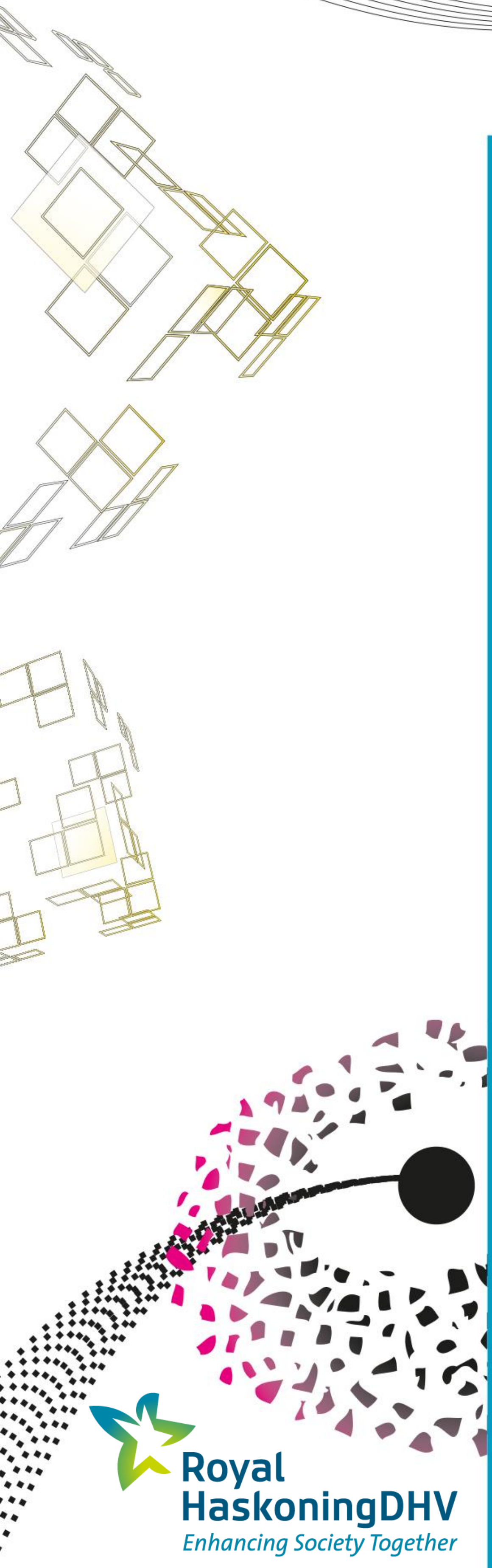

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RAILWAY CAPACITY EFFECTS OF ERTMS, 3 KV DC OVERHEAD POWER AND ATO ON A DUTCH RAILWAY NETWORK

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PREFACE

This thesis marks the completion of my study in Civil Engineering and Management at the University of Twente. Over the past six months, I explored the railway capacity implications of different measures. This subject connected with my interest in the public transport sector, especially the heavy rail sector. I hope my research can provide some insights into what measures should be prioritised for RHDHV, ProRail and NS.

This thesis would not be written without the guidance and feedback I received from my supervisors both at RHDHV and the University of Twente. Therefore, I would like to thank Wouter and Barth for the guidance, feedback about the research goal, good conversations during the lunch and the much-needed guidance with OpenTrack, **or OD as an intern called it**. On the University side, I would like to thank Kostas and Eric for their guidance during the proposal phase of the thesis, providing feedback on the questions and helping me to create a suitable assessment framework. Of course, I would also like to thank Oskar for supervising me over the last six months at the university. Your feedback on the reporting and taking my Christmas break helped me find some moments of reflection during the research.

Over the last six and a half years, I rode the rollercoaster they call student life. During my studies, I had sufficient challenges in organizing events like the annual ConcepT symposium in 2020, with the theme Breaking Barriers. But also with the Volleyball association, where I had an incredible two years on the technical committee, overcoming the challenges of the pandemic that hit during my masters.

Further, I would like to thank everyone who provided some much-needed relaxation and distractions during my sometimes exhausting period of waking up at 5 in the morning to catch the (comfortable) IC towards Utrecht to work at the office. Some examples of this relaxation were the practices with my volleyball team and the movie nights I had with my roommates and some friends.

Finally, I want to thank my parents and brother for supporting me both in a contextual and time-management place. Without their support, I would not have done the several extra activities next to my studies over my six-and-a-half-year journey at the University of Twente. I enjoyed my experience as a student at the University of Twente, where everyone was always willing to help.

I hope you will enjoy reading my report about my master's thesis.

Martijn van Arem

Enschede, March 2023

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SUMMARY

In previous years, NS and ProRail always aimed to provide more frequent service on the Dutch railway network. With this as a goal, the number of trains on the network approached the maximum capacity considering the current safety system, power supply and train control system. The SAAL project increases the frequency of trains on the route from the timetable of 2030. This project focuses on the subnetwork of Schiphol, Amsterdam, Almere and Lelystad. Unfortunately, the intercity services at Amsterdam Central station in the direction of Weesp and back are removed with this project. For intercity passengers, this increases the travel time towards Amsterdam Central station, as they now need to use the slower sprinter services. This research aims to increase the railway network capacity by other means than building extra tracks. After this, the opportunity to reintroduce the intercity service between Hilversum and Amsterdam central station is investigated.

Currently, ProRail is implementing ERTMS/ETCS (European rail traffic management system/European train control system) level 2 on the first parts of the Dutch network, intending to use this signalling system on the whole network eventually. The goal of ERTMS/ETCS is to increase the railway network's safety and interconnectivity with the European railway networks. Another intended change is increasing the overhead current from 1,5 kV DC to 3 kV DC, allowing trains to have an extended period of maximum tractive effort. Further benefits of increasing the overhead current are reduced energy loss due to the higher voltage on the power supply and a more significant benefit from regenerative braking. A third system tested by ProRail is Automatic Train Operation (ATO), with tests conducted on passenger and freight trains for the Dutch network.

An unintended benefit of these systems is the advantageous capacity effects on the network. ERTMS/ETCS increases awareness of location data of the trains and changes the method of providing movement authority to trains, combined with moving the signalling to the driver from the trackside towards inside the cabin. While ERTMS/ETCS level 2 increases the capacity performance of the safety systems, a 3 kV DC overhead current allows trains to exit signalling sections faster, thus reducing the blocking time of these sections. This allows the next train to use those tracks after a shorter time interval. With ATO, safety margins reduce, and the predictability of trains increases. These advantages let the schedulers plan the trains closer together compared to the current situation. Therefore, these three measures individually show their option to increase the number of trains.

A literature study found that reports often investigate these measures individually using line case studies. At the same time, combining the measures and investigating their interactions provides insight into the effectiveness of implementing measures simultaneously on a larger network area. Another finding was the disability of the individual measures of providing sufficient extra capacity to introduce new services. Considering these two findings in the literature, this research aims to close the gap between the individual and combined capacity effects of the measures on the line and network levels.

In line with previous research, this report uses a case study to find the capacity effects of the measures. As one of the aims is the reintroduction of an intercity towards Amsterdam, the network case study includes the routes from Amsterdam to Amersfoort (Gooi line) and the route from Amsterdam Zuid to Almere (part of the SAAL line). These interact near Weesp, joining and then splitting once again. To investigate the combined effects of the measures, the line between Hilversum and Weesp was used as a case study. By using an OpenTrack model, the capacity consumption of the proposed 2030 timetable was investigated.

Table 1: Capacity consumption results from the case studies

	Capacity consumption Line	Capacity consumption Network	Capacity consumption additional train
NS’54/ATB-EG	91,9%	N/A	N/A
NS’54/ATB-EG + 3 kV DC	89,8%	N/A	N/A
NS’54/ATB-EG + ATO	88,3%	N/A	N/A
ERTMS/ETCS level 2	86,2%	96,6%	107,7%
ERTMS/ETCS level 2 + 3 kV DC	84,9%	93,8%	106,5%
ERTMS/ETCS level 2 + ATO	73,3%	85,2%	97,6%
ERTMS/ETCS level 2 + ATO + 3 kV DC	71,8%	82,5%	95,3%

The first part of the simulations investigated the effects of ERTMS/ETCS, 3 kV DC overhead current and ATO over the current situation on a line case study. The results showed that ERTMS/ETCS level 2 was most effective in reducing the capacity consumption, followed by ATO and eventually 3 kV DC overhead current, shown in column 2, rows two to five of Table 1. Column 2, rows six to eight, provides the line case study results with ERTMS/ETCS level 2 signalling system combined with 3 kV DC and ATO.

The first interaction found in this case study is the different effects 3 kV DC overhead current and ATO have under NS’54/ATB-EG (current Dutch signalling system/ “Automatische Trein Beïnvloeding – Eerste Generatie”) and ERTMS/ETCS level 2. Where the effect of 3 kV DC with NS’54/ATB-EG is a 2,1% point reduction, this effect reduces to 1,3% point under ERTMS/ETCS level 2. In contrast to 3 kV DC, ATO provides extra benefits with ERTMS/ETCS level 2 compared to ATB-EG, increasing from a 3,6% point to a 12,9% point reduction in capacity consumption on the line case. The difference in capacity consumption effects between NS’54/ATB-EG and ERTMS/ETCS level 2 is the way of providing movement authority to the vehicles. With ERTMS/ETCS level 2, the movement authority is based on the braking curve of the actual vehicle with quick release after the trackside infrastructure detects that the train has passed. While NS’54/ATB-EG provides movement authority on a block entrance basis as no exact location of trains is known.

The final scenario shows that the improvement by ATO actually increases the effect of 3 kV DC under ERTMS/ETCS level 2. Increased deceleration under braking from ATO complements the faster acceleration of 3 kV DC under the ERTMS/ETCS level 2 signalling system with braking-based movement authority. With the improved braking, the ETCS braking curves need less distance headway to allow conflict-free operations. Therefore trains can depart after shorter intervals from the stations. The explanation is the increased deceleration under braking of ATO over conventional trains. This improved braking reduces the reserved distance under ERTMS/ETCS level 2 in front of the train, which is needed for track speed movement authority.

The effect of the network elements in the case study resulted in minor differences in the reductions of the capacity consumption for the measures. This difference results from the movement of the bottlenecks from Hilversum and Weesp on the line case study to edge stations and Weesp in the network case. The distances between bottlenecks of the different train-type interactions move further apart. Thus the initial capacity under the ERTMS/ETCS level 2 scenario is 10,4% points higher than the line study.

With the capacity consumption reductions changing slightly between the measures, the network infrastructure is the most influential factor in capacity consumption reductions. The final reduction of ERTMS/ETCS level 2, 3 kV DC and ATO is comparable between the line and network case studies with just a 0,3% point difference, where the line case study found the larger reduction.

