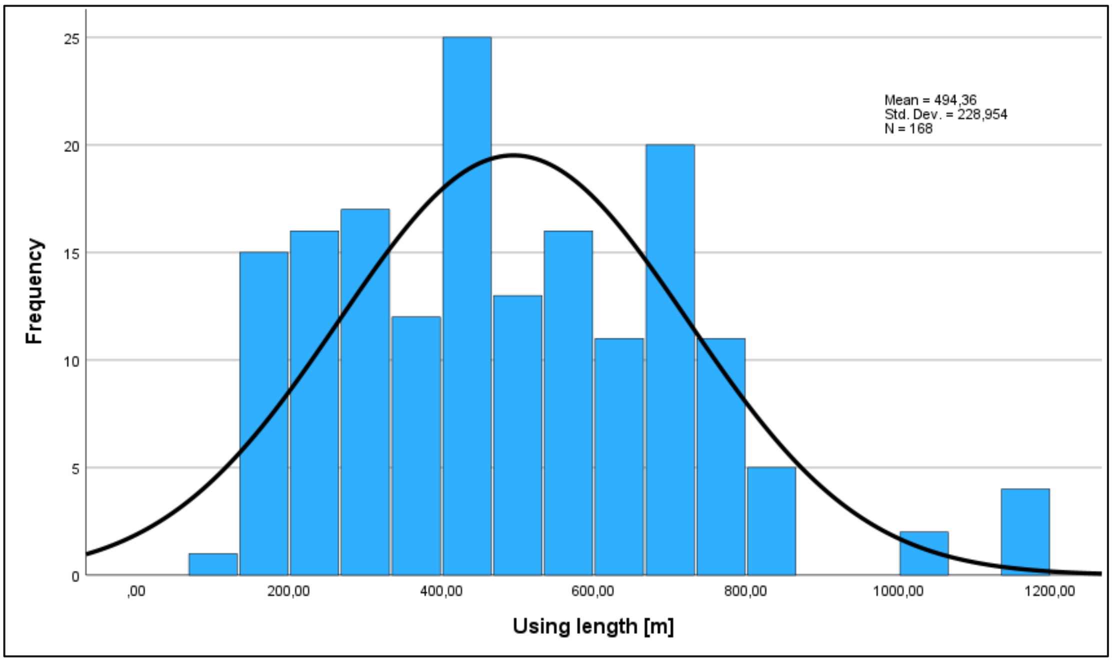

Figure 31: Distribution of Using length

Source: Own illustration in IBM SPSS Statistics Version 29.0.0.0. based on data from Appendix F (Analysis of the distance to danger point)

As shown in Figure 32, this distribution looks different for the distance to the danger point. Here, the range is between 30 m and 50 m, which is noticeably often represented. The average distance is 73.29 m. This means that overlaps of up to 50 m would be possible on average. Longer overlaps would therefore lead to operational restrictions. However, it should be kept in mind that three of the four lines considered are in Austria, where a 50 m overlap is applied over 40 km/h, as shown in the previous text. If this analysis is carried out with different lines from other countries, this distribution of distances would change. Therefore, the consideration of the using length and distance to the danger point is carried out for every line separately in in Chapter 4 (Verification of the approach at Railway junctions). Furthermore, a boxplot with a representation of the four lines can be found in Figure 33.

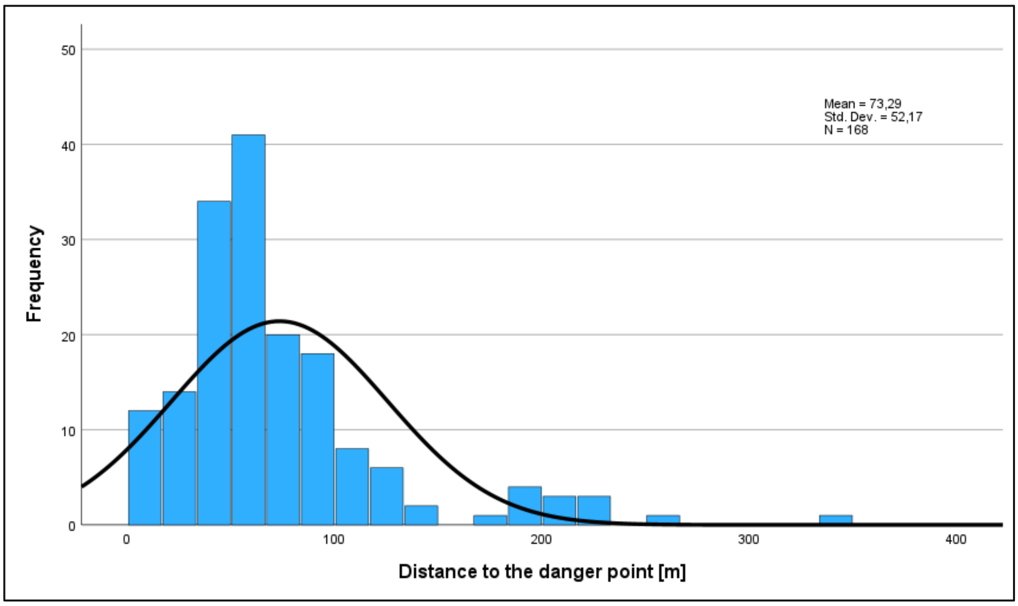

Figure 32: Distribution of Overlap length

Source: Own illustration in IBM SPSS Statistics Version 29.0.0.0. based on data from Appendix F (Analysis of the distance to danger point)

The data also shows that 120 of 168 data points (71.43%) have a distance to the danger point of over 50 m. That is 71,43 %. A boxplot subdivided according to distance is intended to take a closer look at this aspect. Figure 33 shows that the interquartile range is lowest on the route from Zagreb to Dugo Selo and Zagreb Resnik. However, there are still outliers in both directions. For example, as compared long distance of 224 m in Zagreb Resnik, the median is 57m. On the Salzburger Lokalbahn, the distances to danger points are much more scattered, as can be seen from the longer whiskers. There is also a single outlier, which is in Salzburg Itzling. The interquartile range is significantly higher in this case. The median is 82.5 m. On the Südbahn, the distribution tends to be in the lower range. However, there are simple outliers and one extreme outlier. The extreme outlier is in Leobersdorf. The median is 60 m. The picture is similar to the Stammstrecke. However, in contrast to the Südbahn line, there are only two outliers. A simple outlier in Wien Mitte with 223 m and an extreme outlier with 346 m in Wien Praterstern. The median is 62.5 m.

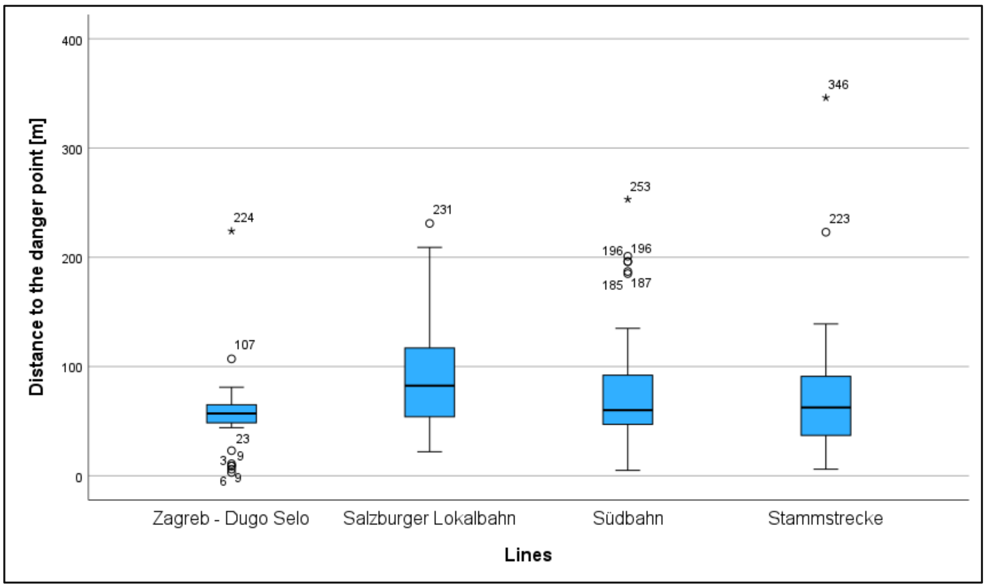

Figure 33: Boxplots of Overlaps

Source: Own illustration in IBM SPSS Statistics Version 29.0.0.0. based on data from Appendix F (Analysis of the distance to danger point)

The approach of Dynamic Overlaps

In Luxembourg, there is an approach with a variation of the release speed. Depending on the available overlap, different release speeds are transmitted. For example, for overlaps of less than 100 m, the maximum release speed is 25 km/h. For overlaps longer than this, the release speed is 40 km/h. If there is no overlap or only a very short one, the release speed is 0 km/h. In ETCS Level 1, however, a Euroloop must then also be used to transfer a new MA (Feltz et al., 2004, p. 17). It would be therefore interesting if it is possible to use this approach to shorten the overlap. So, if needed, an adaptive shortening or lengthening of overlaps could affect the release speed. With zero overlap, the braking curve starts earlier, as the SvL is at the same location as the EoA. Another option, which has already been described above, is to vary the overlap. However, the Danger point must be kept free to avoid operational restrictions. This means that the shorter the overlap, the shorter the Using length. This relationship is illustrated in Figure 34. A track section of 500 m is considered. If this is to be fully utilised, 0 m overlap is possible. If a 50 m overlap is used, the using length is reduced to 450 m. With a 120 m overlap, the using length would be only 380 m.

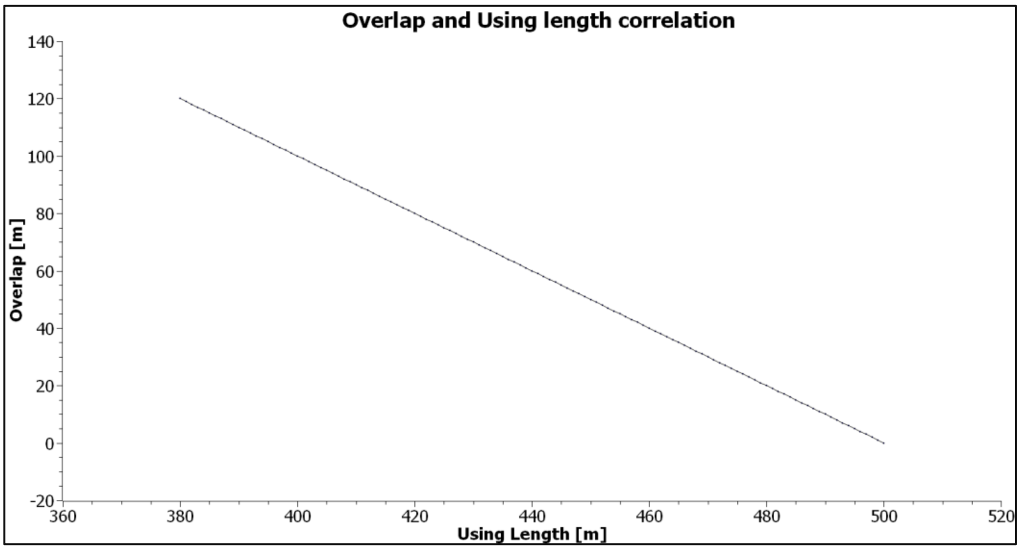

Figure 34: Correlation between Overlap and Using length

Source: Own illustration in SciDAVis 2.7

However, these considerations are difficult to practice. Even if no signals are present in ETCS Level 2 and Level 3 hybrid, a block division is still present. However, this cannot be changed depending on the application, as can be seen in Chapter 2.1.4 (ERTMS / ETCS). But it is possible to use a route with different overlaps and to vary the speed, as is done in Luxembourg with the release speed. Recommendations for the optimum overlap in each case depending on the speed under ETCS are discussed in detail in the dissertation of Busse (2021).

In the context of this work, the effect of the overlap will be analysed in different scenarios. On the one hand, in a station when two trains are crossing each other. And on the other hand, when two trains are following each other. Typical overlap lengths are used for this purpose. The aim is to show what effects overlaps have on capacity. However, it is not intended to provide a recommendation for the length of overlaps. Also, this thesis does not evaluate the fundamental need of overlaps, although the main reasons for overlaps have been discussed at the beginning of this chapter.

3.6.2 Speed restriction at turnouts

As already described with LZB, it is also possible with ETCS that the line speed can be driven up to the beginning of a turnout area when entering stations. Therefore, it is recommended to switch off the line-side signals if they are still in use with ETCS Level 2, to avoid contradictory signalling (Geiß, 2002b, p. 39). This aspect is described in Chapter 2.1.2 (LZB (Continuous train control system)).

Figure 35 shows a train route through a turnout in the diverging route. In the selected case, the turnout speed for this route would be 40 km/h. If the train is using lineside signals, the expected speed restriction is signalled for the first time at the distance signal. The driver must now reduce the speed to 40 km/h up to the main signal, which must be respected until the end of the train has left the turnout area. Below this, it is shown how the speed limits would be if the speed restriction were only applied from the turnout area.

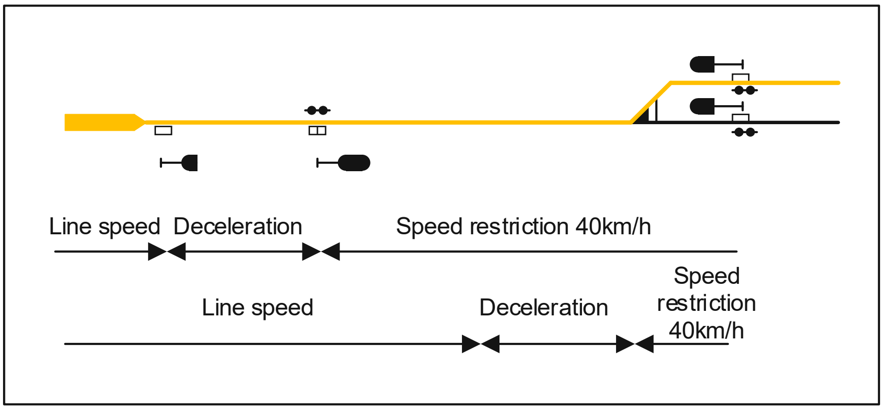

Figure 35: Comparison of track speed and signalling speed

Source: Own sketch in MS Visio based on §82 (2) EisbBBV Eisenbahnbau- und -betriebsverordnung (2008)

The theoretical description above will be analysed in various scenarios in the practical part of this work to demonstrate the effects of the measure. However, one scenario will be analysed in more detail at Sesvete station in this section. The description of this line can be found in Chapter 4.3 (Railway node Sesvete). For this example, a passenger train, which is entering the Station Sesvete from Zagreb Main Station in the Direction to Dugo Selo is used. This train is entering the station from home signal A to the exit signal D5, which means, that the train must use a turnout in the diverging direction. The line speed is 100 km/h, and the turnout speed is 40 km/h. The distance from home signal A to the turnout is 507 m. A class HŽ6112 EMU is used.

In the first case, it is considered that the train is already travelling at 40 km/h from the home signal. In the second case, the 40 km/h is only permitted from the turnout. The speed-distance diagram shows a visible difference. The braking process in the second case is initiated about 200 m later. The red curve in Figure 36 shows this braking process for the first case. The blue curve shows the second case.

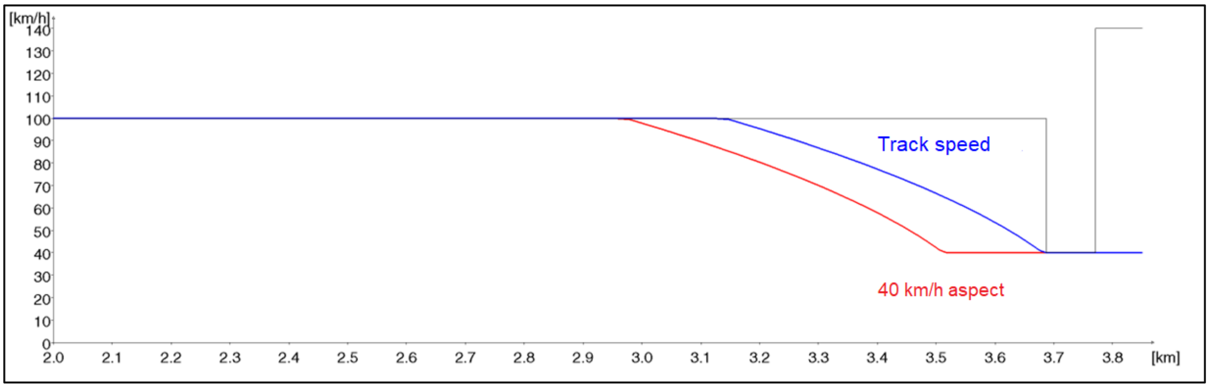

Figure 36: Train diagram (Speed - distance)

Source: Own illustration in OpenTrack Version 1.10.3.

The situation shown in Figure 36 is to be expected and can already be derived without a simulation. More interesting is an analysis of the time difference between these two scenarios. To calculate the difference a fixed location on the route is chosen, at which both trains are travelling at the same speed again (40 km/h). As can be seen in Figure 37, at this point there is a time difference of 9 s between the two scenarios. The train that runs with line speed until the turnout is at the destination track at 07:02:33. This scenario is shown in blue. The train, which runs at 40 km/h from the home signal, arrives at the destination track at 07:02:42. This scenario is shown in red.

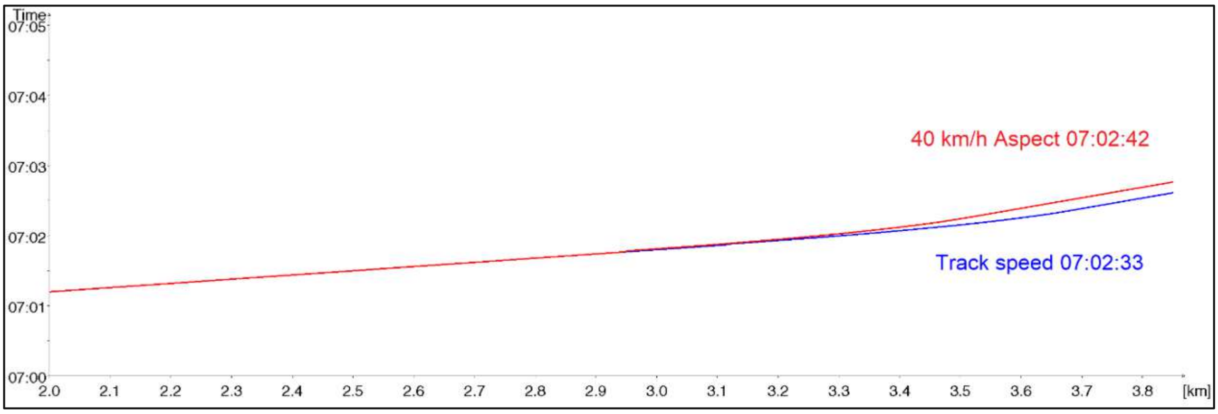

Figure 37: Train diagram (Time - distance)

Source: Own illustration in OpenTrack Version 1.10.3.

It can be concluded that this measure already has an impact at one station. Therefore, this measure will be applied to various scenarios in the further part of the thesis to evaluate how headway time can be reduced by this measure.

Another aspect of the turnouts is, that ETCS would enable more precise speed limits for the trains (Fahrgastverband PRO BAHN Fachauschuss Fernverkehr, 2023, p. 5). At the moment, in Germany it is only allowed to show speeds in increments of 10 km/h. For example, 50-60-70 km/h (DB Netz AG, 2018b, p. 10). On the other hand the possible speed on the infrastructure could be higher. Turnouts with a 500 m radius would allow a diverging speed of 65 km/h (Maschek, 2015, p. 66). That means that not only the speed from the home signal to the turnout could be increased with ETCS, but also the speed of the turnout itself.

3.6.3 ETCS Level 3

Before changing the block division, the moving block function should be used. This should be done to determine the minimum headway times, that can be achieved on a certain line. The moving block represents the physical lower limit up to which the trains can safely follow each other. Further reducing this headway can then only be achieved by adjusting the station stops or by adjusting the running speeds of trains. This can be, as described above, in the case of turnouts, or also the harmonization of the speeds of two different trains. This means that the headways of trains with ETCS Level 3 moving can act as a target time for the new block division. With ETCS Level 2 discrete block and shorter block division, the headway will be shorter. It can be tried to archive a headway time close the moving block. For the trains, using the moving block function, a safety margin of 50 m is chosen. As can be seen in Chapter 3.6.1 (Overlaps), this is the typical safety route length in Austria. A safety margin is applied not only behind the train but also after the MA (Borlälv et al., 2023, p. 53). The 50 m margin will also be used as a standard for the overlaps in other simulations.

3.6.4 ETCS Level 2 with shorter blocks / Level 3 Hybrid

In this chapter, it will be described how the block division is applied in the simulations. When line-side signalling is used, the basis for block divisions is the braking distance of the fastest train, whether it is used in one or more-aspect signalling (Pachl, 2021b, pp. 43–44). When ETCS is applied as a second train protection system, both the line-side signal and the block division remain. As mentioned in Chapter 2.1.4.1 (ETCS Levels) it is possible to transmit a MA to a certain point, which means that subblocks can be invented. Also, every train has its specific braking curve and starts at different locations to brake (Fehlauer, 2018, p. 76). The subblocks are marked with ETCS marker boards. To check the track occupation, it is necessary to use TTD with axle counters or track circuits. But not only for the whole blocks with line-side signal, also for the subsections own TTD equipment is needed. If Level 3 Hybrid is used, then it is possible to invent virtual block sections without marker boards and TTD via the VBF. Therefore, it is necessary to ensure the train integrity, to ensure that the VSS is cleared. The differences in the blocking times of a train with PZB, a train with ETCS and TIMS and a train with ETCS without TIMS are visualized in Figure 10. There are differences between these three train types in the headway.

Beneath these differences in the headway there is another important fact. For subsections with TTD, there are still required marker boards, with all the associated additional costs (installation, maintenance, etc.). Of course, these subsections with TTD can be used of all trains with ETCS and are also released in the same way. Subsections without TTD can be used for the MA for all ETCS trains but are only released separately by a train with TIMS. However, the principles of block division remain unchanged and are therefore discussed below.

Since subsections with ETCS Level 2 require axle counting equipment, a minimum section length is required to ensure that at least one axle of the train is in the axle counting section. In practice, a 30 m length has become established for this (U. Maschek, Interview, 8 February 2023, ll. 160–168). In addition to the axle counters, balises for ETCS are also required here. With Level 3 hybrid, no axle counters are required for the virtual subsections, but the balises are still needed. This means that an appropriate section length must be selected in terms of the arrangement of the respective data points and balises alone, especially in the platform area, which allows the balises to be installed (Achilles et al., 2023, p. 23). In the present work, a minimum of 50 m is selected, as this corresponds to the overlap length.

It is planned to use ETCS with virtual blocks for the upgrade of the main suburban railway line in Vienna. The block lengths will be 30 m and 70 m in the stations. At the time of writing this dissertation, the project has only just begun, so it is not possible to discuss the block division and its impact on Vienna suburban railway line in more detail (Begic, 2023, pp. 9–12).

But there were different projects with similar targets. Various measures are being used to modernize the Stuttgart junctions. The block division was also analysed. The findings from this are discussed here. General findings relating to the increase in capacity from the Stuttgart junctions can be found in Chapter 3.6.5 (Further measurements).

For the block division, it must be considered whether it is a route in which blocks with ETCS marker boards are realized in addition to line-side signals or without line-side signals only with ETCS marker boards. For example, if the conventional signals remain, no block marker boards can be placed within sight distance of the distance signal. Also, they cannot be placed within the overlap of light signals. In addition, the electrical switching section for the overhead line cannot be subdivided to prevent trains from coming to a standstill within this area. This also applies to turnouts (Denißen et al., 2021, pp. 61–62).

Under the dual equipment (ETCS and PZB) on the Stuttgart S-Bahn, a shorter block division is planned on the platforms with 55 m long high-performance blocks. This block division can already reduce headway times compared to the original block division (Inegnierugemeinschaft ‘Machbarkeitsstudie ETCS S-Bahn Stuttgart’, 2019, p. 283).

In further investigations, the corresponding specifications for ETCS at the Stuttgart junction were adapted and the minimum block lengths were reduced to 30 m, leading to a higher reduction of the headway (Neuhäuser et al., 2021, p. 25).

3.6.5 Further measurements

In addition to these measures from the train and traffic control perspective, there are also some projects in which infrastructure adaptions are carried out besides these measures. A mix of methods is often used to influence capacity. For this reason, practical examples are considered before the practical simulations are done. There are currently various expansion and new construction projects in the railway sector, but as this is not the focus of this work, only a few projects will be outlined as examples. Cases from London and Germany will be shown. On the one hand, the Thameslink program and the Crossrail project in London are chosen. In Germany, the Stuttgart digital node (Digitaler Knoten Stuttgart) and the second main suburban railway line in Munich (2. Stammstrecke) will be analysed.

Thameslink core section

The Thameslink programme is a reconstruction of the north-south link through the city of London. Thameslink is connecting different destinations in the south-east of England. Thereby the different lines cross London. The core section, which carries the main load of trains, is in London between St. Pancras International and Blackfriars, with Farringdon and City Thameslink stations in between (Farrell et al., 2020, pp. 63–64). An interesting aspect is, that within this core sections the interstation areas are only double-track lines (Reichert, 2023). Also the station City Thameslink only has two main tracks, which are used with long platforms. These two platform tracks are divided with ETCS marker boards into subblocks. There is a conductor rail and a catenary system, which enables vehicles with different power supply to use the line. The core section is highly utilized with 24 trains per hour in each direction, which means that the headway is only 2.5 minutes (Armstrong & Preston, 2019, p. 2). To better understand how this is realized, the used technique is analysed. Like other main corridors, the threading into the core section is a particular challenge. ATO over ETCS is used to harmonize the train movements as far as possible and to adapt the speeds to each other (Tasler & Knollmann, 2018, p. 12). In addition, Siemens Desiro City Class 700 traction units are used, which are 50% longer than the previous vehicles and can accommodate 80% more passengers. Furthermore, the boarding and alighting of passengers will be optimised by adapting the boarding areas of the rolling stock (Siemens Presse, 2016, pp. 1–2).

To enable ETCS Level 2 there is an RBC from Siemens and a modified GSM-R to transmit the MA. Whereby the traffic is controlled from the Rail Operating Centre (ROC) in Three Bridges. Where also a central DAS server is provided, which calculates the optimal driving behaviour for the ATO and non-ATO sections. Beneath ETCS Level 2 there is used the national train protection system outside of the city area. But these two systems, the Tran Protection and Warning System (TPWS) and the Automatic Warning System (AWS) can also be used as a fallback in the core section. Therefore, the line-side signalling type KO2 remained also in the ETCS area. Since the track circuits were already divided within the respective block sections, a division into several blocks for ETCS can take place. To avoid contradictory signalling, warning aspects for entering a partial block are shown here on the physical signals. If a train is now travelling under ATO in the core section, the train is brought to a standstill by the ATO at the stopping points. At the same time, a dwell time countdown is determined according to the planned journey time to the next station and the current traffic data. Once this countdown has expired, the journey should be continued. This would allow a technical headway time of two minutes to be realized. It should be also mentioned that this project is the first commercial use of ATO over ETCS (Booth, 2015, pp. 33–36).

Crossrail project (Elizabeth Line London)

In addition to the Thameslink north-south connection, an east-west connection was planned in the Crossrail project. Crossrail, which is now called the Elizabeth Line, has the same aim as Thameslink of realizing a 24 trains per hour. Existing sections to the west and east of London are linked with a new line through the city (Luzern, 2016, pp. 52–54). Even if the train density to be achieved is the same, the realisation is significantly different (Emery, 2017, pp. 6–7).

The British TPWS and AWS are used on the outer branches of the Elizabeth Line. ETCS is also used on the branch towards Heathrow Airport. There are plans to extend the ETCS sections in the future. But in contrast, CBTC is used in the city centre area. In this context, ERTMS/ETCS has been selected as the supervising system of the three train control systems (Crossrail Ltd, 2019, p. 2).

As part of this project, the operator Mass Transit Railway Elizabeth Line (MTREL) has implemented various measures to optimise the line. It is described that it is known from the past that there is often too little coordination between project developers and simulation experts and thus the benefits of the simulations are not utilized. For this reason, the simulation experts were already involved in the line development in this project and the results were considered in further decisions. This also resulted in adjustments to the requirements in terms of capacity. The simulation was therefore already used in the bid preparation phase. For example, it was possible to show that a delay in the opening of the Central Tunnel would lead to too many conflicts if the existing Paddington station were relocated and that alternative timetables were required. For further construction measures to optimize capacity, investigations were carried out to show the effects on traffic during the construction work to extend the platforms. It can be concluded that the early use of simulations reduces delays and reduce costs (Medeossi et al., 2023, pp. 1–6).

Stuttgart digital node

The Stuttgart digital junction is a railway infrastructure renewal project. In addition to the Stuttgart junction, the Stuttgart Main Station is rebuilt. This will take place under the existing terminus station. In addition to the construction of the Main Station, new railway lines will also be built. This alone has no relevance to the dissertation. However, this project also involves the renewal of the control-command and signalling technology on around 500 km of track. In addition to digital interlocking instead of electrical interlocking, ETCS will also be implemented. Initial plans to implement ETCS Level 2 only on the long-distance lines have now been cancelled and the node will be ETCS Level 2 only without line-side signals. Only signals for shunting movements remain. One aspect of this project is that double equipment with light signals reduces reliability, as light signals themselves are a source of interference and are generally also affected in the event of an ETCS failure (Drescher, 2022, pp. 29–31).

In addition to the digital interlockings, ETCS and shorter blocks, ATO GoA-2, FRMCS and a Traffic Management Service will also be used, leading to a higher possible number of trains as well as an adjustment of the braking curves that are not too flattened (Flöter et al., 2022, pp. 42–43; Schröder et al., 2021, pp. 52–58).

Beneath the Stuttgart digital node, there is also a suburban railway line running with ATO over ETCS in Hamburg, which is achieving GoA-2 on the line and GoA-4 in the depot to change the direction (Schröder et al., 2021, pp. 52–58).

2. Main Suburban railway line Munich (2. Stammstrecke)

Munich has a suburban railway line that runs through the city centre from the Donnersbergerbrücke bridge via the Main Station and Isartor to the Ostbahnhof. As written in Chapter 2.1.2 (LZB (Continuous train control system)), this section is already equipped with LZB and has CIR-ELKE high-performance blocks to use the infrastructure as much as possible. In addition, the line has been optimised and the number of trains has been increased from 24 to 30 trains per hour per direction. To deal with an increase in traffic, a second main suburban line is being built. This project is called 2. Stammstrecke München. It will be built to relieve the bottleneck in the city centre and increase the reliability. The new line runs from Laim via the main railway station and Marienhof to the Ostbahnhof and Leuchtenbergring. This line will also have a capacity of 30 trains per hour and direction (DB Netz AG, 2010, pp. 45–47).

Figure 38 shows the lines with suburban traffic in Munich. The lines are labelled with S and the line number. The daily train pairs on a working day are shown in black. It can be seen the 1. Stammstrecke between Donnersbergerbrücke and Ostbahnhof and the planned 2. Stammstrecke between Laim and Leuchtenbergring.

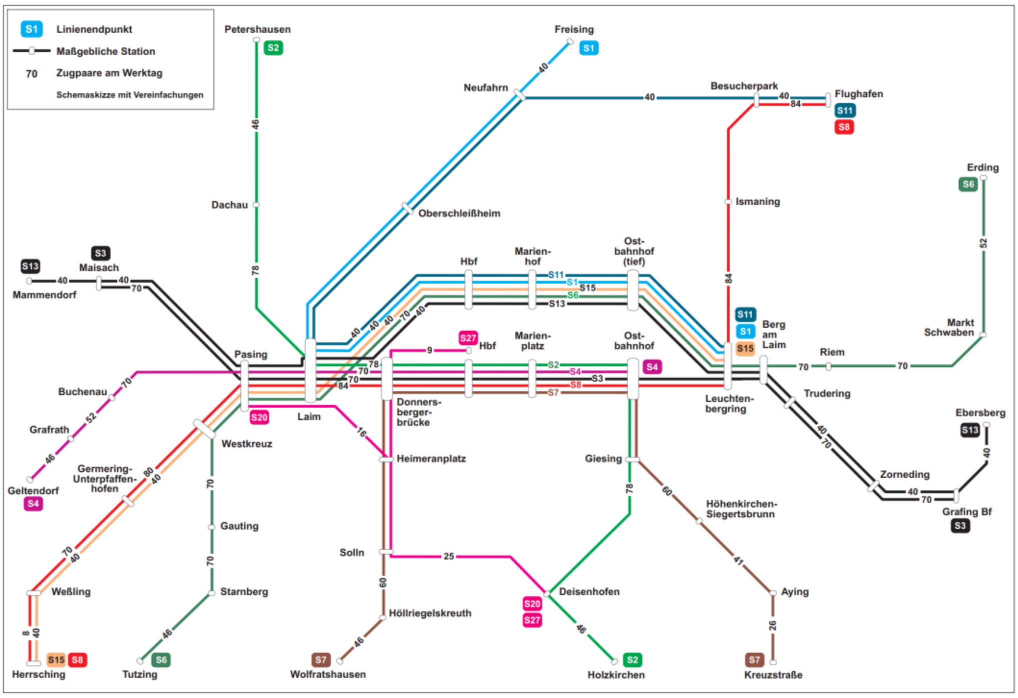

Figure 38: Suburban railway lines in Munich

Source: Figure taken from INTRAPLAN Consult GmbH (2012, p. 9)

It is relevant for this work that certain factors are already considered during construction. For example, the junction in Laim is not crossing existing tracks. The alignment follows a free space located in the middle of the existing station and is then swivelled over the existing track via a bridge. With this level-free junction, there are no route restrictions. Before the

Donnersbergerbrücke, the new line goes underground and passes under the existing Stammstrecke. At the Main Station and in the new Marienhof station, centre platforms are provided between the two tracks. But there will also be side platforms for both tracks. This means that two platform edges are provided for each track in these two stations. That allows for the use of the Spanish solution (INTRAPLAN Consult GmbH, 2012, pp. 16–17).

This is a measure where alighting passengers leave a train via the centre platform, for example, while new passengers board via the side platform. In this way, the dwell time can be kept as short as possible and passenger change can be optimized (Bär et al., 2019, p. 44).

At Ostbahnhof, only a centre platform is planned due to the predicted lower passenger numbers. The integration into the Leuchtenbergring will again take place without crossing existing tracks at the entrance of the station. In addition, Leuchtenbergring will have six platform edges instead of four, which exist now (DB Netz AG, 2010, pp. 71–89).

These examples show that the planning of new infrastructure systems can already be designed in such a way that short headways are achieved, and passenger flows are optimised. There are also other approaches to influence capacity, for example, through the use of a traffic management system or adaptive train routing. However, these aspects are not the focus of this work and are therefore not included in the simulation. Nevertheless, they offer starting points for further research of capacity optimization.

4 Verification of the approach at Railway junctions

In this chapter, the approaches, presented before, are used on different models. These models of railway infrastructure will be used to prove the impact of the methods. For this purpose, different study regions are chosen. Which consists of different railway nodes and railway lines. But, besides the rail infrastructure, there must be defined train paths. The RIL 405 defines the appropriate limits of the study area as two neighbouring nodes around the station (DB Netz AG, 2008, p. 6). That means investigations are on a whole line or at least with surrounding stations.

At this point, it should be noted that within this thesis the focuses lie on railway stations. From the perspective of the signalling technology, the station area can be defined as railway stations are areas within the railway network, which have at least one switch and the possibility for trains to start or end, turn, or cross each other at this station. Home signals or trapeze markers serve as a separation from the open line (§11 (1) EisbBBV - Eisenbahnbau- und -betriebsverordnung, 2008).

In addition to stations, however, the term node is often found in a wide variety of works. The term node, however, is used for different purposes. In the network statements of ÖBB Infrastructure AG, for example, the term node can be found for two purposes. On the one hand, a node can mean, a station that serves as a symmetry node in a timetable for passenger transport (node-transit-node model). On the other hand, in freight transport, a node can be a major railway station where freight is manipulated and a considerable amount of freight wagons is shunted, i.e., a shunting node (ÖBB Infrastructure AG, 2022a, pp. 40–45).

However, it is more common to define a node as a railway station where two railway lines are connected, and trains run between them (Weingand, 2021, pp. 308–309). This definition will also be used for nodes in this paper. Nevertheless, it should be noted that there are also narrower definitions. Bendfeldt (2005) defines three different types of stations: nodes where there is an infrastructural connection in the operation program; limited nodes where there is an infrastructure connection but no connections in the operation plan. In addition, there are stations, which have no infrastructural connection, i.e. which are no nodes (Bendfeldt, 2005, p. 34).

Selection of the testing environment

In addition to the definition of which station types are used, it is important to determine which traffic should occur in the region to be investigated. Lines with freight traffic only play a subordinate role in this analysis. Although these exist, they are often only bypass routes, such as the St. Polten freight train bypass (Güterzugumfahrung). But there are also planned bypass lines, such as Freiburg or Rosenheim (Hofmarcher & Beran, 2015, p. 55; Jänsch, 2021, p. 98).

Therefore, specific study regions are chosen. There is mixed traffic in most of the network. The requirements can be subdivided into three sub-items, like the passenger and freight traffic or the infrastructure.

Passenger traffic

In the selected study area, suburban trains (S-Bahn) should stop at every stop. In addition, there should be regional traffic with different stopping patterns. Long-distance traffic should also be used, whereby it should stop at the main railway station and offer interchange connections.

Freight traffic

There should be freight traffic on the test environment, which operates at the same time when passenger trains are operating. Freight trains should start or end in the study area.

Infrastructure

The Austrian railway infrastructure, in 2020 had 3386 km of double-track and 2221 km of single-track, which means that 39% are single-track lines (Schienen-Control GmbH, 2021). In such a model, a single-track line should be analysed, which is heavily used, and the trains have to cross each other which could show more conflict situations compared to the same amount of traffic at a double-track line.

Based on the mentioned key points, lines in Austria and Croatia as well as fictive lines were selected.

Figure 39, an overview map, shows Austria, and parts of Croatia, where the real lines are located. It is a map in which the Rail Freight Corridor (RFC) 10 is illustrated. The Austrian simulations are not based on this, but the aim is to show how the railway systems in these two countries are connected.

Figure 39:Overview map of the investigated areas

Source: Picture adapted and taken from RFC AWB (2019)

Figure 40 shows the different simulation models, which are used for this work. It should be mentioned that not every railway line is investigated with the same measurements or for the same investigation purpose. For example, shorter block division will not be used in all models, although it can lead to higher capacity. Both types, the lines from the real environment and the fictive lines, can be categorized into single and double-track lines. Also regarding the type of traffic, categorization is possible.

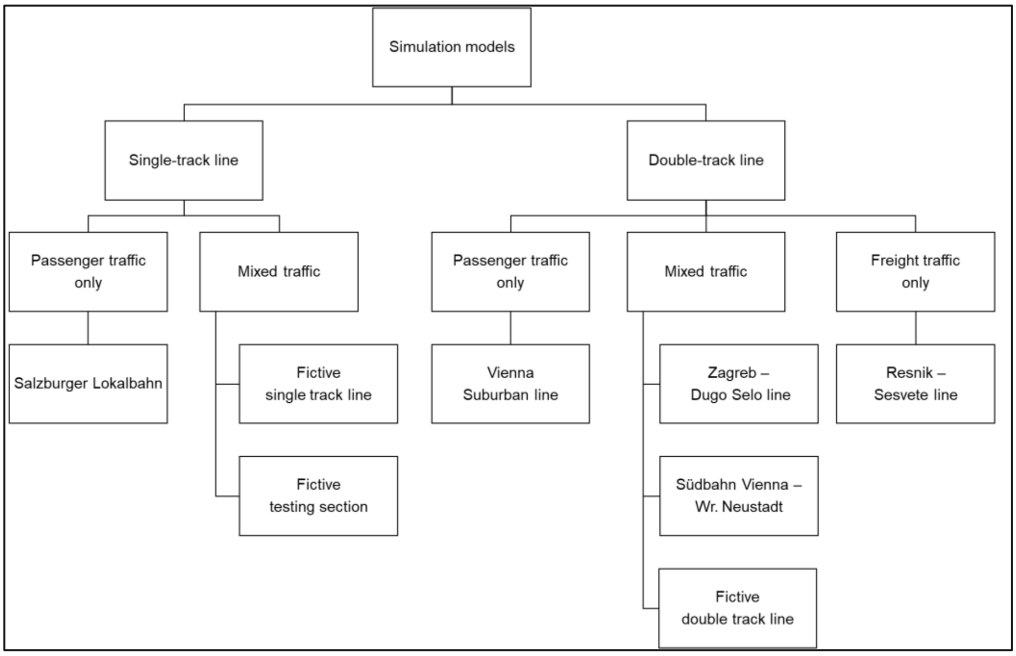

Figure 40: Used simulation models

Source: Own illustration

Single-track line

Passenger traffic only

- Salzburger Lokalbahn

The Salzburger Lokalbahn (SLB) is a branch line that runs from Salzburg's main railway station to Bürmoos and Lamprechtshausen. It is a branch line with dense passenger traffic. Due to the single-track, there are frequent crossings.(Salzburg AG, 2022, pp. 10–11) Although there is a freight train in addition to the passenger traffic, it does not play a significant role in the timetable. This line is therefore categorised as a line with only passenger traffic for this work (Salzburg AG, 2023). The simulation environment is based on a study carried out by Schöbel (2022).

Mixed traffic

- Fictive single-track line

In the context of the sustainable intermodal transport chains through optimization of rail operations (NITOB) project, a simulation infrastructure was created. This infrastructure also has its weaknesses. These weaknesses will be analysed more in-depth as part of this dissertation. Therefore, the single-track is analysed and used for this purpose here (Anderluh et al., 2023, p. 37).

- Fictive testing section

To test different measurements and their impact in a very simple way a single-track section is simulated. Measurements such as block division and virtual blocks are used. The fictive railway line is limited by two station stops.

Double-track line

Passenger traffic only

- Main suburban line Vienna (Stammstrecke)

The Stammstrecke is the busiest line in Austria. It is a suburban line that is also used by regional trains from Lower Austria. However, they have the same stopping pattern in the timetable as the suburban trains. In addition, the City Airport Train (CAT) also runs on the section from Wien Mitte to Wien Rennweg (ÖBB Personenverkehr AG, 2022b). In the past, there were also long-distance trains from Salzburg via Wien Meidling to Wien Praterstern operated by the railway undertaking WESTbahn. That led to different conflicts in between CAT, ÖBB Personenverkehr and WESTbahn (RailBUSINESS Editorial note, 2017, p. 3). This thesis continues from the findings of Wirth & Schöbel (2020, pp. 21–26). The used simulation is therefore based on the adapted version with ETCS (Wirth, 2019).

Mixed traffic

- Zagreb – Dugo Selo line

The line from Zagreb Main Station to Dugo Selo is one of the most utilized lines in Croatia. The section from Zagreb to Sesvete is mainly used by passenger traffic. From the node Sesvete to Dugo Selo, mixed traffic can be found. Due to the heterogeneity of the train characteristics and the routes into the node, this offers various starting points, which will be addressed in this work (HŽ Infrastruktura, 2021). The simulation model is based on Haramina (2022).

- Südbahn Vienna – Wr. Neustadt

The Südbahn is a railway line that runs southbound from Vienna. The busiest section is between Vienna and Wiener Neustadt. It is particularly interesting to note that long-distance trains and freight trains also run on this line in addition to suburban trains and local trains. Some traffic will be diverted in the future over a second southbound line to Wiener Neustadt and the local traffic on the Südbahn will be increased (Bundesministerium Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, 2020, pp. 5–6). In this work, it is used the line model and layout before a reconstruction of the track in Leobersdorf took place (ÖBB Personenverkehr AG, 2022a; Zajicek, 2022). The Simulation model is taken from Zajicek (2022).

- Fictive double-track line

Similar to the fictive single-track line, a double-track line was also created in the NITOB project. Based on the fact that both lines are connected in a node, this line is also used for the node analysis.

Freight traffic only

- Zagreb Resnik - Sesvete

The Zagreb bypass is used as a freight-only route. The Zagreb Resnik - Sesvete section is considered in the simulation. However, the section is used in combination with the Zagreb Main Station - Dugo Selo line. The line is included, as this allows the integration into the Sesvete node to be considered. As discussed below, this leads to restrictions in passenger traffic under the current conditions (HŽ Infrastruktura, 2021). For this study, as for the Zagreb - Dugo Selo line, the results of the research of Duvnjak et al (2020, p. 55) are used. For this purpose, the appropriate infrastructure simulation is taken (Haramina, 2022).

Simulation approach

Following the description of the selected routes in the previous text, it is now described the used simulation approach. First, it must be considered whether the simulations can be used without errors. For this purpose, all routes, paths, signals, and individual elements are checked. Restricted speed is also used for the turnouts, depending on the type of interlocking.

And these are considered in the simulation. Subsequently, itineraries are generated based on the planned train paths.

Afterwards, the rolling stock model is adapted or created. The chosen trains can be seen in each simulation description. More details about the rolling stock data can be found in Appendix L (Used rolling stock data). For the rolling stock, it is important to use the same trains for the different variants. Therefore, the same types are used, except from the simulation on the Zagreb Resnik – Sesvete line. A locomotive without ETCS is used to pull the freight trains, except for testing the capacity affecting aspects, where an electrical locomotive with ETCS is used.

As mentioned, if necessary, the infrastructure is adapted to compare the results of the different lines. However, not all lines are examined in the same way: overlaps are added or changed according to the rulebook. The line-side signalling and the related sight distances are checked and adapted to the rulebooks. For the reference variant ("Base variant"), the train protection system PZB is used. Before the headway for the variant can be determined, the used trains and the routes need to be determined. Initially, the weak points of the simulation are searched and typical train movements over this point are analysed. These typical train movements are also happening in the real environment, so they illustrate different following sequences of two trains. For each sequence, the headway is calculated, and the different measures are applied at this line. Whereby the basic variant is a reference as a zero variant. Furthermore, ETCS Level 2 is implemented for the same scenarios and the headways are calculated. Then, in the third variant, the track speed to the turnouts is used and the headways are calculated again. Based on that, ETCS Level 3 with a moving block is invented to find out the headways, with a 50 m safety margin as the minimal possible headway. That means, if Level 2 and Level 3 are compared, it can be seen which headway can be achieved by the shorter block division, which is handed out later. For this purpose, one approach with shorter blocks will be simulated after the results of all variants are compared.

Figure 41 shows the procedure used for the railway node Sesvete in a process diagram, to visualize the individual steps:

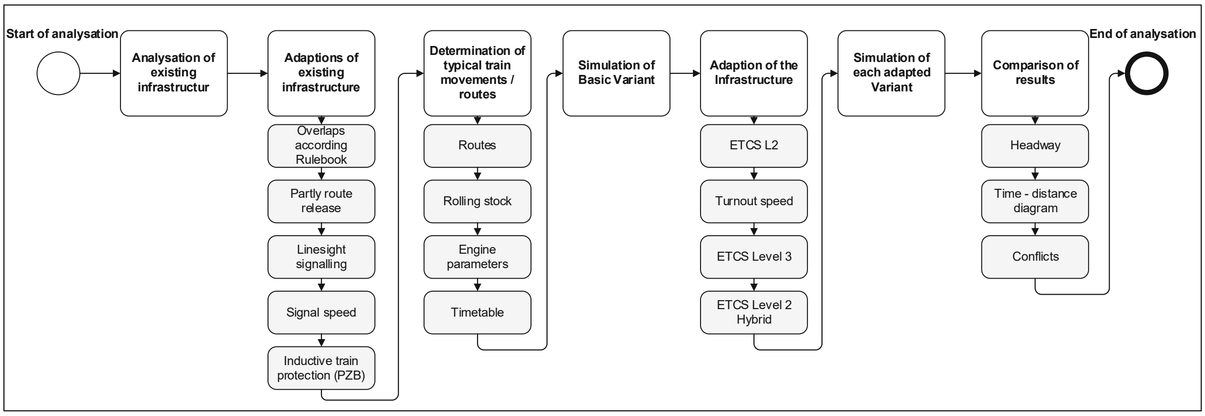

Figure 41: Workflow of simulations

Source: Own sketch in MS Visio

In the following part of this chapter, the simulations will be described in an order depending on the fact that simpler infrastructure easily shows if the measures change anything or not. The most detailed analysis can be found in the Station Sesvete because there the infrastructure must be adapted before the measures can be applied. Moreover, there can be a mix of traffic with several excluding routes.

4.1 Fictive railway line

A single-track section is chosen as the first simulation example. This line contains two stops and an open line. The open line between the exit signal of the A-station and the home signal of the B-station is six kilometres long. But in this simulation the trains are only passing the two stations. The interstation section is divided into six equal blocks of 1 km each. The home and exit signals have physical line-side signals and axle counters. The subsections in between are equipped with virtual block signals. However, they are also without axle counters. A VBF system is used, and the corresponding virtual blocks are called VSS. A more detailed explanation can be found in chapter 2.1.4.1 (ETCS Levels). The condition applied here corresponds to the ETCS Level 3 Hybrid.

In addition to the described infrastructure, two turnouts also are inserted to correctly survey the headway times for the section. The two sides of the turnouts were designed with an identical length and the turnout changeover time was set to 0 s. Such a changing time is not real, but this creates a possibility to make following trains comparable in the software. This means that the train in front runs on the straight section in the test. The second train comes following from the bottom left, travels along the section between the two stations and exits to the bottom right. With this approach, the evaluated section lies between the home signal of A-station and the exit signal of B-station. Figure 42 shows the track layout with the corresponding sections and signals. As this is visually a long straight line, it is graphically adapted to be shown here. For this purpose, the infrastructure is drawn downwards to the left of A-station and to the right of B-station. This has no effect on the simulation.

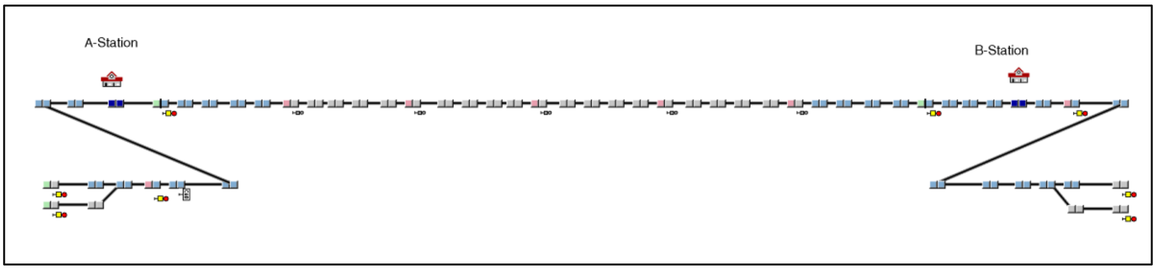

Figure 42: Track layout of the fictive single-track line

Source: Own illustration in OpenTrack Version 1.10.3 – Simulation Fictive railway line

Table 5 shows the different model trains, used for further consideration. More detailed information about the rolling stock data can be found in Appendix L (Used rolling stock data).

Table 5: Model trains for the simulation at Fictive railway line

Source: Table based on described Rolling stock from Appendix L (Used rolling stock data)

Type of train	Engine	Wagons
Suburban train (ST)	ÖBB 4024	

The first step is to investigate how the ETCS affects the scenario. For this purpose, a suburban train of the ÖBB 4024 series is used. Three different trains are created. The first runs with the PZB train protection system and uses the line-side signals. In addition, an identical EMU is used, which runs with ETCS Level 2 and cab signalling. A third train with ETCS and TIMS is also used, for the second application in Chapter 4.1.1 (Virtual blocks).

If a train with PZB and a train with ETCS can be seen when the trains pass through both stations, there is no difference between a train with ETCS and without ETCS. The differences only become apparent during the braking process. Figure 43 shows how deceleration has a different effect on the two train protection systems. In blue, the train with ETCS is shown, which begins to brake earlier but weaker. To come to a standstill, the deceleration is increased again at km 6.6. In comparison, the PZB-guided train, which brakes later but with more continuous deceleration, is shown in red.

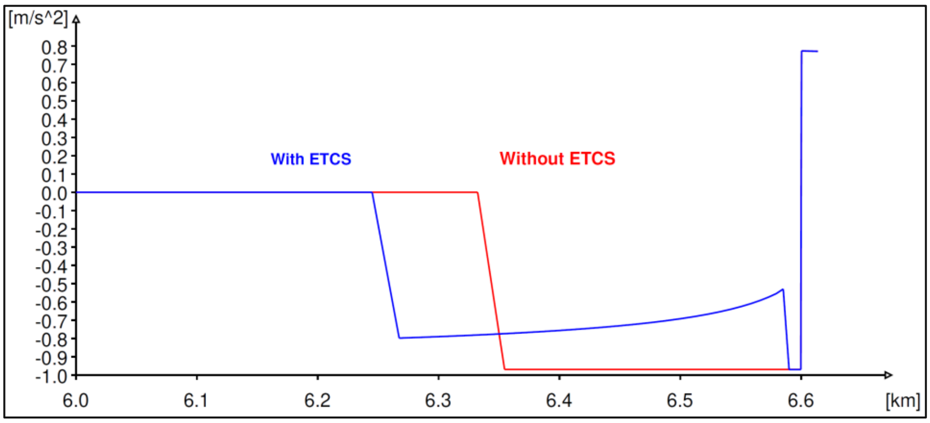

Figure 43: Train diagram (acceleration-distance) with ETCS and non ETCS train

Source: Own illustration in OpenTrack Version 1.10.3 – Simulation Fictive railway line

4.1.1 Virtual blocks

The next step is the subdivision into VSS described above. The first described train with PZB, if running as the first train, is called 1005. If the PZB train is the second one, it is designated as 1015. With the same scheme the train with ETCS Level 2 and cab signalling is named 1007 or 1017. This train uses the virtual blocks. However, it does not have a TIMS. Therefore, it can use the virtual blocks in front of it to obtain an MA. However, it does not clear the VSS after leaving it but occupies it until it has cleared the axle counter at the end of the physical block. The situation is different for the third train type called 1009 or 1019, which has ETCS Level 2 and TIMS and uses cab signalling. It can therefore use the virtual blocks in front of it and immediately release them again after leaving. This type of train can therefore take full advantage of the ETCS Level 3 Hybrid. Figure 44 shows the three train types. The PZB train is shown in red, the ETCS train in blue and the ETCS including the TIMS train in violet.

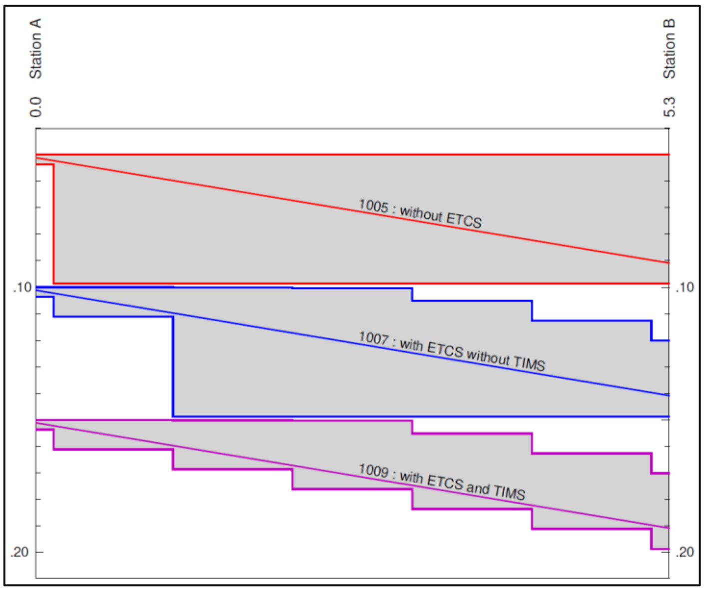

Figure 44: Blocking times of different train types

Source: Own illustration in OpenTrack Version 1.10.3 – Simulation Fictive railway line

It can be seen, in Figure 44, that different headways can be achieved with the three train types. If only trains with PZB and ETCS without TIMS are used, the benefits of the shorter VSS cannot be fully used. If a train with TIMS follows a train without TIMS, there is no benefit. When the order of the two trains is changed, the headway can be shortened. To collect data, the three trains are tested in nine different combinations, to calculate the headway. The results of the headway calculation can be found in Table 6, which proves the visual conclusions. A significant delta can be seen between two PZB trains and two TIMS trains, with 184 s.

Table 6: Headway comparison of trains with PZB / ETCS / TIMS

Source: Table based on OpenTrack Version 1.10.3 – Simulation Fictive railway line

	First train	**Second train**	**Headway [s]**
1	PZB	PZB	300
2	PZB	ETCS	291
3	PZB	ETCS & TIMS	291
4	ETCS	PZB	301
5	ETCS	ETCS	292
6	ETCS	ETCS & TIMS	292
7	ETCS & TIMS	PZB	301
8	ETCS & TIMS	ETCS	116
9	ETCS & TIMS	ETCS & TIMS	116
		Δ Headway	**184**

4.1.2 Headway as measurement criterium

As the example of the fictive railway line shows, headways are used to verify whether measures are effective. However, it should be noted that headways are not equivalent to capacity. Whereby at station headways, a distinction is made between four different combinations. A departure-departure, arrival-arrival, arrival-departure and departure-arrival headway. This fact will be respected in the simulations later (Pachl, 2014, p. 34). Besides the stations the headway has also established itself as the basis for analyzing the line capacity. The advantage here is that the existence of a minimum headway and a buffer provides the basis for further capacity calculation (Čičak et al., 2002, pp. 110–111; Pachl, 2014, pp. 34–35). Nevertheless, headways are a decisive factor in the capacity calculation, as explained in Chapter 3 (Capacity). For example, a shorter train headway is possible with a more homogeneous timetable than with a heterogeneous timetable (Pachl, 2013b, p. 46). The blocking times are essential for the occupancy of a section and especially for the capacity (Kogel & Nießen, 2015, p. 76).

It can also be considered, that if the headway between two trains is shorter, then the capacity consumption is lower. Therefore, different approaches are using this value for investigations of capacity (Landex, 2009, p. 19). The use of the headways as a principle has become a standard in stations and lines.

To illustrate this correlation, two scenarios are created. One scenario is where a train with PZB is used and in the second a train with ETCS+TIMS is used. At the beginning, these trains are sent every 15 minutes in a three-hour timeframe from Station A to Station B. That means there are 12 PZB and 12 ETCS+TIMS trains. The PZB trains are running from 06:00 to 09:00 and the ETCS+TIMS trains are running from 12:00 to 15:00.

In the upper part of Figure 45, the time-distance diagrams of these trains are visible. It can be seen how the blocking times differ. In the next step the UIC 406 method is used to calculate the capacity consumption of these two examples. Therefore, the timetable is compressed. As headway, the minimal headway is presented in Table 6. To avoid delay propagation buffer times between the trains are added to the technical minimum headway. This usually happens according to the operational rules of the infrastructure operator, which is described in Chapter 3.1 (Definition of capacity). In this example, for the compression one-minute buffer is used (Kaminsky, 2001, p. 119). It is also common to compress the existing timetable without a buffer. This allows the determination of the exploitation time and the buffer (Pachl, 2014, p. 38).

The compressed timetable can be seen in Figure 45 below the original timetable. The occupancy time for the PZB trains is 71.1 min and for the ETCS+TIMS trains is 37.7 min.

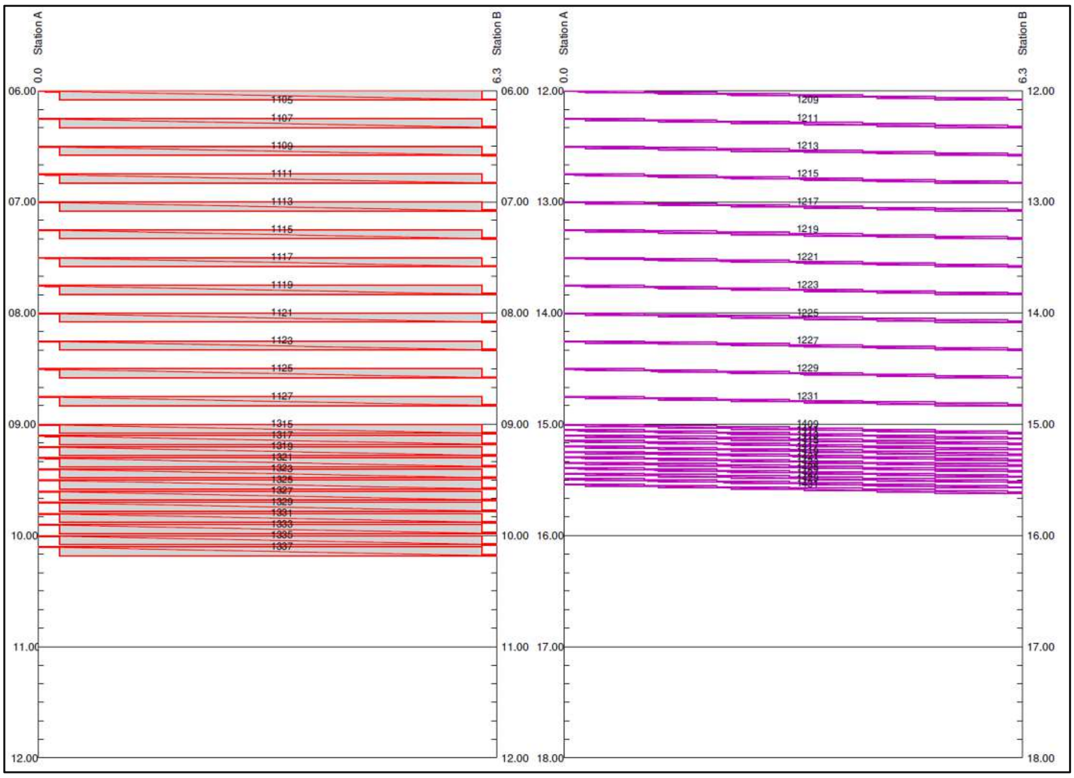

Figure 45: Time-distance diagram of PZB and ETCS+TIMS trains

Source: Own illustration in OpenTrack Version 1.10.3 – Simulation Fictive railway line

Beside the occupancy time also the capacity calculation for these two examples is calculated. This can be found in Formula 21 & 22.

<u>Capacity consumption for the PZB trains:</u>

$$O_R \;= \frac{t_O}{t_D} \times 100 = \frac{71{,}1\;min}{180\;min} \times 100 = 39.50\;\%$$

$$A_R \;= \left[\frac{100}{O_R} - 1\right] \times 100 = \left[\frac{100}{75} - 1\right] \times 100 = 33.33\;\%$$

$$C_C \;= \frac{t_O \times (1 + A_R)}{t_D} \times 100 = \frac{71.1\;min \times (1 + 0.3333)}{180\;min} \times 100 = 52.67\;\%$$

Formula 21: Capacity calculation for the PZB trains

Source: Calculation based on Formula 6 (Capacity calculation according to UIC 406)

Capacity consumption for the ETCS+TIMS trains

$$\begin{aligned}
O_R &= \frac{t_O}{t_D} \times 100 = \frac{37.7\ min}{180\ min} \times 100 = 20.94\ \% \\
A_R &= \left[\frac{100}{O_R} - 1\right] \times 100 = \left[\frac{100}{75} - 1\right] \times 100 = 33.33\ \% \\
C_C &= \frac{t_O \times (1 + A_R)}{t_D} \times 100 = \frac{37.7\ min \times (1 + 0.3333)}{180\ min} \times 100 = 27.93\ \%
\end{aligned}$$

Formula 22: Capacity calculation for the ETCS+TIMS trains
Source: Calculation based on Formula 6 (Capacity calculation according to UIC 406)

With the capacity consumption it is possible to determine the quality of service. However the purpose of this investigation is to show if the headways have a relation to the capacity. It can be shown that there is a direct relation between the shorter headways and better values for the capacity consumption. That means it would be possible to add more trains and achieve the same quality of service as in the PZB scenario.

4.2 Salzburger Lokalbahn

The Salzburger Lokalbahn is a standard gauge branch line from the city of Salzburg to the northern part of the country Salzburg. In the network statement the network is described as three different railway lines. The line from Salzburg Main Station (Hbf - Hauptbahnhof). Platform 11-12 to Lamprechtshausen and from Bürmos to Ostermiething. Additionally, there is a connection to the ÖBB infrastructure from Salzburg Hbf to Salzburg Itzling (Salzburg AG, 2022, pp. 10–11).

Figure 46 shows a part of a map with the public transport network of the city of Salzburg with the SLB. The line of the SLB from Salzburg Hbf. to Ostermiething and to Lamprechtshausen is marked in red.

Figure 46: City of Salzburg Public Transport map
Source: Picture adapted and taken from Salzburg AG (2022, pp. 10–11)

The network has a total length of 37 km and is electrified with 1000 Volt DC. The line is equipped with direct traffic control with additional signals (Salzburg AG, 2022, pp. 10–11). From today’s perspective, different infrastructure adaptions and new line sections are planned. The project is called S-Link and there will be also changes in the signalling equipment. For example, the electronic interlockings and ETCS should be implemented as a second train protection system. After the old rolling stock is renewed, only ETCS should remain as a train protection system (Salzburger Landtag, 2023, pp. 2–3).

This line is a single-track line, with several crossing stations and, in parts, a selective double-track section. For example, the section between Salzburg Hbf. Platform 11-12 to just before Maria Plain - Plainbrücke it is double-tracked. On the section between Salzburg to Lamprechtshausen, crossing stations can be found in Bergheim, Anthering, Weitwörth-Nussdorf and in Oberndorf Bahnhof. On the section between Bürmoos and Ostermiething, a crossing station is available in Riedersbach. Furthermore, Lamprechtshausen and Ostermiething are double-tracked (Reichert, 2023). To better understand the interactions of traffic on this line it is necessary to analyse the existing passenger trains on this line. For this purpose, the traffic at Anthering station is analysed. The station is chosen because it is located in the Section between Salzburg and Bürmoos and the station has short distances between the exit signals and the danger point, which will be investigated in Chapter 4.2.2 (Overlap analysis). The working hours are from 05:00 to 01:00. Except for the last hour of operation, there is always a 30 min interval for each direction. During rush hours, this is condensed up to four trains per hour and direction. This means that a total of eight trains per hour running through Anthering station during rush hour. As described above, there are several crossing stops on the line, including this station. Figure 47 shows the trains per hour in Anthering in the timetable period 2021/2022. An hourly tabular list of the trains can be found in Appendix A (Timetable evaluation Anthering).

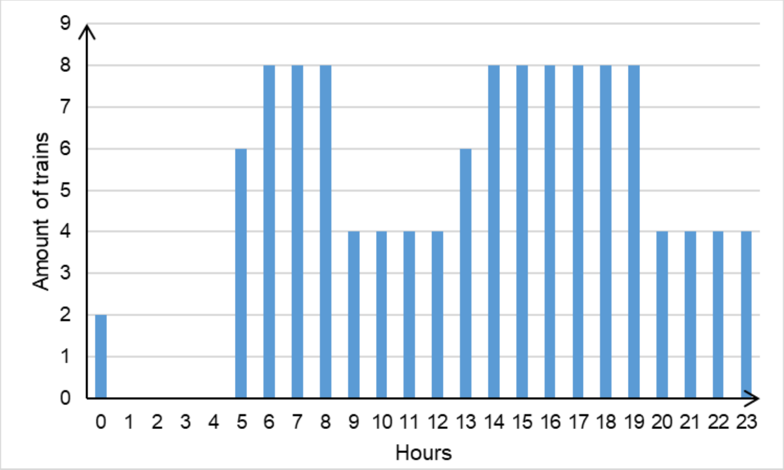

Figure 47: Trains in Anthering per hour - Timetable 2021/2022

Source: Diagram based on Salzburg AG (2021)

In addition to the daily hydrograph just presented, it is also investigated how the occupancy of the two tracks during the morning peak looks like. For this purpose, Figure 48 shows the occupancy of the two platforms in the period between 06:00 and 09:00.

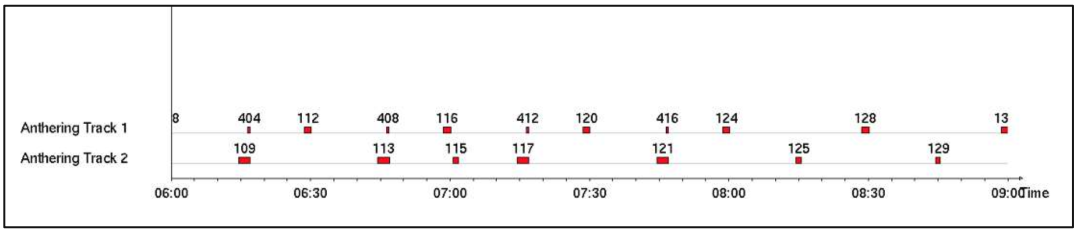

Figure 48: Occupation diagram Station Anthering

Source: Own illustration in OpenTrack Version 1.10.3 – Simulation Salzburger Lokalbahn

Figure 49 shows the tracks of the different railway stations with their using length and the distance to the danger point. It can be seen, that in the station Weitwörth-Nussdorf und Bürmoos the using length of the tracks is significantly longer. Beneath the using length, the distance to the danger point is significantly longer in Salzburg Itzling and Riedersbach.

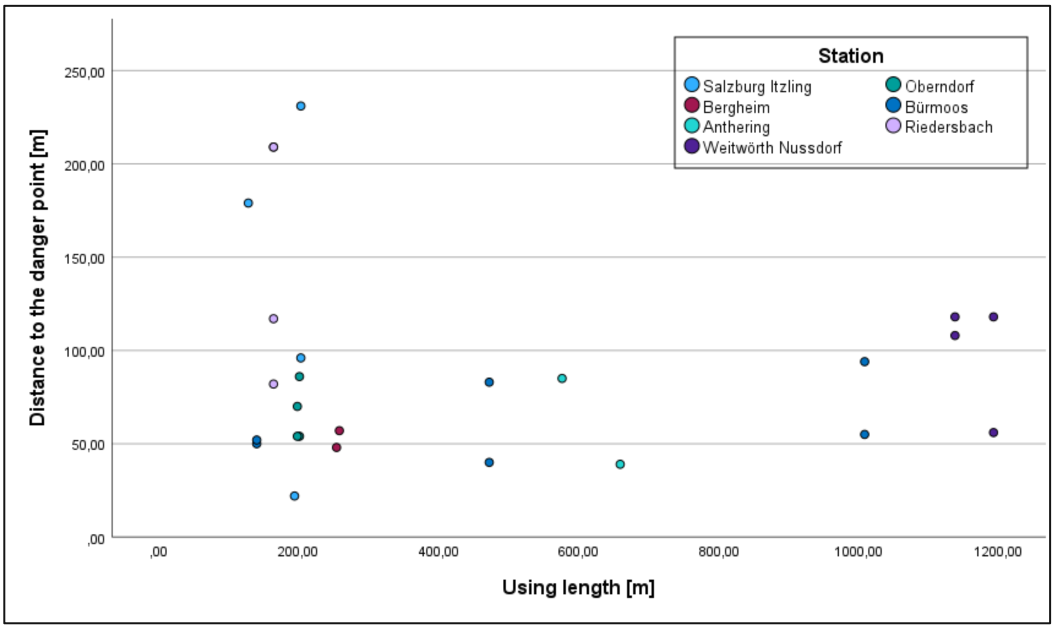

Figure 49: Correlation Using length and distance to the danger point at SLB
Source: Own illustration in IBM SPSS Statistics Version 29.0.0.0. based on data from Appendix F (Analysis of the distance to danger point)Appendix F Analysis of the distance to the danger point

Figure 6 shows the different model trains, used for further consideration. More detailed information about the rolling stock data can be found in Appendix L (Used rolling stock data).

Table 7: Model trains for the simulation at SLB
Source: Table based on described Rolling stock from Appendix L (Used rolling stock data)

Type of train	Engine	Wagons
Local train (LT)	ET 50+50+50	

4.2.1 Block division

In the existing timetable, it can already be concluded where railway stations for crossings are necessary. In this work, however, the question arises whether a denser interval can be achieved through shorter block division and thus the capacity can be increased. For this purpose, the existing timetable is used as the initial situation. Figure 50 shows the time-distance diagram from 06:00 to 07:00. Existing trains from the real timetable are drawn in red. In a free timeslot, there would be an additional train possible from Salzburg to Lamprechtshausen, which is drawn in blue. However, it should be noted that this train is only a consideration. It is therefore questionable whether there is market demand, as the direction of the load in the morning is towards Salzburg. This is because the city of Salzburg has more commuters in than out (STATISTIK AUSTRIA - Bundesanstalt Statistik Österreich, 2020). For an additional train from Lamprechtshausen to Salzburg the existing infrastructure offers not enough crossing stations. The black line in Figure 48 shows how an additional train could be placed, and where crossings would be necessary. At this stage, the design is made only graphically, with stops only at the crossing stations. To realize this train path crossing could be in Oberndorf Bahnhof, which is an existing station with two tracks. The two other crossings would be in Muntigl and on the open line. Muntigl is only a stop today and the second point would be along the open line between Acharting and Pabing. This means that even the construction of new stations would be required to enable this new train.

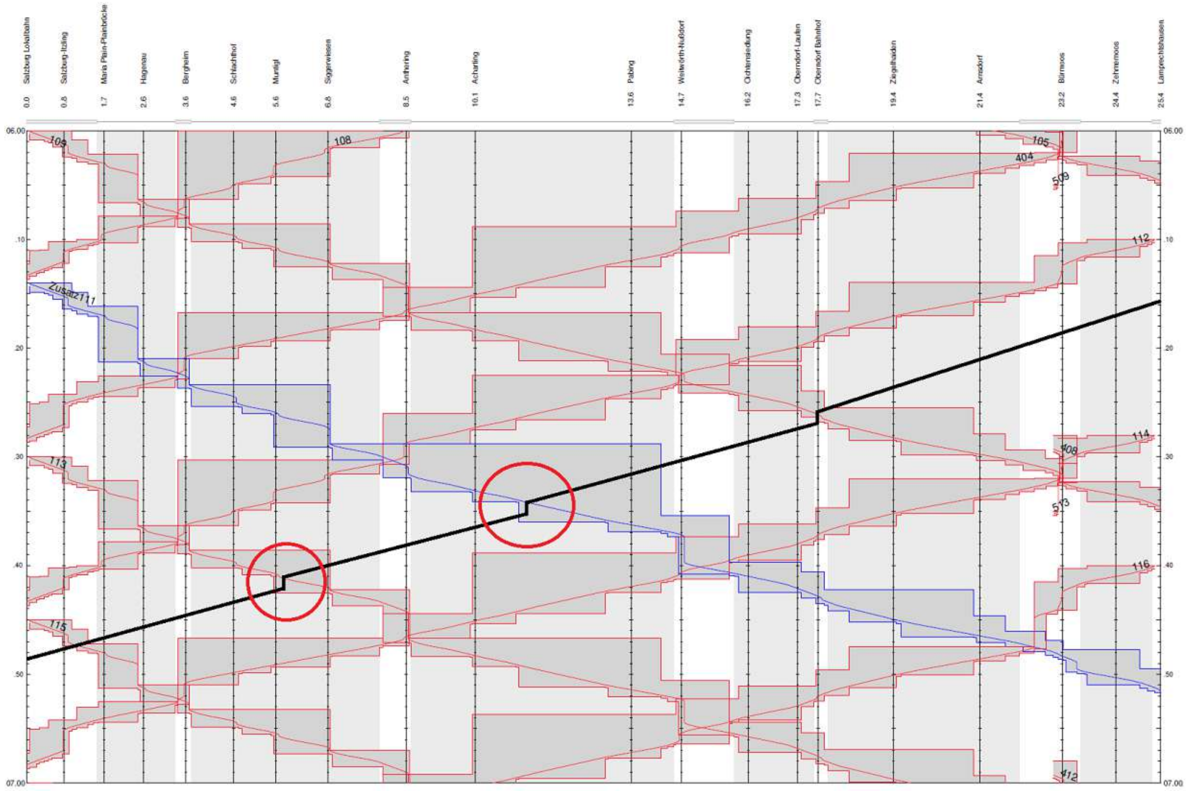

Figure 50: Time – distance diagram Salzburg Lokalbahn to Lamprechtshausen

Source: Own illustration in OpenTrack Version 1.10.3 – Simulation Salzburger Lokalbahn

However, with an increasing number of trains, the risk of delays and delay transmission increases. Therefore, in this work, the possibility of increasing capacity through infrastructure measures will not be furtherly explored.

Instead, it will be investigated how a block division can increase capacity. For this purpose, an electrical multiple unit of the ET 50+50+50 series will be used in the direction from Salzburg to Lamprechtshausen. The stopping pattern from the existing timetable is used and the headway time is calculated with the OpenTrack headway calculator. The two trains are operated with ETCS Level 2 with discrete block and ETCS Level 3 with moving block. With these two trains four combinations are possible. As Figure 51 shows, the headway for two Level 2 trains is 261 s. If a Level 3 train follows a Level 2 train, the headway time is already 141 s. The situation is different when a Level 2 follows a Level 3 train. Then the headway time is 261 s as in the first case. The shortest possible headway can be seen with two Level 3 trains. It is then 71 s.

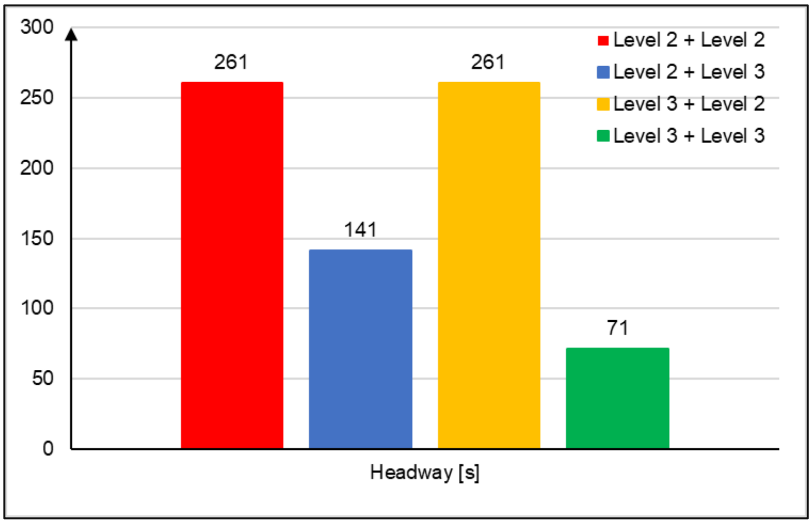

Figure 51: Comparison of headways on the SLB

Source: Own illustration based on the results of the OpenTrack Version 1.10.3 – Simulation Salzburger Lokalbahn

This investigation shows that a significant headway time reduction can be achieved by using moving blocks with a 50 m safety margin. In Chapter 4.1.1 (Virtual blocks) it was already shown that shorter block sections can reduce headway times. So, at this point it is also hypothesised that in this case, the headway time will also decrease with shorter block sections. The headway time of 71 s, which can be achieved with ETCS Level 3 and moving blocks, represents a lower limit towards which the headway time tends when the block lengths are shortened. This aspect will be verified in an example on the railway line from Zagreb to Dugo Selo in Chapter 4.3 (Railway node Sesvete).

The question now arises as to how the shortened headway times affect the timetable on the single-track line. For this purpose, the existing timetable is simulated with trains using moving blocks instead of discrete blocks. It has been found that no significant differences are recognisable up to the first crossing station (Bergheim). However, the duration of the crossing is shortened. As a result, train 105 leaves the station Bergheim earlier than with a discrete block. As a result, trains 105 and 404 do not meet at Anthering station. In terms of time, the trains would meet on the single-track section, which is not possible. To solve this deadlock, the dwell time of the trains in the stations could now be adjusted accordingly to extend it so that the crossings can again take place in the station as planned. However, this does not lead to any improvement. It only makes the timetable more robust. Therefore, the use of Level 3 Moving Block to increase capacity has no positive effect on this single-track line.