To answer the question of whether an intercity between Amsterdam Central station and Amersfoort is possible, a train path is proposed after the freight trains on the Gooi line. This timing requires a high track capacity, as the intercity train speed is significantly higher than the freight train. This analysis uses the found capacity consumption reduction for the intercity between Amsterdam and Amersfoort. For ERTMS/ETCS level 2 with and without 3 kV DC overhead power, the capacity consumption is higher than 100%, showing that the required time for conflict-free dispatching of trains is more than the planning in the timetable.

With ERTMS/ETCS level 2 and ATO, the timetable's capacity consumption, including the additional train paths, is a maximum of 99,6% at track 4 in Weesp. This capacity consumption includes the safety factors of the Dutch assessment method. When including 3 kV DC overhead power with ERTMS/ETCS level 2 and ATO, the capacity consumption is reduced to a maximum of 97,5%, providing some extra buffer times for trains to catch delays while providing a faster alternative between Amsterdam Central station and Amersfoort. Therefore, further investment into ATO is recommended for both creating an option to increase the robustness of the timetable and the opportunity of providing an intercity service between Amsterdam Central station and Amersfoort. Upgrading to both 3 kV DC and ERTMS/ETCS will provide further capacity benefits as side effects of these measures.

TABLE OF CONTENT

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1. INTRODUCTION

Within the introduction, first, the problem description for the research is given (Section 1.1). From this problem description, a research goal is derived in Section 1.3. To achieve the research goal, a set of questions is provided in Section 1.4. Section 1.5 outlines the methodology used to answer the question.

1.1 PROBLEM DESCRIPTION

The Dutch railway network's utilisation has approached the current systems and infrastructure capacity limit. Therefore, the number of trains on the infrastructure approaches the upper bound of a stable railway network (Kerssies, 2019). The programmes like Programma Hoog frequent Spoor or pilot projects with high-frequency timetables like every ten minutes a train ask for an increase in the number of trains per hour. Ideally, the time interval between the trains on the routes in these programs is ten minutes or less (Ministry of I&W, 2019). The current projects design infrastructure for the proposed interval between trains considering the future timetable. An area on the Dutch network not in the scope of the improvement programs but reaching the maximum number of trains for the current infrastructural limitations is the Gooi line, which runs from Amersfoort to Amsterdam.

A neighbouring route that influences operations on the Gooi line is the SAAL (Schiphol, Amsterdam, Almere Lelystad) line. Option model II of the 2030 timetable for the SAAL line changes some routes in the greater Amsterdam Area (van Wijk, 2020). This change also affects some trains on the Gooi line. On both the Gooi and SAAL lines, all intercity services towards Amsterdam central station are either replaced by sprinter services or redirected towards Amsterdam Zuid. For passengers to Amsterdam Central station, the travel time increases compared to when they originally travelled by intercity. The Ministry of Infrastructure and Waterstaat Recently published a document stating the desire to have an intercity service towards Amsterdam Central Station (Ministry of I&W, 2022). As there is no room to expand the infrastructure along most of the Gooi and SAAL lines, alternative measures are required to alter the number of trains on the lines.

ProRail already considers three measures for implementation on their railway network (ProRail, 2016, 2021c, 2022). The increase in the number of tracks is not feasible as there is no room available on most routes and the extra tracks' costs. The proposed measures are as follows; firstly, a change in the safety and signalling system from NS'54 and the Dutch train protection system “Automatische Trein Beïnvloeding – Eerste Generatie” (ATB-EG) to European Rail Traffic Management System (ERTMS) with the included automatic train protection system of European Train Control System (ETCS) level 2; secondly, the increase in overhead current from 1500 V DC to 3000 V DC; and thirdly, the implementation of Automatic Train Operations (ATO) on the Dutch network.

Although possibly not the direct purpose of the interventions, the three aforementioned measures are also likely to improve the network's operational efficiency (de Pundert et al., 2010; Reijnen, 2017; Vergroesen, 2020). Still, ERTMS/ETCS level 2 and the increase to 3 kV DC overhead current did not individually increase the number of train paths over the situation. In contrast, Vergroesen (2020) proved that ATO increased efficiency under ERTMS/ETCS level 3. The combination of these three measures provides a good effect on the capacity of the Dutch railway network and is investigated within this research.

1.2 RESEARCH GAP

In the literature, multiple papers investigate the effects of different measures. A typical approach in these papers is to investigate a single measure on a simulated line. Table 2 gives an overview of relevant studies investigating the effects on the capacity of the railway for the mentioned measures, illustrating that relevant capacity studies often consider either multiple signalling systems combined with another measure or replacing the line case study with a network study. A V in Table 2 indicates the measure's presence and the case study type.

An early study of the capacity effects of ERTMS/ETCS level 2 found a 10% increase in railway capacity (Barter, 2008). This study found the effects of a line case study for a passenger service towards London’s Charing Cross without network interactions. A study of the Italian railway network found an increase in the capacity to a 3-minute time headway between trains at the station of Florance (Colla et al., 2018). This research aimed to eliminate delays due to an overused network, which was possible with the 10% capacity increase.

Further, Ljubaj et al. (2018) found an increase in capacity from the current signalling system in Croatia and ERTMS level 2 on a single-tracked railway line of 30 extra train paths a day, allowing 50% more trains a day on the railway line, this study included some alterations to the infrastructure. The Dutch situation is different, with a decreased use capacity in the railway found of 9% point with ERTMS/ETCS level 2 over NS’54/ATB-EG (Jansen, 2019; Vergroesen, 2020). Both studies considered this capacity benefit insufficient for implementing new train paths for the Dutch network. Thus, the nature of the traffic composition and infrastructure layout is essential for the effects of the measurement.

Within both these reports, ERTMS/ETCS hybrid level 3's capacity effects were also investigated and allowed for an average decrease of 16,5% point in the capacity decrease. A train path increase is possible in the line case study in the report of Jansen (2019) but not in the network study of Vergroessen (2020), indicating the importance of the network elements and further underlining the importance of a correct case study location.

For the increase in power supply, a benefit of 4,3% point was found under NS’54/ATB-EG. This increase is roughly half compared to ERTMS/ETCS level 2 (Reijnen, 2017). However, combined, there might be an option to allow for further capacity benefits. The final promising measure is ATO, where Vergroessen (2020) found a decrease in the capacity consumption of 30-43% points combined with ERTMS/ETCS hybrid level 3. The range in reduction is due to the difference in buffer time implemented for the trains. This capacity effect was, obviously, able to increase the number of train paths on the network study.

Most relevant research investigated (multiple) signalling systems on a line case study. 3 kV DC overhead current is not investigated for the Dutch situation with ERTMS/ETCS (Reijnen, 2017). Furthermore, the only combination of future scenarios was the combination of ERTMS/ETCS level 2 to hybrid level 3 (Vergroesen, 2020).

Further, the literature often focuses on the measure's effects on a line case study. For the Dutch situation, namely an interconnected railway network, the effects of a line study will not directly translate to a network study. The reason for this is the potential change of bottleneck locations. A long stretch of railway line without network elements is more likely to have a bottleneck at the start or end of the considered area than an interconnected network. The stations or switching areas in a network are often the bottlenecks (Bazant & Vesely, 2015).

Table 2: Overview of capacity studies in the literature.

Author	ERTMS/ETCS	3 kV DC or change in current	ATO	Line	Network
Vergroessen (2020)	Level 2/Hybrid level 3		V		V
Reijnen (2017)	N/A	V		V	
Jansen (2019)	From level 1 to Hybrid Level 3			V	
Colla et al. (2018)	High-density level 2				V
Barter (2008)	Level 2			V	
Van der Meulen (2022)	Level 3			V	
Ljubaj et al. (2018)	Level 2			V	

1.3 RESEARCH GOAL

This research aims to investigate the capacity effects of ERTMS/ETCS level 2, 3 kV DC and ATO over the current infrastructure of The Netherlands. The capacity effects might be able to facilitate new train paths. Next, there is a possible difference in capacity effects between implementing the measures on a line and a network as the desire exists for an intercity service towards Amsterdam Central station combined with the proposed train pattern in the SAAL model II. This research aims to combine the investigation of the translation of effects of measures from a railway line to railway network capacity. Therefore, this research aims to investigate to which extent the combination of ERTMS/ETCS level 2, 3 kV DC overhead current and ATO can enable the addition of a train path on heavily used railway lines in the network, such as the Dutch situation.

1.4 RESEARCH QUESTIONS

As introduced in Section 2.2, a set of questions were drawn up to reach the research goal. This set of questions contains the following main research question:

What are the differences when comparing the individual capacity effects of the implementation of ERTMS/ETCS level 2, increasing the overhead current to 3 kV DC and the implementation of ATO with combinations of the measures on a line and network level?

To answer this question, a set of subquestions is formulated to structure the research. These questions will serve different goals. The first subquestion aims to give some insight into the theoretical advantages of each measure. Afterwards, the second subquestion uses microsimulation to investigate the effects of the different measures on a line, with the third question continuing on this by expanding to the network effects. Lastly, the fourth question aims to give direction towards the research goal and introduce new train paths to the network. Therefore, the set of subquestions is:

1. What are the individual capacity effects of ERTMS/ETCS level 2, the increase to 3 kV DC overhead current and ATO?
2. What is the (combined) line capacity effect of ERTMS/ETCS level 2, the increase to 3 kV DC overhead current and ATO?
3. What are the differences in effects of the individual and combined measures when considering line and network capacity?
4. Is there an opportunity to increase the number of trains on a network using the combined effects of the different measures when looking at the Gooi line?

1.5 METHODOLOGY

The research questions are answered using two main methods. For the first question, information is gathered about the different measures and requirements for the network. For the answer to questions two, three and four, a simulation is used to generate the answer.

1.5.1 Information gathering

Information about the different measures is required to answer the first question. This information is gathered in two ways, as a literature search will not suffice to find the modelling implications of the three measures. Interviews with experts will confirm the findings of the technical details found in the literature search and provide the current methods of mirroring the measures in microsimulation models. This combination of methods closes the gap between international and Dutch simulation practices.

1.5.2 Simulation

As the measures introduced in Section 1.1 are costly to implement, a standard tool researchers use is microsimulation. A simulation will also be the method used to investigate the effects of the measures in terms of travel time and capacity effects. Several software packages are suitable for the task of assessing the measures. Options used in the past are RailSys and OpenTrack, these two software packages are the most used microsimulation packages in the railway industry and research (Zinser et al., 2018). In the literature, both options are viable alternatives to evaluate capacity effects. For a short overview of examples, see Table 3.