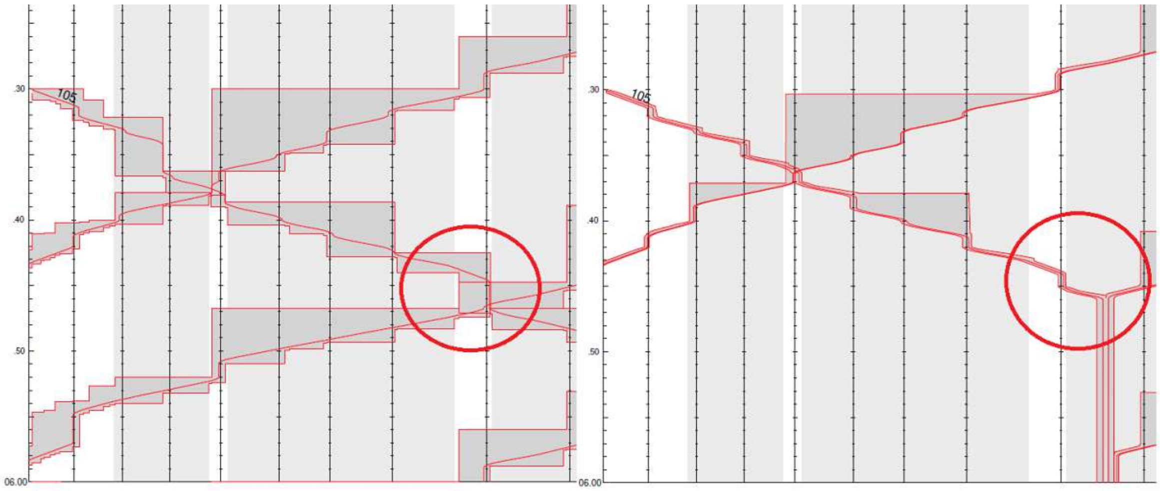

Figure 52: Comparison of discrete and moving block

Source: Own illustration in OpenTrack Version 1.10.3 – Simulation Salzburger Lokalbahn

4.2.2 Overlap analysis

In addition to the block division, the topic of overlaps will also be investigated in this model. Based on the infrastructure, several railway stations have distances from the signal to the danger point under 50 m. If overlaps are not integrated in the interlocking, then there are no restrictions, when trains cross each other in the stations. The situation is different when an overlap is used that reaches over the danger point and leads to restrictions in the opposite direction of travel. This will be discussed by using the example of Anthering station. This station has 85 m between the exit signal and the danger point on the main track in the direction of Salzburg. On the second track in the direction of Lamprechtshausen, there are only 39 m between the exit signal and the danger point. Considering the Austrian rules, it is necessary to have an overlap of 50 m after the route. This can be avoided at a speed of no more than 40 km/h, but the authority also recommends that an overlap should be provided (§22/1-2 EisbBBV - Eisenbahnbau- und -betriebsverordnung, 2008).

In view of various accidents caused by signal crossing, there have already been recommendations from the authorities to increase the overlap.(Sicherheitsuntersuchungsstelle des Bundes, 2021b, p. 66)

In addition to this possibility, the Railway Construction and Operation Ordinance in Austria also provides for the possibility of deviating from the prescribed 50 m at a speed of over 40 km/h. This is the case if a train control system is used which can safely bring the train to a halt independently (§22/3 EisbBBV - Eisenbahnbau- und -betriebsverordnung, 2008). This requirement can be fulfilled with ETCS in Full Supervision mode.

With reference to the station, it should be investigated how an overlap of 0 m and one of 50 m affect railway operations. Figure 53 shows a sketch of this station with the using lengths and the distances between signals and the danger point.

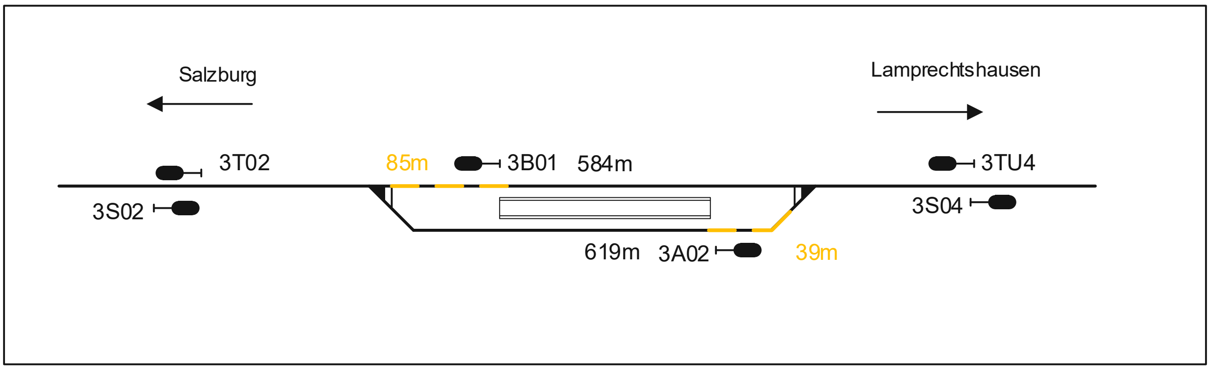

Figure 53: Sketch of the track layout in Anthering

Source: Own sketch in Vision based on Schöbel (2022)

As in the previous chapter, two EMUs of the ET 50+50+50 series are used for this investigation. The scenario is a train from Salzburg to Lamprechtshausen and a train from Lamprechtshausen to Salzburg crossing each other in Anthering. This is a typical situation, which happens also in the real timetable (Salzburg AG, 2021). The minimum dwell time of both trains in this consideration is 30 s. This should only be exceeded if this is needed for operational processes, in this case, the crossing. To prove the impact of the overlap on the operational processes the train order will be also varied, which means that in one case the train from Salzburg arrives first and, in another scenario the train from Lamprechtshausen arrives first. To determine the minimum headways, the headway calculator from OpenTrack cannot be used at this point, as the trains travel in the opposite direction and do not use the same track in the station. Therefore, as an alternative, two so-called instruments are used in the simulation, which are located at the two turnouts. As additional input, instruments are placed at the station Muntigl and Pabling. These instruments log the passing times and calculate the headway of the trains. The minimal headway is then achieved by changing the timetable of the second train in a manner that the blocking times of the two trains are as near as possible without any conflict. Figure 54 shows one of these four scenarios, where train 105 is entering the station before train 400 enters Anthering.

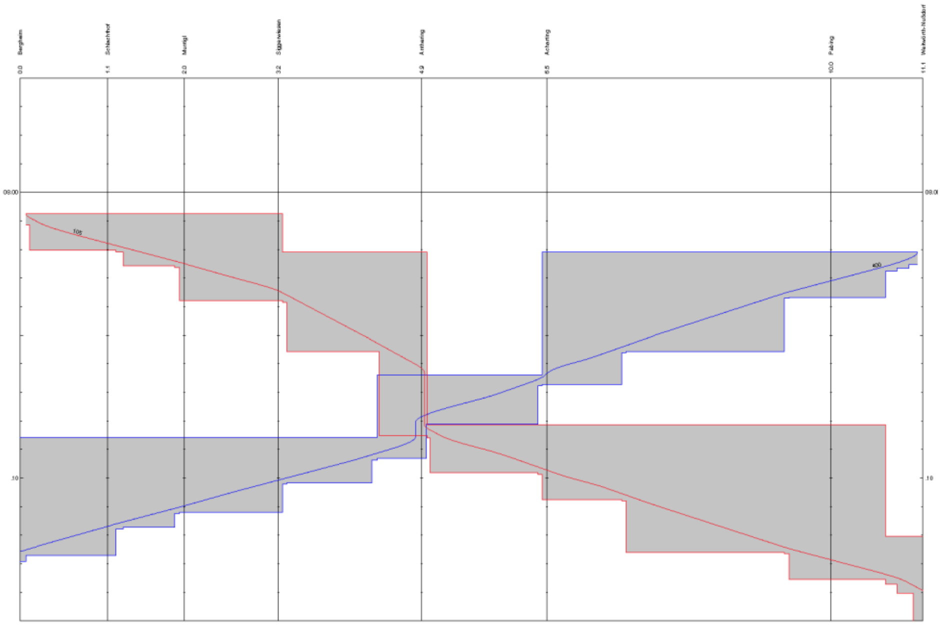

Figure 54: Crossing in Anthering - First train 105 second train 400 both with Overlaps

Source: Own illustration in OpenTrack Version 1.10.3 – Simulation Salzburger Lokalbahn

Based on these considerations, it can be seen that if train 400 is the first train, the headway times with and without overlap remain the same. In Muntigl, the headway is 310 s, at the left turnout in Anthering 40 s, at the right turnout in Anthering 254 s and in Pabling the headway is 794 s. Beneath the headway, the dwell time of train 400 is 129 s and of train 105 the dwell time is 30 s. There is no difference in between these headways in the two scenarios because the overlap from the route for train 400 is not reaching the route from train 105, which means they are not affecting each other when entering the station.

If train 105 is planned as the first train in Anthering, then this train is reserving the route and the overlap. Which is affecting the route of train 400. That leads to the fact that train 400 cannot enter until the overlap is released. Without the overlap, not only the headway before approaching the station Anthering can be shortened, but also the dwell time can be reduced accordingly. The result is a difference of 36 s in the headway which can be seen in Table 8.

Table 8: Comparison of headway times from train 105 and 400 with or without overlap

Source: Table based on the results of the OpenTrack Version 1.10.3 – Simulation Salzburger Lokalbahn

	Dwell time [s]		**Headway [s]**			
	Train 105	**Train 400**	**Muntigl**	**Ant left**	**Ant right**	**Pabling**
50m	109	30	509	239	35	586
0m	73	30	473	203	35	575
Δ Time	**36**	**0**	**36**	**36**	**0**	**11**

However, the overlap does not only affect the other train by blocking the route. It also influences the braking curve of the train that takes the overlap. To show which impact the different overlaps have on the braking curve, the ERA braking curves simulation tool is used. Within this tool, an EMU-type ET 50+50+50 of the SLB is simulated. Because of the reason that this vehicle is not used with ETCS now, several standard values from the simulation tool are used. Certainly some values are adapted to the vehicle, for example, the train length the braked weight percentage and the tonnage. In the simulation, a lambda train is chosen for the braking model in the brake position P. Figure 55 shows the braking curves with the different surveillance curves for a train with 0 m distance from EoA to SvL (= Overlap).

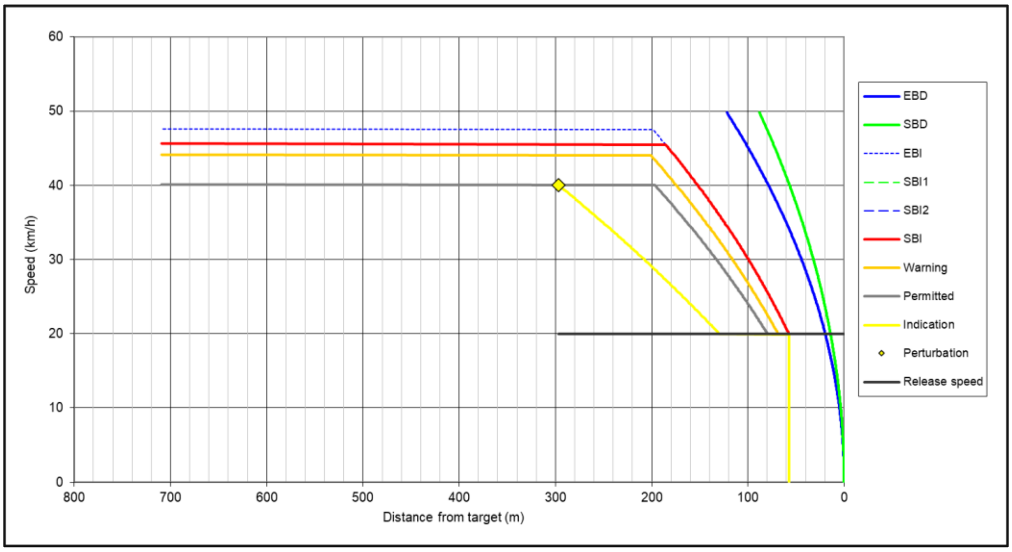

Figure 55: Braking Curves for ET 50+50+50 – Overlap 0m

Source: Own diagram created with ERA braking curves simulation tool (European Agency for Railways, 2020)

If the train driver follows the permitted curve, the braking should start 196.72 m before the signal. The different calculated braking distances for the release speed of 20 km/h can be seen in Table 9.

Table 9: Calculated Braking distances for Overlap 0m

Source: Table created with ERA braking curves simulation tool (European Agency for Railways, 2020) based on Appendix H (ERA Braking Curves Simulation Tool Input parameters)

Initial speed (km/h)	Distance from target (m)							Release speed (km/h)
	Perturbation	Indication	Permitted	Warning	SBI	EBI	StartRSM	
40,00	296,72	296,72	196,72	174,50	152,27	152,27	57,53	20

If now the 50 m overlap between EoA and SvL is used, the braking curve array also changes. Figure 56 shows the various braking curves where the differences between these two variants can be seen.

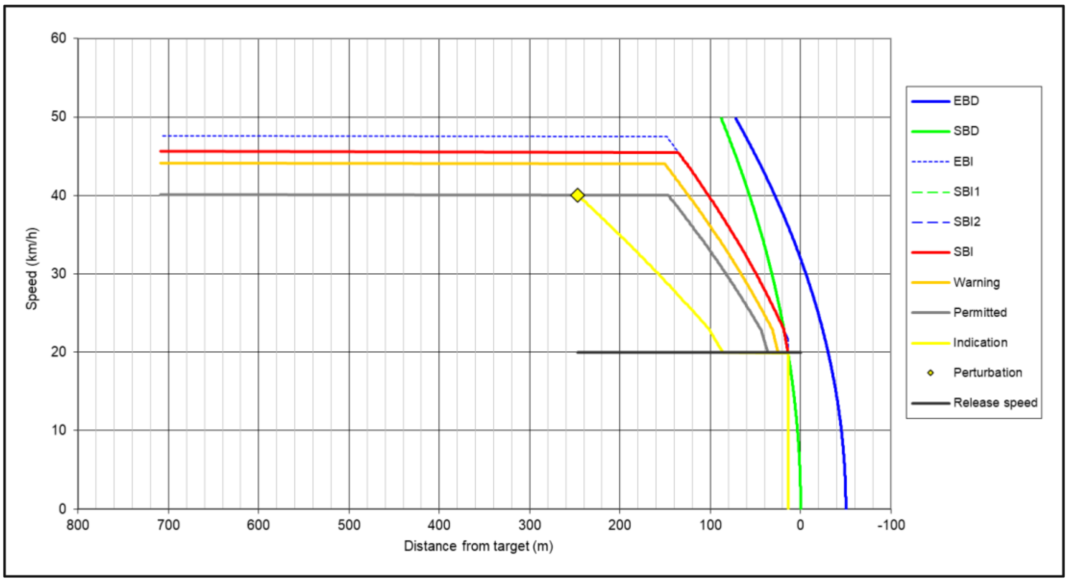

Figure 56: Braking Curves for ET 50+50+50 - Overlap 50m

Source: Own diagram created with ERA braking curves simulation tool (European Agency for Railways, 2020)

As in the first scenario, the braking distances for these braking curves can be taken from the ERA braking curves simulation tool. It can be seen that the curve for the permitted speed is moved from 196.72 m to 146.72 m before the signal. This corresponds to the distance of the added overlap. The detailed values can be seen in Table 10.

Table 10: Calculated Braking distances for Overlap 50m

Source: Table created with ERA braking curves simulation tool (European Agency for Railways, 2020) based on Appendix H (ERA Braking Curves Simulation Tool Input parameters)

Initial speed (km/h)	Distance from target (m)							Release speed (km/h)
	Perturbation	Indication	Permitted	Warning	SBI	EBI	StartRSM	
40,00	246,72	246,72	146,72	124,50	102,27	102,27	14,18	20

When interpreting the two variants only visually, it appears as if in the two curves only the brake application point is delayed. However, this assumption is not correct, as the curves differ, even if they are not clearly visible in this representation. For this purpose, the speed to the respective position with 0 m overlap and 50 m overlap were listed. This table can be seen in Appendix G (Comparision of Braking distances). The difference remains constant in the range from 40 to 22.90 km/h and is 6.64 m. After that, the difference decreases linearly. It would now also be possible to calculate the time differences of the two braking curves. However, such an in-depth analysis will not be done here, as this only contributes to answering the research question to a limited extent. More in-depth considerations of the ETCS braking curves with recommendations for certain line speeds and braked weight percentage can be found in the dissertation from Busse (2021). For this purpose, the overlap is again considered. The time components of the individual speed ranges are shown. Formula 23 shows in the first line the distribution with overlap. Afterwards, it shows how these changes without the overlap and track speed. It shows that the train can run longer at line speed. At the same time, the range in which the train can run at 40 km/h decreases because braking takes longer.

Time consumption with 50 m overlap without track speed:

$$\sum t_{tot50} = t_{ls} + t_{b40} + t_{40} + t_{b0}$$

Changed time consumption with 0 m Overlap but with track speed

$$\sum t_{tot0} = \uparrow t_{ls} + t_{b40} + \downarrow t_{40} + \uparrow t_{b0}$$

Σttot(5)0………Total time with 50 m or 0 m Overlap [s]
tls……………...Time with line speed [s]
tb40…………….Time with deceleration from line speed to 40 km/h [s]
t40……………..Time with speed of 40 km/h [s]
tb0…………….Time with deceleration from 40 km/h to 0 km/h [s]

Formula 23: Time consumption without or with overlap

Source: Formula based on consideration regarding Figure 57 (Schematic braking curves)

However, it must be mentioned that the use of line speed is not technically related to the modified overlap and can be used also without ETCS. Therefore, this example should show the difference in using or not using this measure. This is seen in this work as a possibility to save time, which results from a flatter, longer-lasting braking curve. As in Chapter 3.6.2 (Speed restriction at turnouts), the possibility of track speed is shown by the cab signalling through ETCS. In practice, the line-side signals are off to avoid deviating signal terms (Trinckauf, 2012, p. 11). In principle, however, the application of track speed can also be implemented by a purely operational measure, i.e. the driver is allowed to drive at track speed up to the start of the points. In contrast to ETCS, the responsibility remains to the driver.

Figure 57 shows a track layout with the described two variants. For each scenario, a schematic braking curve is drawn. With this figure, it is easier to understand the changes, which appear by using the Overlap or using no Overlap but track speed to the turnout.

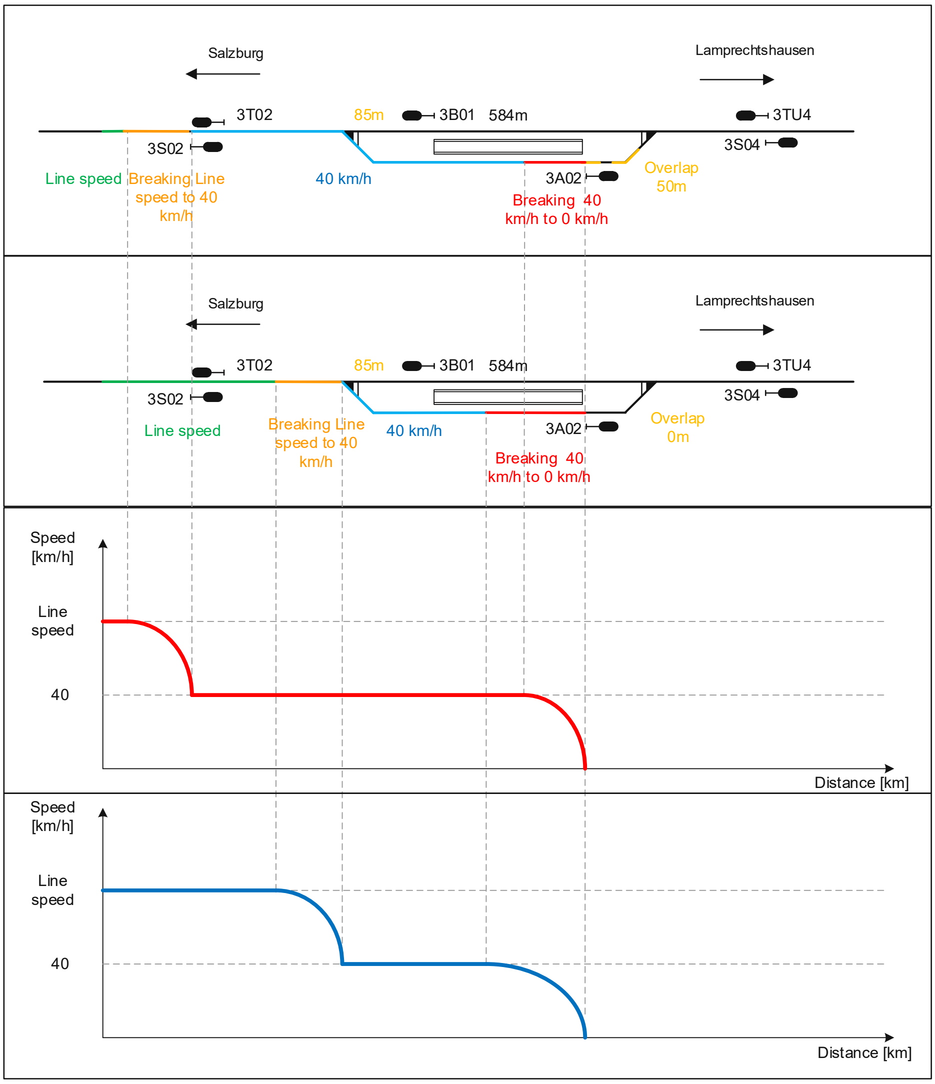

Figure 57: Schematic braking curves

Source: Own sketch in MS Visio

To practically determine how the time consumption differs between these variants, a point of comparison is created. This point is located before the start of the braking curve. More precisely, it is placed 200 m before the exit signal. Since the onset of braking is 196.72 m before the signal, there is no effect of the different braking curves. Only the comparison between the time difference with line speed and 40 km/h from the home signal to this point is calculated.

The same train type is used for the comparison, only a different colour is chosen for the train category to recognize the differences better visually. The colours are chosen identically as in Figure 57. The train that must run at 40 km/h from the home signal is red and the train that must reach this speed before the switch is blue. Figure 58 shows the evaluation of the comparison. It can be seen how much earlier the train must start braking. This is slightly less than 1 km. In relation to the total distance of 1104 m between the home signal and the position of the turnout, this is a considerable range. This also influences the travel time. The difference at the measuring point 200 m before the exit signal is 49 s. The first train runs through this point at 08:04:31 and the second train at 08:05:20.

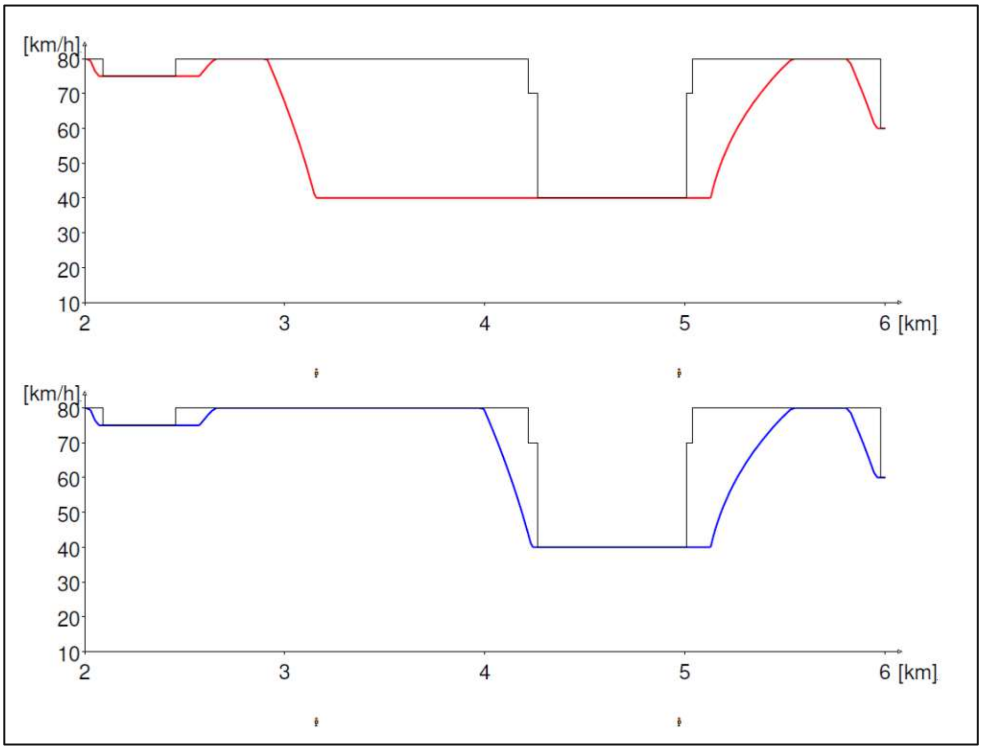

Figure 58: Speed - distance comparison in Anthering

Source: Own illustration in OpenTrack Version 1.10.3 – Simulation Salzburger Lokalbahn

This measure could compensate for flatter braking curves that result from shortening the overlap. At the same time, this is a question that must also be evaluated with a risk analysis and the findings that are presented are not a recommendation to omit overlaps. In addition to the already mentioned dissertation by Busse (2021), also Maschek (2011, pp. 45–49) deals with the optimal length of overlaps, where recommendations for the respective train protection systems are given.

4.3 Railway node Sesvete

The railway station Sesvete is a junction station from the railway lines Zagreb Glavni Kolodvor (Main station), Dugo Selo (M102) and Sesvete-Sava (M401), whereby this railway station is a part of a triangle of lines with the marshalling yard in the middle. In this work the freight line M401 will be investigated only to Zagreb Resnik, which is the neighbouring railway node. The main importance of the railway junction Sesvete is also, that the RFC 6 Mediterranean and the RFC 10 Alpine-Western Balkan are leading through the station (Rail Net Europe, 2020).

Beneath the freight traffic, there is a service with suburban trains from Zagreb Main Station to Dugo Selo. These trains are stopping at every station, including Sesvete. The long-distance traffic trains from Serbia and Hungary are passing this station. For a better illustration, Figure 59 shows an overview of the railway lines and RFC in Croatia, whereby the RFC 10 is blue and the RFC 6 is red. The station Sesvete is marked with yellow.

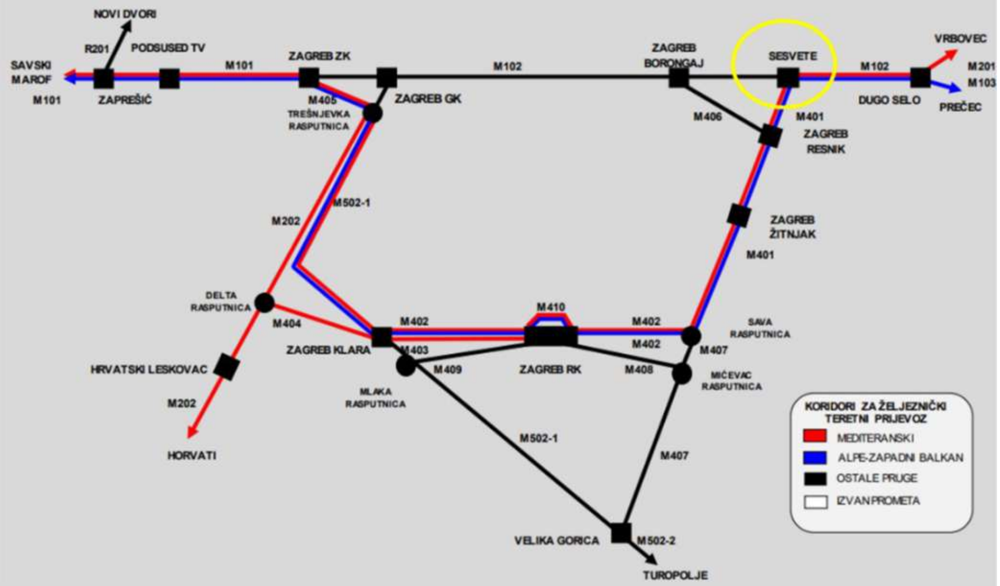

Figure 59: Railway node Zagreb with RFC

Source: Picture marked and taken from HŽ Infrastruktura d.o.o. (2021, p. 110 / 2.1-2.)

At Sesvete station, the double-track line from Zagreb Main Station and the double-track line from Zagreb Resnik join. It then gets a double-track line in the direction of Dugo Selo. It should be noted here that the continuous main tracks lead from Dugo Selo to Zagreb Main Station, and when running to and from Zagreb Resnik trains must necessarily pass by switched turnouts. However, over the last-mentioned line runs the RFC. The station itself consists of two shunting tracks, one siding, two continuous tracks and three station tracks. There are also two platforms with 150 m using length and one platform with 80 m length (Čičak et al., 2016, p. 26). For the illustration, the existing characteristics of the station have been simplified and shown in Figure 60.

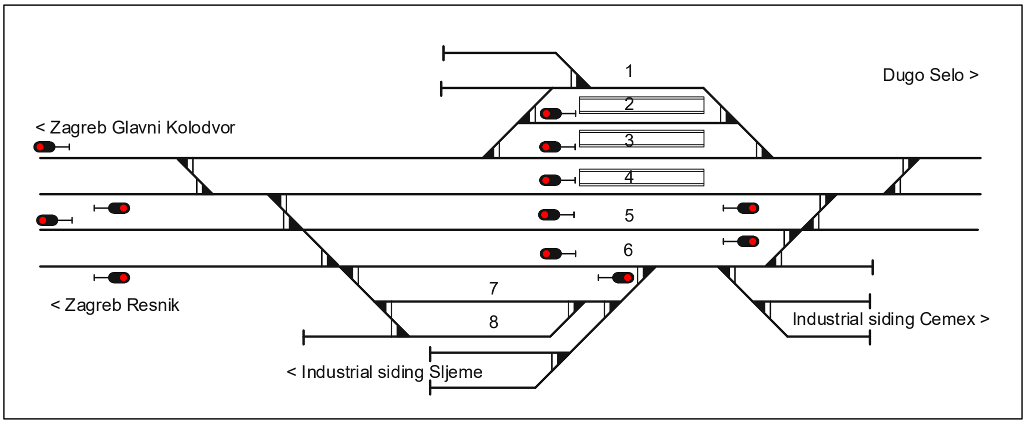

Figure 60: Schematic track layout in Sesvete

Source: Own illustration in OpenTrack Version 1.10.3 based on Čičak et al. (2016, p. 26)

Only mono-directional traffic is possible on this line. Furthermore, turnouts at the entrances from Zagreb Main Station and Dugo Selo are not available for both tracks, which restricts the possibility of setting routes to all tracks. But this fact will be considered in more detail in the further part of this chapter in the context of the simulation. Before that, an assessment of the existing operation will be made. For a comprehensive estimation of the traffic at the station, the timetable operated in the year 2021/2022 is used and considered for one working day. This shows that most traffic occurs between 06:00 to 07:00 and 15:00 to 16:00. 15 trains are operated in each of these two hours, but the composition of passenger traffic, long-distance traffic and freight trains is not identical. The detailed number and type of trains can be seen in the daily graph in Figure 61 or in the table in Appendix B (Timetable evaluation Sesvete).

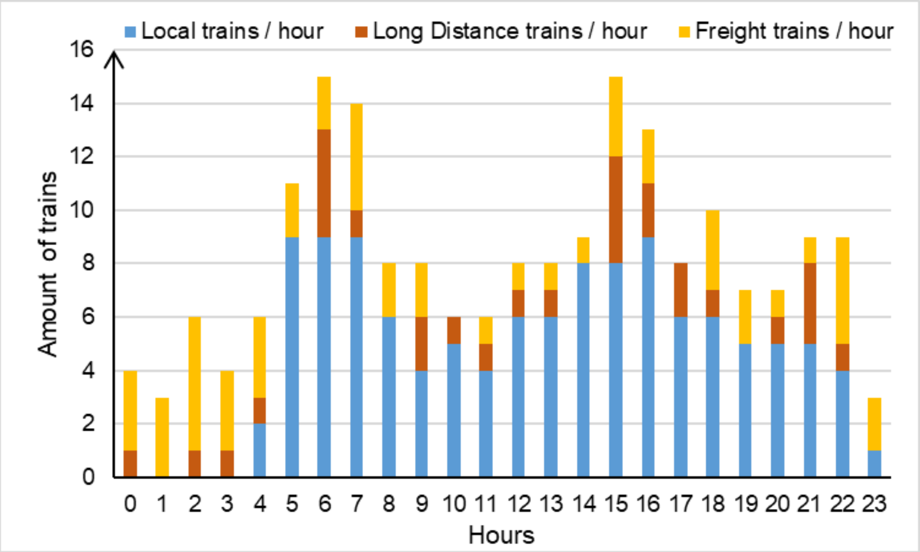

Figure 61: Trains per hour in Sesvete

Source: Own illustration based on Timetable 2021/22 taken from HŽ Infrastruktura (2021)

In the existing layout, there are also restrictions because there is no bi-directional traffic, and it is not possible to use all tracks from every side. If a train comes from Zagreb Main Station it can only use the track 4, 5 or 6. This means, that for a passenger train there is only the possibility to use the platform beneath track 4. If it is planned to overtake a stopping train in Sesvete, there would only be the possibility of sending this train over track 5 or 6, which leads to a deceleration, because the train must use the turnout areas. In the other direction a passenger train can use every platform. From Resnik, it is only possible to come to the tracks 5 and 6. Every train coming from Dugo Selo in the direction of Resnik must cross the track in the opposite direction, which leads to a bottleneck which will be investigated.

Now the line speed outside of the Station in the Direction from Zagreb Main Station to Dugo Selo is 140 km/h. In the other direction, it is announced that the speed between Sesvetski Kraljevec and Sesvete is 140 km/h. Between Sesvete and Čulinec the permitted speed is 120 km/h. In the direction to Resnik the speed outside of the station is limited to 100 km/h. Inside Station Sesvete the speed limit is 60 km/h.(HŽ Infrastrukture d.o.o., 2021, pp. 125–138) During an on-site visit in the spring of 2022 there were ongoing construction works and other limitations, which led to a lower speed in practice. However, these non-permanent restrictions and the lower speed have no impact on the programmed overlaps in the interlocking. Behind the exit signals the overlap must be 50 m if the permitted speed is limited to 100 km/h. This 50 m is the minimal length of the overlap, and the Croatian rulebook describes also other lengths for higher speeds and types of signals (home signals, protecting signals, exit signals) where the length of an overlap can reach 150 m (Članak 94 Pravilnik o načinu i uvjetima za sigurno odvijanje i upravljanje željezničkim prometom, 2022).

If the sections from Zagreb Main Station to Dugo Selo and from Zagreb Resnik to Sesvete is considered on this basis, it can be seen that the median length of the distance to the danger point is 57 m and only two values are over 100 m. Figure 62 shows a plot of the distance to the danger points in nearby stations.

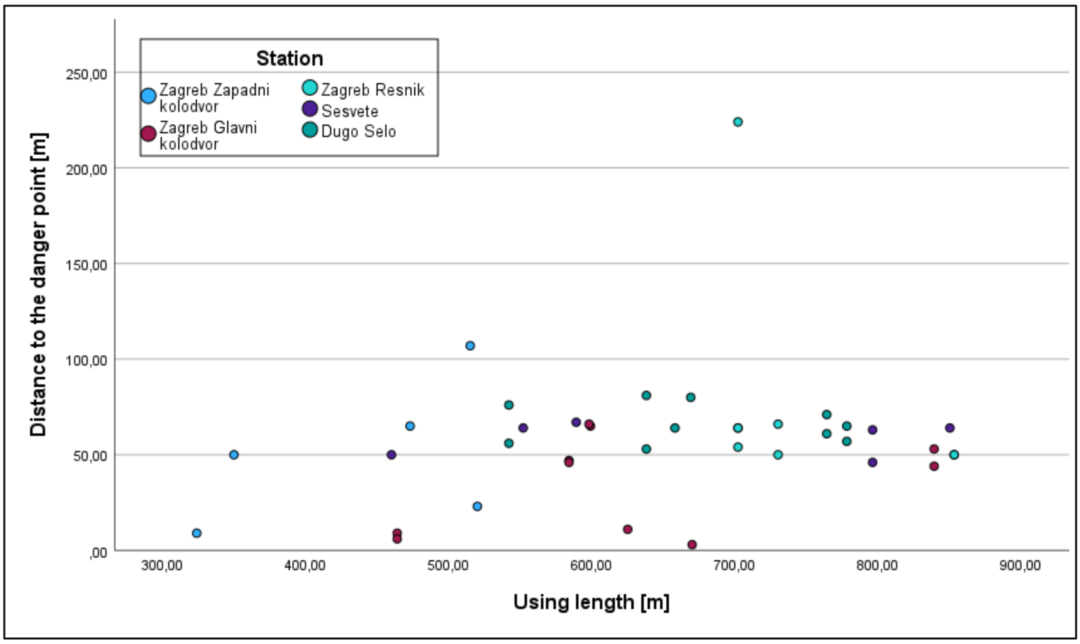

Figure 62: Correlation Using length and distance to the danger point

Source: Own illustration in IBM SPSS Statistics Version 29.0.0.0. based on data from Appendix F (Analysis of the distance to danger point)

Interlocking table

In Spring 2022, even with the reduced speed, different limitations lead to disruptions and delays. The reasons are the longer overlaps, which are programmed into the interlocking logic. They cannot be shortened if there is a speed restriction. But it should be mentioned, that if an interlocking is planned, it is possible to program routes with different speeds for the same track (ÖBB Infrastructure AG, 2023a). For this work, it is assumed, that routes in the same direction exclude each other, when there could be an overlap reaching into the other route. The interlocking table can be used to compare different layout variants. With the interlocking table, the excluding routes ratio can be calculated (Lindner, 2011, pp. 2–3).

Table 11 shows the interlocking table in a simplified form, where 1 stands for incompatible routes which exclude each other, and 0 stands for compatible routes.

Table 11: Simplified interlocking table Sesvete

Source: Table based on Čičak et al. (2016, p. 26) and on Site Visit in Sesvete in May 2022

routes	conflicting routes																			
	A-D4	A-D5	A-D6	C-D5	C-D6	B-E2	B-E3	B-E4	B-E5	B-E6	E2-ZGGK	E3-ZGGK	E4-ZGGK	E5-ZGGK	E6-ZGGK	E5-ZGRS	E6-ZGRS	D4-DS	D5-DS	D6-DS
A-D4	1	1	1	0	0	0	0	1	1	1	0	0	1	1	1	0	0	0	1	1
A-D5	1	1	1	1	0	0	0	0	1	1	0	0	1	1	1	1	1	1	0	1
A-D6	1	1	1	1	1	0	0	1	1	1	0	0	1	1	1	1	1	0	0	0
C-D5	0	1	1	1	1	0	0	1	1	1	0	0	0	1	1	1	1	1	0	1
C-D6	0	0	1	1	1	0	0	0	1	1	0	0	0	0	1	0	1	1	1	0
B-E2	0	0	0	0	0	1	1	1	1	1	0	1	1	1	1	0	0	0	0	0
B-E3	0	0	0	0	0	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0
B-E4	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	0	0	1	1	1
B-E5	1	1	1	1	0	1	1	1	1	1	0	0	0	0	1	0	1	1	1	1
B-E6	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1
E2-ZGGK	0	0	0	0	0	1	1	0	0	0	1	1	1	1	1	0	0	0	0	0
E3-ZGGK	0	0	0	0	0	1	1	0	0	0	1	1	1	1	1	0	0	0	0	0
E4-ZGGK	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
E5-ZGGK	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0
E6-ZGGK	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1
E5-ZGRS	0	1	1	1	0	0	0	0	0	0	1	1	1	0	0	1	1	0	1	0
E6-ZGRS	0	1	1	1	1	0	1	1	1	0	0	0	0	1	1	1	1	0	0	1
D4-DS	0	1	1	1	1	0	0	1	1	1	0	0	1	0	0	0	0	1	1	1
D5-DS	1	0	1	0	1	0	0	1	1	1	0	0	0	1	0	1	0	1	1	1
D6-DS	1	1	0	1	0	0	0	1	1	1	0	0	0	0	1	0	1	1	1	1

Based on Pachl (2013b, pp. 151–153), there can be calculated the rate of incompatible routes.

$$Excluding\ routes\colon \eta = \frac{\sum a_{ij}}{n^2} = \frac{235}{20^2} = 0{,}588 = 59\ \%$$

η………………Excluding ratio,

Σaij……………Total number of exclusions (1 exclusion, 0 no exclusion),

n………………Number of Routes.