Table 3: Examples of research using either OpenTrack or RailSys

OpenTrack	(Cuppi et al. (2021), Dicembre & Ricci (2011), Ljubaj et al. (2018) Tischer et al. (2020)
RailSys	Jansen (2019), Mattalia (2007), Reijnen (2017), Rosberg & Thorslund (2020), Vergroesen (2020)

When using a simulation to test a newly proposed measure, the aim is to estimate the measure's effects as closely as possible (Abril et al., 2008). Microsimulation is an effective tool, as implementing the measures in an in-situ test is expensive, whereas a software licence is much cheaper. The simulation package can approach the Dutch situation with a high level of detail. Nash and Huerlimann (2004) listed three main reasons why simulation software helps evaluate future strategies in the railway industries:

1. Understanding of rail line capacity
2. Understanding the overall impact of the alternation of the intensively interrelated infrastructure in the network
3. Reduce long-term operating costs due to poor planning on infrastructure.

As mentioned, two specific simulation packages are often used for the microscopic simulation of a railway network: RailSys and OpenTrack (Opentrack Railway Technology Ltd., 2020; Rail Management Consultants International GmbH, 2022). Both these packages are specifically designed to simulate a railway system and, thus, have many variables aimed at mirroring any railway system as closely as possible. Some of the information these microsimulations can provide for the evaluation of future measures on a railway system is (Opentrack Railway Technology Ltd., 2020):

- The analysation of the capacity of lines and stations
- Calculation of minimum headways
- Rolling stock studies

- Running time calculation
- Timetable construction
- Evaluating and designing various signalling systems

These tools allow for implementing different measures by changing the input, which helps estimate the effects of these measures. For example, changing the signalling system towards ERTMS/ETCS will change how trains gain movement authority on the network. In comparison, ATO changes the actual behaviour of the vehicles.

The developers of Both RailSys and OpenTrack claim that these assessments can be made with their packages (Opentrack Railway Technology Ltd., 2020; Rail Management Consultants International GmbH, 2022). Within the literature, RailSys is the more commonly used tool for capacity assessment. The reasoning behind this is the inclusion of a timetable compression tool within the package of RailSys, which is not available in OpenTrack. The timetable assessment method is introduced in more detail in Section 2.2.

The choice of the software package used was made with the licence availability. There was no licence for RailSys available for the research, and there was a Dutch railway network, and a licence was available for OpenTrack. OpenTrack was used for the research.

1.5.3 Required input

The input used to calculate the capacity effects of the measures is divided into multiple categories. Firstly, the infrastructure in OpenTrack consists of double vertices and edges. The edges connect the vertices. An advantage of OpenTrack is the possibility of giving the vertices a kilometre reference. The software can calculate the length of an edge using these references. The edges also contain the maximum track speed, divided into multiple categories like freight, passengers or ERTMS/ETCS. A power supply can be linked to the edges to create a realistic network image. For example, the Dutch network has different overhead power supply systems; therefore, the model contains edges linked to different power supplies. At the vertices, the opportunity exists to add trackside safety equipment, including reserve time for changing switches, inducing speed limits lower than track speed or adding an object to start ERTMS/ETCS signalling. The last part of the infrastructure is the station area, where stops in the timetable can be defined and used.

A second input is the type of rolling stock used on the network. In this "engine shed", the performance parameters of the trains are stored. These parameters include, for example, the tractive effort of a locomotive or train set, the braking behaviours assigned to safety systems, the length of a created combination and the maximum speed of operations. These factors allow for a close representation of the rolling stock, allowing the simulation of performance on different overhead systems. The input can contain the tractive power of a train type for multiple power supply systems.

The last input required for the simulation of a railway is the timetable. The timetable contains at least the departure time of the train at the first location, for example, the basic hour pat. A further inclusion of the timetable is the locations where the train requires a stop. These locations' names refer to a station in the model's infrastructure. When different stations get departure times assigned, the timetable is also an opportunity to evaluate the network's performance by comparing the number of possible trains within a time frame. Still, the primary purpose of the timetable is to provide trains on the network with times at which they need to be at the stations. For the simulation, a train combination is assigned to a timetable while following a route defined in the infrastructure.

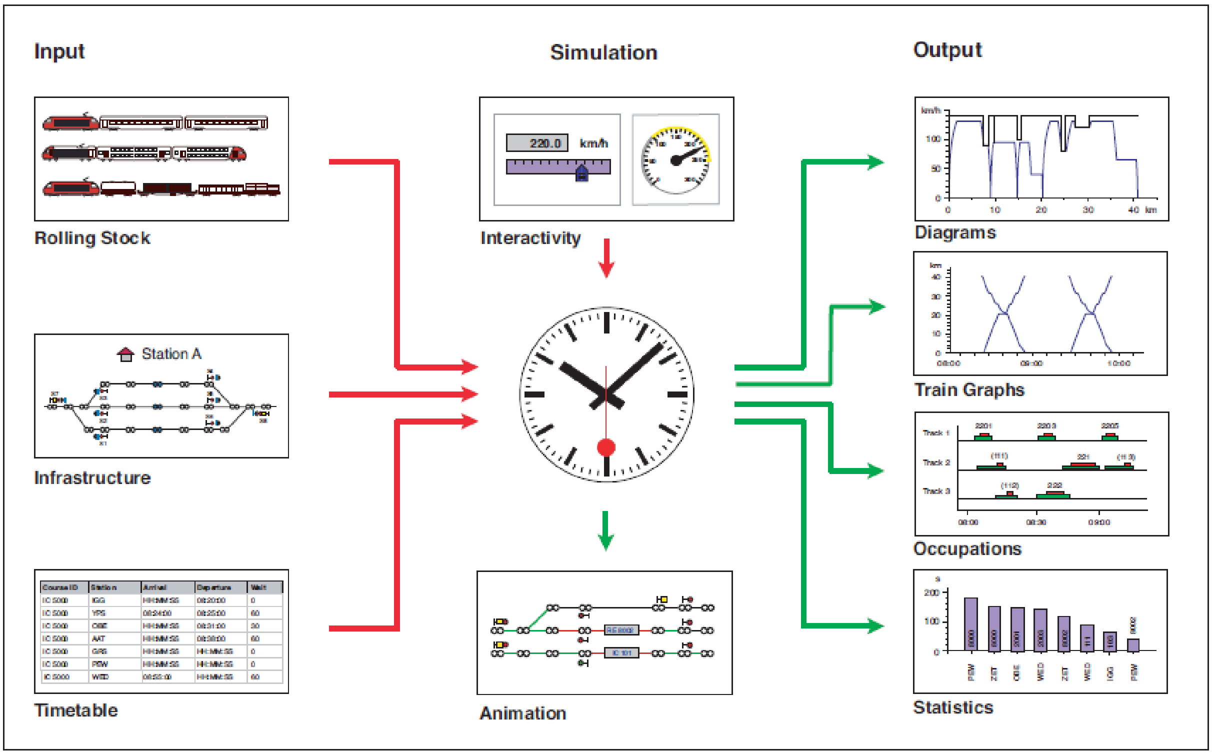


Figure 1: Input and output of OpenTrack (Opentrack Railway Technology Ltd., 2020)

Used input

This research uses the following input for the basic model of the line case scenario, with changes for the other scenarios as described in Section 2.6.

The infrastructure for the base scenario is the current infrastructure with layout changes proposed in Amsterdam and Amersfoort in the projects PHS Amsterdam and Amersfoort Westside. There are plans to alter the infrastructure by removing switches and increasing the maximum speed on the tracks by 2030. RHDHV provides this network infrastructure with a copy of their Dutch infrastructure file for OpenTrack.

The model of RHDHV also provides the rolling stock and their performance. Due to data limitations, only three types of rolling stock are on the network. An SLT (sprinter light train) with six carriages is used for sprinter and regional express trains. The (international) intercities use a VIRM (Verlengd InterRegio Matrieel) train of 6 carriages. Lastly, the freight trains use a BR189 (Baureihe 189) locomotive weighing 140 tons. The length and weight of these rolling stock types are selected as this is the worst-performing formation of the rolling stock type and thus provides robustness if they fit in the timetable.

The reference timetable for all the scenarios used in the research is the proposed timetable for 2030. In different cases, slightly different selections are made only to include the timetable for the infrastructure parts used in the study. For example, the reference timetable on the line is a part of the timetable on the network, which is a cutout from the full proposed timetable.

1.5.4 Possible output

There are four main categories and one possible helpful extra output generated by the simulation, indicated by the green arrows in Figure 1. The helpful output is an animation of the trains on the network. This animation is turned off as the simulation model's speed is reduced due to the visualization of the train. Next to the reservations of trains and the possible conflict solving, there is little use in the animation for capacity assessment. For the capacity assessment, the train graphs give more insight. In these graphs, the time-distance graph of the route shows the track occupation induced by a travelling train. With this visualization, trains can be planned in a free-flowing schedule. These train paths are visualizations of the realized timetable as conflicts appear in the time-distance graph. The realized timetable provides the different travel times for the scenarios. Further uses of the time-distance graphs are with the compression of the timetable, as the shown conflicts indicate the non-conflict-free dispatching and the design of a new timetable, as possible train paths are visualised in the graphs.

These train graphs can already give insight into how much capacity the train operations use when compressed. While this is derivable from these graphs, the speed, acceleration and deceleration can also be found in the graphs. For these performance indicators, the speed-distance diagram creates a more straightforward overview. The speed-distance diagram makes the differences between the speed profile induced by the implemented measures on the network. The speed distance diagrams provide the option to investigate the interaction of measures with one another and declare the possible differences in capacity effects of the measures.

Further, the output contains summarizing statistics and platform occupation graphs. The study does not use these as the platforms' occupation does not translate directly into track or network occupation. A place where the platform occupation is practical is the communication of a timetable at a specific station. For example, a platform occupation figure can contain all information about the direction of entry and exit of trains for a complex station like Zwolle or Utrecht.

1.6 OUTLOOK REPORT

This section gives a short overview of the structure of the report. Chapter 2 provides the background for the railway capacity (Section 2.1). Further, the assessment method for the capacity of the case studies is provided in Section 2.2. Afterwards, Sections 2.3 to 2.5 provide technical information about the measures to be assessed in the study. At the end of Chapter 2, the changes in the OpenTrack simulation are provided in Section 2.6.

In Chapter 3, the two case study locations, including the scenarios and trains on the cases, are introduced before the results of the capacity assessments are provided in Chapter 4. The investigation towards the possibility of increasing the number of train paths between Amersfoort and Amsterdam is given in Chapter 5. Afterwards, Chapters 6 and 7 provide the discussion and conclusions, where reflections on the question and research goal are provided.

2. BACKGROUND

Within this chapter, information is given about several aspects of the research. This information is the result of a literature search and expert interviews. The aim is to provide insight into the different effects of the measures as introduced in Section 2.1. First, Section 2.1 provides the definitions of capacity on the railways. Afterwards, two different capacity assessment methods are introduced in Section 2.2. After the railway capacity chapters, the capacity effects and technical details of ERTMS/ETCS level 2, 3 kV DC overhead current and ATO are provided (Sections 2.3, 2.4 and 2.5, respectively). Finally, this chapter summarises the parameters that change with the implementation of certain measures in the simulation in Section 2.6.

2.1 RAILWAY CAPACITY

The upper bound of the railway capacity can be calculated with an easy formula. Unfortunately, this calculation is far from operational due to safety and operational constraints used by railway operators. These constraints result in multiple different definitions of capacity in the literature. First, Section 2.1.1 gives the anatomy of a railway network to understand the following explanation of the different indicators to describe the capacity of a railway track (Section 2.1.2). Afterwards, Section 2.1.3 translates the track capacity to a network capacity.

2.1.1 Railway network

The railway network consists of multiple components, which all function in the network's safety and performance. This section briefly describes the different components of a network, which are described from a network and infrastructure level.

From a strategic view, the network consists of nodes and routes. The nodes are at the start and end of a route. The nodes could also be switching lanes or stations where a route between two nodes also includes whether a train will stop at the next node or continue onwards. The stopping patterns allow multiple routes between two nodes on the same infrastructure. Depending on the user's view, the nodes are at least located at all stations or switching yards. With the switching yards, the possibility exists to dispatch a train on different lines.

With multiple routes, itineraries are created, describing the journey a train will follow from start to end. These itineraries are allocated to a train using the timetable. The timetable is the second option to describe the stations where the train stops. Each train on the network receives its timetable, which describes its movement. The type of simulation determines the importance of this timetable. For example, a capacity assessment only requires the starting times of trains for conflict-free operations and the stops, including minimum dwell time at stations. Other, more operational train schedule feasibility studies also require connections between different trains and can use predetermined departure times.

The network's physical side contains tracks and switches for the trains to run on their allocated routes. These route changes often happen at major stations where switching lanes are present. The switching lanes are not necessarily limited to the stations and can exist at other locations on the network. While the switching lanes consist of single block sections, the interlocking allows different trains on the block when the given routes are provided by trains without physical conflicts on the tracks.

2.1.2 Track capacity indicators

As introduced at the start of the section, the railway literature uses multiple indicators for track capacity. While most try to describe the same measures, slight differences exist. Within the literature, four main measures describe the capacity of a railway line or network (Abril et al., 2008). The following section lists the four main capacity indicators for line capacity and the relations between them.

- *Theoretical capacity*: The theoretical capacity is the maximum number of trains that can use the track in an hour (Kraft, 1982). This capacity is only used in literature and not by operators, as the calculation assumes perfect running conditions. All factors influencing capacity, like the homogenous train composition, are assumed to be optimal in rolling stock and service patterns. The headway between the trains is the minimum headway allowed by the infrastructure. With these optimal factors, the theoretical capacity is calculated with a formula. The travel time between two signals determines the capacity, as this is where the lowest number of trains can travel over the line. The calculation assumes a single track, thus, does not include network factors. The theoretical capacity is not possible to run in a stable situation, as it considers no outside factors like weather or variations in driver behaviour. Therefore, the theoretical capacity is the upper bound of the track capacity, as Figure 2 depicts.
- *Practical capacity*: Compared to the theoretical capacity, the practical capacity considers more realistic network operations. These differences can be found in the safety margins, the reliability factors and the more realistic traffic composition implemented in the assessment. Where the theoretical capacity is the upper bound of the capacity in a literal way, the practical capacity considers the operational wishes of both the network and train operators. It is thus reduced compared to the theoretical capacity. Usually, the practical capacity is roughly 60-75% of the theoretical capacity, shown in Figure 2, varying with the operator's requirements (Kraft, 1982). Thus, a way to describe the theoretical capacity is the maximum number of trains on the network with realistic network operations. This capacity definition is, therefore, the most realistic measure for the maximum capacity of a network.
- *Used capacity* or *capacity consumption*: The used capacity is the time needed by the planned traffic on the line or network (Kraft, 1982). Considering the scheduling margins, this capacity measure is theoretically observable from the field if the trains are scheduled with the lowest conflict-free time headway. The literature uses capacity consumption as an assessment measure. The value given to the capacity consumption is the maximum time a piece of infrastructure is shown as occupied during operations.
- *Available or remaining capacity*: The available capacity is the last type mentioned in the literature. The difference between theoretical and used capacity consumption is the available consumption. Therefore, this measure is an indication of the possible increase in the traffic volume of a network. The main issue is the misleading nature of the measure, as the available capacity is useful when a train path is addable over the whole itinerary. If there is a problem with the capacity, this capacity is, in this case, considered lost capacity.

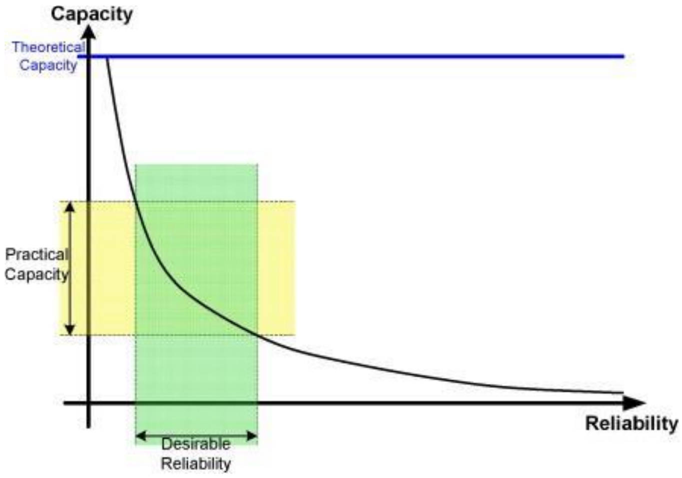


Figure 2: Practical capacity while considering the desired reliability level (Abril et al., 2008).

In the remainder of this study, when there is mention of railway capacity railway on the tracks or the network, the practical capacity is meant. The reason behind this is the diverse nature of the Dutch traffic composition described in Chapter 3 further in the report, combined with the safety and reliability factors used within the case study. The result of the assessment is a percentage indicating the required time for the compressed version of the timetable over the time planned in the proposed timetable.

2.1.3 Network capacity

As described in Section 3.1.2, the capacities typically consider lines on a railway line, disregarding most of the network elements. A couple of factors limit the direct translation of this line capacity to a network capacity. In a network, different routes influence one another. Therefore, the capacity bottleneck can move from the longest travel time over a block towards an area with network interactions. These interactions include a switch's direction change and trains' connections for transfer at stations.

This change in bottleneck location can impact the capacity consumption on the line. The effect on capacity consumption is primarily negative, as longer travel times without overtaking result in longer time intervals required between fast and slow trains. An example where the capacity consumption might drop is an interchange in lines. At the interchange, the trains from different routes intertwine, with the direction of switches often changing and multiple directions of trains using the same track. These trains from multiple directions are not included in the line capacity, as the scope of the study should not include trains on other lines at the start and end stations, for example. Therefore, the change in scope of the study will likely move the bottlenecks towards the areas where multiple lines intersect.

For the case study of this research, the expectation is that the capacity bottleneck is around the station of Weesp and switching lanes. At the line, the bottleneck is expected at the start or end for successive train movements. With these network interactions, there is a possibility that measures behave differently or less effectively compared to a line. Therefore, the study aims first to identify the interactions of the measures with one another and then implement the measures on a network case study, where the network interactions can be analysed.

2.2 CAPACITY ASSESSMENT

In Section 2.1.2, capacity consumption was introduced. This value related to a line segment helps calculate what part of the time the railway track is used. To evaluate the capacity consumption of a line or network, the most commonly used method in the literature is the UIC code 406 (International Union of Railways, 2013). UIC code 406 describes a method to compress a timetable as far as possible without introducing conflicts between trains. While this method is frequently adopted in the literature, ProRail uses a slightly different method to calculate the track capacity consumption on the Dutch network (ProRail, 2018). Calculating the blocking times of signalling blocks is the main difference between the methods, as the method of ProRail incorporates robustness for the Dutch situation specifically. Therefore, this section will provide insight into the two timetable compression methods.

2.2.1 UIC code 406

The UIC code 406, or the timetable compression method of UIC, aims to provide a standard method for all railways to asses the network's excess capacity. The first step is the definition of the research scope and view. When a study area is large, the suggestion is to start with a strategic view of the network. This strategic approach identifies the possible bottlenecks of a network. These suspected bottleneck areas then receive extra attention for capacity calculation. The UIC code 406 suggests a tactical view to assess the possible bottleneck areas, considering more infrastructure details like the placement of signals and switches.

With the view and rough indication of the bottleneck area determined, the boundaries of the study area need to be determined. With these borders, it is possible to select the sections for evaluation. These evaluation sections are chosen with the study's goal in mind, for example, adding a train path to the timetable. In UIC code 406, the route of this train path is defined as the train path line section. In contrast, all other routes in evaluation are line sections.

These train path line sections must contain all the tracks for the proposed extra paths. With possible extra focus on switching lanes. Afterwards, line sections represent the whole train path line section. Some typical locations where two line sections meet are an alteration in the number of available tracks or the number of trains of the line sections. The exact determination of the boundaries of these line sections influences the results of the capacity consumption and thus needs to be selected carefully. The capacity consumption of the line can be calculated after compression with the following Formula.

$$Capacity\ Consumption\ [\%] = \frac{Occupancy\ Time + Additional\ Times}{Defined\ Time\ Period} * 100 \qquad (1)$$

For each selected line section, the formula gives the capacity consumption. These additional introduce the option for safety margins in the timetable and are 0 for the UIC code 406, with the capacity consumption calculated for all the blocks in the study area. The maximum value retrieved from this formula equals the normative value for the capacity consumption over the selected period. The included trains need a starting point within the selected period, considering the non-compressed timetable. When there is a recurring pattern with the trains, the first train of the period could be added after the last train to visualize the capacity consumption in the time distance diagram. Figure 3 shows this visualization for a fictive 1-hour compressed timetable by the last white/green dashed train path.

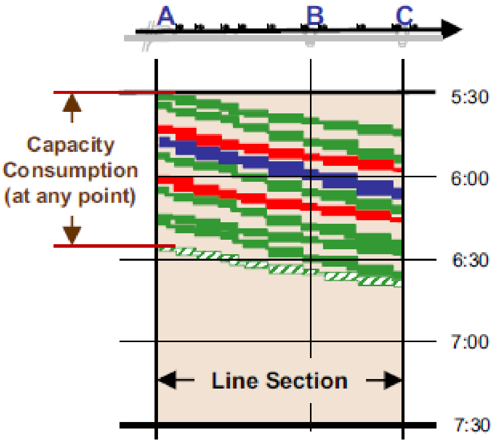


Figure 3: Distance time diagram with an example of the determination of the capacity consumption by adding the first train after the assessed period (International Union of Railways, 2013).