Formula 24: Calculation of excluding routes

Source: Calculation based on Pachl (2013b, pp. 151–153)

To compare the existing layout with adaptions, it is necessary to use the same rolling stock data in OpenTrack for the different variants. For this purpose, typical trains are chosen which are also used there in reality. The suburban trains are often running with an EMU type HŽ 6112. For the local train, a double EMU of the two HŽ 6112 is chosen, like they are used for the train 2202 between Koprivnica and Zagreb Main Station. The long-distance train is based on the IC 540 Slavonija between Vinkovci and Zagreb Main Station. For the freight train, a typical tonnage and engine is taken (Dvořák, 2022a).

Table 12 shows the different model trains, used for further consideration. More detailed information about the rolling stock data can be found in Appendix L (Used rolling stock data).

Table 12: Model trains for Infrastructure Adaption in Sesvete

Source: Table based on described Rolling stock from Appendix L (Used rolling stock data)

Type of train	Engine	Wagons
Suburban train (ST)	HŽ 6112	
Local train (LT)	2 x HŽ 6112	
Long distance train (LDT)	HŽ 1142	Aeelt + Beemt + 4 x Bee
Freight train (FT)	HŽ 1141	6 * 90t + 6 * 80t + 6 * 25t + 2 * 15t

Headway times

For the investigation of the utilization, a minimal headway between two trains means that the infrastructure can be used more sophisticatedly. Therefore, approaches, which are trying to minimize the minimal headway between two trains to maximize the utilization can be found in the scientific literature (Vignali et al., 2020, p. 2). But also several capacity calculation methods, like the British CUI method, explained in Chapter 3.4.5 (Stochastic models), use the minimum headway as a basis for capacity assessment (Sameni et al., 2011, p. 20). Based on these considerations, two turnouts in the station are chosen, on which the minimal headway is measured. This is necessary because the trains are running on different tracks, so there must be a defined point to measure the headway time. One is located on track 4, between the two turnouts on the eastern exit (turnout 5 and 4). This point is chosen because of freight trains to Zagreb Resnik, which are crossing this track against the direction of the passenger trains to Dugo Selo. The second is located on the track above, track 3 between turnout 8 and 1. This point is chosen to compare the headways with the other point, because there is only traffic in one direction, so these headways can be compared with the bi-directional situations. The measurement points are equipped with an instrument in OpenTrack. From this approach, twelve situations are simulated. Half of the situations will be investigated on track 4 and the others will be investigated at track 3. Each scenario is carried out with two trains, for example a freight train following a suburban train. Then in the next scenario the order of the trains is changed. To get the minimal headway the trains are placed in the timetable, that the blocking times are as near as possible. As a framework condition, there should not be any disturbance caused by the other train, which means no conflict should appear, for example, that one train must decelerate or stop at a closed signal. Every scenario is created at another hour in the timetable, for example at 12:00 the first scenario starts, whereby the simulation time starts at 11:45 and ends at 12:15. The scenarios are simulated in more simulation runs, but there is no delay or disturbance planned. To verify the results, headways between two trains in the same direction are cross-checked with the headway calculator from OpenTrack. Table 13 shows the minimal headway times for the described situations.

Table 13: Headway times existing layout

Source: Table based on the results of the OpenTrack Version 1.10.3 – Simulation railway node Sesvete

					Simulation Time		**Headway [s]**	
Nr.	**Area**	**First train**	**Second train**	**Tried time**	**From**	**To**	**0 Variant**	**Adapted**
1	Track 4 between turnout 5 and 4	ST (ZGGK-DS)	FT (ZGRS-DS)	12:00	11:45	12:15	84	|
2	Track 4 between turnout 5 and 4	FT (ZGRS-DS)	ST (ZGGK-DS)	13:00	12:45	13:15	296	|
3	Track 4 between turnout 5 and 4	ST (ZGGK-DS)	FT (DS-ZGRS)	14:00	13:45	14:15	132	|
4	Track 4 between turnout 5 and 4	FT (DS-ZGRS)	ST (ZGGK-DS)	15:00	14:45	15:15	231	|
5	Track 4 between turnout 5 and 4	ST (ZGGK-DS)	LDT (ZGGK-DS)	16:00	15:45	16:15	152	|
6	Track 4 between turnout 5 and 4	LDT (ZGGK-DS)	ST (ZGGK-DS)	17:00	16:45	17:15	249	|
7	Track 3 between turnout 8 and 1	FT (DS-ZGRS)	ST (DS-ZGGK)	18:00	17:45	18:15	108	|
8	Track 3 between turnout 8 and 1	ST (DS-ZGGK)	FT (DS-ZGRS)	19:00	18:45	19:15	109	|
9	Track 3 between turnout 8 and 1	ST (DS-ZGGK)	LDT (DS-ZGGK)	20:00	19:45	20:15	259	|
10	Track 3 between turnout 8 and 1	LDT (DS-ZGGK)	ST (DS-ZGGK)	21:00	20:45	21:15	192	|
11	Track 3 between turnout 8 and 1	ST (DS-SSV Tr. 2)	LDT (DS-ZGGK)	22:00	21:45	22:15	93	|
12	Track 3 between turnout 8 and 1	LDT (DS-ZGGK)	ST (DS-SSV Tr. 2)	23:00	22:45	23:15	100	|

From the headway times it can be seen, that the already described situation of a freight train from and to Zagreb Resnik is a limitation in the existing layout. Therefore, this situation will be examined in more detail. A typical situation which could be seen in practice is that a freight train from Dugo Selo is approaching the station and gets a route to Zagreb Resnik. At the same time or while the freight train is passing through the station, a passenger train is approaching to Sesvete from Zagreb Main Station. But the train cannot enter the station because the overlap for this route would lead into the route of the freight train. That leads to an unplanned stop for the passenger train in front of the home signal until the freight train completely released the route, because partial route release is not available. This situation was also noticeable during the on-site visit. Figure 63 visualizes the described situation.

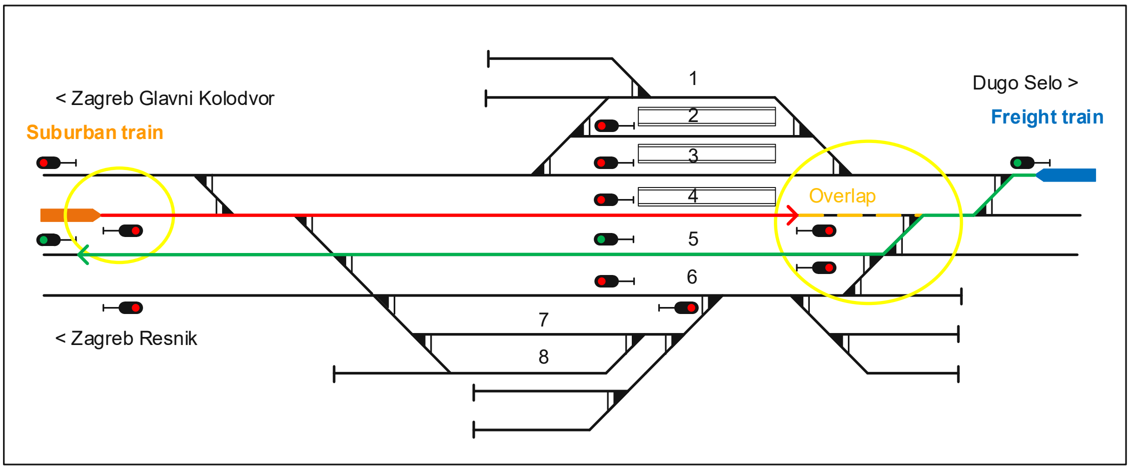

Figure 63: Route conflict track four

Source: Own sketch in MS Visio based on Čičak et al. (2016, p. 26)

To have a better overview of the impact of this situation on daily operations, the probability of the obstruction of the two routes will be calculated. To calculate the two probabilities, it is necessary to know how many trains are using the routes and how long they are blocking it. For this purpose, the amount of the trains is taken from the time-distance diagram of the timetable 2021/2022 (HŽ Infrastrukture d.o.o., 2019). The duration how long the blocks are reserved will be calculated from the simulation model. The amount of the suburban trains from Zagreb Main Station to Dugo Selo will be called z_1 and the amount freight trains from Dugo Selo to Zagreb Resnik are called z_2. For suburban trains from Zagreb Main Station to Dugo Selo, the fact that the overlap for the station is leading into the turnout area, means that also the blocking time for the block from the home signal to the exit signal must be taken into consideration. That leads to a blocking time of 4.10 min for the suburban train and of 2.43 min for the freight train. In the time period from 15:00 to 17:00, there are running 13 passenger trains in the direction of Dugo Selo, and three freight trains are running from Dugo Selo to Zagreb Resnik.

To calculate the probability of obstruction of two routes, the formulas based on Pachl (2013b, pp. 151–155) are used, which will be presented in Formula 25.

$$P_{Obst1} = \frac{z_2 * t_{bt2}}{t_I} = \frac{3 * 2.43\ min}{120\ min} = 6.08\ \%$$

$$P_{Obst2} = \frac{z_1 * t_{bt1}}{t_I} = \frac{13 * 4.10\ min}{120\ min} = 44.42\ \%$$

$$n_{Obst1} = z_1 * P_{Obst1} = t_{bt2} * \frac{z_1 * z_2}{t_I} = 2.43\ min * \frac{13 * 3}{120\ min} = 0.790$$

$$n_{Obst2} = z_2 * P_{Obst2} = t_{bt1} * \frac{z_2 * z_1}{t_I} = 4.10\ min * \frac{3 * 13}{120\ min} = 1.333$$

$$\begin{aligned} \sum n_{Obst} = n_{Obst1} + n_{Obst2} &= \frac{z_1 * z_2 * (t_{bt1} + t_{bt2})}{t_I} \\ &= \frac{13 * 3 * (4.10\ \text{min} + 2.43\ \text{min})}{120\ min} = 2.122 \end{aligned}$$

$P_{Obst1/2}$ ......Probability of obstructions for trains on route 1 and 2 [1],
$z_{1/2}$..........Number of trains on route 1 and 2 [1],
$t_{bt1/2}$.........Blocking time of the obstruction point of route 1 and 2 [min],
t_I.............selected time window [min],
$n_{Obst1/2}$.......expected level of obstructions on route 1 and 2 [1],
Σnobst......Total number of obstructions [1].

Formula 25: Probability of obstruction

Source: Calculation based on Formulas taken from Pachl (2013b, pp. 151–155)

This calculation assumes as a simplification that all these 13 trains are stopping in Sesvete, in the reality the majority stops but not all of them. But it can be seen, that the obstruction of the route from a suburban train is a limitation in the traffic. As an additional obstacle there should be mentioned, that freight trains from Zagreb Resnik to Dugo Selo are using the same turnout area and coming from track 6 to track 4. So, it can be shown, that for this turnout, measurements to improve the situation should be foreseen.

4.3.1 Adaption of the existing infrastructure Layout

Based on the previous chapter, there will be several measures to improve the station Sesvete. The main task followed by the research of Duvnjak et al. (2020, p. 55) is to enable a cyclic timetable. Also there should be a rotating suburban train to the Airport via Velika Gorica (Grad Zagreb, 2022). For this purpose, a connection between track five and four is needed, which allows also trains coming from track 2 to run to Zagreb Resnik. That is enabled with two new turnouts. But there will be also other requirements for the traffic, leading to two new stops for the suburban trains in Sesvetska Sopnica and Sesvetska Sela (Čičak et al., 2016, p. 30). Therefore, it is necessary to have a platform where suburban trains from Zagreb Main Station can approach and change the direction back to the Main Station. For this purpose, track 2 is selected, because here trains can wait without disturbing the traffic. To also enable traffic when there is a disturbance at tracks 5 or 6, an additional connection from track 4 to 3 is created at the eastern entrance of the station. To decrease the headways, partial route release can be used as a measure for increasing capacity (Li & Martin, 2014, p. 18). For this reason partial route release is supposed for every route from and to the station. How partial route release affects the headway can be seen in an example in Figure 64, whereby this example shows an simplified track layout from the fictive railway node A2.

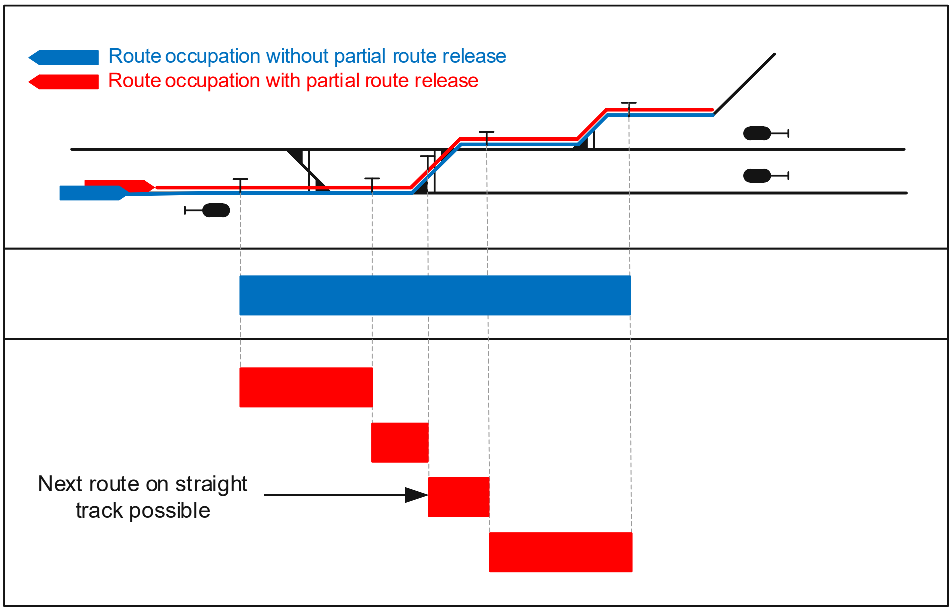

Figure 64: Comparison of route occupation without and with partly route release

Source: Own sketch in MS Visio based on Sieber (2014, p. 14)

Also, it should be mentioned that the Croatian regulations allow the overlap starts at the stopping point of a train, whereby the train must be shorter than 150 m and if there is the minimal overlap length to the fouling point indicator (Članak 110 Pravilnik o načinu i uvjetima za sigurno odvijanje i upravljanje željezničkim prometom, 2022). This is discussed generally in Chapter 3.6.1 (Overlaps). This aspect is only applicable on the suburban trains or shorter local trains. Therefore, in this investigation. the minimal overlap of 50 m was used after every signal, with the condition that no overlap reaches the danger point and every turnout after an exit signal can be used for other routes.

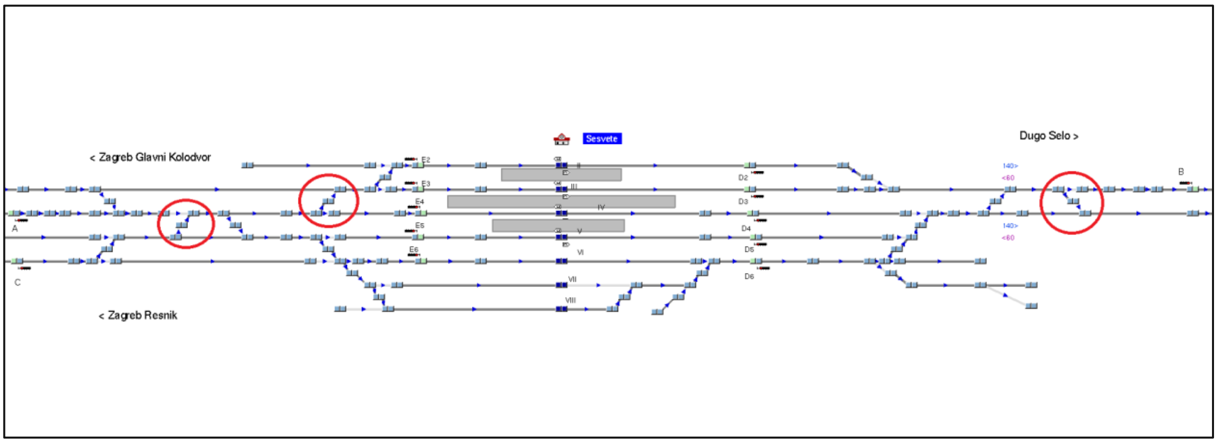

Figure 65: Recommendation for an adapted layout

Source: Figure taken from OpenTrack Version 1.10.3 – Simulation railway node Sesvete

Adapted interlocking table

Based on the new turnouts and the considerations belonging to the overlaps, there are now 30 possible routes, which results can be seen in Table 14. These routes are checked again on their excluding rate to compare it with the existing one and calculate the relative improvement.

Table 14: Adapted interlocking table Sesvete

Source: Table based on Figure 65

routes	conflicting routes																													
	A-D2	A-D3	A-D4	A-D5	A-D6	C-D2	C-D3	C-D4	C-D5	C-D6	B-E2	B-E3	B-E4	B-E5	B-6	E2-ZGGK	E3-ZGGK	E4-ZGGK	E5-ZGGK	E6-ZGGK	E2-ZGRS	E3-ZGRS	E4-ZGRS	E5-ZGRS	E6-ZGRS	D2-DS	D3-DS	D4-DS	D5-DS	D6-DS
A-D2	1	1	1	1	1	1	1	1	0	0	1	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
A-D3	1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
A-D4	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0
A-D5	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0
A-D6	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	1	1	1	0	0	1	1	1	0	0	0	0	0
C-D2	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
C-D3	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
C-D4	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0
C-D5	0	0	0	1	1	1	1	1	1	1	0	0	0	1	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0
C-D6	0	0	0	0	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0
B-E2	1	0	0	0	0	1	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
B-E3	0	1	0	0	0	0	1	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
B-E4	0	0	1	0	0	0	0	1	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
B-E5	0	0	0	1	0	0	0	0	1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
B-6	0	0	0	0	1	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
E2-ZGGK	1	1	0	0	0	1	1	0	0	0	1	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	0	0	0	0
E3-ZGGK	1	1	0	0	0	1	1	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0
E4-ZGGK	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	1	1	1	1	1	1	1	0	0	0	0	0	1	0	0
E5-ZGGK	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0
E6-ZGGK	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1
E2-ZGRS	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
E3-ZGRS	1	1	1	1	1	1	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0
E4-ZGRS	1	1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	0	1	1	1	1	1	1	1	1	0	0	1	0	0
E5-ZGRS	0	0	0	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	0
E6-ZGRS	0	0	0	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	0	0	0	0	1
D2-DS	1	0	0	0	0	1	0	0	0	0	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	1	1	1	1	1
D3-DS	0	1	0	0	0	0	1	0	0	0	1	1	1	1	1	0	1	0	0	0	0	1	0	0	0	1	1	1	1	1
D4-DS	0	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	1	0	0	0	0	1	0	0	1	1	1	1	1
D5-DS	0	0	0	1	0	0	0	0	1	0	0	0	1	1	1	0	0	0	1	0	0	0	0	1	0	1	1	1	1	1
D6-DS	0	0	0	0	1	0	0	0	0	1	0	0	1	1	1	0	0	0	0	1	0	0	0	0	1	1	1	1	1	1

$$Excluding\ routes: \eta = \frac{\sum a_{ij}}{n^2} = \frac{463}{30^2} = 0.514 = 51\ \%$$

$$Relative\ improvement = 1 - \left(\frac{\frac{\sum a_{ijnew}}{n^2{}_{new}}}{\frac{\sum a_{ijold}}{n^2{}_{old}}} \right) = 1 - \left(\frac{\frac{463}{30^2}}{\frac{235}{20^2}} \right) = 0.124$$

$$= 12.4\ \%$$

η………………Excluding ratio [%],

Σaij……………Total number of exclusions [1],

n………………Number of Routes [1].

Formula 26: Comparison of excluding grade

Source: Formula taken from Pachl (2013b, p. 156)

Comparison of the headway times

To have an overview of the impact of the different measures, the minimal headway between different trains is simulated again at the adapted infrastructure with the same train parameters. Table 15 shows the minimal headways without conflicts in the timetable at the existing infrastructure and at the adapted infrastructure.

Table 15: Comparison of the minimal headway times

Source: Table based on the results of the OpenTrack Version 1.10.3 – Simulation railway node Sesvete

					Simulation Time		Headway [s]		
Nr.	**Area**	**First train**	**Second train**	**Tried time**	**From**	**To**	**0 Variant**	**Adapted**	**Delta**
1	Track 4 between turnout 5 and 4	ST (ZGGK-DS)	FT (ZGRS-DS)	12:00	11:45	12:15	84	84	0
2	Track 4 between turnout 5 and 4	FT (ZGRS-DS)	ST (ZGGK-DS)	13:00	12:45	13:15	296	161	135
3	Track 4 between turnout 5 and 4	ST (ZGGK-DS)	FT (DS-ZGRS)	14:00	13:45	14:15	132	132	0
4	Track 4 between turnout 5 and 4	FT (DS-ZGRS)	ST (ZGGK-DS)	15:00	14:45	15:15	231	94	137
5	Track 4 between turnout 5 and 4	ST (ZGGK-DS)	LDT (ZGGK-DS)	16:00	15:45	16:15	152	104	48
6	Track 4 between turnout 5 and 4	LDT (ZGGK-DS)	ST (ZGGK-DS)	17:00	16:45	17:15	249	197	52
7	Track 3 between turnout 8 and 1	FT (DS-ZGRS)	ST (DS-ZGGK)	18:00	17:45	18:15	108	108	0
8	Track 3 between turnout 8 and 1	ST (DS-ZGGK)	FT (DS-ZGRS)	19:00	18:45	19:15	169	162	7
9	Track 3 between turnout 8 and 1	ST (DS-ZGGK)	LDT (DS-ZGGK)	20:00	19:45	20:15	259	202	57
10	Track 3 between turnout 8 and 1	LDT (DS-ZGGK)	ST (DS-ZGGK)	21:00	20:45	21:15	192	135	57
11	Track 3 between turnout 8 and 1	ST (DS-SSV Tr. 2)	LDT (DS-ZGGK)	22:00	21:45	22:15	93	91	2
12	Track 3 between turnout 8 and 1	LDT (DS-ZGGK)	ST (DS-SSV Tr. 2)	23:00	22:45	23:15	100	100	0

Possible timetable

For the proposal of a new cyclic timetable in the peak hours, there will be a mixed traffic, as in the existing situation. For the long-distance trains, there should be a train from Zagreb Main Station to Koprivnica and further every two hours and every two hours a train from Zagreb Main Station to Vinkovci and further. In the other direction the trains should have the same pattern. As local trains, a double EMU of two HŽ 6112 will be supposed, which will be separated in Dugo Selo, one EMU goes further to Koprivnica, and one runs to Slavonski Brod. There should also be at least one path for a freight train from Dugo Selo to Zagreb Resnik and one train from Zagreb Resnik to Dugo Selo. The suburban trains should run every 15 min between Zagreb Main Station and Sesvete. One of this trains will end in Sesvete, and a second train will change the direction a run further to the Airport. Figure 66 shows a time-distance diagram of the described traffic, without the Airport connection. Instead, it shows two suburban trains per hour changing the direction.

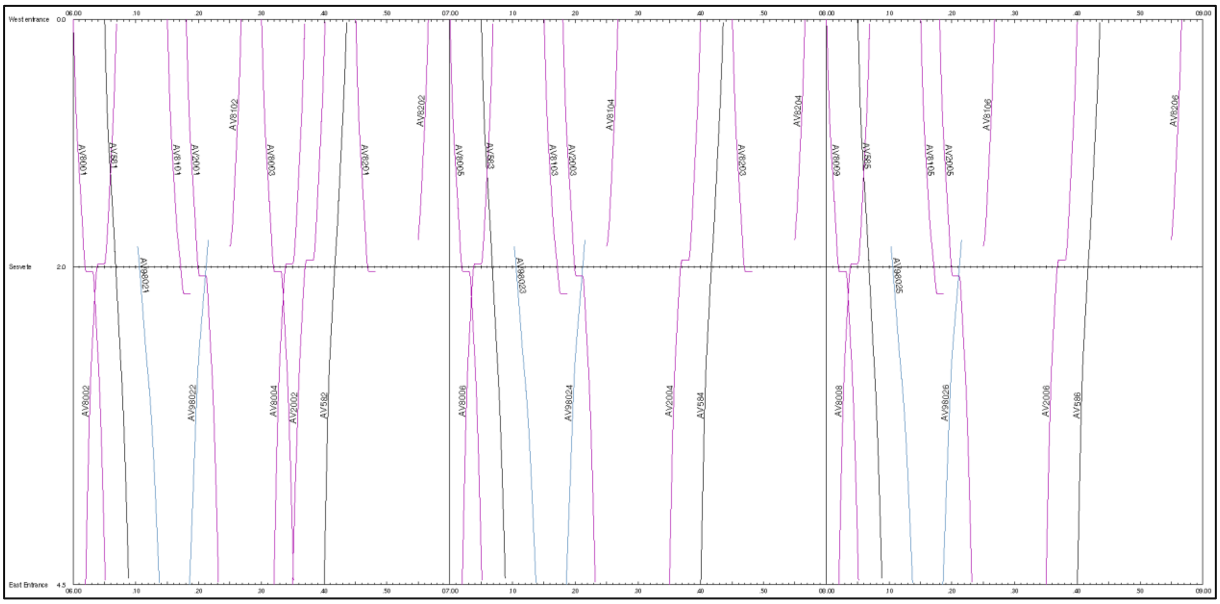

Figure 66: Time-distance diagram of the new timetable

Source: Figure taken from OpenTrack 1.10.3 – Simulation Railway node Sesvete

Results of the Infrastructure adaption

In the investigation an adapted layout in Sesvete with a changed track layout between Maksimir (MKS), Trnava (TRN) and Čulinec (CLN) is analysed. With these adaptions a denser timetable is possible. There are more conflict-free train routes possible at the same time. Also, the fact that several suburban trains end in Sesvete or change the direction, enables that freight trains can pass through the station from Dugo Selo to Zagreb Resnik at the same time. This is also enabled through the concept of the local trains using double sets of EMUs, which are operated together in between Zagreb Main Station and Dugo Selo. This is based on the idea that the areas around Sesvete and Dugo Selo are declared bottlenecks(Alpine- Western Balkan RFC Project Management Office, 2021, p. 38). In Dugo Selo these trains are diverted and this measure should be checked in detailed research, in order to find out how big the capacity impact is. Within this concept, an additional working site for train drivers must be in Dugo Selo, where they start or end their shifts for the local trains. As it can be seen in Table 15, the improvements are not achieved in every scenario. Overall, a significant improvement can be concluded, especially in situations where two compared trains are running in another direction. The delta of these headways for the different situations can be also visualized, so it is easier to identify in which situations the headways were shortened. This visualization is handed out in Figure 67.

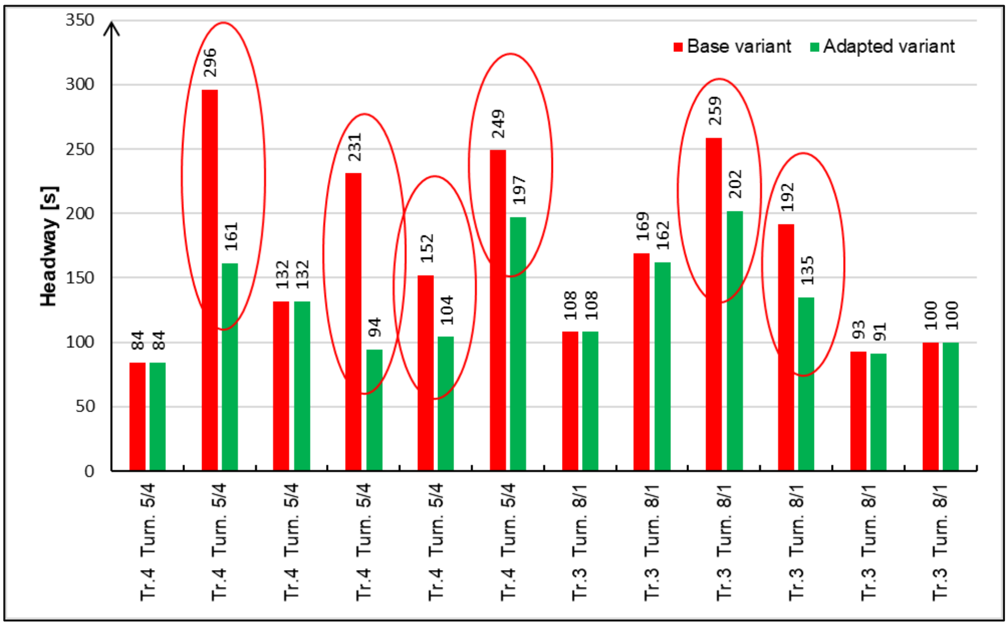

Figure 67: Comparison of the infrastructure variants

Source: Own illustration based on the results of the OpenTrack Version 1.10.3 – Simulation railway node Sesvete

In the further investigation of the railway node, the effects of using different train and traffic control systems on the capacity will be analysed.

4.3.2 Implementation of ETCS Level 2

To implement ETCS Level 2 on the whole railway line between Zagreb Main Station and Dugo Selo, as well as from Zagreb Resnik to Sesvete, different adjustments are needed. First, the line must be equipped with GSM-R, which enables the transmission of MA from the RBC to the train. Besides that, OpenTrack requires placed signals, which are defining the section, where cab signalling is used. As it can be seen in Figure 68, these signals are placed at the beginning of each route, as well as at end signal for cab signalling (Hürlimann & Nash, 2017, p. 25).

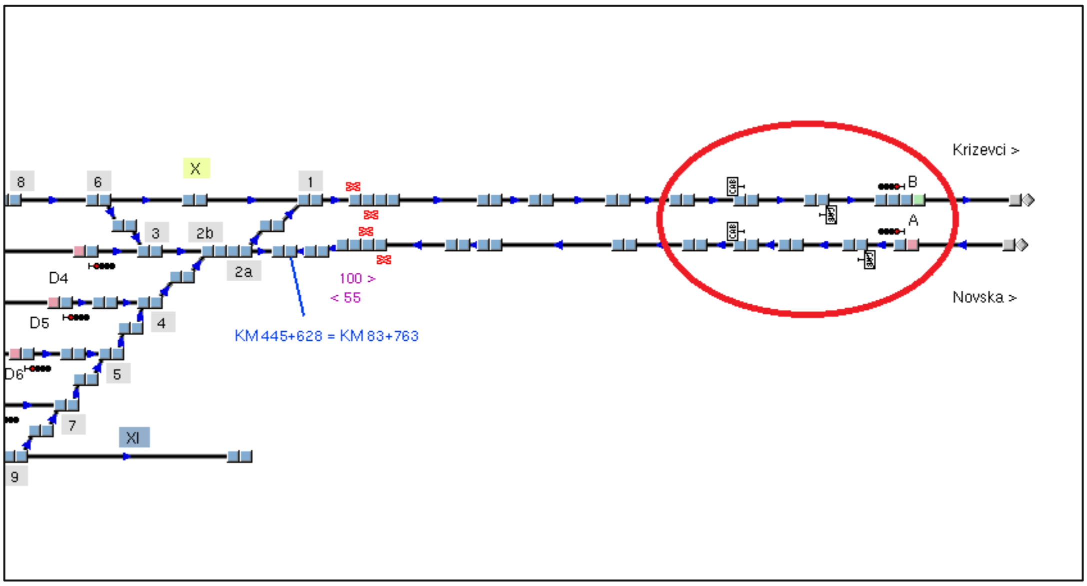

Figure 68: Cab signalling signs on the infrastructure

Source: Picture taken from OpenTrack Version 1.10.3 – Simulation Railway node Sesvete

Beneath the infrastructure adaptions, it is also required to change the train parameters. As mentioned in Chapter 2.1.4.3 (ETCS Braking Curves) the braking curves under ETCS are not identical to the braking curves of PZB. Therefore, it is necessary to calculate the deceleration of the trains. For this purpose, the so-called UIC formula is used. Formula 13 shows the used UIC formula.

$$a = -(C1 + C2 * \lambda)$$

a…..………..Deceleration [m/s^2],
C1…..………Coefficient factor (independent coefficient [0.069],
C2………..…Coefficient factor (coefficient dependent on λ) [0.006],
λ……………. Braked weight percentage [%].

Formula 27: Deceleration formula according to UIC

Source: Formula taken from Hürlimann & Nash (2017, p. 84)

After this calculation, the so-called Function table (non-ETCS / ETCS) is chosen in OpenTrack to enable that the train is using the appropriate braking behaviour. Also, the computation method is chosen, according to the ETCS specification (Hürlimann & Nash, 2017, p. 71).

4.3.3 ETCS Level 2 and Track speed at turnouts

Like in the SLB model, line speed until the beginning of the turnouts is also used in this simulation. This is called Track speed in OpenTrack. For sure, this measurement only affects trains that are using turnouts in the diverging route. In the case of Sesvete freight trains from and to Dugo Selo must use turnouts in this way. That means the distance from the home signal to the turnout for trains from Dugo Selo is 443 m, where trains could still run with line speed. For this purpose, this measure is also used and every route from the exit signals and from the home signals is changed to track speed.

4.3.4 ETCS Level 3

The headway is suitable for evaluating the effects of the changed block division, since it can also be reduced with a shorter block division (Vignali et al., 2020, p. 2). Moving Block is a suitable method for determining the minimum train running time in which a reduction is possible. Therefore, within the scope of the study in Sesvete, all train journeys were switched to Moving Block and it is determined how the train time behaves in comparison to the existing block division. However, a safety margin of 50 m is chosen which, in this specific example corresponds to the length of the overlap used.

One scenario of the two following trains will be explained more in detail because it shows the effect of the moving block and the different stopping pattern. Figure 69 shows a time-distance diagram from Zagreb Resnik to Dugo Selo (DS). The first train is a suburban train from Zagreb Main Station to Dugo Selo, which appears in the time-distance diagram in Sesvete. In Sesvete and Dugo Selo the E1003 has a dwell time of 60 s. In Sesvetski Kraljevec (SKR), the train stops for 30 s. A freight train follows the suburban train. The Z1001 is running with no stop and a maximum speed of 80 km/h. It can be seen in this example, that the dwell time is the limiting factor. If the dwell time is also 60 s in Sesvetski Kraljevec, the headway between the two trains, in the section of Sesvete to Sesvetski Kraljevec, would be increased.

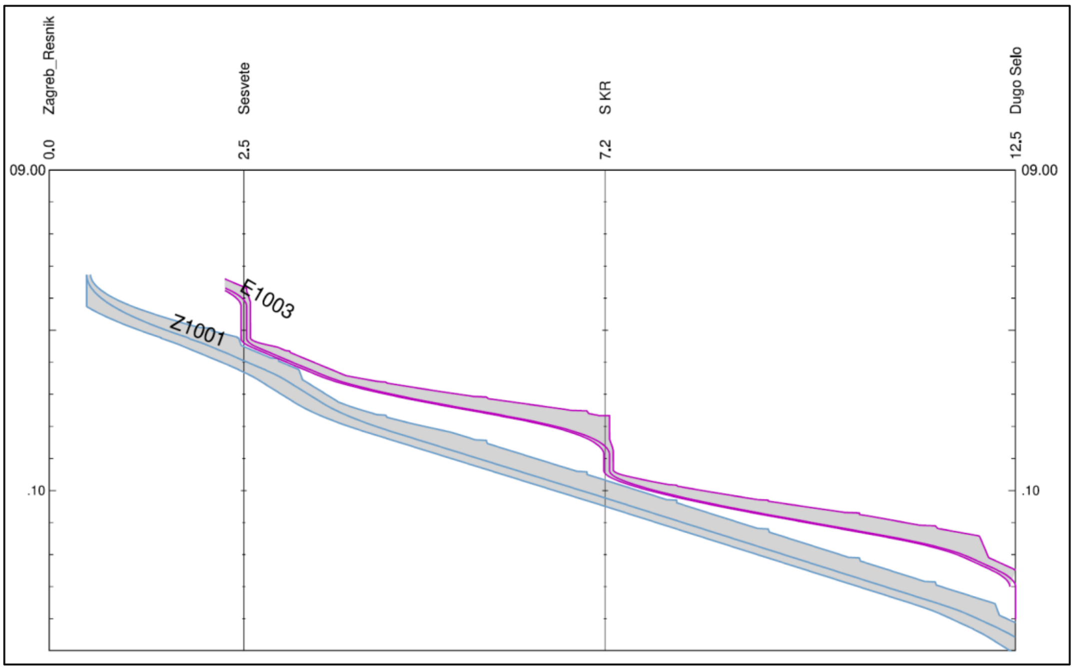

Figure 69: Moving block of suburban train and freight train

Source: Own illustration in OpenTrack Version 1.10.3 – Simulation railway node Sesvete

4.3.5 ETCS Level 2 with Track speed and shorter blocks

To determine how the existing blocks can be divided, the first step is to calculate the existing lengths. In doing so, the continuous main track from Zagreb Main Station to Dugo Selo and in the opposite direction is analysed. Furthermore, the side tracks between Maksimir and Čulinec and vice versa will be surveyed. For the freight traffic, Zagreb Resnik to Sesvete and back is analysed. To calculate the block lengths, the adapted infrastructure model is used and the distance between the respective main signals is measured. A detailed list of each block length is presented in Appendix I (Block division in the railway node Sesvete).

For the section between Zagreb Main Station to Dugo Selo the total length is 20.582 km with 18 blocks and an average block length of 1.143 km. For the new block divisions, the existing ones are divided into sub-sections of approximately 500 m. This means that the physical blocks are divided into one to four sub-sections, depending on the length of the physical block. For the divisions the principles for block division are respected, which are described in Chapter 3.6.4 (ETCS Level 2 with shorter blocks / Level 3 Hybrid).

The Zagreb Resnik to Sesvete section is significantly shorter at 3.146 km. This section has three physical blocks, which have an average block length of 1.049 km. These physical blocks can be divided into one to three sub-blocks. In the opposite direction, the station in Zagreb Resnik is resulting in a total length of 4.120 km. This section has three physical blocks, with an average block length of 1.373 m. These are then divided into sub-blocks of two to three sub-sections. The exact subdivisions can be found in Table 45 & 46 included in Appendix I (Block division in the railway node Sesvete).

In addition, the sidetracks in the four-track section between Maksimir and Čulinec from the research of Duvnjak, on which this work is based, were also analysed (Duvnjak et al., 2020, p. 55). The main tracks were considered in the analysis of Zagreb Main Station to Dugo Selo. The side tracks are therefore analysed at this point. Starting from the home signals to the exit signals of the respective direction of travel. For both directions the distance is similar with 1.168 km in the direction of Zagreb Main Station and 1.120 km to Dugo Selo. Both directions have four physical block sections, and each physical block can be divided into between two and three subsections. As before, the detailed list can be found in Appendix I (Block division in the railway node Sesvete).

4.3.6 Results for the node Sesvete

As already shown in the previous investigations, the eastern station entrance represents a bottleneck, whereby the situation could be optimized by the measures implemented before. Based on these investigations, the measures will now be further implemented. In the infrastructure study, however, a traction unit of the HŽ 1141 series is used, whereas in this consideration, locomotive with ETCS is used. For this purpose, an electric locomotive of the Vectron series is selected. Table 16 shows the trains used in this investigation. More detailed information about the rolling stock data can be found in Appendix L (Used rolling stock data).

Table 16: Model trains for capacity measurements in Sesvete

Source: Table based on described Rolling stock from Appendix L (Used rolling stock data)

Type of train	Engine	Wagons
Suburban train (ST)	HŽ 6112	
Freight train (FT)	Vectron 193	6 * 90t + 6 * 80t + 6 * 25t + 2 * 15t

Train movements

Figure 70 shows the different train movements which are selected for the trains. The upper part of the figure shows the track layout from the eastern part of the Sesvete station and the four-track section between Maksimir and Čulinec. As described a suburban train and a freight train are used. In the direction from Dugo Selo to Zagreb Main Station, there is a suburban train with a stop in all stations running on the straight track, the used train number for this train is 8002. The second train from Dugo Selo to Zagreb Main Station is also a suburban train, but this train uses the side track in the four-track section. Beneath these two trains with a running path on the whole line, there are also two trains with shorter paths only between Maksimir and

Čulinec. Train 8008 is using the side track and 8006 is using the straight track. In the third part of Figure 70, the next scenario is shown. There the characteristics of train 8002 are used again, this train is named 5004. In the other direction a suburban train from Zagreb Main Station to Dugo Selo is used, with a stop at every station. The train is called 5005. The third train in this scenario is a freight train running from Dugo Selo to Zabreb Resnik. For this purpose, the train with the train number 5002 is changing the track over the turnout area. In the lower part of the figure, two trains in the four-track section are used. The suburban train on the straight track is train 1005. The train on the side track is called 1007. The third suburban train, which is called 1003, runs from Zagreb Main Station to Dugo Selo with a stop in every station. Beneath the suburban trains, in this scenario, there is also a freight train that runs from Zagreb Resnik to Dugo Selo.

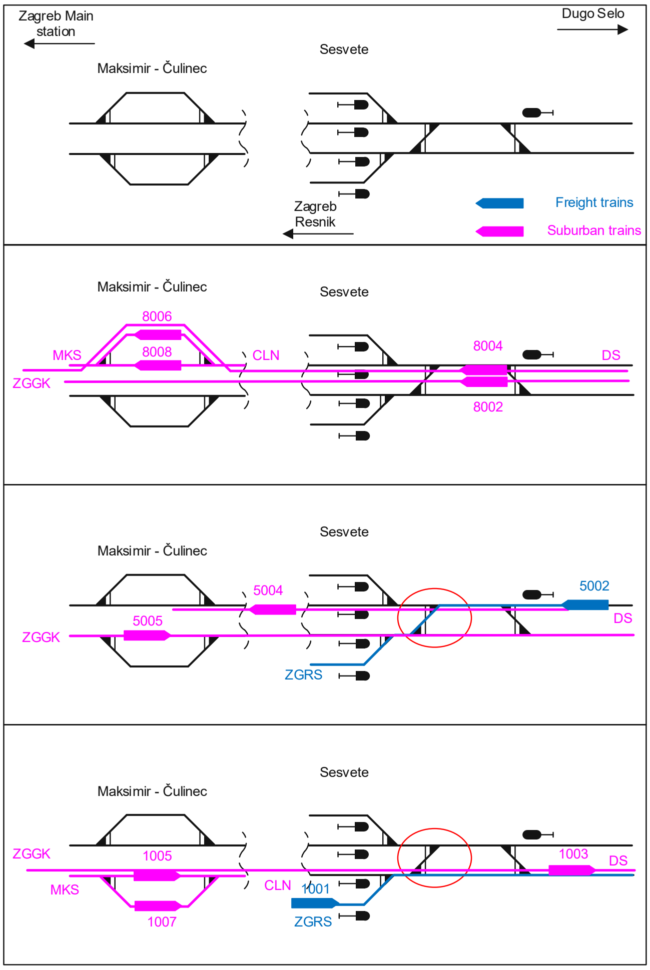

Figure 70: Tested train movements

Source: Own sketch in MS Visio

During the simulation, it becomes clear that the headway comparison is not possible for all trains, as some of the routes do not share at least parts of their path. For example, freight trains and suburban trains, which only run on the four-track section. For this reason, the calculated data is preselected to find out plausible results for the headway calculation. The following data is therefore the selected data.

Table 17 & 18 show the headway comparison of the different variants used for the different trains. In each case, one train is followed by a second train and the minimum headway is determined. The respective variants can also be seen in the tables.

Table 17: Headway Comparison Sesvete part one in seconds

Source: Table based on Results of OpenTrack Version 1.10.3 – Simulation railway node Sesvete

First train	8002	8002	8004	8008	8008	5002	5002	5002	5004
Second train	8002	8004	8002	8004	8008	5002	5004	5005	5002
Base Variant	633	345	688	409	359	374	374	87	291
ETCS	654	368	711	426	373	374	374	87	291
ETCS Track Speed	654	729	239	352	343	318	318	87	218
ETCS 500 m Block	245	649	124	322	222	196	221	62	114
ETCS Moving Block	105	105	105	136	121	74	174	51	9

Table 18: Headway Comparison Sesvete part two in seconds

Source: Table based on Results of OpenTrack Version 1.10.3 – Simulation railway node Sesvete

First train	5004	5005	1001	1001	1003	1003	1003	1007	1007
Second train	5004	5005	1001	1003	1001	1003	1005	1003	1007
Base Variant	633	348	294	232	177	342	155	133	325
ETCS	654	359	294	234	202	359	162	134	339
ETCS Track Speed	654	245	240	178	154	359	160	134	316
ETCS 500 m Block	245	214	182	164	144	214	165	117	205
ETCS Moving Block	105	106	72	77	43	106	95	40	95

A complete list of every simulation can be found in Appendix J (Raw data railway node Sesvete). Figure 71 shows the results of the tested cases. However, in some cases investigation did not appear to make sense. For example, those cases where the trains only run on the four-track section with those that use the entire route. In most cases with ETCS Level 2 the headway remains like the original variant or is even higher. This can be explained by the flatter braking curves. In the case, where turnouts are used in the diverging direction, it can be seen, that track speed leads to a reduced headway.

The use of the moving block leads to the most significant headway reduction. As expected, the headway at 500 m is between the values for the ETCS Track Speed variant and the ETCS Moving Block variant. With a block length of 500 m, the headway is on average 133 s less than with the base variant. However, it is noticeable that the shorter blocks do not lead to an even reduction in all examples but differ depending on the train sequence.

Figure 71 shows the use cases discussed in graphical form.

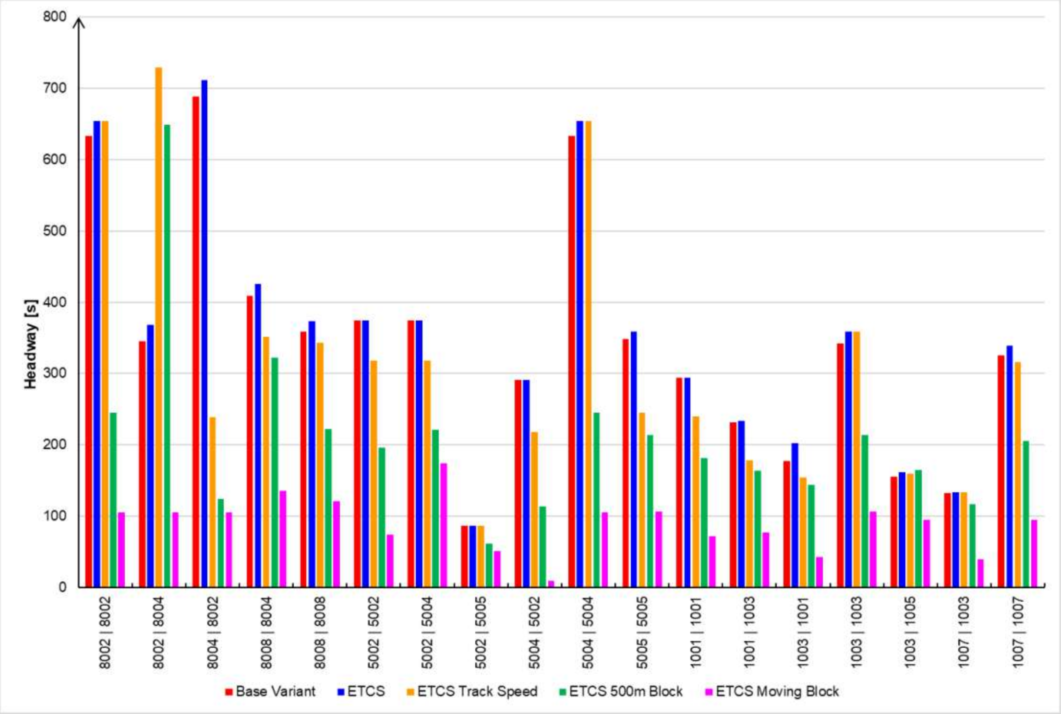

Figure 71: Comparison of headways in Sesvete

Source: Own illustration based on the results of the OpenTrack Version 1.10.3 – Simulation railway node Sesvete

4.4 Südbahn Wien Meidling – Wr. Neustadt

Beneath the Vienna suburban railway line between Wien Floridsdorf and Wien Meidling, the Südbahn, especially in the area between Wien Meidling and Mödling, is one of the busiest lines in Austria (ÖBB Infrastructure AG, 2020a, pp. 2–3). It is a mixed-traffic line, which has freight traffic in addition to local, suburban and long-distance passenger traffic. The majority of the trains are passenger trains. Suburban trains are running on the entire route, but most of them runs between Wien Meidling and Mödling (ÖBB Personenverkehr AG, 2022a).

Figure 72 shows the line of the Südbahn within the yellow rectangle from Wien Meidling via Mödling and Baden to Wiener Neustadt. Also running in a southbound direction is the Pottendorfer line, marked as 106 in the figure, recently rebuilt to double-track. After that, long-distance trains will run via the Pottendorfer line, which will enable a denser passenger service for local trains on the Südbahn (Plank & Poimer, 2017, p. 656).

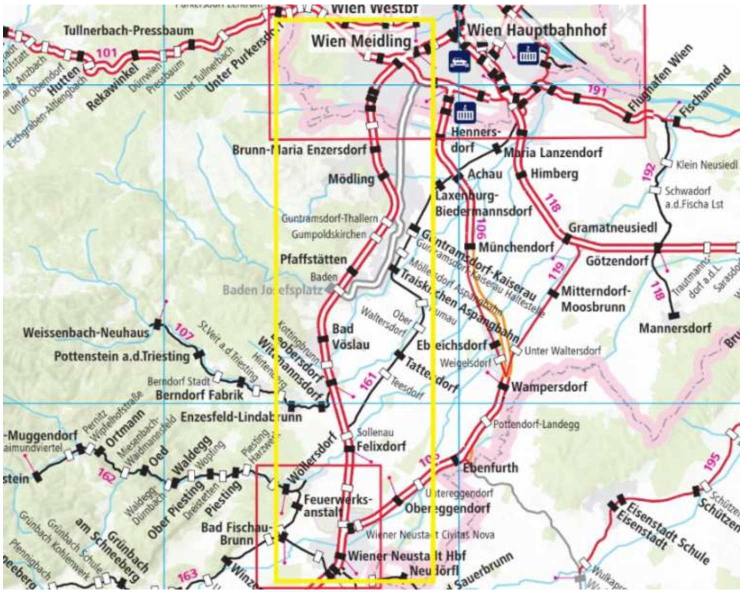

Figure 72: Infrastructure map with Südbahn

Source: Picture marked and taken from ÖBB Infrastructure AG (2023d)

If the timetable of passenger traffic is considered for the station Mödling, 322 trains a day that stop or pass through it can be counted at the station. However, this consideration does not include freight traffic, which also passes through this station. Figure 73 shows an overview of passenger traffic with a clearly recognisable morning and afternoon peak. An hourly tabular list of the trains can be found in Appendix C (Timetable evaluation Mödling).

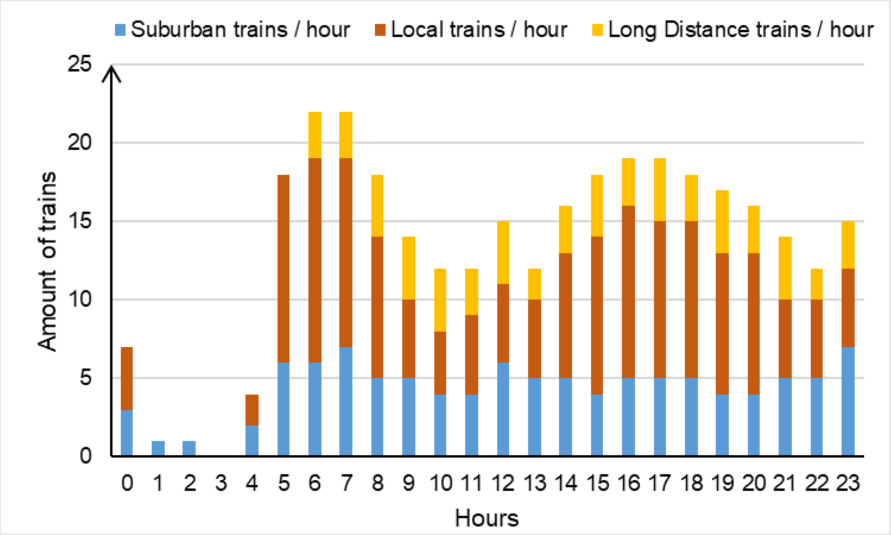

Figure 73: Trains per hour in Mödling

Source: Own illustration based on ÖBB Personenverkehr AG (2022a)

In addition to the number of trains, the surveys relating to the correlation between the using length and distance to the danger point are also analysed.The diagram of the two parameters shown in Figure 74 is analysed, and it can be seen that the using length is widely scattered in the range between 200 and 800 m. Simple outliers can be seen in the distance to the danger point and an extreme outlier in Leobersdorf. Regarding the distance to the danger point, it can also be seen that a large proportion of the measured values are in the range of up to 100 m. The median is located at 60 m.

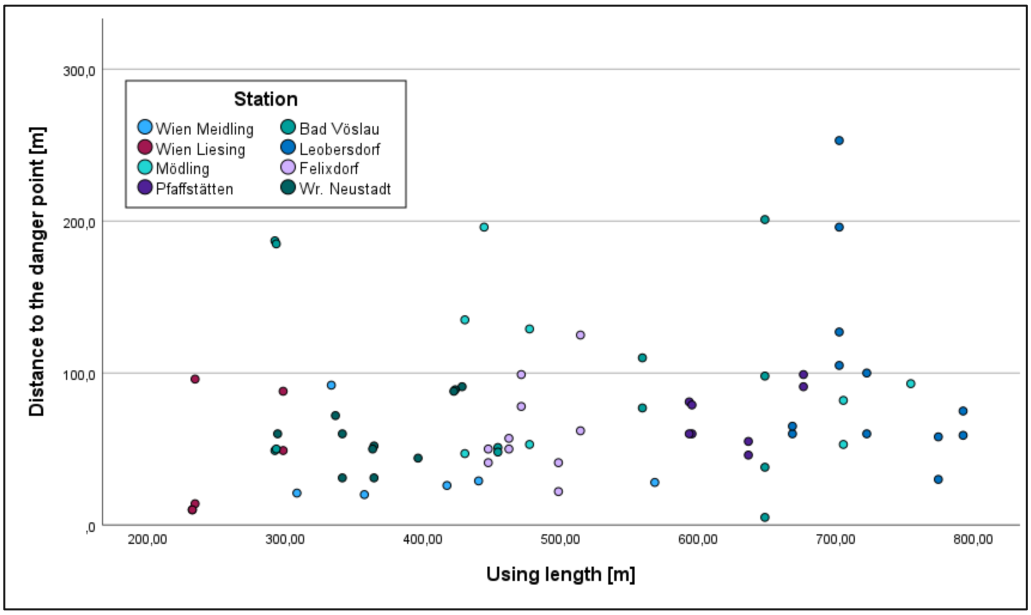

Figure 74: Correlation Using length and distance to the danger point at Südbahn

Source: Own illustration in IBM SPSS Statistics Version 29.0.0.0. based on data from Appendix F (Analysis of the distance to danger point)

Table 19 shows the different model trains, used for further consideration. More detailed information about the rolling stock data can be found in Appendix L (Used rolling stock data).

Table 19: Model trains for the simulation at Südbahn

Source: Table based on described Rolling stock from Appendix L (Used rolling stock data)

Type of train	**Engine**	**Wagons**
Suburban train (ST)	ÖBB 4746	

4.4.1 Overlap comparison Meidling – Mödling

On this line, the effect of different overlaps lengths for a suburban train from Wien Meidling to Mödling is analysed. For the train path the straight track with platforms is used, whereas in Wien Liesing the side track with a platform is used. The duration of the dwell time in each station is 30 s in the simulations. This means that breaking to a standstill is necessary, which also shows the differences in the use of ETCS. For this simulation, a class 4746 EMU is used, which is equipped in one case with PZB and a second time as a train with ETCS. These two types are tested in four possible train following cases. For each of the four cases, the overlap is then completely removed, which means that 0 m is selected. Then the overlap is set to 50 m, which is usual in Austria, and in a third scenario it is set to 200 m. Table 20 shows the four cases with the results of the headway comparison.

Table 20: Headway Comparison Meidling – Mödling

Source: Table based on Results of OpenTrack Version 1.10.3 – Simulation Südbahn

Trains		Headway [s]		
First	**Second**	**0 m**	**50 m**	**200 m**
PZB	PZB	137	156	160
PZB	ETCS	110	136	138
ETCS	PZB	172	185	190
ETCS	ETCS	143	162	166

Beneath the results in the table, Figure 75 shows the investigated cases graphically. The headway with 0 m overlap is shown in red. The overlap of 50 m is shown in blue and the headway with 200 m is shown in green. With two PZB trains, the difference between 200 m and 0 m overlap is 23 s. With two ETCS trains this difference is also 23 s. With a PZB train followed by an ETCS train, this difference increases to 28 s. In the reverse order, the time is reduced to 18 s.

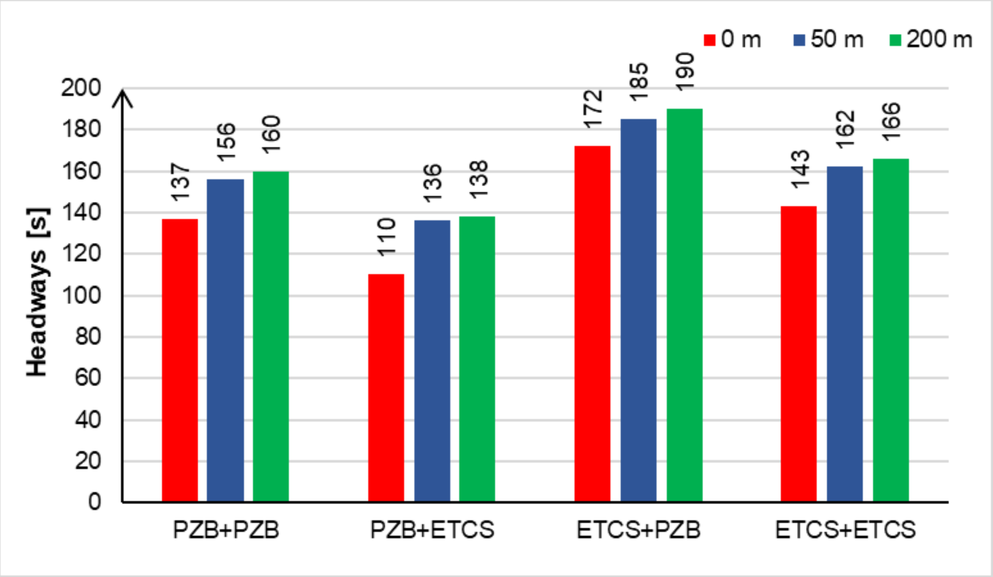

Figure 75: Headway comparison Meidling – Mödling

Source: Own illustration based on the results of the OpenTrack Version 1.10.3 – Simulation Südbahn

The headway shows a direct correlation to the increasing overlaps. At the same time, with ETCS the braking curves lead to a flatter braking curves which increases the headway.

4.4.2 Four-track expansion Meidling – Mödling

Due to the high-capacity utilisation, the Südbahn is classified as congested between Wien Meidling and Mödling (ÖBB Infrastructure AG, 2022a, p. 47). Therefore, it is planned to redesign this section and build a four-track section between Meidling and Mödling. Beneath the existing railway stations, there will be two new stations, the first one Wien Benyastraße and the second Brunn Europaring (ÖBB Infrastructure AG, 2023e, p. 2). The planning documents show that the track layout in the stations will also be changed. In the existing double-track stops, for example, there are side platforms at the edge of each track. Due to the different stopping patterns, the headway times for following trains will increase accordingly if the first train stops at the station. In the extension scenario, the accelerated trains that do not stop at every station use the two outer tracks. The suburban trains with stops at all stations use the inner two tracks, therefore, they can be overtaken without restrictions. There is now an island platform between the two inner tracks at some stations (TEAM IBBS-STOIK-TECTON, 2021). Figure 76 shows an excerpt from the planning documents. It shows a cross-section of the new Brunn Europaring stop. In addition to the four tracks, the island platform between the two inner tracks, which is accessible to passengers via a passenger tunnel, is also recognisable.

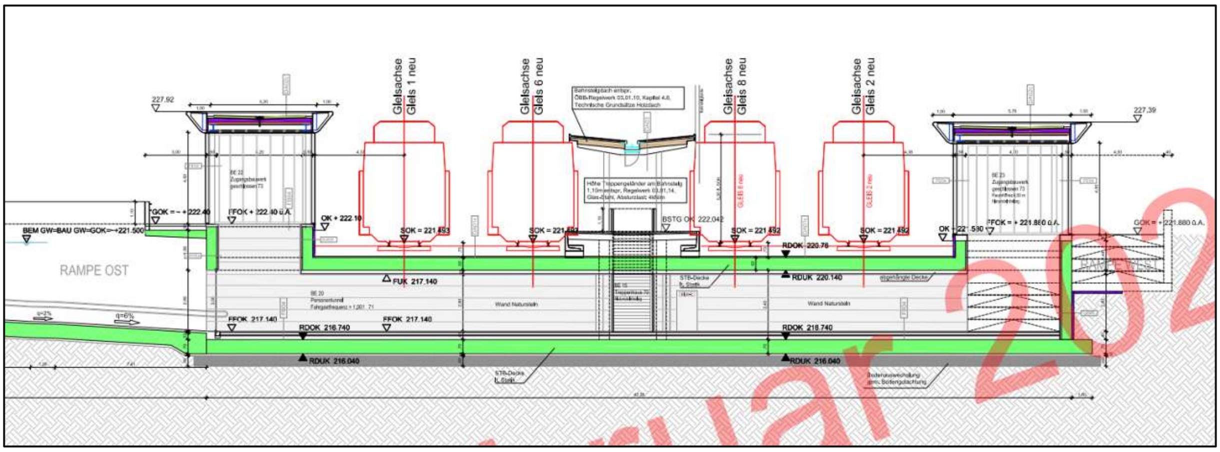

Figure 76: Excerpt of the station Brunn Europaring

Source: Picture formatted and taken from TREUSCH architecture ZT-GMBH (2022)

In addition to the infrastructure measures, it is also planned to equip the line with ETCS (ÖBB Infrastructure AG, 2023f). After the expansion, there should be a suburban train every five minutes between Wien Meidling and Wien Liesing. Between Wien Liesing and Mödling this tact should be ten minutes. Besides the suburban trains, eight local express trains in each direction with more stops and local express trains with lesser stops twice an hour between Wien Meidling and Wiener Neustadt are planned (ÖBB Infrastructure AG, 2023e, p. 5). This requires not only the expansion of the line but also the transfer of existing traffic, such as long-distance traffic, to the Pottendorfer line (Plank & Poimer, 2017, p. 656).

4.5 S-Bahn Vienna

The main suburban railway line in Vienna between Wien Meidling and Wien Floridsdorf is called Stammstrecke. This core section connects with railway lines in Niederösterreich which means that together with suburban trains which are running only within the core section, there are also local trains, which are running from the northern part of Niederösterreich through Vienna to the southern part of Niederösterreich or vice versa (Verkehrsverbund Ost-Region Gesellschaft m.b.H., 2022). As mentioned at the beginning of Chapter 4 (Verification of the approach at Railway junctions), in the past there were also long distance trains using this line to Wien Praterstern and the City Airport Train to Wien Mitte, which is still operated (RailBUSINESS Editorial note, 2017, p. 3). The line is equipped with at least one or two platforms for each direction, with a platform length of 150 m and the train protection system PZB is used on the line (Steindl, 2021, p. 46).

Figure 77 shows the line from Wien Meidling to Wien Floridsdorf, with a yellow frame. It can be also seen how the Stammstrecke is linked with other railway lines in the area. For example, from Wien Meidling, the line is connected to the Südbahn in the southern direction or in Wien Rennweg to Schwechat and the Airport.

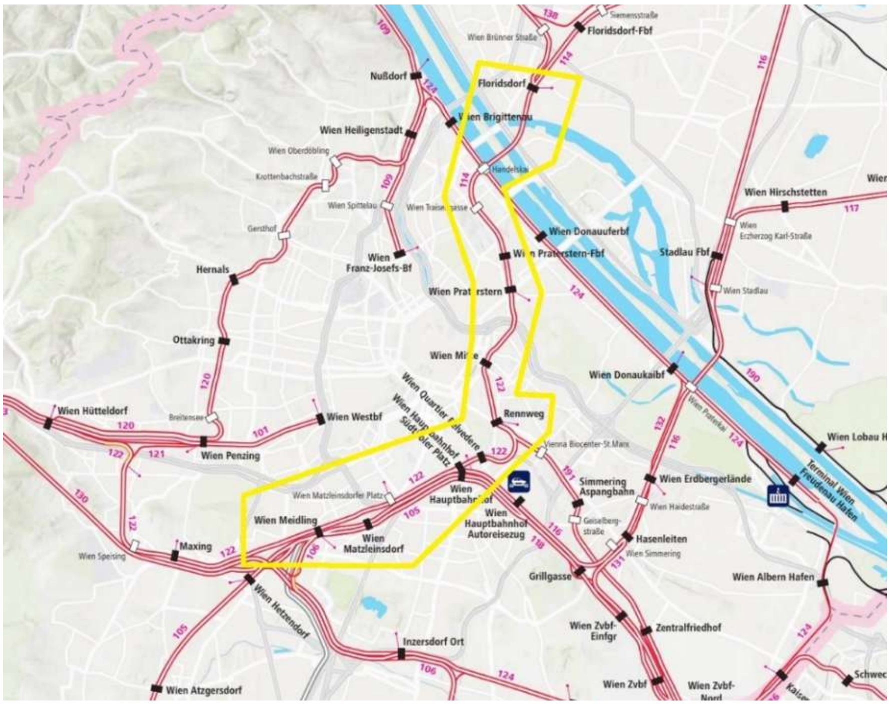

Figure 77: Infrastructure map with S-Bahn Vienna

Source: Picture taken from and marked ÖBB Infrastructure AG (2023d)

Figure 78 shows the correlation between the using length and the distance to the danger point. The results are comparable to the Südbahn. Most of the distances to danger points are within 100 m. The mean is 62.5 m. There is one simple outliner in Wien Mitte and one extreme outliner in Wien Praterstern.

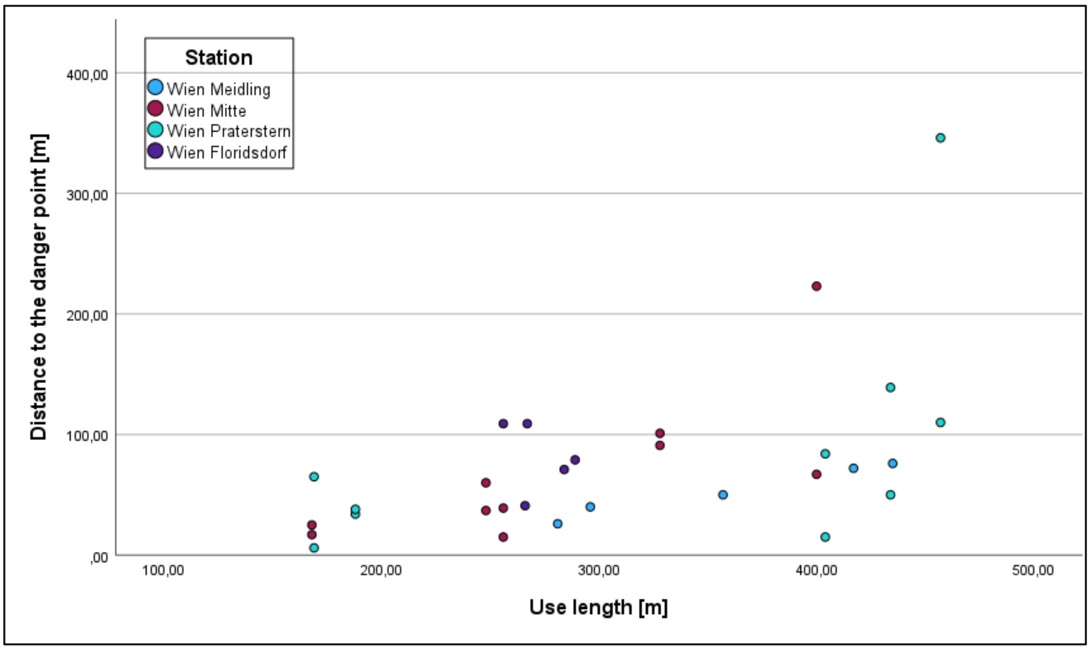

Figure 78: Correlation Using length and distance to the danger point

Source: Own illustration in IBM SPSS Statistics Version 29.0.0.0. based on data from Appendix F (Analysis of the distance to danger point)

Currently, a three-minute headway is possible, although this is not always fully used and there are also longer headways outside rush hour (Steindl, 2021, pp. 46–47). In total, however, over 700 trains run on the core section every day. On weekdays, there is a break in service in the second and third hours of the day. During weekends, the suburban trains are running all night long. Wien Rennweg is chosen to analyse the timetable, as CAT trains as well as local trains and suburban trains in the direction of Schwechat Airport also run here in addition to the traffic between Wien Floridsdorf and Wien Meidling. This makes the section between Wien Mitte and Wien Rennweg the busiest section of this line (ÖBB Personenverkehr AG, 2022b). Figure 79 shows the trains per hour in Wien Rennweg. In Appendix D (Timetable evaluation Stammstrecke) a detailed table for the number of trains can be found.

Figure 79: Trains per hour in Wien Rennweg

Source: Own illustration based on ÖBB Personenverkehr AG (2022b)

The investigation of the S-Bahn in Vienna within this dissertation is based on a study by Wirth, which deals with the implementation of shorter block sections and ETCS and their impact on railway operations. It is shown that shorter blocks in the station areas lead to a smaller headway time of more than 25 s compared to conventional block division and the use of PZB. According to the study, more improvements could be achieved by introducing ETCS Level 3, but this would require additional prerequisites such as TIMS(Wirth & Schöbel, 2020, pp. 25–26).

In the following two examples, the adapted version of the simulation is used. Therefore, the version with ETCS Level 2 is used and applied. In this version, the shortened block sections in the station areas can also be found.

Like in the investigation of the Südbahn, also in this one a Siemens Desiro ML is used. Table 19 shows the model train, used for further considerations. More detailed information about the rolling stock data can be found in Appendix L (Used rolling stock data).

Table 21: Model trains for the simulation at Stammstrecke

Source: Table based on described Rolling stock from Appendix L (Used rolling stock data)

Type of train	**Engine**	**Wagons**
Suburban train (ST)	ÖBB 4746	

4.5.1 Stopping pattern

Looking at the alignment and the different stops along the line, two short distances between stops are noticeable. The first short section is between Wien Südtirolerplatz (Main Station) and the Quartier Belvedere, where the distance is around 500 m. The second short section is between Wien Traisengasse and Wien Handelskai. The distance between the two stops there is around 800 m. It would therefore be conceivable to relocate stations. This subchapter will analyze whether this would improve headway times in this specific case. As the station Südtirolerplatz is located at the Main Station, it is not conceivable to relocate the stop there. As in the first example, the relocation of these two stops is also a rather theoretical example. Neither the actual transport needs of the passengers nor the transfer connections are considered. The Wien Handelskai stop is a transfer point to metro line U6 and the starting point for the suburban railway line S45 (Verkehrsverbund Ost-Region Gesellschaft m.b.H., 2022). However, the second example will be analyzed. The fictive station Allerheiligenpark is located between the Wien Traisengasse and Wien Handelskai, which is why a newly planned station is also called like this (Stadt Wien, 2023). The Allerheiligenpark station is 400 m away from the existing stations.

For analysing the effects of this adjustment, eight different train sequences are considered. A train route is created from Wien Meidling to Wien Floridsdorf. Here, two trains with this route follow each other. In one case, a 30-second dwell time and in the other a 60 s dwell time is applied at the stations. The same is repeated with a route from Wien Mitte to Wien Floridsdorf. Here too, a distinction is made between 30 and 60 s stops. All cases are simulated with the existing stops and the headways are calculated. The Allerheiligenpark station is then created, and the trains no longer stop at Wien Traisengasse and Wien Handelskai.

Figure 80 shows the time-distance diagram for all variants. The two first trains are running from Wien Mitte to Wien Floridsdorf with a dwell time of 30 s. The first one has stops in the existing stations. The second one has only a stop in Allerheiligenpark. The following trains run from Wien Meidling to Wien Floridsdorf; the first one stops in Wien Traisengasse and Wien

Handelskai, the second one only in Wien Allerheiligenpark. The same sequence is repeated with the same train orders, but with a dwell time of 60 s.

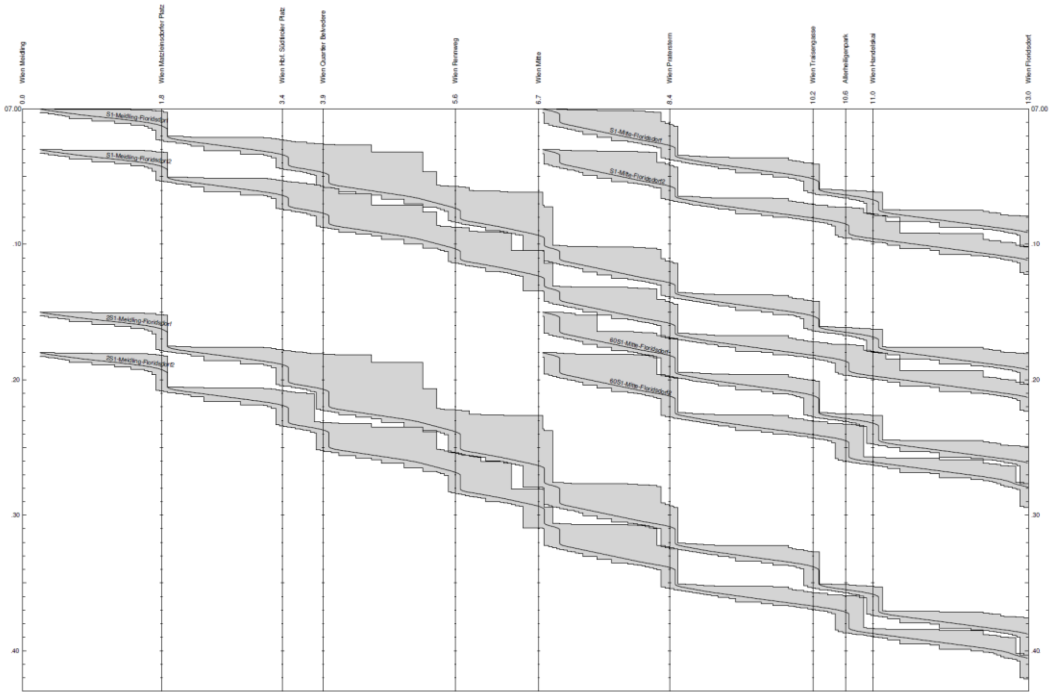

Figure 80: Time-distance diagram with and without station Allerheiligenpark

Source: Own illustration in OpenTrack Version 1.10.3 – Simulation S-Bahn Vienna

It can be shown that the different stopping patterns don’t affect the headway time. As it can be seen in Table 22, the headway for the trains running from Wien Meidling to Wien Floridsdorf is identical. The headways from Wien Mitte to Wien Floridsdorf also have no significant difference. Here only a delta of 1 s exists. These results, in combination with the time-distance diagram, show that the headway is determined in the section between Wien Meidling and Wien Mitte.

Table 22: Headway times with different stopping pattern

Source: Table based on Results of OpenTrack Version 1.10.3 – Simulation S-Bahn Vienna

	Stop in Traisengasse und Handelskai		only Allerheiligenpark	
Dwell time [s]	30	60	30	60
Headway [s] Mi to F	132	192	132	192
Headway [s] Hz to F	94	124	93	123

4.5.2 Four-track section Wien Rennweg – Wien Mitte

As described above, the area between Wien Meidling and Wien Mitte is mainly responsible for the headway. The next example therefore looks at the area between Wien Rennweg and Wien Mitte, which, as described at the beginning, is the most utilized section of the route. The fact that the CAT passes through Wien Rennweg without stopping and starts or ends in Wien Mitte is a particularly interesting point of investigation. The branching off to the route to the airport is on the south side after the station Wien Rennweg. The existing infrastructure is shown in the upper section of Figure 81.

Based on this, a four-track section will be built between the two stations. This will connect the four tracks after the Wien Rennweg station with the four station tracks in Wien Mitte. The arrangement of the turnouts will only be supplemented so that the transition between the individual track connections is possible. The two turnout connections that originally existed for the two lower tracks were kept. This means that it is still possible for the CAT to move up one track from the bottom track, as this is where the platform for the CAT runs in Wien Mitte. These connections are shown at the bottom of Figure 81.

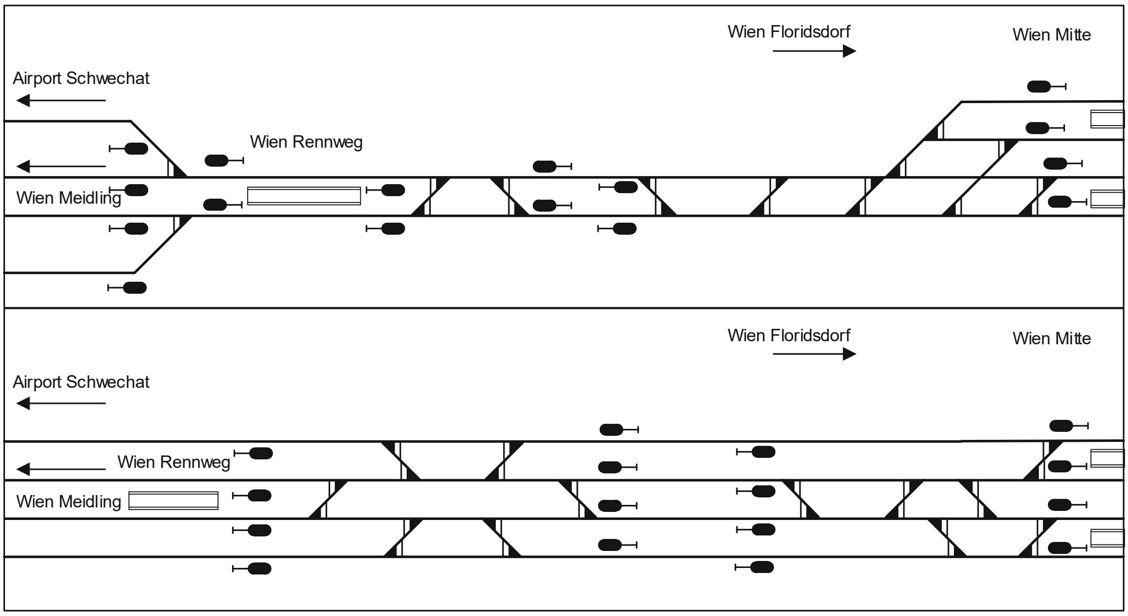

Figure 81: Existing and adapted track layout between Wien Rennweg and Wien Mitte

Source: Own sketch in MS Visio. Upper part based on Wirth (2019)

Table 23 shows the different model trains used for the investigations of the four-track section. More detailed information about the rolling stock data can be found in Appendix L (Used rolling stock data).

Table 23: Model trains for the four-track section at Stammstrecke

Source: Table based on described Rolling stock from Appendix L (Used rolling stock data)

Type of train	Engine	Wagons
Suburban train (ST)	ÖBB 4746	
City Airport Train (CAT)	ÖBB 1016	3 *Bmpz-dl + Bmpz-ds (150t 81m)

Different sequences are formed with these two different model trains. A CAT which runs from the Airport in the direction of Wien Mitte and changes to the second track from below after Wien Rennweg. An S7, which runs from the airport in the direction of Wien Floridsdorf, which remains on the bottom track. And an S1 from Wien Meidling to Wien Floridsdorf, which changes to the bottom track after Wien Rennweg. Nine different train sequences can be built from these three trains. It can be shown that the four-track section does not have an effect in all cases and even leads to a wors headway in some cases. The results can be seen in Table 24. For example, there is no significant difference between the two CAT trains, as the difference is only one second. The situation is similar with an S7 following a CAT, where the train headway can be reduced by four seconds. However, this is a marginal difference. Especially in situations where routes cross each other, the headway times increase. For example, in the case of a CAT following an S1, the headway time is extended by 161 s compared to the original variant. The headway is also increased if a CAT follows a S7 or a S1. In all other cases, the four-track system shortens the headway times by up to 120 s.