For a correct capacity assessment, the period used for the compressed timetable should contain the maximum number of trains possible. For some networks, this could be during peak hours, but for the Dutch situation, where the schedule is made using a basic hourly pattern, the normative period can be selected from most hours during the day. This study considers all scheduled trains in a basic hour on the Dutch network.

The occupation time induced by a train travelling over the infrastructure used in Formula 1 consists of four main components. These components are shared by both the UIC code 406 and the method used by ProRail. Figure 4 visualizes the factors that compose a block section's occupation time. These factors are divided into four categories:

1. Safety margins before entering the block (consisting of: time for route formation, time for visual distance and time for approach section).
2. Journey time over the block
3. Time for clearing the block
4. Release time of the block

The proposed measures for the safety system, infrastructure and train control influence the length of each blocking time component. Sections 2.3, 2.4 and 2.5 introduce the expected effects of each measure.

After the occupation time of all line sections is calculated, the UIC code 406 adds additional times for the desired level of service and thus tries to reduce the impacts of delays. No safety margins are considered in the initial occupancy time of the UIC code 406. Formula 2 considers the safety margins for the level of service as given in Table 4. This so-called additional time rate is relative to the occupancy time on the network, as it is defined as a percentage of the occupancy time for a specific traffic composition present on the network.

$$Capacity\ Consumption\ [\%] = \frac{Occupancy\ Time * (1 + additional\ time\ rate)}{Defined\ Time\ Period} * 100 \qquad (2)$$

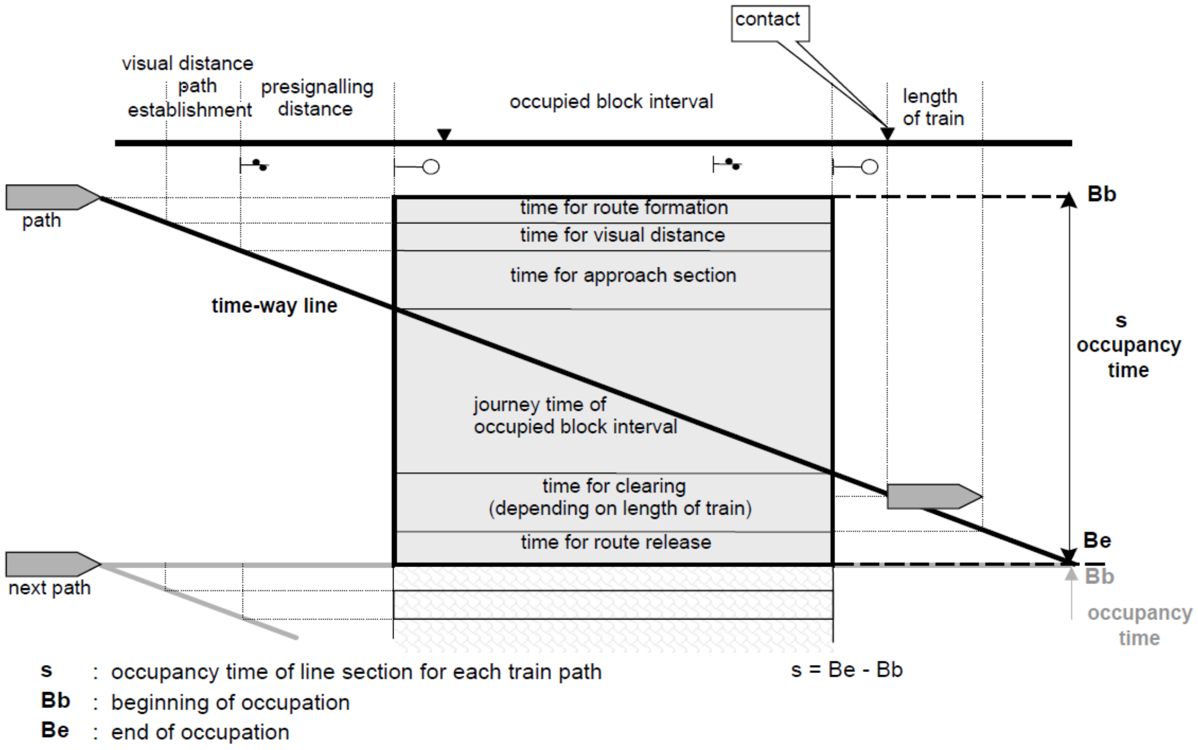


Figure 4: Physical attributes of the occupation time of a block section (International Union of Railways, 2013)

As Table 4 shows, there are different additional times for traffic compositions. For the Dutch situation, with mixed traffic over most of the network and a daily pattern, the additional time used in Formula 2 is 1,67 times the occupancy time.

2.2.2 Dutch assessment method

Compared to the UIC code 406 capacity assessment method, ProRail has different requirements for capacity assessment (ProRail, 2018). The method of ProRail adds a time buffer per train path to the time release of the block category. Increasing the time for the route release allows for evaluating measures that increase reliability. The UIC method has no opportunity for this other than reducing the additional time rates. Further, the Dutch method reduces the performance of trains, as described in Table 5. With these performance reductions, the simulation introduces some slack driving times to accommodate differences between the trains over the day. As the simulation always provides similar driving times with conflict-free operations, this performance reduction gives the operator a buffer to catch delays on the simulated network.

Table 4: UIC code 406 additional time rates (International Union of Railways, 2013)

Type of Line	Peak hour	Daily Period
Dedicated suburban passenger traffic	18%	43%
Dedicated high-speed line	33%	67%
Mixed-traffic line	33%	67%

Table 5: Normative reduction in performance (ProRail, 2021a)

Standard performance reduction	**4%**
When the conductor is involved in the departure procedure at stations	1%
When the group of drivers is flexible	1%
When the rolling stock is not logistical independent	1%

The main network of The Netherlands receives all 7% of performance reductions. During the departure at the station, the conductor closes the doors after the route is cleared for departure. Next, the drivers of NS operate all over the network, not receiving a fixed route to operate and thus introducing uncertainties. The rolling stock NS uses is planned on multiple routes in a day. So when there is a disruption on a line, this can cascade towards other lines. With the standard deduction of train performance to introduce slack driving times, the standard driving time buffer introduced by the Dutch assessment method is 7%. Therefore, passenger trains on the network will perform at 93% during the simulations.

Next to the reduction in driving time performance, there is the minimum follow-up time buffer. The use of the buffer is to reduce the human variance in the timetable. The Dutch method considers the 60-second buffer for the operation of trains where the conductor influences the departure and a 30-second buffer with a single-person operation. For sprinter trains on the SAAL line, the 30-second buffer is used.

2.2.3 Used assessment method.

For this study, the assessment method that will be used primarily is the Dutch method that ProRail uses. The advantage of this method over the UIC method is that buffers, as included when constructing the Dutch Timetable, can be assumed to create a sufficient buffer to catch up with disruptions. Next, the UIC method aims to provide a single method for all national railway networks. In contrast, the Dutch assessment method is developed to suit the needs of the high-frequency mixed-traffic operation in The Netherlands.

A further advantage of the Dutch capacity assessment method is considering the buffer time per train. This buffer time allows more options to simulate the different measures, which will be introduced in Sections 2.3, 2.4 and 2.5. The UIC method is less flexible in this area, as the initial capacity assessment is done without safety margins, and this is a fixed number for multiple national railways.

Previous research compared the Dutch and UIC methods (Vergroesen, 2020), where the conclusion was that the UIC method was more lenient than the Dutch method due to the buffer times required between trains. Therefore, the more strict Dutch method is chosen to generate the results regarding capacity consumption.

2.3 SIGNALLING AND SAFETY SYSTEM

The first of three measures to be assessed is the change from the legacy NS'54/ATB-EG system to ERTMS/ETCS level 2. NS’54/ATB-EG and ERTMS/ETCS (level 2) are introduced, and the relevant technical details of the systems are introduced.

The signalling system provides the train driver with information about the track ahead. For this communication, different alternatives are available with different amounts of information and forms of communication to the driver. Section 3.3.1 introduces the current system of

NS’54/ATB-EG, after which ERTMS/ETCS is introduced in Section 2.3.2. A more detailed explanation of the level that ProRail considers will be in Section 2.3.3.

2.3.1 NS’54/ATB-EG

Most of the Dutch network's current signalling and safety system is the NS’54/ATB-EG legacy system (ProRail, 2020). This system uses a three-aspect signalling system, where the signal contains information about the following two or more blocks ahead. Using track circuits, the NS’54 system determines the track occupation ahead of the train. When the following two or sometimes more blocks are free, the trackside signal will show a green state to the driver. The yellow aspect is shown when the driver can continue into the next block at a reduced speed. A yellow aspect also indicates that the next block is occupied, and thus the driver has to prepare to stop at the next signal. A red signal indicates danger and should not be ignored by the driver.

The signalling system NS’54 can show reduced maximum track speed by using light matrixes under the signals. This speed is also communicated with the automatic train protection system (ATP), in this case, ATB-EG. The ATB-EG receives the maximum allowed speed by the electric frequency used in the so-called track circuits, a trackside train detection system. The maximum speed can have five values: 140km/h, 130 km/h, 80 km/h, 60 km/h and 40 km/h. ATB-EG communicates the allowed speed to the driver using indicative lights in the cabin. When a driver does not comply with the given speed limit, ATB-EG intervenes and initiates an emergency braking cycle. These five speed steps already introduce a possibility to improve capacity, as reducing the speed difference between steps allows for an optimized speed profile. Also, under ATB-EG, the worst-performing train under braking is the standard when calculating the block occupations and the block's allowed speed.

2.3.2 European Rail Traffic Management System

The European Rail Traffic Management system is developed as the new European train safety system standard. The system aims to create a new standard ATP system for the European train network, replacing the various national systems. The ERTMS/ETCS system has several main components (UIC, 2022).

1. European Train Control System includes the signalling system, the control of movement authority of trains, the interface for interlockings and the communication to the onboard ATP systems.
2. GSM-R will be used for communication between the train and the controller. With level 1, this will only be from train to trackside. At level 2 and above, two-way communication is possible. GSM-R is based on the publicly available GSM network, with some railway-specific properties.
3. The European Train Management Layer is an operational management system optimising train movement. This layer can be used by customers, staff, or railway operators to exchange information.

The ERTMS/ETCS is available at different levels (European Commission, 2022a). The levels differ in the data type communicated with the RBC and the train. These levels range up to level 3. Level 1 uses ERTMS/ETCS equipment to support a legacy signalling system to provide more optimal braking indicators for the driver, serving as an automatic train protection system. Level 2 transfers the trackside signalling to in-cabin signalling and takes over the track detection of the legacy trackside train detection systems. Level 3 is a form of moving block signalling, where no blocks are defined on the signalling system's infrastructure, forming a virtual occupation block around them that defines the occupied parts.