Table 24: Headway comparison four-track section

Source: Table based on Results of OpenTrack Version 1.10.3 – Simulation S-Bahn Vienna

First	Second	Origin [s]	Adapted [s]	Delta [s]
CAT	CAT	348	347	1
CAT	S7	62	58	4
CAT	S1	51	212	-161
S7	CAT	127	195	-68
S7	S7	244	124	120
S7	S1	244	165	79
S1	CAT	136	182	-46
S1	S7	244	195	49
S1	S1	244	138	106

This study shows that certain situations lead to an improvement in the headway, but if routes cross each other, this leads to a higher headway. However, it should be noted that the four-track section can also have an impact on the robustness of the timetable. It can also have an impact on availability, for example in the event of turnout failures.

There could be also variants in which the route to the Airport is integrated level-free. As a result, routes between S1 trains and those from the Airport would no longer cross. However, as with the variant shown above, it would no longer be possible for the station Wien Rennweg to be operated with just one platform. This consideration can be seen in Figure 83.

Like in the example of Allerheiligenpark, it should be noted that this is a fictive example, in which performance was analyzed based only on operational considerations. No requirements or traffic flows are analysed.

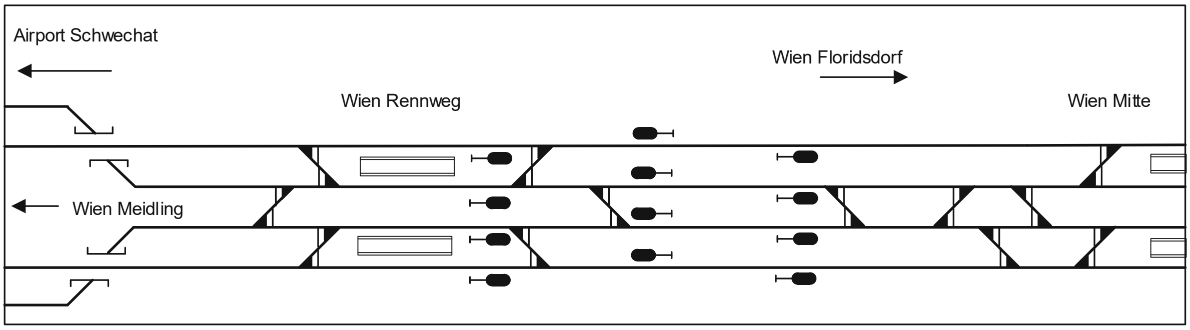

Figure 82: Proposal for an adapted track layout between Wien Rennweg and Wien Mitte

Source: Own visualization in MS Visio based on OpenTrack Simulation – S-Bahn Vienna

4.5.3 Adaption of the S-Bahn

In practice, a modernization of the line between Wien Meidling and Wien Floridsdorf is planned. The aim is to increase the number of trains up to 900 per day. As with the other practical examples, various measures are required to achieve this target. On the infrastructure side, the platforms in the existing stations will be extended to 220 m to allow longer trains for more passengers. In addition, extra capacity for rolling stock will be created (RailBUSINESS Editorial note, 2020, p. 38). Regarding the rolling stock, the aim is to ensure homogeneous driving behaviour, with the entrance areas also being optimized for passenger changes. In addition, the vehicles will be equipped with ETCS Baseline 3 On-Board Unit (Steindl, 2021, pp. 46–47). ETCS Level 2 only will be used as a train protection system. This will require two RBCs and the existing interlockings will be converted to electronic interlockings or adapted if electronic interlockings are already in place. In addition, virtual subsections will be used to get train headways of 2.5 min. The implementation is planned for December 2027 (Begic, 2023, pp. 7–14).

4.6 Fictive railway node A2

The basis for this simulation is the Research Project NITOB (Sustainable intermodal transport chains through optimization of rail operations) from the Carl Ritter von Ghega Institute. Part of this project was to create a simulation environment and simulate typical passenger and freight traffic. For this purpose, two lines are created. A double-track line and a single-track line are both connected. This connection is in the so-called railway node A2. This station itself is roughly similar in its structure to the railway station Brenner/Brennero at the border between Austria and Italy. Although this station has the function of a node in the model, the track configuration has also been simplified (Anderluh et al., 2023, pp. 34–48). Figure 83 shows the layout of the station with optical adaptions for this work.

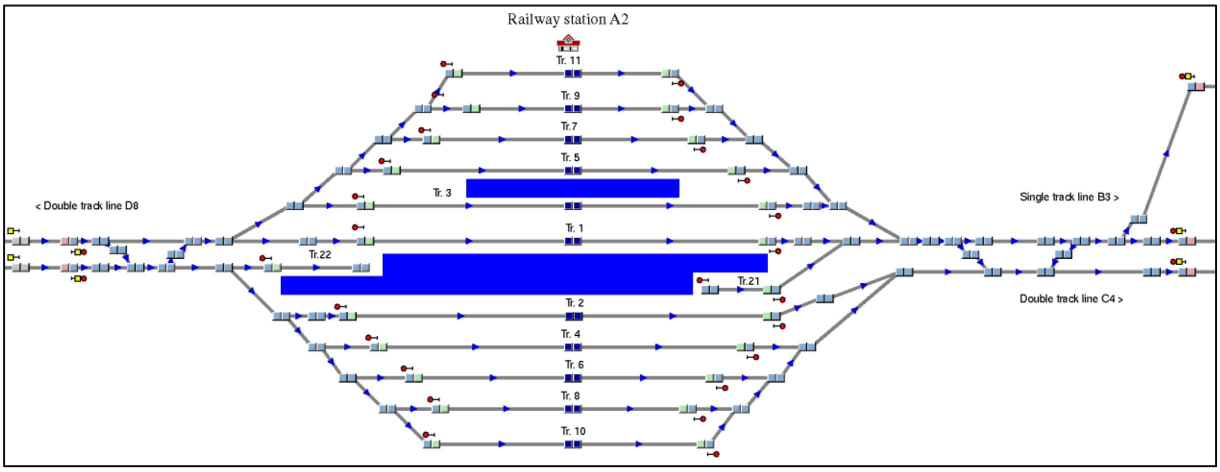

Figure 83: Track characteristic railway station A2

Source: Picture taken from OpenTrack Version 1.10.3 – Simulation Fictive railway node A2

For the NITOB project, a tact timetable is created with long-distance, local, suburban and freight trains. The timetable is oriented towards railway node A2, where long-distance trains stop on the double-track line on the hour. Local trains stop at junction A2 in both directions every half hour. Suburban trains are also scheduled as feeder and distribution trains to the long-distance and local trains. On the single-track line, there is also one long-distance train and one local train per direction and hour. There is also a local train every half an hour at the railway node A2 in both directions. Further freight trains are scheduled based on this timetable. A detailed analysis of the simulations and line tact maps can be found in a publication (Wagner et al., 2023, p. 164).

The NITOB project showed that further investigations are necessary for node A2, which will be carried out in this dissertation (Anderluh et al., 2023, pp. 54–55).

With the existing timetable the station is crowded and there is a bottleneck in the eastern area of the station. In this work the described bottleneck will be investigated in detail and possible solutions to improve the situation are described. To identify the areas with higher occupation the platform occupation of the existing timetable gives a first overview of the trains, which are running in the station. Figure 84 shows the station-occupation diagram in the period from 08:00 to 09:00.

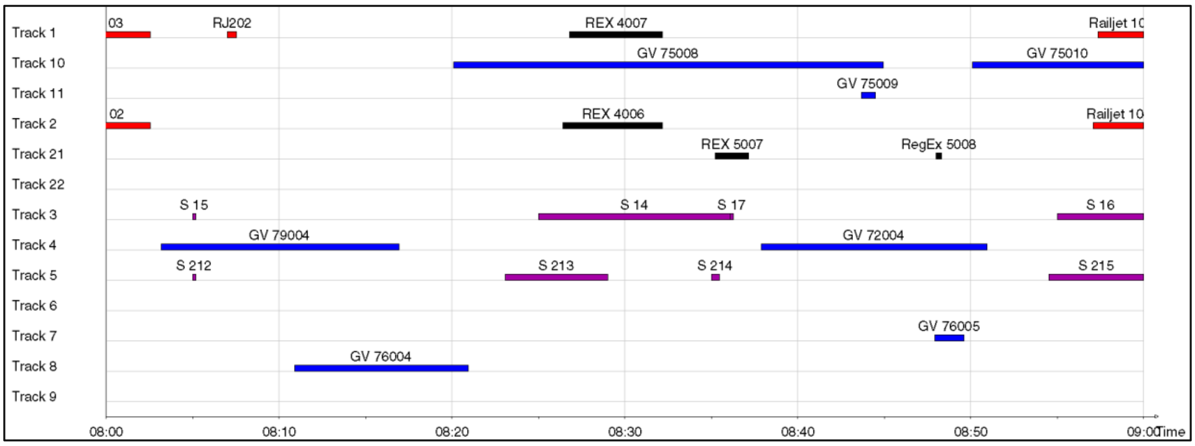

Figure 84: Platform occupation.

Source: Picture taken from OpenTrack Version 1.10.3 – Simulation Fictive railway node A2

An analysis of these trains and their entering and exiting routes shows that the main traffic load is handled by tracks 1, 3 and 5. followed by 2 and 21. This context is illustrated in an occupation diagram shown in Figure 85.

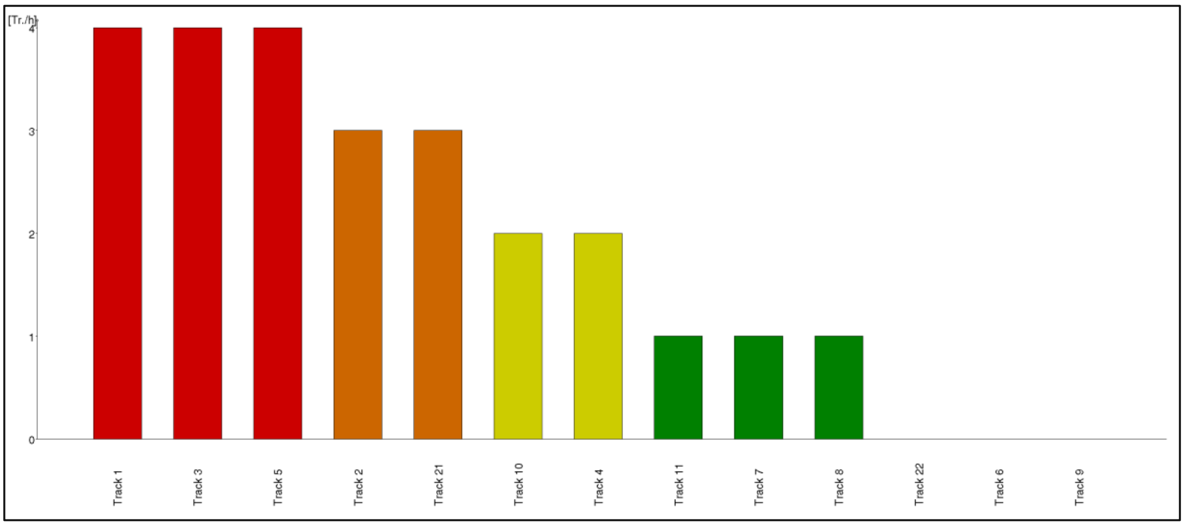

Figure 85: Track occupation in station A2.

Source: Picture taken from OpenTrack Version 1.10.3 – Simulation Fictive railway node A2

These occupations and the fact that the turnout to the single-track is embedded in track 1 make it necessary to investigate how the trains are entering and leaving the station. From the right side, trains from the station C4 are entering A2 and can run further to the station D8 following the station A2 on the double-track line.

Train movements

Figure 86 shows the track layout with the turnout area at the upper track, which is used from every train from and to the single-track line. In the second part of the figure, the routes of the different trains which are used in NITOB are shown. There are also trains that are not shown in the illustration. The suburban trains from A2 to C4 are not considered, as they do not run via the turnout to the single-track line, but change to the lower track before.

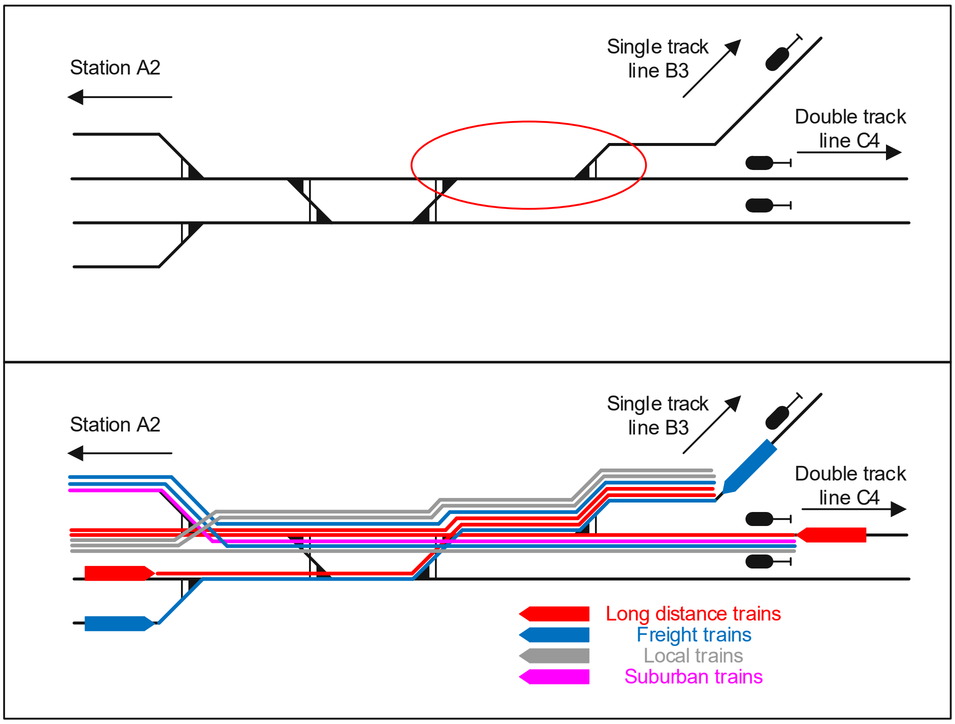

Figure 86: Train movements over turnout area

Source: Own sketch in MS Visio based on OpenTrack Simulation – Fictive railway node A2

It can be summarized that ten different trains can be found in the investigated environment:

- Regional train from double-track to single-track line (REX DT ST),
- Regional train from single-track to double-track line (REX ST DT),
- Regional train from C4 to D8 (REX DT DT),
- Suburban train from C4 to A2 (S-Bahn DT A2),
- Long-distance train from double-track to single-track line (RJ DT ST),
- Long-distance train from single-track to double-track (RJ ST DT),
- Long-distance train from C4 to D8 (RJ DT DT),
- Freight train double-track to single-track (FT DT ST),
- Freight train single-track to double-track (FT ST-DT),
- Freight train C4 to D8 (FT DT DT).

Now different variants are investigated to see how the running time and the headway of the trains can be affected. The basis for the investigations is the existing layout, which will be used to compare any changes. For this purpose, every train type, will be used. Figure 87 shows the different simulated trains.

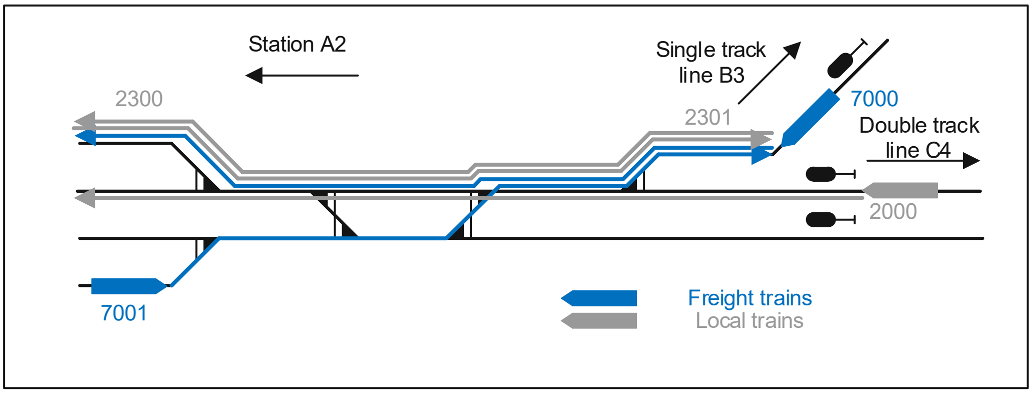

Figure 87: Simulated trains

Source: Own sketch in MS Visio based on OpenTrack Simulation – Fictive railway node A2

Table 25 shows the different model trains used for the investigations of the four-track section. More detailed information about the rolling stock data can be found in Appendix L (Used rolling stock data).

Table 25: Model trains for the railway node A2

Source: Table based on described Rolling stock from Appendix L (Used rolling stock data)

Type of train	**Engine**	**Wagons**
Suburban train (ST)	ÖBB 4744	
Freight train (FT)	ÖBB 1293	15*90t (15* Wagon type Zacns)

For the investigation the following variants are simulated:

- Variant 0: Existing layout,
- Variant 1: ETCS Level 2,
- Variant 2: ETCS Level 2 with track speed,
- Variant 3: ETCS Level 2 with track speed and max block length of 200 m,
- Variant 4: ETCS Level 3 Moving block with a safety margin of 50 m.

Some of the cases described above were selected for calculation using the headway calculator. Table 26 & 27 show the results of the investigation, whereby the tested scenarios with a first and second train are shown in the different variants. The headway is shown in seconds. For some of the possible train constellations mentioned above, no results can be obtained with the headway calculator. Therefore, the two tables contain those that are plausible and relevant. The complete tables can be found in Appendix K (Raw data fictive railway node A2).

Table 26: Headway Comparison Fictive railway node A2 part one

Source: Table based on Results of OpenTrack Version 1.10.3 – Simulation Fictive railway node A2

First train	2000	2000	2000	2300	2300	2301	2301
Second train	2000	2301	7000	2301	7000	2301	7001
0 Base Variant	266	127	127	192	125	391	391
1 ETCS	255	126	122	192	137	391	391
2 ETCS Track Speed	255	94	113	126	105	209	209
3 ETCS 200 m Block	255	94	68	126	53	152	77
4 ETCS Moving Block	96	85	34	119	18	81	35

Table 27: Headway Comparison Fictive railway node A2 part two

Source: Table based on Results of OpenTrack Version 1.10.3 – Simulation Fictive railway node A2

First train	7000	7000	7000	7000	7000	7001	7001
Second train	2000	2300	2301	7000	7001	2301	7001
0 Base Variant	142	292	212	828	204	444	444
1 ETCS	142	291	212	857	204	440	440
2 ETCS Track Speed	117	245	154	792	178	311	311
3 ETCS 200 m Block	49	162	154	678	88	110	121
4 ETCS Moving Block	13	133	147	663	71	61	79

Figure 88 shows the results of the investigation in a diagram. This diagram shows that the headway decreases in all cases with shorter block sections and with the ETCS Moving Block variant. However, there are also examples in which the difference is smaller, for example, two freight trains with the train number 7000 following each other. As in the Sesvete node, this example shows that with shorter block-distances the headway tends to the value of the moving block. In addition, it can also be seen that the change by applying the track speed up to the turnouts only brings an improvement in those cases, in which turnouts are also used in the diverging way. Furthermore, in some cases it can be seen that the use of ETCS without further adjustments leads to a worse headway, compared to the Base Variant with PZB. This is clearly recognizable with freight trains following each other with train number 7000. The flatter braking curves, therefore, have a visible effect on the headway times here. However, it can also be shown that, despite the braking curves, a reduction in headway times is achieved compared to the original variant, if the line speed is allowed to run to the turnout areas.

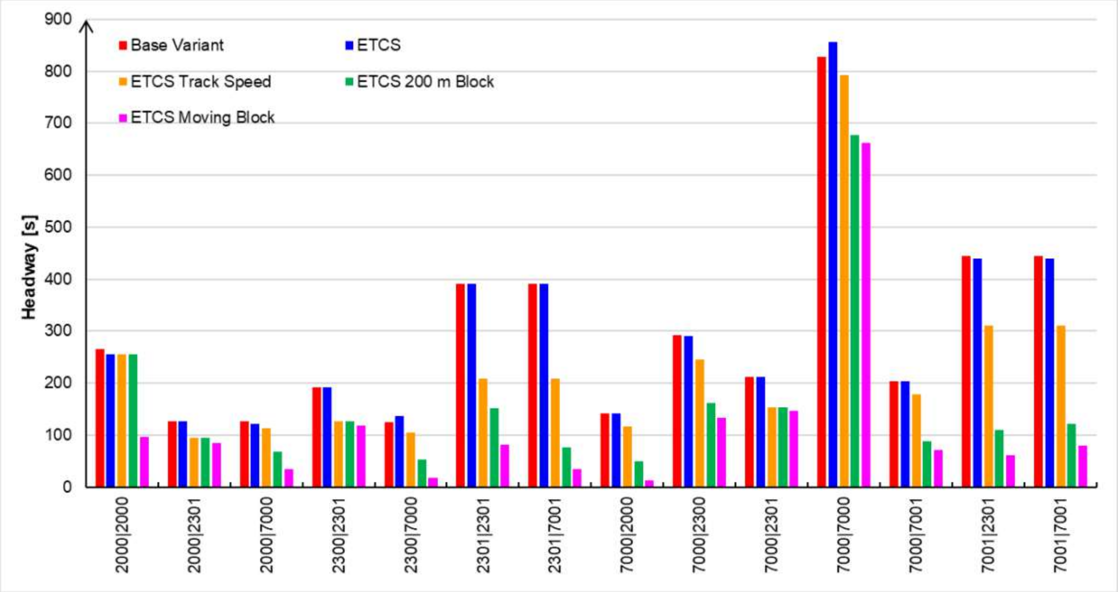

Figure 88: Comparison of headways on the Fictive railway node A2

Source: Own illustration based results from OpenTrack Version 1.10.3 – Simulation Fictive railway node A2

5 Results of the simulations

The simulations and results carried out in the previous chapter are furtherly analyzed and presented here. The aim is to illustrate the changes resulting from the modifications. A quantification of the results allows an assessment of the effectiveness of the respective measure. When analyzing the simulations, however, not all implemented changes can be considered, or not in a common form. For this reason, only the simulation of the fictive railway node A2 and the Sesvete node are shown in combination. The other lines are shown separately. Where possible, changes are shown as a percentage of the standard value measured before their implementation. This can be, for example, a train sequence with two trains with PZB following each other. Their headway is displayed as 100% and variants are calculated thereon. Thus, as in the case of railway node Sesvete and the fictitious railway node A2, two different railway lines can be compared with each other.

Fictive railway line

Different train protection systems are tested on the fictive railway line. A distinction is made between trains with PZB, ETCS and ETCS+TIMS. Trains with PZB can only clear the physical blocks and only release them again after leaving. Trains with ETCS can use the virtual blocks in front of the train, but they can only release the entire physical block. Trains with ETCS+TIMS use virtual blocks and release them individually. This relationship can also be seen when looking at the headway as shown in Table 6. This already shows that seven of the nine measured values are close together. This becomes even clearer in the visualization according to percentage deviations, as in Figure 89. In relation to the base variant, where two trains with PZB are analyzed, this value remains unchanged in two further cases. These are the cases in which the second train is with PZB and only runs with line-side signals. In four cases, there is just a slight not significant deviation of 3% if the second train has ETCS. Two cases where the advantage of ETCS Level 3 Hybrid has a higher effect is when a train with ETCS follows a train with ETCS+TIMS. Likewise, when two trains with such equipment follow each other, all system advantages can be used and there is a significant reduction in headway until 39% of the original variant.

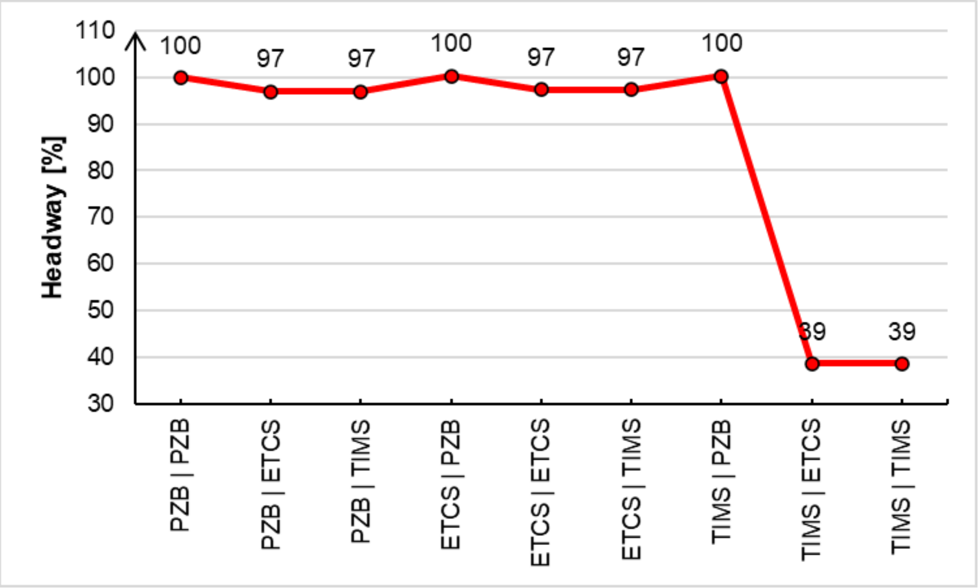

Figure 89: Percentual comparison of headways at fictive railway line

Source: Own illustration based on the results of OpenTrack Version 1.10.3 – Simulation Fictive railway line

Salzburger Lokalbahn

The study of the Salzburger Lokalbahn shows how the headway times of ETCS Level 2 and Level 3 Moving Block differ. If the second train is a train with ETCS Level 2, then it makes no difference whether the first train is equipped with ETCS Level 2 or Level 3: the headway remains unchanged at 261 s. This value is used as a comparison value and is regarded as 100%. If a Level 2 train is followed by a Level 3 train, the headway is already reduced by 46-54% of the initial value. With two trains operated with moving blocks, a headway of only 27% of the original value can be achieved. These correlations are shown in Figure 90.

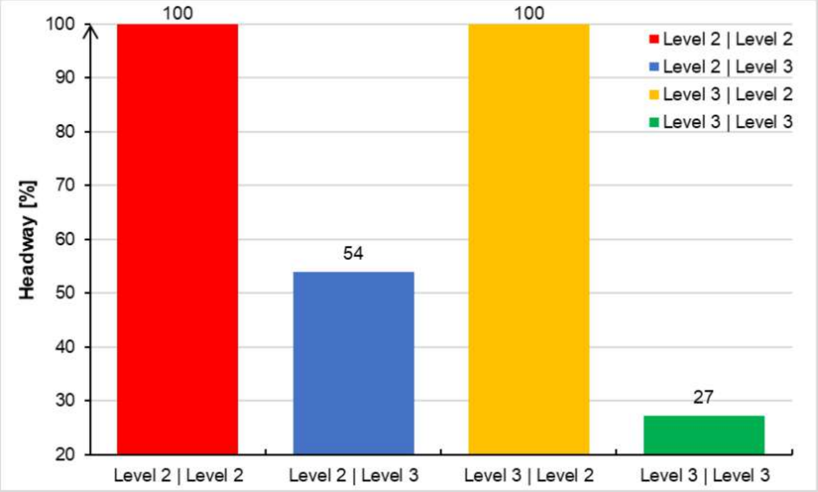

Figure 90: Percentual comparison of headways at Salzburger Lokalbahn

Source: Own illustration based on the results of OpenTrack Version 1.10.3 – Simulation Salzburger Lokalbahn

However, shortening the headway time with the ETCS Level 3 Moving Block does not lead to a practical increase in capacity, as the crossings on the single-track line no longer take place at the existing crossing stations. The second aspect of this investigation is the use of overlaps and flatter braking curves with ETCS. It is shown that using the line speed up to the start of the turnout can save 49 s of journey time, which compensates for the lost time due to a flatter braking curve.

Südbahn

In this scenario, the effect of changing the overlap is analyzed. In addition to varying the overlap, the train protection system is also changed. However, the reference value in this case is not the PZB train. For this study, the comparison is based on the 0 m overlap, which corresponds to 100% headway for all train sequences. Based on this, the change at 50 m and 200 m is analyzed. The results can be seen in Figure 91.

Several aspects are visible in this. Train sequences with different train protection systems, i.e. PZB and ETCS or vice-versa, differ significantly from each other. For example, the increase in the case of an ETCS followed by a PZB train is only 8% at 50 m, which is significantly lower than for a PZB train followed by an ETCS train. The latter shows an increase of 24%. With the same train protection systems for both trains, the increases differ by only one percentage and are 13% (ETCS) and 14% (PZB). The increase in the headway from 50 to 200 m is significantly lower than from 0 to 50 m. The difference between 50 and 200 m is 1-3% only. The use of different overlaps has an effect on both train protection systems.

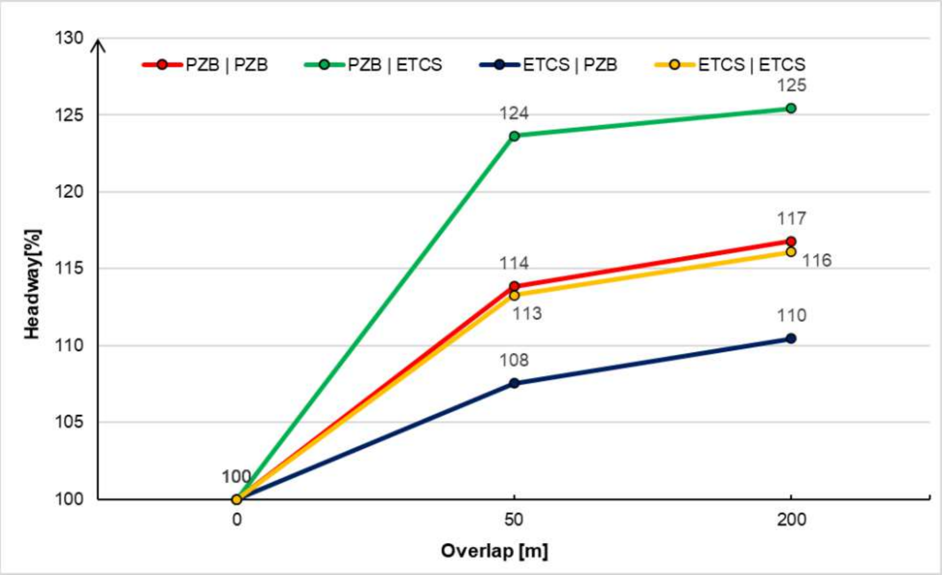

Figure 91: Percentual comparison of headways with different overlaps

Source: Own illustration based on the results of OpenTrack Version 1.10.3 – Simulation Südbahn

S-Bahn Vienna

The effect of the four-track section on the Wien Rennweg - Wien Mitte section of the Vienna S-Bahn is analysed. As can be seen in Figure 92, there are no standardised results, but these depend on the respective train sequence. As discussed in the detailed description, routes that cross each other in the 4-track section result in a higher headway. This occurs significantly with a CAT followed by an S1, an S7 followed by a CAT and an S1 followed by an S7. Significant shortening is recognisable with an S7 followed by an S7, an S7 followed by an S1, an S1 followed by an S7 and an S1 followed by an S1. Although there are differences in the other train sequences, these differences are only marginal. It should be noted that, unlike the other diagrams in this chapter, this illustration contains the headway in seconds. In the other examples, this is shown in %.

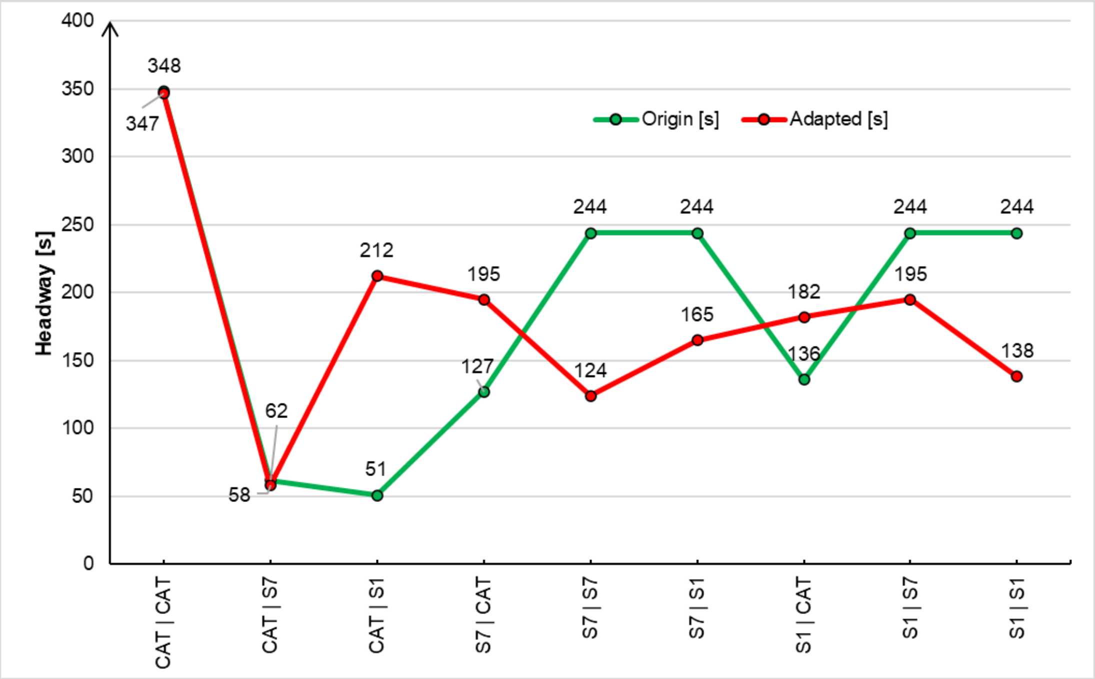

Figure 92: Headway comparison double-track and four-track section in seconds
Source: Own illustration based on the results of OpenTrack Version 1.10.3 – Simulation S-Bahn Vienna

Sesvete and railway node A2

As described, the railway node Sesvete and the fictive railway node A2 are analysed together because the same measures are applied (Figure 93). In the case of Sesvete, in the base variant, the infrastructure has already been adapted to a comparable level. Besides this, the length of the shorter block sections differs, with a 500 m block being used in the Sesvete node and 200 m blocks in the fictive railway node A2. This parameter is therefore only comparable to a limited extent. In general, however, based on the original variant, the headway with ETCS Level 2 remains the same without further measures or even increases by 3% at the Sesvete node. In the other variants, the headway then falls in both simulation environments. The variant with the shorter blocks is of interest here. The headway for node A2 decreases to 52% of the initial value and for node Sesvete to 67% of the initial value. This clearly shows that the headways are converging towards the moving block.

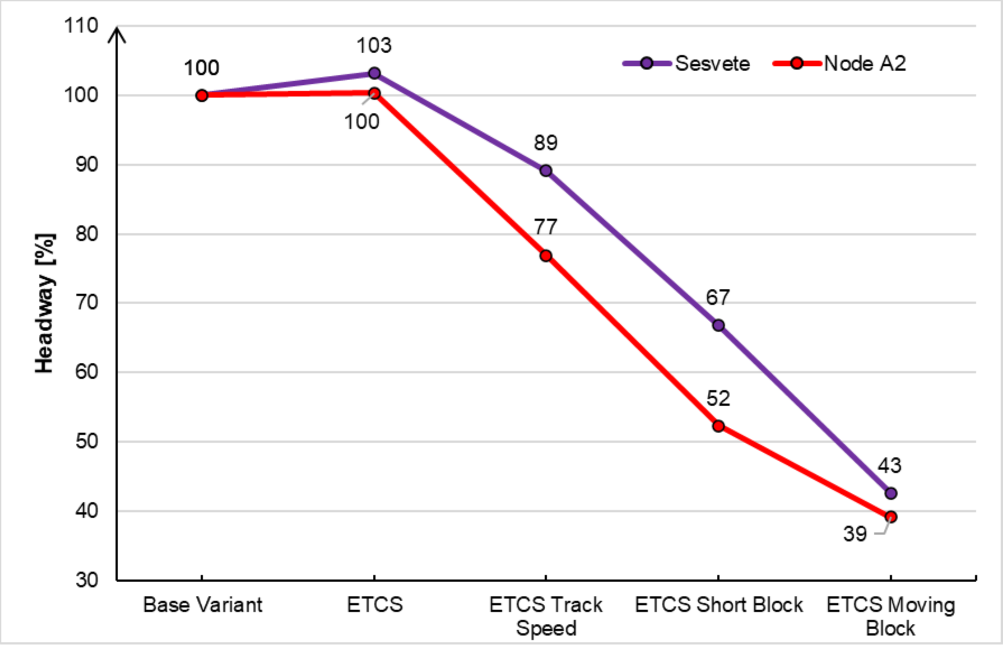

Figure 93: Percentual comparison of headways at node Sesvete and A2

Source: Own illustration based on the results of OpenTrack Version 1.10.3 – Simulation Fictive railway node A2

5.1 Overview of the results

Based on the results described above, an overview scheme is shown in Table 28, which covers all simulation scenarios. Beneath the parameters of the model, there is a description of the used measurements. The headway in the base variant is always referred to as 100% Based on this, the determined headway of certain variants is taken and shown in percentage of the base variant. All percentage values are rounded without decimal place. From this value, the largest difference is determined. At the Salzburger Lokalbahn, the simulations are grouped as two independent comparisons. The same is done at the S-Bahn Vienna, because there are also no connected scenarios. The railway node Sesvete is different, because in this simulation more infrastructure adaptions are done. For this purpose, a second column of Headway in percentage and the largest differences is invented. In the first headway column, the infrastructure layout before the adaptation is not taken into account, to allow a comparison with the Fictive railway node. In the second column, this variant is taken into consideration and every used measure is compared with the old infrastructure layout. Therefore, there are two columns for the largest differences.

Table 28: Overview of the simulation results

Source: Table based on the results and parameters of the OpenTrack simulation

Nr	Model	Region			Tracks	Traffic in Simulations	Measurement	Headway %	considering all adaptions [%]	**Largest difference [%]**	**considering all adaptions [%]**
		Austria	Croatia	Fictive							
1	Fictive railway line			X	Single	Passenger	Base Variant with PZBtrains	100	|	|	|
2	Fictive railway line			X	Single	Passenger	ETCS Level 3 Hybrid (Virtual blocks)	39	|	**61**	|
3	Salzburger Lokalbahn	X			Single	Passenger	Base Variant ETCS Level 2	100	|	|	|
4	Salzburger Lokalbahn	X			Single	Passenger	Moving Block One Direction ETCS Level 3	27	|	**73**	|
5	Salzburger Lokalbahn	X			Single	Passenger	Without Overlap	100	|	|	|
6	Salzburger Lokalbahn	X			Single	Passenger	Overlap analysis (Flatter ETCS braking curve not considered)	87	|	**13**	|
7	Railway node Sesvete		X		Double	Mixed	Without Infrastructure adaption	100	100	|	|
8	Railway node Sesvete		X		Double	Mixed	Infrastructure adaption	76	76	|	|
9	Railway node Sesvete		X		Double	Mixed	Base Variant (Infrastructure adaption)	100	76	|	|
10	Railway node Sesvete		X		Double	Mixed	ETCS Level 2	103	78	|	|
11	Railway node Sesvete		X		Double	Mixed	ETCS Level 2 with track speed	89	68	|	|
12	Railway node Sesvete		X		Double	Mixed	ETCS Level 2 with shorter blocks	67	51	|	|
13	Railway node Sesvete		X		Double	Mixed	ETCS Level 3	43	33	**57**	**67**
14	Südbahn	X			Double	Passenger	Overlap 0m	100	|	**17**	|
15	Südbahn	X			Double	Passenger	Overlap 50m	115	|	|	|
16	Südbahn	X			Double	Passenger	Overlap 200m	117	|	|	|
17	S-Bahn Vienna	X			Double	Passenger	Existing stopping pattern	100	|	|	|
18	S-Bahn Vienna	X			Double	Passenger	New station Allerheiligenpark	100	|	**0**	|
19	S-Bahn Vienna	X			Double	Passenger	Double-track section	100	|	|	|
20	S-Bahn Vienna	X			Four-tra	Passenger	Four-track expansion	95	|	**5**	|
21	Fictive railway node			X	Double	Mixed	Base Variant	100	|	|	|
22	Fictive railway node			X	Double	Mixed	ETCS Level 2	100	|	|	|
23	Fictive railway node			X	Double	Mixed	ETCS Level 2 with track speed	77	|	|	|
24	Fictive railway node			X	Double	Mixed	ETCS Level 2 with shorter blocks	52	|	|	|
25	Fictive railway node			X	Double	Mixed	ETCS Level 3	39	|	**61**	|

5.2 SWOT Analysis

The various analyses have shown that each variant has advantages and disadvantages. For this reason, a SWOT analysis should be carried out. SWOT analyses are a management tool that were first used in the 1960s to strategically evaluate various projects. Whereby the internal and external environment is also assessed (Phadermrod et al., 2019, pp. 1–2). The main component is the recording of strengths, weaknesses, opportunities, and threats in a matrix (Helms & Nixon, 2010, pp. 215–218). Based on this matrix, the relationship between the individual factors is analyzed. This is done on one hand from the perspective of the positive areas, i.e. the strengths, and a second time from the perspective of the negative areas, i.e. the weaknesses. For this purpose, the correlations between strengths and opportunities are created to find out how these two can be used. The strengths and threats are also analyzed together to find out how the strengths can be used to deal with the threats. In addition, the weaknesses and opportunities are analyzed to see what makes it difficult to exploit the opportunities. It also looks at how the weaknesses can lead to threats (Künzli, 2012, pp. 127–128).

As part of the analysis presented here, the measures used in the dissertation are considered. In summary, these are the use of ETCS Level 2, track speed up to the start of the turnout, shorter block sections, ETCS Level 3 and the variation of overlaps. The SWOT parameters for each of these measures are combined in a matrix, which can be seen in Chapter 5.2.1 (Basis for SWOT Analysis). Based on this consideration the measures used in the railway node Sesvete and the fictive railway node A2 are combined in a matrix. Table 34 shows the strengths, weaknesses, opportunities and threats of the described measures. Based on this characteristic there will be an analysis after the table.

5.2.1 Basis for SWOT Analysis

The assessments are based on the findings of this thesis. The sources for the mentioned assessments can therefore be found in the corresponding chapters of the thesis.

Overlap variation

Table 29 shows the different parameters of the Overlap variation.

Table 29: SWOT Analysis Overlap variation

Source: Table based on results of this thesis

Strengths • Adjustable overlaps make it possible to respond individually to the operating situation. In the case of crossings in stations, slower entries could shorten the overlap.	**Weaknesses** • Overlaps have predefined lengths in many countries, so a change would require modifications to the regulations in many places. In addition, shortening the overlap leads to flatter braking curves and therefore to time delays in approaching the stations.
Opportunities • Reduction in train running times and fewer operational restrictions due to crossing routes. This can result in lower exclusion rates for interlocking tables.	**Threats** • Without permanent monitoring of the braking curve under PZB, the probability of reaching the danger point in the event of a signal overrun is increased. Under ETCS, this is countered by monitoring the braking curve. The speed is calculated at the end of SvL.

ETCS Level 2

Table 30 shows the different parameters of the measure ETCS Level 2.

Table 30: SWOT Analysis ETCS Level 2

Source: Table based on results of this thesis

Strengths • The biggest advantage of ETCS Level 2 is that train movements are continuously monitored in FS mode. Furthermore, line-side signals can be removed from the track.	**Weaknesses** • Different baselines or country-specific operating rules counteract the full utilization of the interoperability benefits.
Opportunities • By using cab signalling, higher speeds are possible than with PZB.	**Threats** • Depending on the braking model, this results in more restrictive braking curves and therefore longer headway.

ETCS Level 2 with track speed

Table 31 shows the different parameters of the measure ETCS Level 2 with track speed.

Table 31: SWOT Analysis ETCS Level 2 with track speed

Source: Table based on results of this thesis

Strengths	**Weaknesses**
• This measure leads to effective time savings for trains, which only must travel at a reduced speed before the turnouts.	• If turnouts are only used in a straight direction, no reduced speed is required, so there is no benefit of this measure.
Opportunities	**Threats**
• Using the line speed until the beginning of a turnout can compensate for the time caused by using restrictive ETCS braking curves.	• If line-side signalling is still used and the signals are not switched to dark, the application of this measure leads to inconsistent signalling aspects at the signal and on the cab signalling.

ETCS Level 2 with shorter blocks

Table 32 shows the different parameters of the measure ETCS Level 2 with shorter blocks.

Table 32: SWOT Analysis ETCS Level 2 with shorter blocks

Source: Table based on results of this thesis

Strengths	**Weaknesses**
• The headway can be shortened due to the shorter block division, which means that the distance between two trains can be reduced. The shorter the block sections, the closer the headway tends to a moving block.	• If shorter blocks are equipped with physical TTD, like axle counters, then there are required minimum lengths.
Opportunities	**Threats**
• The use of ETCS Level 2 with shorter blocks can further reduce the train headway time on routes that are already heavily used.	• If VSS without TTD are used like in ETCS Level 3 Hybrid, the advantages can be fully used only from trains with ETCS and TIMS.

ETCS Level 3

Table 33 shows the different parameters of the measure ETCS Level 3 with a moving block.

Table 33: SWOT Analysis ETCS Level 3

Source: Table based on results of this thesis

Strengths	**Weaknesses**
• Under ETCS Level 3, the shortest possible headway can be achieved, and the capacity of the investigated line section can be fully utilized.	• ETCS Level 3 Moving Block is currently still in development and further specifications are required. So, the use will only be possible in the future.
Opportunities	**Threats**
• ETCS Level 3 can simplify the line-side equipment and offer new possibilities for railway operations.	• If the ETCS Level 3 Moving Block fails, operation in a fallback level is no longer possible, or only under very restricted conditions.

5.2.2 SWOT Analysis of Sesvete and Railway node A2

Table 34 shows the different parameters of the used measures in the railway node Sesvete and the fictive railway node A2.

Table 34: SWOT Analysis of Sesvete and Railway node A2

Source: Table based on results of this thesis

Strengths	**Weaknesses**
• High impact on headways without huge infrastructure adaptions • Shorter headways especially through divided block sections. The shorter the block sections, the closer the headway tends to a moving block. • A continuous train protection system supervises the braking curves and allowed speeds. • Line speeds just before turnouts begin and not from the home signals • The approach is simply transferable to other lines	• The approach was tested only on two similar railway systems. • No benefits, when turnouts are used in a straight direction. • Headway depending on the block length. If physical TTD is used with more blocks there is more complexity and costs for the TTD • When physical TTD is used, a minimum section length is required, to ensure at least one axle in the section • Impact on single track is not a shorter headway compared to existing systems, but a more robust timetable
Opportunities	**Threats**
• Can be used on lines, which are highly utilized • Compensating of flatter ETCS braking curve with using the line speed until the turnouts. • Higher speeds than with PZB are possible through cab signalling. • The approach can be used to show potential on lines	• More restrictive braking curves, if the braking model is not adapted • Inconsistent signalling aspect between cab signalling and line-side signalling, if the latter is not switched to dark. • Full benefits only with trains equipped with ETCS and TIMS. • Until now no stochastic simulation is carried out with the measures

Strengths and Opportunities

It turns out that the headway reduction creates an opportunity to deal with the increasingly busy railway lines. The shorter block division allows shorter headways. In addition, the continuous supervision of the braking curves and cab signalling allows higher speeds. Line speed up to just before the danger points (turnouts) makes it possible to compensate flatter ETCS braking curves. The approach can easily be simulated on other routes.

Strengths and Threats

The more restrictive braking curves can be compensated by the line speed just before the turnouts. The full potential can only be utilised by trains equipped with ETCS+TIMS, however, improvements to the initial variant can be noticed beforehand. With cab-signalling, it seems possible to switch the line-side signals to dark or remove them completely. However, the line would then only be able to be travelled as ETCS-only.

Weaknesses and Opportunities

Even if the measures are only applied to two comparable railway systems until now, they can easily be implemented on other lines or simulation networks. The necessary physical TTD can also be an advantage for highly utilised lines, as vehicles without TIMS can also use the benefits. Furthermore, it is possible that trains can follow each other faster, especially at station areas.

Weaknesses and Threats

Shorter headways on single-track lines can only be achieved if the trains are travelling in the same direction. For trains travelling in the opposite direction, shorter journey times result in changes in crossing stops. Considerable infrastructure interventions would be necessary to counteract this. The improvements can therefore be used to make an existing timetable more stable.

Generally referred to as the aspect whose full benefits can only be utilised with ETCS+TIMS (ETCS Level 3 Hybrid) or with a higher number of axle counters, the principle of the shorter blocks is comparable (ETCS Level 2 with shorter blocks). In one case, the axle counters must be significantly increased and an investment in the infrastructure is therefore necessary; in the other case an investment in the rolling stock is necessary to ensure train integrity.

6 Conclusion and discussion

In this thesis, it is investigated how the station capacity can be increased by using train control methods. Different approaches for train control are used. In Austria and Germany, a common system is the inductive train protection system PZB. Here the trains are only supervised in front of danger points. CBTC is also used in urban transport systems and, for example, on a narrow-gauge railway in Switzerland. In contrast, LZB has become established in the high-speed network in Germany. This is a continuous train control system It is relevant for this work that a high-performance block was created with LZB under CIR-ELKE, particularly in highly utilized sections. In operational terms, this is comparable to ETCS Level 3 Hybrid. However, LZB will no longer be developed further. Lines with LZB will be converted to ETCS in the future. Regarding ETCS, different levels are used in the course of this work, with discrete or moving blocks. In the case of discrete blocks, different considerations are made for block division to see what effects this has on capacity. However, to estimate the effects, it must first be determined how capacity is defined. There are many similar definitions and subdivisions in the literature. For example, it can be said, that capacity is the possible number of trains that can run over a section of a track in a defined period, while keeping constant the characteristics of the trains. There are various methods for capacity determination. For example, the constructive method, the optimization method, the parametric method, statistical deterministic methods, and stochastic models. In this thesis, the simulation method, which is part of the stochastic models alongside the analytical method, is used. The simulation considers how the performance behaviour of different train sequences behaves when parameters are changed. The first step is to test which headway is achieved with PZB. This is followed by using ETCS and then the line speed is also permitted up to the turnout area. In addition, the block sections are divided, and moving blocks are used. The effects of this on a single-track line at crossings and how the use of overlaps influences this headway is also investigated.

The investigations show that the use of ETCS Level 3 Hybrid or Level 2 with shorter blocks instead of PZB can reduce the headway by 61% on the fictive railway line. Another example also shows that the use of an ETCS Level 3 Moving Block instead of ETCS Level 2 can reduce the headway by 73% at the Salzburger Lokalbahn. The investigation of overlaps showed an increase when using 50 m overlap instead of 0 m overlap on the Südbahn. The headway of PZB-guided trains increased by 13%. Extending the overlap to 200 m, on the other hand, only led to a further increase of 3%. Furthermore, a comparison of a double-track section and a 4-track section at the S-Bahn Vienna showed how the headway changes. It was clear that the relevant factor is whether the routes cross each other. In addition, with two short distances between stops, it was possible to show that headways cannot necessarily be shortened by removing a stop. The relevant time components can lie on the entire route of the train and not directly in the analyzed station. However, it was evident that, as optimization progresses, the dwell time of trains becomes a headway-determining component. A comparison of the railway node Sesvete and the fictive railway node A2 showed that the use of ETCS and allowing line speed up to the turnouts significantly reduces the headway. This comparison is made with line-side signalling, where a train already must run at the reduced speed from an entry signal. As already mentioned above, ETCS with shorter block sections or moving blocks showed a further significant headway reduction.

6.1 Implications

The use of ETCS Level 3 Hybrid is therefore a good option to reduce headways and increase capacity for existing lines. However, it must be mentioned that the possible increase in capacity can only be fully utilized if all trains are equipped with ETCS and TIMS. In mixed operation with PZB trains or when a ETCS train without TIMS runs ahead of a TIMS train, no significant improvements to the existing system can be expected. It has also been shown that the use of ETCS Level 1 or 2 while using the existing block division does not change the capacity and, in the worst case even increase the headway due to the flatter braking curves. It is therefore essential to consider optimised braking curves and vehicle dynamics parameters during the ETCS implementation. For example, good acceleration behaviour can compensate for the disadvantages. The question also arises of what changes would result from using the permitted braking curve. Furthermore, it is also evident that not only train and traffic control parameters influence capacity, but also other parameters such as passenger exchange times, which must also be considered in this context.

6.2 Limitations

The selected studies represent two countries and fictive examples. Rolling stock were selected that has individual engine parameters. It would therefore be worth investigating how the results change if, for example, trains with poorer driving dynamics characteristics were selected. It would be interesting to see whether the percentage change between the analyzed variants is nevertheless comparable to the results presented here. Furthermore, the simulation in the OpenTrack software is based on timetables and train priorities with which different variants and scenarios are modelled. However, this is not a general analysis but a specific one. This should therefore be seen as a limitation compared to other analyses.(Friedrich, 2021, p. 4)

Within the dissertation, the topic of ETCS braking curves is applied using the example of the Salzburger Lokalbahn. However, this topic is not applied beyond this and makes sense to investigate this topic in further research.

6.3 Discourse on results

When considering the simulated driving behaviour, it must always be considered that this corresponds to an optimum situation if the selected parameters are chosen accordingly. In practice, this is not the case with a human driver. Even if DAS provides some help for this, the optimization of the driving behaviour is necessary for optimum utilization of the available track capacity and ATO over ETCS makes this possible. The combination with the proposed solutions can therefore be considered.

6.4 Perspective

The results presented in the dissertation show that the adaptions offer an opportunity to optimize capacity. This makes it possible to increase the performance of existing lines or to reduce delays while using the same timetable or the knock-on delays to other trains. The planned use of ETCS Level 3 Hybrid on real railway lines will provide findings from real environments over the next few years, enabling more precise conclusions. Until then, however, further investigations and simulations are necessary. One starting point could be to vary different block lengths on existing lines. For example, it would make sense to use different block lengths on the Südbahn. The interesting thing here could be how this affects the section between Mödling and Wiener Neustadt, which is not being extended to four-tracks. However, regardless of which examples are simulated, it would make sense to simulate a whole timetable under the changed conditions to investigate which effects are recognizable. In a further step, it is possible to use stochastic approaches in the investigation to analyze whether, for example, there are any effects on the robustness of the timetable.

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Abbreviations

AFB	Automatische Fahr- und Bremssteuerung
ARAMIS	Advanced Railway Automation Management Information System
ASTREE	Automation of train spacing in real time
ATC	Automatic Train Control
ATO	Automatic Train Operation
ATO over ETCS	Automatic Train Operation over European Train Control System
ATP	Automatic Train Protection
ATR	Adaptive Train Routing
ATS	Automatic Train Supervision
AWS	Automatic Warning System
BLT	Baselland Transport AG
BSC	Basic Station Controller
BTS	Base Transceiver Station
BTSF	Betrieblich-technische-Systemfunktionen / Operational-technical system functions
CAT	City Airport Train
CATO	Computer-Aided Train Operation
CBTC	Communications - Based Train Control
CFL	Société Nationale des Chemins de Fer Luxembourgeois
CIR – ELKE	Computer Integrated Railroading - Erhöhung der Leistungsfähigkeit im Kernnetz
CLN	Čulinec
COTS	Commercial off-the-shelf
CRRD	Congestion-Related Reactionary Delay
CUI	Capacity Utilization Index
DAC	Digital Automatic Coupling
DAC4EU	Digital Automatic Coupling for Europe
DACIO	Digital Automated Coupling in Infrastructure Operations
DAS	DAS
DB	Deutsche Bahn
DMI	Driver Machine Interface
DS	Dugo Selo
EBD	Emergency Brake Deceleration
EBI	Emergency Brake Intervention
EBuLa - ESF	Elektronischer Buchfahrplan und Verzeichnis der Langsamfahrstellen – Energiesparende Fahrweise / Electronic timetable and list of areas with speed restrictions – energy saving driving mode
EC	Euro City
EDDP	European DAC Delivery Programme
EisbBBV	Eisenbahnbau- und -betriebsverordnung
EMU	Electrical Multiple Unit
EoA	End of Authority
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
EU	European Union
FRMCS	Future Railway Mobile Communication System
FS	Full Supervision
GoA	Grades of Automation

GSM-R	Global System for Mobile Communication - Rail (GSM-R)
GUI	Graphical User Interface
Hbf	Main Station / Hauptbahnhof
HMI	Human Machine Interface
LBK	LZB-Blockkennzeichen / LZB block marker
LEU	Line-side electronic unit
LMA	Limit of Authority
LS	Limited Supervision
LTE	Long Termin Evolution
LUKS	Leistungsfähigkeitsuntersuchung von Knoten und Strecken
LZB	Linienzugbeeinflussung / Continuous train control
MA	Movement authority
MKS	Maksimir
MSC	Mobile Switching Center
MTREL	Mass Transit Railway Elizabeth Line
NTC	National Train Control
PZB	Punktuelle Zugbeeinflussung / Intermittent train protection
RBC	Radio Block Centre
RFC	Rail Freight Corridor
RIL	Richtlinie / Guideline
ROC	Railway Operating Centre
S-Bahn	Schnellbahn / Suburban train
SBD	Service Brake Deceleration
SBI	Service Brake Intervention
SFA	Signal Fixe d'Autorisation
SH	Shunting
SIL	Safety Integrated Level
SKR	Sesvetski Kraljevec
SLB	Salzburger Lokalbahn
SLS	Streckenleistungsfähigkeit und -simulation / Line performance and -simulation
SSV	Sesvete
STM	Specific Transmission Module
STRESI	Streckensimulation / Linesimulation
SvL	Supervised Location
TETRA	Terrestrial Trunked Radio
TIMS	Train integrity monitoring system
TMS	Traffic Management System)
TPWS	Train Protection and Warning System
TRN	Trnava
TSI	Technical Specifications for Interoperability
TSI CCS	Technical Specification for Interoperability - Command, Control and Signalling
TTD	Trackside train detection
UIC	International Union of Railways
VBF	Virtual Block Function
VSS	Virtual sub section
ZGGK	Zagreb Glavni Kolodvor / Zagreb Main Station
ZGRS	Zagreb Resnik
ZLR	Zuglaufregelung / Train control regulation
ŽSR	Železničná spoločnosť Slovensko

Appendix

Appendix A Timetable evaluation Anthering

The analysis of the timetable can be seen in Table 35, whereby the timetable of the year 2021/22 is used. As station Anthering is chosen and trains in both directions are considered.

Table 35: Trains per hour in Anthering

Source: Table based on Timetable 2021/22 taken from Salzburg AG (2021)

Hour	Local trains / hour	Freight trains / hour	Trains / hour
0	2		2
1	0		0
2	0		0
3	0		0
4	0		0
5	6		6
6	8		8
7	8		8
8	8		8
9	4		4
10	4		4
11	4		4
12	4		4
13	6		6
14	8		8
15	8		8
16	8		8
17	8		8
18	8		8
19	8		8
20	4		4
21	4		4
22	4		4
23	4		4
	Trains in 24h		**118**

Appendix B Timetable evaluation Sesvete

Table 36 shows the trains per hour in Sesvete based on the timetable of 2021/22. Trains in every direction are considered.

Table 36: Trains per hour in Sesvete

Source: Table based on Timetable 2021/22 taken from HŽ Infrastruktura (2021)

Hour	**Local trains / hour**	**Long Distance trains / hour**	**Freight trains / hour**	**Trains / hour**
0	0	1	3	4
1	0	0	3	3
2	0	1	5	6
3	0	1	3	4
4	2	1	3	6
5	9	0	2	11
6	9	4	2	15
7	9	1	4	14
8	6	0	2	8
9	4	2	2	8
10	5	1	0	6
11	4	1	1	6
12	6	1	1	8
13	6	1	1	8
14	8	0	1	9
15	8	4	3	15
16	9	2	2	13
17	6	2	0	8
18	6	1	3	10
19	5	0	2	7
20	5	1	1	7
21	5	3	1	9
22	4	1	4	9
23	1	0	2	3
	Trains in 24h			**197**

Appendix C Timetable evaluation Mödling

The analysis of the timetable can be seen in Table 37, whereby the timetable of the timetable year 2022/23 is used. As station Mödling is chosen and trains in both directions are considered.

Table 37: Trains per hour in Mödling

Source: Table based on Timetable 2022/23 taken from ÖBB Personenverkehr AG (2022a)

Hour	**Suburban trains / hour**	**Local trains / hour**	**Long Distance trains / hour**	**Trains / hour**
0	3	4	0	7
1	1	0	0	1
2	1	0	0	1
3	0	0	0	0
4	2	2	0	4
5	6	12	0	18
6	6	13	3	22
7	7	12	3	22
8	5	9	4	18
9	5	5	4	14
10	4	4	4	12
11	4	5	3	12
12	6	5	4	15
13	5	5	2	12
14	5	8	3	16
15	4	10	4	18
16	5	11	3	19
17	5	10	4	19
18	5	10	3	18
19	4	9	4	17
20	4	9	3	16
21	5	5	4	14
22	5	5	2	12
23	7	5	3	15
Trains in 24h	**104**	**158**	**60**	**322**

Appendix D Timetable evaluation Stammstrecke

The analysis of the timetable can be seen in Table 38, whereby the timetable of the year 2023 is used. As station Wien Rennweg is chosen and trains in all directions are considered.

Table 38: Trains per hour in Wien Rennweg

Source: Table based on the timetable 2022/23 taken from ÖBB Personenverkehr AG (2022b)

Hour	Suburban trains / hour	Local trains / hour	CAT	Trains / hour
0	15	2	0	17
1	8	1	0	9
2	0	0	0	0
3	0	0	0	0
4	13	4	0	17
5	15	16	1	32
6	19	14	4	37
7	25	13	4	42
8	21	14	4	39
9	20	12	4	36
10	21	7	4	32
11	20	7	4	31
12	21	8	4	33
13	19	9	4	32
14	20	14	4	38
15	19	13	4	36
16	19	16	4	39
17	19	16	4	39
18	19	15	4	38
19	20	15	4	39
20	19	14	4	37
21	19	9	4	32
22	18	6	4	28
23	18	6	3	27
Trains in 24h	**407**	**231**	**72**	**710**

Appendix E Comparison of Overlaps

Table 39 shows the different approaches of the Overlaps in Europe.

Table 39: Comparison of Overlaps

Country	**Length [m]**	**Comment**	**Source**
Albania	-	Now barely any signalling system in use	Own visit in Albania in April 2022
Austria	0….50	Up to 40 km/h 0m then 50m	(§22/5 EisbBBV - Eisenbahnbau- und -betriebsverordnung, 2008)
Belgium	50....100	100m in nodes with more lines	(Maschek, 2011, p. 32)
Bosnia and Hercegowina	50-300	In normal circumstances 100-200m. Maximum 300m but not shorter than 50m. According to the Saobraćajni Pravilnik for the Republika Srpska there the overlap is defined with 50m. (Članak 54. Službeni Glasnik Republike Srpske, 2020)	(Članak 37(6). Službeni Glasnik Bosne i Hercegovine, 2014)
Bulgaria	150		(Republic of Bulgaria. DP National Company railway infrastructure, 2013, p. 5)
Croatia	50…150	Depending on the speed and type of signal	(Članak 110. Pravilnik o načinu i uvjetima za sigurno odvijanje i upravljanje željezničkim prometom (In Croatian: Rulebook on the manner and conditions for the safe operation and management of railway traffic), 2022)
Czech Republic	0		(Maschek, 2011, p. 32)

Denmark	0		(S. Harrod, mail communication, 22 February 2022, ll. 45–66)
France	1500	On conventional lines no overlap. At high-speed lines one block, but at least 1500m	(Maschek, 2011, pp. 30–31)
Germany	50…100 …200	Depending on the Speed	(Maschek, 2011, p. 29)
Greece	60….100	Up to 120km/h 60m above 100m.	(K. Liberis, mail communication, 16 February 2022, ll. 27–38)
Hungary	50		(MÁV ZRT. -Pályavasúti Üzemeltetési Főigazgatóság, 2008, pp. 215–216)
Italy	100		(Maschek, 2011, p. 32)
Kosovo	-	Now barely any signalling system in use	Own visit in Kosovo in April 2022
Lichtenstein	50	Infrastructure is operated from ÖBB Infrastructure AG with a concession of the government of Liechtenstein.	(Liechtensteinische Landesverwaltung, 2020)
Luxembourg	0…100	The network is equipped with ETCS. If the distance to the danger point is under 100m the release speed is 25 km/h, if the distance is more than 100m the release speed can be increased to 40 km/h.	(Maschek, 2011, p. 31)
Montenegro	50		(Član 11. Ministarstvo saobraćaja i pomorstva, 2019)
Netherlands	0	No use of overlaps	(D. Van der Maij, mail communication, 28 February 2022, ll. 27–38)

North Macedonia		Not examined	
Norway	0…400		(Maschek, 2011, p. 32)
Poland		Not examined	
Romania	0….200	200m for home signals, 100m for exit signals with speed over 40km/h under this speed 50m. There can be 0m overlap when the speed is restricted to 20 km/h	(Compania Națională de Căi Ferate ”CFR” – SA, 2013, pp. 1–3)
Serbia	50		(Članak 54. Zajednica Jugoslovenskih Željeznica, 1994)
Slovakia	0		(H. Seelmann, mail communication, 18 January 2022, ll. 19–26)
Slovenia	50	If the overlap is shorter there has to be a sign, which signalizes the shorter overlap	(Kociper et al., 2018, p. 142; 24. Člen Signalni pravilnik (In Slovenian: Rules on the signalling-safety devices), 2018)
Spain	50		(Maschek, 2011, p. 32)
Sweden	200	Reduction at lower speeds possible	(Maschek, 2011, p. 32)
Switzerland	40….200	Depending on the speed. From 1 to 49km/h 40m then every additional 10km/h 5m more. Over 160km/h 200m. Different length for narrow gauge lines from 30 to 65m.	(Bundesamt für Verkehr, 2016, p. 12)
Turkey		Not examined	
United Kingdom	46…274	Shorter if more aspect signalling. 46m if speed is limited to 24 km/h	(Maschek, 2011, p. 32)

Appendix F Analysis of the distance to the danger point

For the analysis of the correlation of the Using length and the distance to the danger point data from the used simulation is used. Table 40 shows the collected data.

Table 40: Using length and distance to the danger point

Source: Table based on the parameters of the OpenTrack simulation

Nr.	Track name	Station Name	Station Nr.	Line	Line Nr.	Using length [m]	Distance to Danger point [m]
1	Zagreb Zapadni 1	Zagreb Zapadni kolodvor	1	Zagreb - Dugo Selo	100	324	9
2	Zagreb Zapadni 2	Zagreb Zapadni kolodvor	1	Zagreb - Dugo Selo	100	350	50
3	Zagreb Zapadni 3	Zagreb Zapadni kolodvor	1	Zagreb - Dugo Selo	100	473	65
4	Zagreb Zapadni 4	Zagreb Zapadni kolodvor	1	Zagreb - Dugo Selo	100	520	23
5	Zagreb Zapadni 5	Zagreb Zapadni kolodvor	1	Zagreb - Dugo Selo	100	515	107
6	Zagreb Glavni Kolodvor 1	Zagreb Glavni kolodvor	2	Zagreb - Dugo Selo	100	625	11
7	Zagreb Glavni Kolodvor 2	Zagreb Glavni kolodvor	2	Zagreb - Dugo Selo	100	839	53
8	Zagreb Glavni Kolodvor 3	Zagreb Glavni kolodvor	2	Zagreb - Dugo Selo	100	598	66
9	Zagreb Glavni Kolodvor 4	Zagreb Glavni kolodvor	2	Zagreb - Dugo Selo	100	584	46
10	Zagreb Glavni Kolodvor 5	Zagreb Glavni kolodvor	2	Zagreb - Dugo Selo	100	464	6
11	Zagreb Resnik 1	Zagreb Resnik	3	Zagreb - Dugo Selo	100	702	64
12	Zagreb Resnik 2	Zagreb Resnik	3	Zagreb - Dugo Selo	100	702	64
13	Zagreb Resnik 3	Zagreb Resnik	3	Zagreb - Dugo Selo	100	853	50
14	Zagreb Resnik4	Zagreb Resnik	3	Zagreb - Dugo Selo	100	730	66
15	Sesvete 4	Sesvete	4	Zagreb - Dugo Selo	100	850	64
16	Sesvete 5	Sesvete	4	Zagreb - Dugo Selo	100	796	63
17	Sesvete 6	Sesvete	4	Zagreb - Dugo Selo	100	589	67
18	Dugo Selo 2	Dugo Selo	5	Zagreb - Dugo Selo	100	542	56
19	Dugo Selo 3	Dugo Selo	5	Zagreb - Dugo Selo	100	638	53
20	Dugo Selo 4	Dugo Selo	5	Zagreb - Dugo Selo	100	778	57
21	Dugo Selo 5	Dugo Selo	5	Zagreb - Dugo Selo	100	764	71
22	Dugo Selo 6	Dugo Selo	5	Zagreb - Dugo Selo	100	669	80
23	Dugo Selo 7	Dugo Selo	5	Zagreb - Dugo Selo	100	658	64
24	Zagreb Glavni Kolodvor 1	Zagreb Glavni kolodvor	2	Zagreb - Dugo Selo	100	670	3
26	Zagreb Glavni Kolodvor 2	Zagreb Glavni kolodvor	2	Zagreb - Dugo Selo	100	839	44
26	Zagreb Glavni Kolodvor 3	Zagreb Glavni kolodvor	2	Zagreb - Dugo Selo	100	599	65
27	Zagreb Glavni Kolodvor 4	Zagreb Glavni kolodvor	2	Zagreb - Dugo Selo	100	584	47
28	Zagreb Glavni Kolodvor 5	Zagreb Glavni kolodvor	2	Zagreb - Dugo Selo	100	464	9
29	Zagreb Resnik 1	Zagreb Resnik	3	Zagreb - Dugo Selo	100	702	224
30	Zagreb Resnik 2	Zagreb Resnik	3	Zagreb - Dugo Selo	100	702	54
31	Zagreb Resnik 3	Zagreb Resnik	3	Zagreb - Dugo Selo	100	853	50
32	Zagreb Resnik4	Zagreb Resnik	3	Zagreb - Dugo Selo	100	730	50
33	Sesvete 2	Sesvete	4	Zagreb - Dugo Selo	100	460	50
34	Sesvete 3	Sesvete	4	Zagreb - Dugo Selo	100	552	64
35	Sesvete 5	Sesvete	4	Zagreb - Dugo Selo	100	796	46
36	Dugo Selo 2	Dugo Selo	5	Zagreb - Dugo Selo	100	542	76
37	Dugo Selo 3	Dugo Selo	5	Zagreb - Dugo Selo	100	638	81
38	Dugo Selo 4	Dugo Selo	5	Zagreb - Dugo Selo	100	778	65
39	Dugo Selo 5	Dugo Selo	5	Zagreb - Dugo Selo	100	764	61

40 Salzburg Itzling Track 1	Salzburg Itzling	10 Salzburger Lokalbahn	101	203	96
41 Salzburg Itzling Track 1	Salzburg Itzling	10 Salzburger Lokalbahn	101	203	231
42 Salzburg Itzling Track 2	Salzburg Itzling	10 Salzburger Lokalbahn	101	194	22
43 Salzburg Itzling Track 2	Salzburg Itzling	10 Salzburger Lokalbahn	101	128	179
44 Bergheim Track 1	Bergheim	11 Salzburger Lokalbahn	101	258	57
45 Bergheim Track 2	Bergheim	11 Salzburger Lokalbahn	101	254	48
46 Anthering	Anthering	12 Salzburger Lokalbahn	101	659	39
47 Anthering	Anthering	12 Salzburger Lokalbahn	101	576	85
48 Weithwörth Nussdorf Track 1	Weithwörth Nussdorf	13 Salzburger Lokalbahn	101	1137	118
49 Weithwörth Nussdorf Track 1	Weithwörth Nussdorf	13 Salzburger Lokalbahn	101	1137	108
50 Weithwörth Nussdorf Track 2	Weithwörth Nussdorf	13 Salzburger Lokalbahn	101	1192	118
51 Weithwörth Nussdorf Track 2	Weithwörth Nussdorf	13 Salzburger Lokalbahn	101	1192	56
52 Oberndorf Track 1	Oberndorf	14 Salzburger Lokalbahn	101	201	86
53 Oberndorf Track 1	Oberndorf	14 Salzburger Lokalbahn	101	201	54
54 Oberndorf Track 2	Oberndorf	14 Salzburger Lokalbahn	101	198	70
55 Oberndorf Track 2	Oberndorf	14 Salzburger Lokalbahn	101	198	54
56 Bürmoos Track 1	Bürmoos	15 Salzburger Lokalbahn	101	140	50
57 Bürmoos Track 1	Bürmoos	15 Salzburger Lokalbahn	101	140	52
58 Bürmoos Track 2	Bürmoos	15 Salzburger Lokalbahn	101	472	40
59 Bürmoos Track 2	Bürmoos	15 Salzburger Lokalbahn	101	472	83
60 Bürmoos Track 3	Bürmoos	15 Salzburger Lokalbahn	101	1008	94
61 Bürmoos Track 3	Bürmoos	15 Salzburger Lokalbahn	101	1008	55
62 Riedersbach Track 1	Riedersbach	16 Salzburger Lokalbahn	101	164	117
63 Riedersbach Track 1	Riedersbach	16 Salzburger Lokalbahn	101	164	209
64 Riedersbach Track 2	Riedersbach	16 Salzburger Lokalbahn	101	164	82
65 Riedersbach Track 2	Riedersbach	16 Salzburger Lokalbahn	101	164	209
66 Wien Meidling Track 1	Wien Meidling	17 Südbahn	102	568	28
67 Wien Meidling Track 2	Wien Meidling	17 Südbahn	102	440	29
68 Wien Meidling Track 4	Wien Meidling	17 Südbahn	102	417	26
69 Wien Meidling Track 6	Wien Meidling	17 Südbahn	102	357	20
70 Wien Meidling Track 8	Wien Meidling	17 Südbahn	102	308	21
71 Wien Meidling Track 10	Wien Meidling	17 Südbahn	102	333	92
72 Wien Liesing Track 2	Wien Liesing	18 Südbahn	102	298	49
73 Wien Liesing Track 31	Wien Liesing	18 Südbahn	102	232	10
74 Wien Liesing Track 32	Wien Liesing	18 Südbahn	102	234	14
75 Wien Liesing Track 2	Wien Liesing	18 Südbahn	102	298	88
76 Wien Liesing Track 31	Wien Liesing	18 Südbahn	102	232	10
77 Wien Liesing Track 32	Wien Liesing	18 Südbahn	102	234	96
78 Mödling Track 1	Mödling	19 Südbahn	102	754	93
79 Mödling Track 2	Mödling	19 Südbahn	102	477	53
80 Mödling Track 3	Mödling	19 Südbahn	102	705	53

81	Mödling Track 6	Mödling	19	Südbahn	102	430	47
82	Mödling Track 1	Mödling	19	Südbahn	102	444	196
83	Mödling Track 2	Mödling	19	Südbahn	102	477	129
84	Mödling Track 3	Mödling	19	Südbahn	102	705	82
85	Mödling Track 6	Mödling	19	Südbahn	102	430	135
86	Pfaffstätten Track 1	Pfaffstätten	20	Südbahn	102	595	60
87	Pfaffstätten Track 2	Pfaffstätten	20	Südbahn	102	676	99
88	Pfaffstätten Track 3	Pfaffstätten	20	Südbahn	102	593	81
89	Pfaffstätten Track 4	Pfaffstätten	20	Südbahn	102	636	55
90	Pfaffstätten Track 1	Pfaffstätten	20	Südbahn	102	595	79
91	Pfaffstätten Track 2	Pfaffstätten	20	Südbahn	102	676	91
92	Pfaffstätten Track 3	Pfaffstätten	20	Südbahn	102	593	60
93	Pfaffstätten Track 4	Pfaffstätten	20	Südbahn	102	636	46
94	Bad Vöslau Track 1	Bad Vöslau	21	Südbahn	102	559	77
95	Bad Vöslau Track 2	Bad Vöslau	21	Südbahn	102	648	38
96	Bad Vöslau Track 4	Bad Vöslau	21	Südbahn	102	648	5
97	Bad Vöslau Track 3	Bad Vöslau	21	Südbahn	102	454	51
98	Bad Vöslau Track 5	Bad Vöslau	21	Südbahn	102	292	187
99	Bad Vöslau Track 7	Bad Vöslau	21	Südbahn	102	293	185
100	Bad Vöslau Track 1	Bad Vöslau	21	Südbahn	102	559	110
101	Bad Vöslau Track 2	Bad Vöslau	21	Südbahn	102	648	201
102	Bad Vöslau Track 4	Bad Vöslau	21	Südbahn	102	648	98
103	Bad Vöslau Track 3	Bad Vöslau	21	Südbahn	102	454	48
104	Bad Vöslau Track 5	Bad Vöslau	21	Südbahn	102	292	49
105	Bad Vöslau Track 7	Bad Vöslau	21	Südbahn	102	293	50
106	Leobersdorf Track 1	Leobersdorf	22	Südbahn	102	702	127
107	Leobersdorf Track 2	Leobersdorf	22	Südbahn	102	702	196
108	Leobersdorf Track 3	Leobersdorf	22	Südbahn	102	792	75
109	Leobersdorf Track 4	Leobersdorf	22	Südbahn	102	722	100
110	Leobersdorf Track 5	Leobersdorf	22	Südbahn	102	774	30
111	Leobersdorf Track 6	Leobersdorf	22	Südbahn	102	668	60
112	Leobersdorf Track 1	Leobersdorf	22	Südbahn	102	702	253
113	Leobersdorf Track 2	Leobersdorf	22	Südbahn	102	702	105
114	Leobersdorf Track 3	Leobersdorf	22	Südbahn	102	792	59
115	Leobersdorf Track 4	Leobersdorf	22	Südbahn	102	722	60
116	Leobersdorf Track 5	Leobersdorf	22	Südbahn	102	774	58
117	Leobersdorf Track 6	Leobersdorf	22	Südbahn	102	668	65
118	Felixdorf Track 1	Felixdorf	23	Südbahn	102	471	99
119	Felixdorf Track 2	Felixdorf	23	Südbahn	102	514	62
120	Felixdorf Track 3	Felixdorf	23	Südbahn	102	447	41

121	Felixdorf Track 4	Felixdorf	23 Südbahn	102	462	57
122	Felixdorf Track 5	Felixdorf	23 Südbahn	102	498	22
123	Felixdorf Track 1	Felixdorf	23 Südbahn	102	471	78
124	Felixdorf Track 2	Felixdorf	23 Südbahn	102	514	125
125	Felixdorf Track 3	Felixdorf	23 Südbahn	102	447	50
126	Felixdorf Track 4	Felixdorf	23 Südbahn	102	462	50
127	Felixdorf Track 5	Felixdorf	23 Südbahn	102	498	41
128	Wiener Neustadt Hbf Track 1	Wr. Neustadt	24 Südbahn	102	428	91
129	Wiener Neustadt Hbf Track 2	Wr. Neustadt	24 Südbahn	102	423	89
130	Wiener Neustadt Hbf Track 3	Wr. Neustadt	24 Südbahn	102	341	60
131	Wiener Neustadt Hbf Track 3	Wr. Neustadt	24 Südbahn	102	341	31
132	Wiener Neustadt Hbf Track 4	Wr. Neustadt	24 Südbahn	102	422	88
133	Wiener Neustadt Hbf Track 5	Wr. Neustadt	24 Südbahn	102	364	52
134	Wiener Neustadt Hbf Track 5	Wr. Neustadt	24 Südbahn	102	364	31
135	Wiener Neustadt Hbf Track 6	Wr. Neustadt	24 Südbahn	102	363	50
136	Wiener Neustadt Hbf Track 8	Wr. Neustadt	24 Südbahn	102	336	72
137	Wiener Neustadt Hbf Track 1	Wr. Neustadt	24 Südbahn	102	396	44
138	Wiener Neustadt Hbf Track 1	Wr. Neustadt	24 Südbahn	102	294	60
139	Wien Meidling Track 10	Wien Meidling	17 Stammstrecke	103	281	26
140	Wien Meidling Track 8	Wien Meidling	17 Stammstrecke	103	296	40
141	Wien Meidling Track 6	Wien Meidling	17 Stammstrecke	103	357	50
142	Wien Meidling Track 4	Wien Meidling	17 Stammstrecke	103	417	72
143	Wien Meidling Track 2	Wien Meidling	17 Stammstrecke	103	435	76
144	Wien Mitte Track 1	Wien Mitte	25 Stammstrecke	103	400	67
145	Wien Mitte Track 2	Wien Mitte	25 Stammstrecke	103	248	37
146	Wien Mitte Track 3	Wien Mitte	25 Stammstrecke	103	256	39
147	Wien Mitte Track 3 CAT	Wien Mitte	25 Stammstrecke	103	168	17
148	Wien Mitte Track 4	Wien Mitte	25 Stammstrecke	103	328	101
149	Wien Mitte Track 1	Wien Mitte	25 Stammstrecke	103	400	223
150	Wien Mitte Track 2	Wien Mitte	25 Stammstrecke	103	248	60
151	Wien Mitte Track 3	Wien Mitte	25 Stammstrecke	103	256	15
152	Wien Mitte Track 3 CAT	Wien Mitte	25 Stammstrecke	103	168	25
153	Wien Mitte Track 4	Wien Mitte	25 Stammstrecke	103	328	91
154	Wien Praterstern Track 1	Wien Praterstern	26 Stammstrecke	103	457	110
155	Wien Praterstern Track 2	Wien Praterstern	26 Stammstrecke	103	434	50
156	Wien Praterstern Track 3	Wien Praterstern	26 Stammstrecke	103	404	15
157	Wien Praterstern Track 4	Wien Praterstern	26 Stammstrecke	103	169	65
158	Wien Praterstern Track 5	Wien Praterstern	26 Stammstrecke	103	188	34
159	Wien Praterstern Track 1	Wien Praterstern	26 Stammstrecke	103	457	346
160	Wien Praterstern Track 2	Wien Praterstern	26 Stammstrecke	103	434	139
161	Wien Praterstern Track 3	Wien Praterstern	26 Stammstrecke	103	404	84
162	Wien Praterstern Track 4	Wien Praterstern	26 Stammstrecke	103	169	6
163	Wien Praterstern Track 5	Wien Praterstern	26 Stammstrecke	103	188	38
164	Wien Floridsdorf Track 1	Wien Floridsdorf	27 Stammstrecke	103	284	71
165	Wien Floridsdorf Track 2	Wien Floridsdorf	27 Stammstrecke	103	266	41
166	Wien Floridsdorf Track 3	Wien Floridsdorf	27 Stammstrecke	103	289	79
167	Wien Floridsdorf Track 4	Wien Floridsdorf	27 Stammstrecke	103	256	109
168	Wien Floridsdorf Track 5	Wien Floridsdorf	27 Stammstrecke	103	267	109

Appendix G Comparison of Braking distance

Table 41 shows the results of the calculation of braking curves with different Overlap length. For the calculation of the braking curves the ERA Braking Curves Simulation Tool is used with the values from Appendix H (ERA Braking Curves Simulation Tool Input parameters).