For the Dutch network, it was decided that ERTMS/ETCS level 2 will be implemented to replace the NS'54, ATB-EG and ATB-NG (In Dutch: “Automatische Trein Beinvloeding – Nieuwe Generatie”) systems (Ministry of I&W, 2019). The decision to replace the current systems with ERTMS/ETCS has been made because the current system needs to be renewed/replaced shortly to ensure safe railway operations. A second reason is the higher safety standards of the ERTMS/ETCS interface. Eliminating trackside signals to provide information to the driver under ERTMS/ETCS level 2 increases the frequency of movement authority communication.

A further reason is the request of the EU to increase the safety system of some of the corridors to ERTMS/ETCS with the introduction of Trans-European Transport Network projects (TEN-T) (European Commission, 2022b). Of these routes, three are planned on the Dutch infrastructure: The Rhine – Alpine corridor (Amsterdam to the German border), the North Sea – Mideterainian corridor (Amsterdam to the Belgian border) and the North Sea–Baltic Corridor (Amsterdam to both the German border and the Belgian border via Utrecht).

2.3.3 ERTMS/ETCS level 2

ERTMS/ETCS level 2 is an integrated cab signalling and ATP system using fixed block signalling principles, including trackside train detection (European Commission, 2022a). For this system, stop marker boards (SMB) replace trackside signalling. The SMBs give the driver visual aid to identify the block's end. To provide a safe route to the train, trackside train detection is used by the interlockings at station areas and the signalling system on the open track. The route provided by the trackside train detection is translated to a movement authority by the radio block centre (RBC) and communicated to the train. The train then presents the driver with a dynamic speed profile that the driver is supposed to follow to the end of the movement authority. A visual overview of this system is given in Figure 5.

Next to the communication of trackside equipment via the RBC to the train, the train transfers information back at regular intervals. This information contains the location and the speed of the trains. The RBC uses this data to provide extended or new routes and, thus, movement authority for the train. The train then translates this movement authority to show a new dynamic speed profile.

As the GPS of the train has some room for error, the train's exact location is also provided to the RBC after a train passes a group of eurobalises. The eurobalises calibrate the GPS location of the trains after they pass over them. The GPS calibration is necessary as GPS location error increases with the distance travelled from a calibration point. When ERTMS/ETCS is combined with an axle counter to monitor the occupation of the blocks at these locations, it is also possible to calculate the speed of a train. This can be done by offsetting the location of a pair of axle counters.

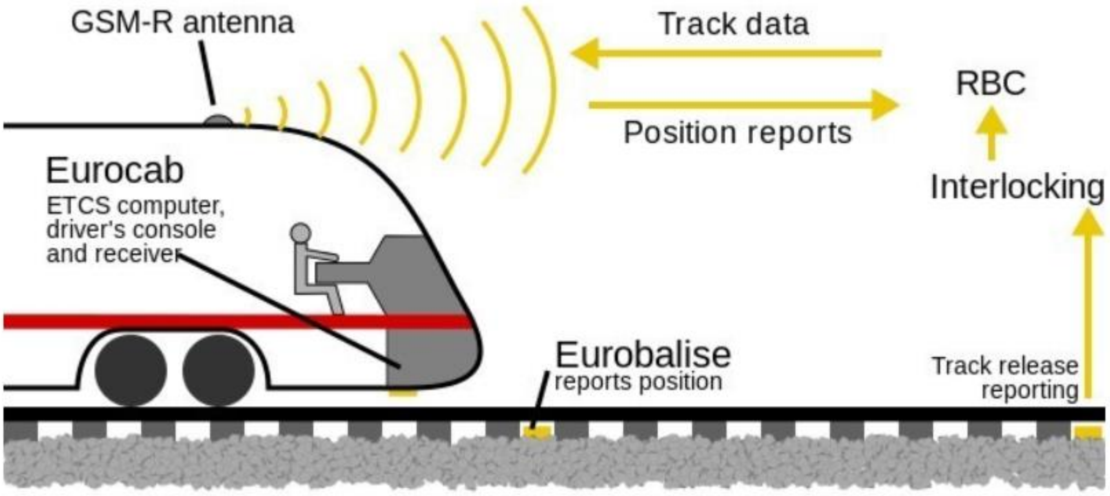


Figure 5: ERTMS/ETCS level 2 setup (European Commission, 2022a)

One of the main advantages over legacy systems is the improved safety of the ERTMS/ETCS level 2 trains equipped with an European vital controller (European Railway Agency, 2020). This device will provide supervision on the braking of the vehicle. With the movement authority, the driver machine interface provides the required information for the required braking before the end of authority is reached. This information is provided until the braking curve reaches the release speed, after which the driver needs to stay under the release speed until the SMB is reached. When the driver fails to comply with the braking supervision, the system will intervene and reduce the speed according to a programmed braking curve (European Commission, 2022a).

The supervision of the braking curves can lead to an increase in the capacity of the track, as the driver is allowed to continue at track speed until the driver machine interface indicates a braking point at the end of authority, specifically calculated for the type of rolling stock. Compared to the legacy system, where the braking curve is calculated for the worst-performing train under braking on the network, the driver must drive at a reduced speed until the next signal. A further advantage of ERTMS/ETCS is the possibility to increase the train's speed directly after the new movement authority is given if the end of authority is within the braking curve of the vehicle.

Lastly, ERTMS/ETCS level 2 reduces the track occupation over NS'54/ATB-EG. The most significant difference is the number of blocks required for safe operations. Under NS'54/ATB-EG, at least two blocks should be unoccupied before the train can continue at track speed. With ERTMS/ETCS level 2, due to the braking-based movement authority, the track speed is provided to the driver when the end of authority is not within the braking curves, which will be explained further in the next section. Therefore, the time spent at track speed increases and the time headways between trains decreases.

ETCS braking curves

As the movement authority depends on a train's braking curve, ETCS has some safety margins built in (European Railway Agency, 2020). First, the system calculates multiple braking curves, which are essential to the system's increased safety. The first and most extreme braking curve is the emergency brake deceleration (EBD) curve. As the name suggests, the distance at which the EBD curve reaches 0 km/h is the minimum distance the train can reach a standstill. As the EBD curve is uncomfortable for passengers and undesirable for the rolling stock owner, there are other intervening and indicative curves for the driver to perform a more comfortable braking action.

The first safety curve protecting the reaching of the EBD is the emergency brake intervention limit (EBI). Factors considered in this calculation are the worst-case scenario for a specific train type. Some of the included factors are the required time for the full deployment of the emergency brake, including possible acceleration and the vehicle's speed. Within the speed used in the calculation, a safety factor compensates for the inaccuracy in the speed measurement.

The EBD and EBI are elements of the ETCS speed and distance monitoring functions, resulting in the ETCS parachute (European Railway Agency, 2020). The parachute aims to ensure that no movement authority is exceeded. Figure 6 shows the EBD and EBI curves as the two most right curves, further showing other warning moments and indication curves used by ETCS. As the EBI is part of the parachute system, the train's computer sends multiple warnings to the driver before reaching the EBI curve. These warnings include the Indication (I), the Permitted speed (P), a Warning indication (W) and the service Brake Intervention (SBI). The proposed system for the Dutch network does not include the SBI, while the I, P and W indication curves are used to provide the driver with information about the movement authority.

The I supervision limit is implemented so that the driver can reduce speed sufficiently not to overpass the Permitted speed curve. After the I supervision limit, the P supervision limit is reached (European Railway Agency, 2020). At this point, the driver has to slow down to a safe speed to avoid the intervention of either the service brake or the emergency brake. At the W supervision limit, a different audible warning is given to the driver to alert him/her that the permitted speed has been exceeded. The indicative alerts given to the driver are often referred to as the ETCS braking curves, as the visualization in a speed-distance graph is a curve, see Figure 6.

In the Dutch system, the ETCS braking curves do not provide the movement authority limit for the whole route (ProRail, 2018). Towards the end of the movement authority, the braking curve is released when the train reaches 15km/h (release speed), and the driver stops at the stop marker board. One exception is when there is not enough room after the stop marker board to the end of the authority point. The driver's behaviour from the release speed is uncertain, requiring safety factors in the planning phase.

Performance gains of ERTMS/ETCS level 2

As mentioned, the main goal of ERTMS/ETCS is the unification of the European train networks, together with increasing the safety of the network. Therefore, a possible capacity increase over legacy signalling and safety systems is not the system's primary goal. Still, compared to the legacy system of NS'54/ATB-EG, there are a few areas where ERTMS/ETCS/ECTS level 2 can increase the capacity of the Dutch railway network.

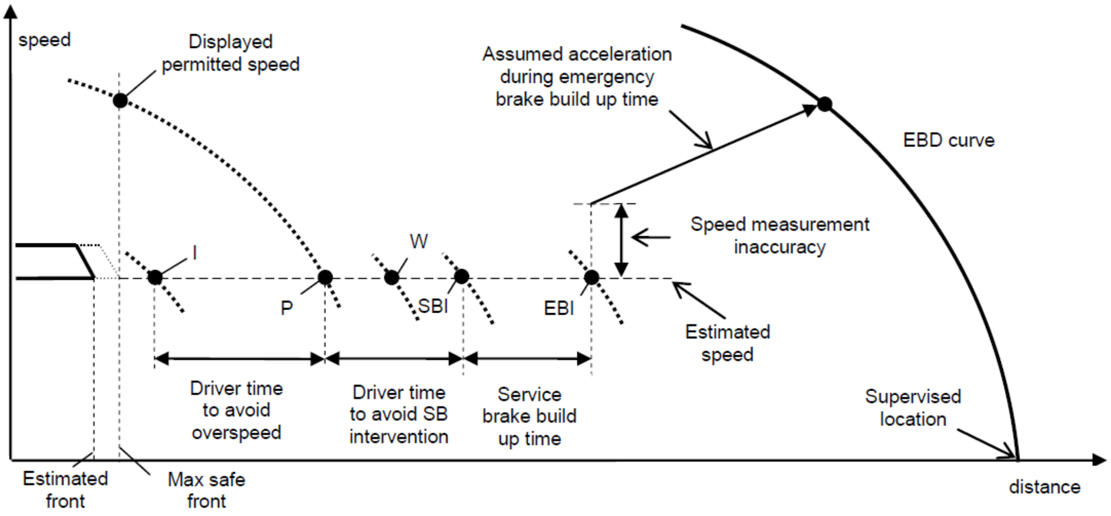


Figure 6: Overview of the EBD braking curve and its related supervision limits (European Railway Agency, 2020)

The speed profile is the first factor positively affecting the railway network's capacity. NS'54/ATB-EG has five monitored speed stages (140km/h, 130 km/h, 80 km/h, 60 km/h and 40 km/h), while the Dutch implementation of ERTMS/ETCS will have steps of 10 km/h(ProRail et al., 2014). The increase in the number of monitored maximum speeds is due to technical improvements and the type of communication of ERTMS/ETCS. ATB-EG communicates the maximum speed via track circuits, whereas ETCS uses GSM-R to communicate between the train and train dispatcher. The track circuits rely on current frequencies, limiting the number of items possible to communicate. The GSM-R method can provide an almost unlimited number of messages to the train.

The track occupation time is another improvement found by changing NS'54/ATB-EG to ERTMS/ETCS level 2. With NS'54, a train has a green signal when the next two sufficiently long blocks are unoccupied. Therefore, after exiting the block, the train leaves a semi-occupied block until the requirements for the block to be unoccupied are met. With ERTMS/ETCS level 2, the block becomes unoccupied after the trackside train detection equipment confirms that all the train axles have left the block. Therefore, ERTMS/ETCS level 2 reduces the required time for a block to clear. The earlier release of a route provides the train quicker with a path where track speed is allowed

For the simulation, the difference in signalling and safety system is simulated with the following changes:

- The trains get marked with ERTMS/ETCS, therefore changing the maximum speed profile of the infrastructure to ERTMS/ETCS and interacting with the signals with ECTS braking curves.
- The signals on the infrastructure become virtual signals, thus marking only marking the locations of the start and end of a signalling block.
- In OpenTrack, remove the speed reductions due to signalling aspects, as the method changes with ERTMS/ETCS and is included in the movement authority.

2.4 OVERHEAD CURRENT

For trains to run, a source of power is required. Multiple options are possible to provide traction for a train. The two most common power supplies are electrical and diesel power. In the Dutch situation, electric trains are favoured. The general view is that electrically powered trains are more sustainable than their diesel counterparts. Next to this is most of the Dutch network electrified with 1,5 kV direct current (ProRail, 2020b). The overhead current provides trains with the needed electricity to power the motors, and the type of overhead current affects, therefore, the performance of the rolling stock. Within this section, an overview of the current situation of overhead current on the Dutch and European railway networks is given. Next, the effect of changing the overhead power is explained using an SLT train as an example of the possible performance change. Lastly, the expected capacity gains are derived from the improvements by the change in a more powerful overhead current system.

2.4.1 Types of overhead power supplies

Over Europe, many different types of power supplies are available. There are two different currents on the catenary on the main Dutch network, not considering border transitions(ProRail, 2020b). These currents are 1,5 kV DC and 25 kV 50 Hz AC, where the second type is only used on the High-speed line and the Betuweroute, with 1,5 kV DC being the power supply for the vast majority of the network.

When comparing this to the rest of Europe, few countries have a dated power supply of 1,5 kV DC. Next to The Netherlands, France is the only other country that uses the same power supply on the catenary for a large part of the network (Simiyu & Davidson, 2021). When comparing this to other European countries, there is a difference between the European high-speed lines, which are often powered with a 25 kV AC overhead current (Reichert, 2022). Most southeast European countries also use the 25 kV AC system.

This overview shows that investment in a different, more powerful overhead power can not only increase the performance of the trains on the network, but there is also the opportunity to increase the interoperability between the Dutch network and the neighbouring countries. This results in a couple of realistic changes in the overhead current. As the German system uses a 15 kV AC system, the Belgium railways have a 3 kV DC system, and there is already a 25 kV AC system on two lines in The Netherlands.

ProRail has decided to investigate the effects of the 3 kV DC alternative after a social cost-benefit analysis (ProRail & NS, 2018). In the cost-benefit analysis report, the AC systems are dropped because the effects of the change would hinder the network's operations for an extended period. The elimination of upgrading to either 15 or 25 kV AC is due to the alterations to the infrastructure required (ProRail & NS, 2018).

2.4.2 Performance gains of the overhead current

A different power supply will affect the performance and components needed for operations on a railway network. The estimations of the performance gain that can be found vary broadly. Some estimations give a large 30-second advantage to 3 kV DC over 1,5 kV per start-stop movement(ProRail, 2016) of a train. Others are more pessimistic, estimating just 2 seconds per start-stop movement (Zoeteman, 2014). With the formulation of driving time improvement per start-stop movement, the acceleration improves driving time. While this assumption is valid, there are more advantages to the increase in voltage, which are found in the operational side of the network and will not significantly affect the capacity (ProRail & NS, 2018).

The rolling stock can draw more power with the increased power on the overhead wires. With the extra available power, there is an option for the different types of rolling stock to produce a higher tractive force (Reijnen, 2017). With the increased tractive power, a higher acceleration can be achieved (Goodman, 2008). This will reduce the time needed to reach the maximum speed and thus decrease the time headway between trains.

In the report of Reijnen (2017), some cases were investigated to find that the running time increases per stop. For Intercity trains, over four different cases, a weighted average of 9,4 seconds running time decrease per station was found, and 5,4 seconds for sprinter trains. An important note is that according to this report, the total running time decrease of both the sprinter and the intercity trains is roughly equal. Still, with the additional stops, the sprinter trains will profit most from the increased overhead power supply as there are typically more instances where acceleration is needed.

The extra tractive effort can explain the decrease in travel time that the trains can provide under a larger current. For the SLT train with ten coaches, Figure 7 gives the estimated tractive effort under different overhead currents. Here it is visible that the train can give the maximum tractive effort for a longer speed interval, thus increasing the average acceleration in a train movement. This maximum tractive effort is limited to provide a 1,5 m/s^2 acceleration, which is considered comfortable for the passengers.

As the trains on the Dutch network run under 1,5 kV overhead current, no estimated data is available for most train types. The data limitation reduces the accuracy of the simulation, as the estimated performances are for the VIRM, SLT and BR189 train types (Paulussen et al., 2017; ProRail & NS, 2018; Reijnen, 2017). Other train types, like the ICNG (Intercity Nieuwe Generatie) and the international train to Germany, are also on the proposed timetable. Within the model, these will be replaced by VIRM trains designed for a similar stopping pattern.

The increased acceleration under the increased overhead power is the primary possibility of providing capacity benefits by reducing the blocking times of the accelerating trains (Fumasoli et al., 2015). The reduction in total travel time per start-stop movent reduces the capacity consumption of the railway.

To simulate the increase to a 3 kV DC overhead current, the model will receive a power supply of 3 kV DC instead of the current of 1.5 kV. With the VIRM, SLT and BR189 having a performance curve for this power supply, OpenTrack will select this tractive effort over the standard for the 1,5 kV overhead current.

2.5 AUTOMATIC TRAIN OPERATIONS

This section explains the technical principles behind ATO, where computers take over the

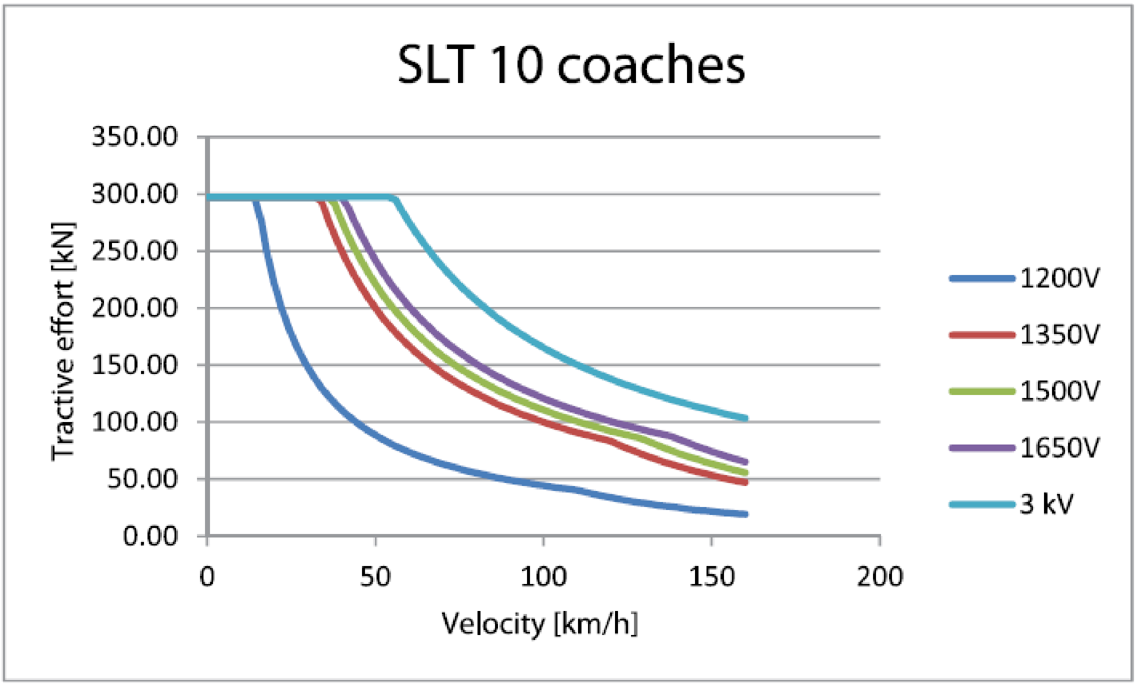


Figure 7: Tractive effort of SLT-10 under different power supply systems (Paulussen et al., 2017)

driving tasks of the human driver. The implementation of ATO will increase operational predictability and efficiency. This Section will first focus on the trains' systems controlled by ATO by introducing the grade of automation in Section 2.5.1. Next, Section 2.5.2 describes the effects of ATO on the movement of the train. Then, the effects are translated to expected capacity effects. Finally, the modelling implications are described.