Table 41: Data of the braking curves

Source: Table based on data of the ERA Braking Curves Simulation Tool

Speed		Distance with	
km/h	m/s	50m Overlap	0m Overlap
40,00	11,11	110,32	116,96
39,90	11,08	109,64	116,28
39,80	11,06	108,96	115,60
39,70	11,03	108,28	114,92
39,60	11,00	107,60	114,24
39,50	10,97	106,92	113,56
39,40	10,94	106,24	112,89
39,30	10,92	105,16	111,80
39,20	10,89	104,48	111,13
39,10	10,86	103,81	110,45
39,00	10,83	103,14	109,78
38,90	10,81	102,47	109,11
38,80	10,78	101,80	108,44
38,70	10,75	101,13	107,77
38,60	10,72	100,46	107,10
38,50	10,69	99,79	106,44
38,40	10,67	99,13	105,77
38,30	10,64	98,46	105,10
38,20	10,61	97,80	104,44
38,10	10,58	97,13	103,78
38,00	10,56	96,47	103,11
37,90	10,53	95,81	102,45
37,80	10,50	95,15	101,79
37,70	10,47	94,49	101,13
37,60	10,44	93,83	100,47
37,50	10,42	93,17	99,82
37,40	10,39	92,52	99,16
37,30	10,36	91,86	98,50
37,20	10,33	91,21	97,85
37,10	10,31	90,55	97,20
37,00	10,28	89,90	96,54
36,90	10,25	89,25	95,89

36,80	10,22	88,60	95,24
36,70	10,19	87,95	94,59
36,60	10,17	87,30	93,94
36,50	10,14	86,65	93,30
36,40	10,11	86,00	92,65
36,30	10,08	85,36	92,00
36,20	10,06	84,71	91,36
36,10	10,03	84,07	90,71
36,00	10,00	83,43	90,07
35,90	9,97	82,79	89,43
35,80	9,94	82,15	88,79
35,70	9,92	81,51	88,15
35,60	9,89	80,87	87,51
35,50	9,86	80,23	86,87
35,40	9,83	79,59	86,24
35,30	9,81	78,96	85,60
35,20	9,78	78,32	84,97
35,10	9,75	77,69	84,33
35,00	9,72	77,05	83,70
34,90	9,69	76,42	83,07
34,80	9,67	75,79	82,44
34,70	9,64	75,16	81,81
34,60	9,61	74,17	80,82
34,50	9,58	73,55	80,19
34,40	9,56	72,92	79,56
34,30	9,53	72,29	78,94
34,20	9,50	71,67	78,31
34,10	9,47	71,05	77,69
34,00	9,44	70,42	77,07
33,90	9,42	69,80	76,45
33,80	9,39	69,18	75,83
33,70	9,36	68,56	75,21
33,60	9,33	67,95	74,59
33,50	9,31	67,33	73,97
33,40	9,28	66,71	73,36
33,30	9,25	66,10	72,74
33,20	9,22	65,48	72,13
33,10	9,19	64,87	71,51
33,00	9,17	64,26	70,90
32,90	9,14	63,65	70,29
32,80	9,11	63,04	69,68
32,70	9,08	62,43	69,07
32,60	9,06	61,82	68,46

32,50	9,03	61,21	67,85
32,40	9,00	60,60	67,25
32,30	8,97	60,00	66,64
32,20	8,94	59,39	66,04
32,10	8,92	58,79	65,44
32,00	8,89	58,19	64,83
31,90	8,86	57,59	64,23
31,80	8,83	56,99	63,63
31,70	8,81	56,39	63,03
31,60	8,78	55,79	62,43
31,50	8,75	55,19	61,84
31,40	8,72	54,59	61,24
31,30	8,69	54,00	60,64
31,20	8,67	53,40	60,05
31,10	8,64	52,81	59,45
31,00	8,61	52,22	58,86
30,90	8,58	51,63	58,27
30,80	8,56	51,04	57,68
30,70	8,53	50,45	57,09
30,60	8,50	49,86	56,50
30,50	8,47	49,27	55,91
30,40	8,44	48,68	55,33
30,30	8,42	48,10	54,74
30,20	8,39	47,51	54,16
30,10	8,36	46,93	53,57
30,00	8,33	46,35	52,99
29,90	8,31	45,77	52,41
29,80	8,28	45,19	51,83
29,70	8,25	44,61	51,26
29,60	8,22	44,04	50,68
29,50	8,19	43,46	50,11
29,40	8,17	42,89	49,53
29,30	8,14	42,32	48,96
29,20	8,11	41,74	48,39
29,10	8,08	41,17	47,82
29,00	8,06	40,60	47,25
28,90	8,03	40,04	46,68
28,80	8,00	39,47	46,11
28,70	7,97	38,90	45,55
28,60	7,94	38,34	44,98
28,50	7,92	37,77	44,41
28,40	7,89	37,21	43,85
28,30	7,86	36,64	43,29

28,20	7,83	36,08	42,73
28,10	7,81	35,52	42,17
28,00	7,78	34,96	41,61
27,90	7,75	34,40	41,05
27,80	7,72	33,84	40,49
27,70	7,69	33,29	39,93
27,60	7,67	32,73	39,38
27,50	7,64	32,18	38,82
27,40	7,61	31,62	38,27
27,30	7,58	31,07	37,71
27,20	7,56	30,52	37,16
27,10	7,53	29,97	36,61
27,00	7,50	29,42	36,06
26,90	7,47	28,87	35,51
26,80	7,44	28,32	34,96
26,70	7,42	27,77	34,42
26,60	7,39	27,23	33,87
26,50	7,36	26,68	33,33
26,40	7,33	26,14	32,78
26,30	7,31	25,59	32,24
26,20	7,28	25,05	31,70
26,10	7,25	24,51	31,15
26,00	7,22	23,97	30,61
25,90	7,19	23,43	30,08
25,80	7,17	22,89	29,54
25,70	7,14	22,36	29,00
25,60	7,11	21,82	28,46
25,50	7,08	21,28	27,93
25,40	7,06	20,75	27,39
25,30	7,03	20,22	26,86
25,20	7,00	19,68	26,33
25,10	6,97	19,15	25,80
25,00	6,94	18,62	25,27
24,90	6,92	18,09	24,74
24,80	6,89	17,56	24,21
24,70	6,86	17,04	23,68
24,60	6,83	16,51	23,15
24,50	6,81	15,98	22,63
24,40	6,78	15,46	22,10
24,30	6,75	14,94	21,58
24,20	6,72	14,41	21,06
24,10	6,69	13,89	20,54
24,00	6,67	13,37	20,02

23,90	6,64	12,85	19,50
23,80	6,61	12,33	18,98
23,70	6,58	11,82	18,46
23,60	6,56	11,30	17,94
23,50	6,53	10,78	17,43
23,40	6,50	10,27	16,91
23,30	6,47	9,76	16,40
23,20	6,44	9,24	15,89
23,10	6,42	8,73	15,38
23,00	6,39	8,22	14,86
22,90	6,36	7,71	14,36
22,80	6,33	7,36	13,85
22,70	6,31	7,09	13,34
22,60	6,28	6,81	12,83
22,50	6,25	6,54	12,33
22,40	6,22	6,27	11,82
22,30	6,19	6,00	11,32
22,20	6,17	5,74	10,81
22,10	6,14	5,47	10,31
22,00	6,11	5,20	9,81
21,90	6,08	4,93	9,31
21,80	6,06	4,67	8,81
21,70	6,03	4,40	8,31
21,60	6,00	4,14	7,82
21,50	5,97	3,87	7,32
21,40	5,94	3,61	6,83
21,30	5,92	3,35	6,33
21,20	5,89	3,09	5,84
21,10	5,86	2,82	5,35
21,00	5,83	2,56	4,86
20,90	5,81	2,30	4,37
20,80	5,78	2,05	3,88
20,70	5,75	1,79	3,39
20,60	5,72	1,53	2,90
20,50	5,69	1,27	2,42
20,40	5,67	1,02	1,93
20,30	5,64	0,76	1,45
20,20	5,61	0,51	0,96
20,10	5,58	0,25	0,48
20,00	5,56	0,00	0,00

Appendix H ERA Braking Curves Simulation Tool Input parameters

Table 42 shows the used parameters in the ERA Braking Curves Simulation Tool.

Table 42: Chosen parameters in the ERA Braking Curves Simulation Tool

Source: Parameters exported from the ERA Braking Curves Simulation Tool

Parameter	**Value**
Train type	Lambda train
Brake position	Passenger train in P
Traction cut off interface	No
Special/ additional brake independent from wheel / track adhesion	No
Speed inaccuracy	Subset-041
Position inaccuracy	Absolut + relative value = 0
Train length	140m
Nominal rotating mass	10%
Distance antenna – train front	5m
Acceleration	0 m/s²
Target type	EoA / SvL
Target speed	0
Distance origin /target	709m
Initial speed	40 km/h
Distance EoA/SvL	0 or 50 m
Release speed	20 km/h
Fixed release speed	
Gradient	0
Permission to use service brake in target speed monitoring	No
Permission to use the guidance curve	No
Permission to inhibit the compensation of the speed measurement inaccuracy	No
Maximum deceleration value under reduced adhesion conditions 1/2/3	3 m/s²
Brake percentage for emergency brake	156%
Conversion Model	
A_Service Brake 01	1,5 m/s²
A_Service Brake 12	1,5 m/s²
Integrated correction factors A_NVP12	1
Integrated correction factors A_NVP23	1,2
Integrated correction factors Kt_int	1,1
Integrated correction factors Kv_int (V) / Kv_Int_x_a(V)/Kv_int_x_b (V)	0,7
Integrated correction factors Kr_int(L)	0,9

Appendix I Block division in the railway node Sesvete

Table 43 shows that the section between Zagreb Main Station and Dugo Selo is 20,582 km long. This line section is divided into 18 blocks with an average block length of 1.143 km. That means, if 500 m block length is used, the blocks must be divided into subsections in between one and four blocks.

Table 43: Block length Zagreb Main Station – Dugo Selo via Main track

Source: Table based on results of the OpenTrack simulation – Railway node Sesvete

No.	Location	Signal type	From	To	Block length [m]	Divided into
1	ZGGK	Exit signal	ZGGK F2	Bs2	2025	4
2	ZGGK-MKS	Block signal	Bs2	MKS B	559	1
3	MKS	Home signal	MKS B	MKS G3	904	2
4	BRG	Protecting signal	MKS G3	BRG G31	1655	3
5	TRN	Protecting signal	BRG G31	CLN D3	1058	2
6	CLN	Exit signal	CLN D3	571	605	1
7	CLN-SSV	Block signal	571	561	818	2
8	CLN-SSV	Block signal	561	SSV A	1183	2
9	SSV	Home signal	SSV A	SSV D4	1354	3
10	SSV	Exit signal	SSV D4	Bs4	1242	2
11	SSV-SKR	Block signal	Bs4	Bs6	1300	2
12	SSV-SKR	Block signal	Bs6	Bs8	1300	2
13	SKR	Block signal	Bs8	Bs10	1179	2
14	SKR-DS	Block signal	Bs10	Bs12	1205	2
15	SKR-DS	Block signal	Bs12	Bs14	1203	2
16	SKR-DS	Block signal	Bs14	DS C	1000	2
17	DS	Home signal	DS C	DS D5	1423	3
18	DS	Exit signal	DS D5	Direction Novska	569	1
				Average block length	**1143**	

Table 44 shows the section length from Dugo Selo to Zagreb Main Station with 21.904 km, which is longer than the other direction. This is because in this direction of examination, the Main Station is crossed up to the protecting signal GR20-SV1. In the opposite direction, a consideration was only carried out from the exit signal of the station. The average block length with 1217 m is comparable. The 18 block sections can also be divided into one to four subsections.

Table 44: Block length Dugo Selo – Zagreb Main Station via Main track

Source: Table based on results of the OpenTrack simulation – Railway node Sesvete

No.	Location	Signal type	From	To	Block length [m]	Divided into
1	DS	Home signal	DS B	DS E3	1223	2
2	DS	Exit signal	DS E3	Bs15	1369	3
3	DS-SKR	Block signal	Bs15	Bs13	1367	3
4	DS-SKR	Block signal	Bs13	Bs11	1200	2
5	SKR	Block signal	Bs11	Bs9	1230	2
6	SKR-SSV	Block signal	Bs9	Bs7	1330	3
7	SKR-SSV	Block signal	Bs7	Bs5	1298	3
8	SKR-SSV	Block signal	Bs5	SSV B	998	2
9	SSV	Home signal	SSV B	SSV E3	1459	3
10	SSV	Exit signal	SSV E3	562	1190	2
11	CLN-SSV	Block signal	572	572	1030	2
12	CLN-SSV	Block signal	572	CLN A	725	1
13	CLN	Home signal	CLN A	K	907	2
14	TRN	Protecting signal	K	BRG G21	2102	4
15	BRG	Protecting signal	BRG G21	MKS E2	979	2
16	MKS	Exit signal	MKS E2	Bs1	753	2
17	MKS-ZGGK	Block signal	Bs1	SSV G	1254	3
18	ZGGK	Home signal	SSV G	GR20V-S1	1490	3
				Average block length	**1217**	

The line length between Zagreb Resnik and Sesvete is with 3.146 km much shorter. It presents three block sections, which can be seen in Table 45.

Table 45: Block length Zagreb Resnik – Sesvete

Source: Table based on results of the OpenTrack simulation – Railway node Sesvete

No.	Location	Signal type	From	To	Block length [m]	Divided into
1	ZGRS	Exit signal	ZGRS D2	SSV C	1592	3
2	SSV	Home signal	SSV C	SSV D6	904	2
3	SSV	Exit signal	SSV D6	Bs4	650	1
				Average block length	**1049**	

Table 46 shows the section from Sesvete to Zagreb Resnik. The consideration begins at the home signal from the direction of Dugo Selo, because the route is crossing there the track in the direction to Dugo Selo.

Table 46: Block length Sesvete – Zagreb Resnik

Source: Table based on results of the OpenTrack simulation – Railway node Sesvete

No.	Location	Signal type	From	To	Block length [m]	Divided into
1	SSV	Home signal	SSV B	SSV E5	1408	3
2	SSV-ZGRS	Exit signal	SSV E5	ZGRS A	1473	3
3	ZGRS	Home signal	ZGRS A	ZGRS E3	1239	2
				Average block length	**1373**	

Table 47 shows the side track of the section between Čulinec and Maksimir. With 4.673 km it presents approximately an identical length like the other direction (Table 48). The four blocks can be divided for both directions in subsections between two and three parts.

Table 47: Block length Čulinec – Maksimir

Source: Table based on results of the OpenTrack simulation – Railway node Sesvete

No.	Location	Signal type	From	To	Block length [m]	Divided into
1	CLN	Home signal	CLN A	CLN G12	1640	3
2	TRN	Protecting signal	CLN G12	TRN G11	1292	3
3	BRG	Protecting signal	TRN G11	BRG E1	832	2
4	MKS	Exit signal	BRG E1	Bs1	909	2
				Average block length	**1168**	

Table 48: Block length Maksimir – Čulinec

Source: Table based on results of the OpenTrack simulation – Railway node Sesvete

No.	Location	Signal type	From	To	Block length [m]	Divided into
1	MKS	Home signal	MKS B	MKS G4	1070	2
2	BRG	Protecting signal	MKS G4	TRN G41	1508	3
3	TRN	Protecting signal	TRN G41	CLN D4	1036	2
4	CLN	Exit signal	CLN D4	571	866	2
				Average block length	**1120**	

Appendix J Raw data railway node Sesvete

In Table 49, 50, 51 and 52 the raw data for the trains described in Chapter 4.3 (Railway node Sesvete) are listed.

Table 49: Raw data Headways [s] for railway node Sesvete part one

Source: Table based on the results of the OpenTrack Version 1.10.3 – Simulation railway node Sesvete

First train	8002	8002	8002	8002	8004	8004	8004	8004
Second train	8002	8004	8006	8008	8002	8004	8006	8008
Base Variant	633	345	71	71	688	409	688	409
ETCS	654	368	72	72	711	368	69	69
ETCS Track Speed	654	729	72	72	239	218	23	23
ETCS 500 m Block	245	649	100		124	159		12
ETCS Moving Block	105	105	120	17	105	105	105	4

Table 50: Raw data Headways [s] for railway node Sesvete part two

Source: Table based on the results of the OpenTrack Version 1.10.3 – Simulation railway node Sesvete

First train	8006	8006	8006	8006	8008	8008	8008	8008
Second train	8002	8004	8006	8008	8002	8004	8006	8008
Base Variant	68	68	624	368	665	409	359	359
ETCS	654	388	335	335	692	426	373	373
ETCS Track Speed	654	305	335	335	653	352	334	343
ETCS 500 m Block	204	224	204	21	78	322	14	222
ETCS Moving Block	136	136	120	17	136	136	21	121

Table 51: Raw data Headways [s] for railway node Sesvete part three

Source: Table based on the results of the OpenTrack Version 1.10.3 – Simulation railway node Sesvete

First train	5002	5002	5002	5004	5004	5005	5005
Second train	5002	5004	5005	5002	5004	5002	5005
Base Variant	374	374	87	291	633	128	348
ETCS	374	374	87	291	654	121	359
ETCS Track Speed	318	318	87	218	654	104	245
ETCS 500 m Block	196	221	62	114	245		214
ETCS Moving Block	74	174	51	9	105	42	106

Table 52: Raw data Headways [s] for railway node Sesvete part four

Table based on the results of the OpenTrack Version 1.10.3 – Simulation railway node Sesvete

First train	1001	1001	1003	1003	1003	1005	1005	1007	1007	1007
Second train	1001	1003	1001	1003	1005	1005	1007	1003	1005	1007
Base Variant	294	232	177	342	155	303	15	133	16	325
ETCS	294	234	202	359	162	193	17	134	17	339
ETCS Track Speed	240	178	154	359	160	192	16	134	17	316
ETCS 500 m Block	182	164	144	214	165	53	16	117	156	205
ETCS Moving Block	72	77	43	106	95	95	10	40	11	95

Appendix K Raw data fictive railway node A2

In Table 53 & 54 the raw data for the trains described in Chapter 4.6 (Fictive railway node A2) are listed.

Table 53: Raw data Headways [s] for fictive railway node A2 part one

Source: Table based on Results of OpenTrack Version 1.10.3 – Simulation Fictive railway node A2

First train	2000	2000	2000	2000	2000	2300	2300	2300	2300	2300
Second train	2000	2300	2301	7000	7001	2000	2300	2301	7000	7001
Base Variant	266	112	127	127	127	123	292	192	125	185
ETCS	255		126	122			286	192	137	
ETCS Track Speed	255		94	113			217	126	105	
ETCS 200 m Block	255		94	68			110	126	53	61
ETCS Moving Block	96		85	34			85	119	18	

Table 54: Raw data Headways [s] for fictive railway node A2 part two

Source: Table based on Results of OpenTrack Version 1.10.3 – Simulation Fictive railway node A2

First train	2301	2301	2301	2301	2301	7000	7000	7000	7000	7000
Second train	2000	2300	2301	7000	7001	2000	2300	2301	7000	7001
Base Variant	69	745	391	813	391	142	292	212	828	204
ETCS		741	391	819	391	142	291	212	857	204
ETCS Track Speed		523	209	597	209	117	245	154	792	178
ETCS 200 m Block		469	152	527	77	49	162	154	678	88
ETCS Moving Block		520	81	589	35	13	133	147	663	71

Appendix L Used rolling stock data

This part of the appendix describes which vehicles are used for the simulation. The technical parameters that are relevant for this work are described. In addition, a sketch from *Vagonweb* and *Bahnschranke* are included to give a better idea of the vehicle. Furthermore, the tractive effort diagram is given, which is used in the simulation.

The following vehicles are used in the simulation:

- Electrical Multiple Unit (EMU) ÖBB Talent 4024 (Table 55, Figure 94 & 95),
- EMU ET 50+50+50 (Table 56, Figure 96 & 97)
- EMU HŽPP 6112 (Table 57, Figure 98 & 99),
- Electrical locomotive HŽ Cargo 1141 (Table 58, Figure 100 & 101),
- Electrical locomotive HŽPP 1142 (Table 59, Figure 102 & 103),
- Electrical locomotive Vectron 193 (Table 60,Figure 104 & 105),
- EMU ÖBB Desiro ML 4746 (Table 61, Figure 106 & 107),
- Electrical locomote CAT ÖBB 1016 (Table 62, Figure 108).

Electrical Multiple Unit (EMU) ÖBB 4024

Table 55: Technical Data EMU ÖBB 4024

Source: Data taken from (Bombardier Transportation, 2023, pp. 9–20; G. Singer, Interview, 20 March 2023, ll. 53–57)

Description	Value
Type	EMU
Maximum speed [km/h]	140
Total weight [t]	116
Length [m]	67
Used train protection system	PZB for Simulation also ETCS + (TIMS)
Braked weight percentage [%]	150
Deceleration [m/s²]	-0,669
Deceleration delay [s]	5

Sketch of the vehicle:

Figure 94: EMU ÖBB 4024

Source: Picture taken from Dvořák (2022c)

Tractive effort diagram:

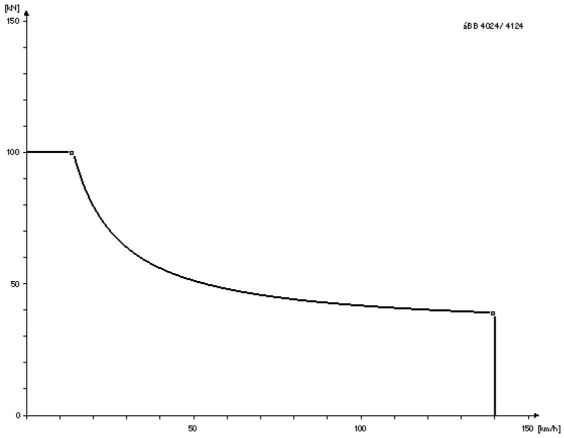

Figure 95: Traction effort diagram EMU ÖBB 4024

Source: Diagram taken from OpenTrack Version 1.10.3 – Simulation Fictive railway line

EMU ET 50+50+50

Table 56: Technical Data EMU ET 50+50+50 (3x ET 40 NF)

Source: Data taken from Schöbel (2022)

Description	**Value**
Type	EMU
Maximum speed [km/h]	80
Total weight [t]	114
Length [m]	190,8
Used train protection system	PZB for Simulation also ETCS
Braked weight percentage [%]	156
Deceleration [m/s²]	-1,005
Deceleration delay [s]	5

Sketch of the vehicle:

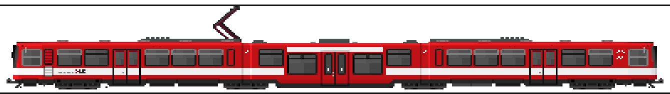

Figure 96: EMU ET 50+50+50

Source: Picture adapted and taken from Laffin (2019)

Tractive effort diagram:

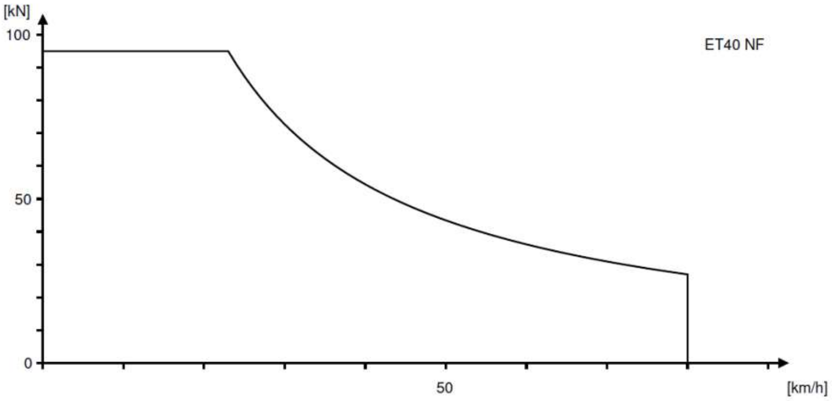

Figure 97: Traction effort diagram EMU ET 40 NF

Source: Diagram taken from Schöbel (2022)

EMU - Hrvatska Željeznice Putnički Prijevoz (HŽPP) 6112

Table 57: Technical Data EMU HŽPP 6112

Source: Data taken from Haramina (2022)

Description	**Value**
Type	EMU
Maximum speed [km/h]	160
Total weight [t]	175
Length [m]	75
Used train protection system	PZB, ETCS
Braked weight percentage [%]	99
Deceleration [m/s²]	-0,663
Deceleration delay [s]	5

Sketch of the vehicle:

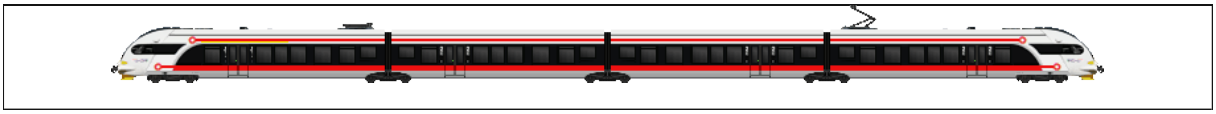

Figure 98: EMU HŽPP 6112

Source: Picture taken from Dvořák (2022b)

Tractive effort diagram:

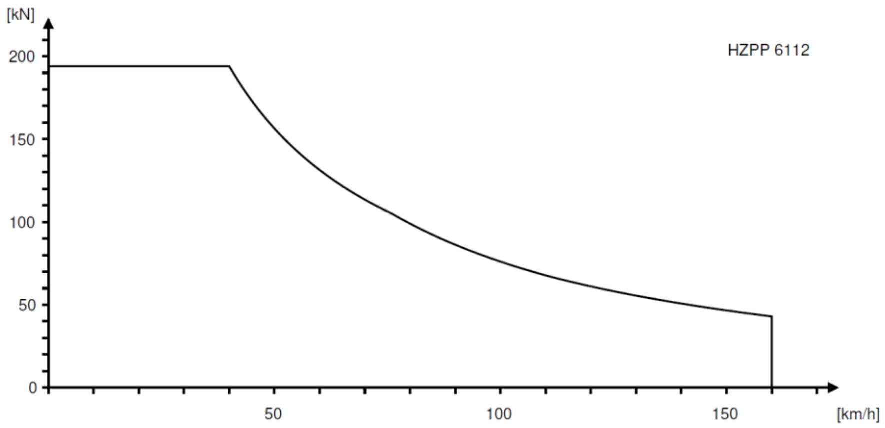

Figure 99: Traction effort diagram EMU HZPP 6112

Source: Diagram taken from Haramina (2022)

Electrical Locomotive - Hrvatska Željeznice Cargo (HŽ Cargo) 1141

Table 58: Technical Data HZPP 1141

Source: Data taken from Haramina (2022)

Description	Value
Type	Electro locomotive
Maximum speed [km/h]	120
Total weight [t]	81
Length [m]	15
Used train protection system	PZB
Braked weight percentage [%]	50
Deceleration [m/s²]	-0,6
Deceleration delay [s]	8

Sketch of the vehicle:

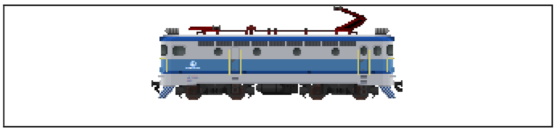

Figure 100: EMU HZPP 1141

Source: Picture taken from Dvořák (2022a)

Tractive effort diagram:

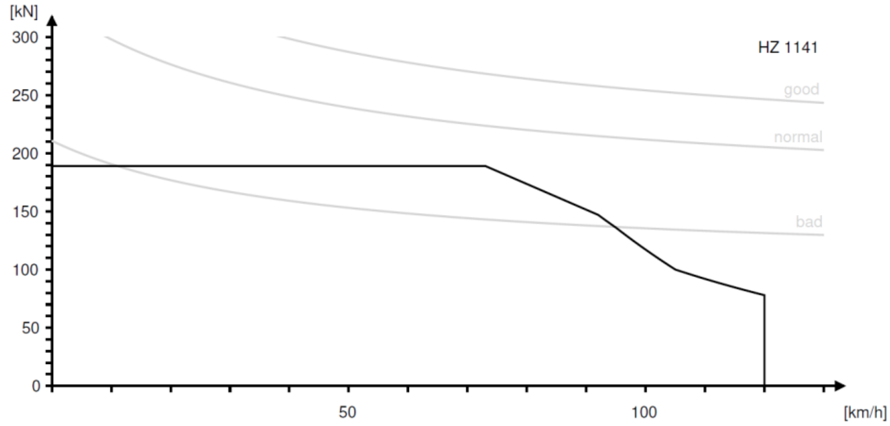

Figure 101: Traction effort diagram HŽ Cargo 1141

Source: Diagram taken from Haramina (2022)

Electrical Locomotive - Hrvatska Selenic Putnički Prijevoz (HŽPP) 1142

Table 59: Technical Data HZPP 1142

Source: Data taken from Haramina (2022)

Description	**Value**
Type	Electro locomotive
Maximum speed [km/h]	160
Total weight [t]	82
Length [m]	16
Used train protection system	PZB
Braked weight percentage [%]	100
Deceleration [m/s²]	-0,669
Deceleration delay [s]	5

Sketch of the vehicle:

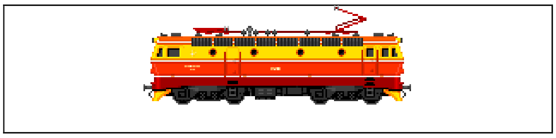

Figure 102: EMU HZPP 1142

Source: Picture taken from Dvořák (2022a)

Tractive effort diagram:

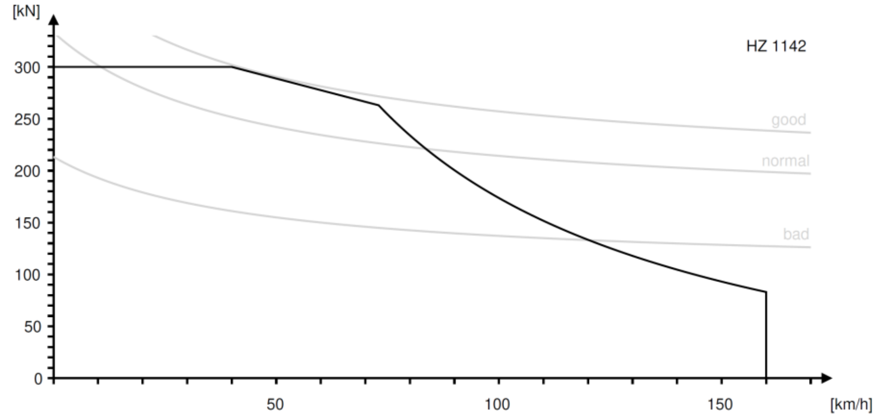

Figure 103: Traction effort diagram HŽPP 1142

Source: Diagram taken from Haramina (2022)

Electrical Locomotive - Vectron 193

Table 60: Technical Data 193

Source: Diagram taken from OpenTrack Version 1.10.3 – Simulation Fictive railway line

Description	**Value**
Type	Electro locomotive
Maximum speed [km/h]	160
Total weight [t]	90
Length [m]	19
Used train protection system	PZB, ETCS
Braked weight percentage [%]	50
Deceleration [m/s²]	-0,369
Deceleration delay [s]	8

Sketch of the vehicle:

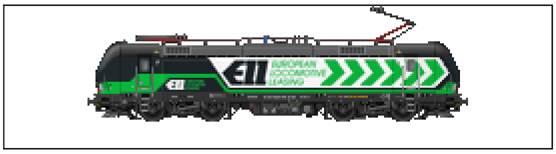

Figure 104: Vectron 193

Source: Picture taken from: Dvořák (2023)

Tractive effort diagram:

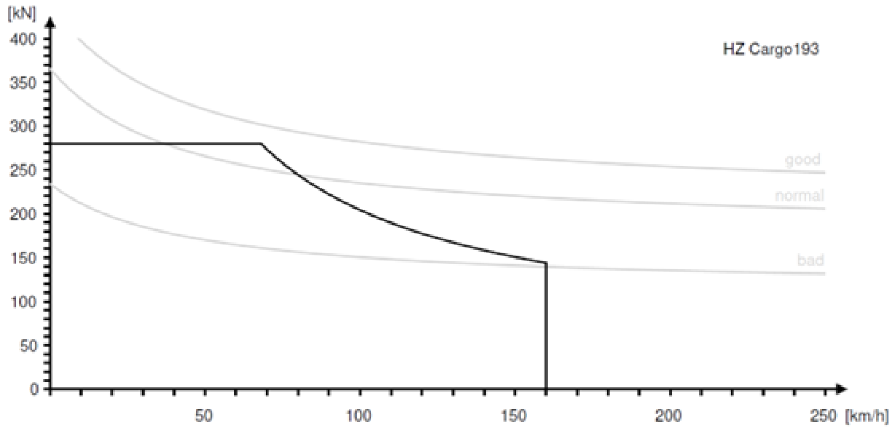

Figure 105: Traction effort diagram 193

Source: Diagram taken from OpenTrack Version 1.10.3 – Simulation Fictive railway line

EMU - ÖBB 4746 Desiro ML

Table 61: Technical Data EMU ÖBB 4746

Source: Data taken from (G. Singer, Interview, 20 March 2023, ll. 56–57)

Description	**Value**
Type	EMU
Maximum speed [km/h]	160
Total weight [t]	144
Length [m]	75
Used train protection system	PZB + ETCS for Simulation also TIMS
Braked weight percentage [%]	199
Deceleration [m/s²]	-1.263
Deceleration delay [s]	5

Sketch of the vehicle:

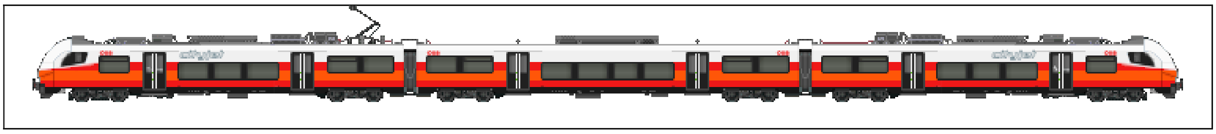

Figure 106: EMU ÖBB 4746

Source: Picture taken from Dvořák (2022c)

Tractive effort diagram:

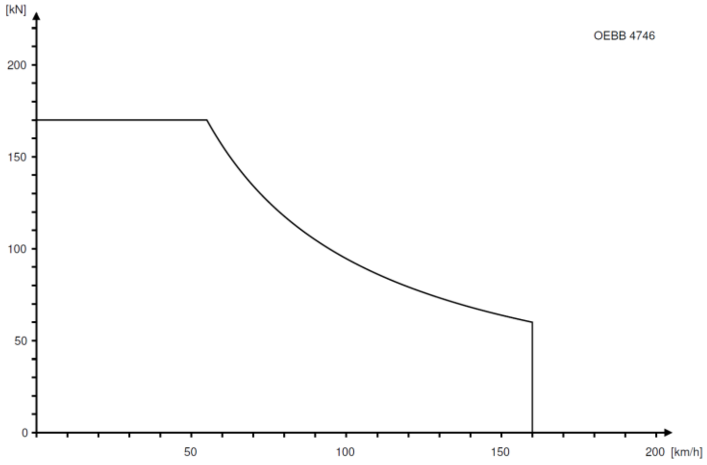

Figure 107: Traction effort diagram EMU ÖBB 4746

Source: Diagram taken from OpenTrack Version 1.10.3 – Simulation Fictive railway line

Electrical Locomotive - CAT ÖBB 1016

Table 62: Technical Data CAT ÖBB 1016
Source: Data taken from Wirth (2019)

Description	**Value**
Type	Electro locomotive
Maximum speed [km/h]	230
Total weight [t]	86
Length [m]	19
Used train protection system	PZB, ETCS
Braked weight percentage [%]	120
Deceleration [m/s²]	-0,789
Deceleration delay [s]	5

Sketch of the vehicle:

Figure 108: CAT ÖBB 1016
Source: Picture taken from Dvořák (2022c)

Tractive effort diagram:

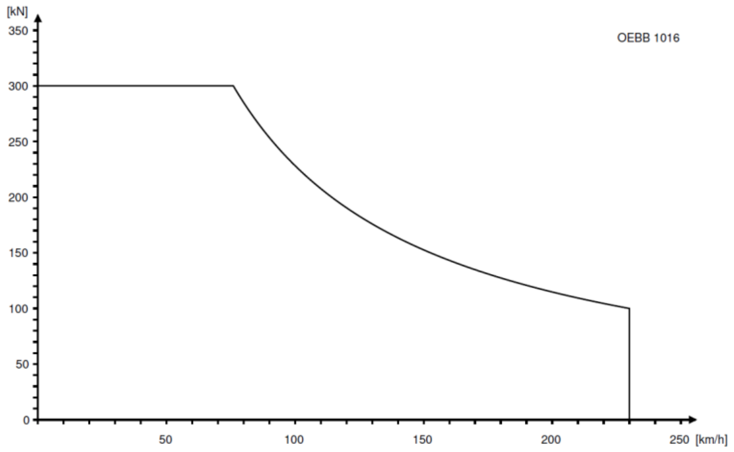

Figure 109: Traction effort diagram 1016
Source: Diagram taken from Wirth (2019)