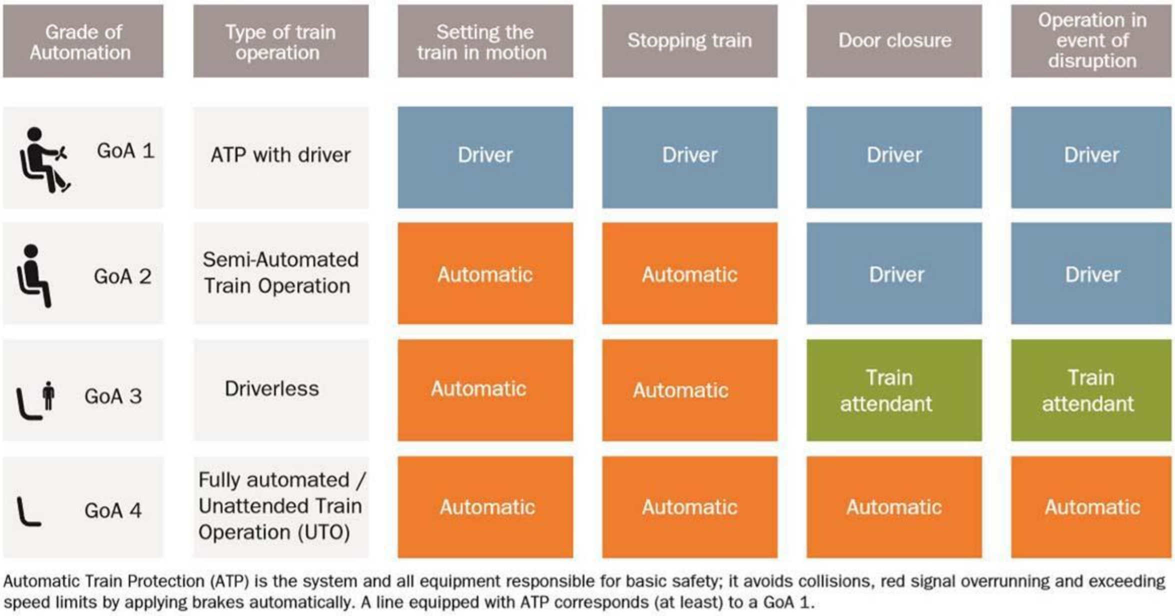
2.5.1 Grades of automation

ATO is a system designed to take control over the driving and, eventually, fully control all systems for the train, including the starting procedure. The area of the operation affected by ATO is the network's capacity, efficiency and costs (ProRail, 2021c), with the grade of automation (GoA) influencing the magnitude of the effects. ProRail and partners are considering GoA 2 operations. A gradation is at the start of automating the operations. For this, grade, ProRail, freight companies and Arriva have already conducted trials (Poulus et al., 2018; ProRail, 2021b). The following paragraphs describe the difference between the Grades of automation.

As mentioned, the level of automation tested by ProRail is GoA 2. The different Grades of automation consist of four (or five) levels. At the lowest level, no computer takes over any of the driving operations of the train, including the ATP systems. Therefore, the current situation on the Dutch railways is GoA 1 as ATB-EG is the ATP system in use, and the driver is in charge of acceleration and braking. With increasing levels of automation, the number of tasks the driver performs is reduced, and eventually, the computer takes over all systems. In Figure 8, the different levels of driving tasks are visualized.

At GoA 0, not included in Figure 8, the driver, as mentioned, has complete control over the train, and no computers help with the driving or safety operations. Therefore, no ATP system is available to the driver. When increasing to GoA 1, the driver is still responsible for all driving tasks. Where the driver fails to follow the directions of the signalling system, the computer intervenes to ensure safe operations. An example of one of these systems is the Dutch ATB-EG or the international ETCS.

At GoA 2, the computer takes over the driving task of the train. Therefore, the driver does not do the acceleration and deceleration anymore. In GoA 2, the driver is still responsible for safe operations and therefore needs to oversee the operations. At stations, the diver is responsible for opening and closing the doors, thus starting the departure procedure. A second responsibility is controlling whether the computer is correctly following the safety systems on the railway line. These responsibilities require a person in the train's cabin at all times.



Grade of Automation	Type of train operation	Setting the train in motion	Stopping train	Door closure	Operation in event of disruption
GoA 1	ATP with driver	Driver	Driver	Driver	Driver
GoA 2	Semi-Automated Train Operation	Automatic	Automatic	Driver	Driver
GoA 3	Driverless	Automatic	Automatic	Train attendant	Train attendant
GoA 4	Fully automated / Unattended Train Operation (UTO)	Automatic	Automatic	Automatic	Automatic

Automatic Train Protection (ATP) is the system and all equipment responsible for basic safety; it avoids collisions, red signal overrunning and exceeding speed limits by applying brakes automatically. A line equipped with ATP corresponds (at least) to a GoA 1.

Figure 8: Grades of Automation for ATO (Vergroesen, 2020)

In the next step, GoA 3, the train's systems can perform all driving tasks and the train attendant, not a driver, can handle the train's disruptions and departure. At this level, the driving operation of the vehicle is reliable enough that no driver needs to be in the train's cabin. Therefore, the driver can do other tasks while the train is moving. The train attendant will be responsible for closing the doors, performing the departure procedure of the train and, in case of disruption, taking the appropriate actions.

At GoA 4, there is no need for human interaction in the entire operation of the railway system. Next to driving the train, the computer handles the departure and disruptions. When reaching GoA 4, the system operates fully autonomously. This system is popular for metro and railway lines in quiet areas. In metro systems, the systems are often fully enclosed and, thus, less prone to disruptions.

When considering the different grades of automation and the ambitions of ProRail, the research will further focus on GoA 2. With this gradation, the need for a driver is still present, and a possibility exists to upgrade the system eventually. Therefore, the operational costs remain at a similar level to those at GoA 1, while ATO increases the efficiency and predictability of operations.

2.5.2 Performance gains of Automatic train operations

As described in the previous paragraph, the operations on the network can profit from the implementation of ATO. The capacity profits from the improved predictability of the ATO operations over the driver's inputs. This includes a more predictable speed profile over the variation of the different drivers. The main last advantage of ATO has improved network safety. The computer makes fewer mistakes than a human driver, requiring a reduced safety margin.

These advantages will provide some alterations in the operation of the network, and some of the safety margin needed by human drivers is reduced. This decreases trains' buffer time by 15 seconds (van der Hoeven, 2020; Vergroesen, 2020). This buffer time reduction was also given in an interview with an expert at ProRail. With the reduced buffer time, headway time in the planning phase reduces. A drawback of this reduced time headway is a smaller time allocation in the schedule to recover delays after using the old buffer times to insert new train paths.

A further advantage is in the braking of the trains. The ATO train must follow the ETCS safety, but the deceleration over human braking increases when braking towards a stop without end of movement authority. Experts at Prorail confirmed during interviews that the deceleration increases to -0,8 m/s^2, as this is still comfortable for the passengers and a -0,3 m/s^2 increase compared to the -0,5 m/s^2 human drivers often reach. Still, at the end of authority, the braking is defined by the ETCS braking curve, as this can be more restrictive than the constant -0,8 m/s^2 breaking acceleration.

The final advantage is in the parameters for the operations on the Dutch network. With the performance reduction percentages in Table 5, scheduled slack driving time in simulations is 7% for passenger trains. As ATO trains are more predictable than humans, ProRail considers the three extra 1% point performance reductions irrelevant for ATO trains. Thus the performance reduction for ATO vehicles to allow for slack driving times is 4%, resulting in a 96% modelling performance for passenger trains.

Considering the advantages of the ATO train operations at GoA2, the following changes to the simulations are made to implement ATO in OpenTrack:

- The constant braking deceleration is -0,8 m/s^2, as the computers will brake at an increased rate
- The block occupation time behind the train reduces by 15 seconds due to the increased predictability of the trains
- The performance of the passenger trains increases from 93% to 96%, as there is less fluctuation in the driving times of ATO trains than humans.

2.6 IMPLEMENTATION OF THE MEASURES IN THE SIMULATION

This section summarises the changes in parameters to implement the different measures over the base scenario in OpenTrack, as the three measures need different changes in parameters for correct implementation. According to literature and experts, the changes in the models' infrastructure or the rolling stock provide an accurate simulation of the different measures. Table 6 summarizes these modelling changes shortly. When a scenario mentions these measures from this point on, these changes are made to the OpenTrack model.

Table 6: Changes in the model made for each of the measures.

Measure	Changes
ERTMS/ETCS level 2	Implementation of a new maximum speed profile
	Changing signalling to virtual signals and removing speed reductions due to signalling aspects
	Change the trains to follow the ERTMS/ETCS speed profile
3 kV DC overhead power	Change the power supply to 3 kV DC
	Ensure the rolling stock has performance curves for 3 kV DC overhead power
	Link the 3 kV DC performance curves to the 3 kV DC power supply
ATO	At the itinerary, change the performance under delay and on-time operations to 96%
	At the itinerary, reduce the additional reservation time by 15 seconds (e.g. IC trains go from 60 to 45 seconds)
	Change the constant braking parameter for the used rolling stock to -0,8 m/s^2

3. CASE STUDY DESCRIPTION

This Chapter introduces the different case studies to find the individual and combined effects of the three measures. Section 4.1 shows the line's location and the network case study in Sections 3.1.1 and 3.1.2, respectively, including a description of the infrastructure and the planned lines. Finally, in Section 3.2, the assumptions and limitations for the simulation are given.

3.1 CASE STUDY SELECTION

As one of the research goals is to investigate the railway capacity on the Dutch network under different measures, two case studies are selected to investigate the effect of the measures on line and network levels. The line case study (Section 3.1.1) mainly focuses on the interactions between the three selected measures. In contrast, the network case study (Section 3.1.2) investigates network interactions, as the interconnected nature of the Dutch railway network can alter the effects.

For the location of the studies, the Gooi line is the focus. As described in the introduction, this line falls outside the scope of current improvement projects of NS and ProRail except for the installation of ERTMS/ETCS level 2 (Ministry of I&W, 2019). The service pattern for 2030 changes for the SAAL line and surrounding network in 2030. This change removes the intercities towards Amsterdam Central station and increases the number of intercities towards Schiphol airport (van Wijk, 2020). Figure 9 shows the proposed route division on the SAAL line, including the service pattern on the Gooi line. As the timetable is from 2030, the proposed infrastructure of 2030 will also be used during the case study.

During the selection of the case study locations, some factors were considered significant. First, the location had to represent a typical Dutch railway line with high-frequency service, resulting in high-capacity usage. Next, the location had to allow the investigation of the difference in capacity effects of measures between the line and network. When combined with the question from RHDHV if reintroducing the intercity between Amsterdam and Amersfoort was possible, the Gooi line combined with the SAAL line provided suitable case study locations for the line and the network studies.

Section 3.1.1 introduces the location of the line case study, which focuses on investigating the combined effects of the measures. In this section, the infrastructure and the proposed service pattern are introduced. Afterwards, the different scenarios for the case study are given. Within Section 3.1.2, the case study of the network is described with a comparable structure.

3.1.1 Line case study

For the single-line case study, the selection is made for a central line on the network, approaching the capacity limit under the Dutch infrastructure parameters. Also, the typical Dutch train traffic composition has to be present on the line to allow for comparing similar network train traffic composition regarding capacity effects. Therefore, the line from Hilversum towards Weesp is selected for the case study. This line has a length of 15,2 km with a single track dedicated to traffic in one direction. Thus on the line, trains cannot overtake one another. On this route, visualized in Figure 9 and inside the blue box, five stations are present, Hilversum (Hvs), Hilversum Mediapark (Hvsm), Bussum Zuid (Bsmz), Naarden Bussum (Ndb) and Weesp (Wp). Except for Hilversum and Weesp, the sprinter trains hinder intercity operations when stopping at stations.

Proposed timetable structure

To assess the capacity effects of the selected measure on the case study, an hour of the proposed 2030 timetable is compressed using the Dutch assessment method introduced in Section 2.2.2. Within the timetable of 2030, four different types of trains will run on the case study route. This section introduces the different train types and their stopping patterns.

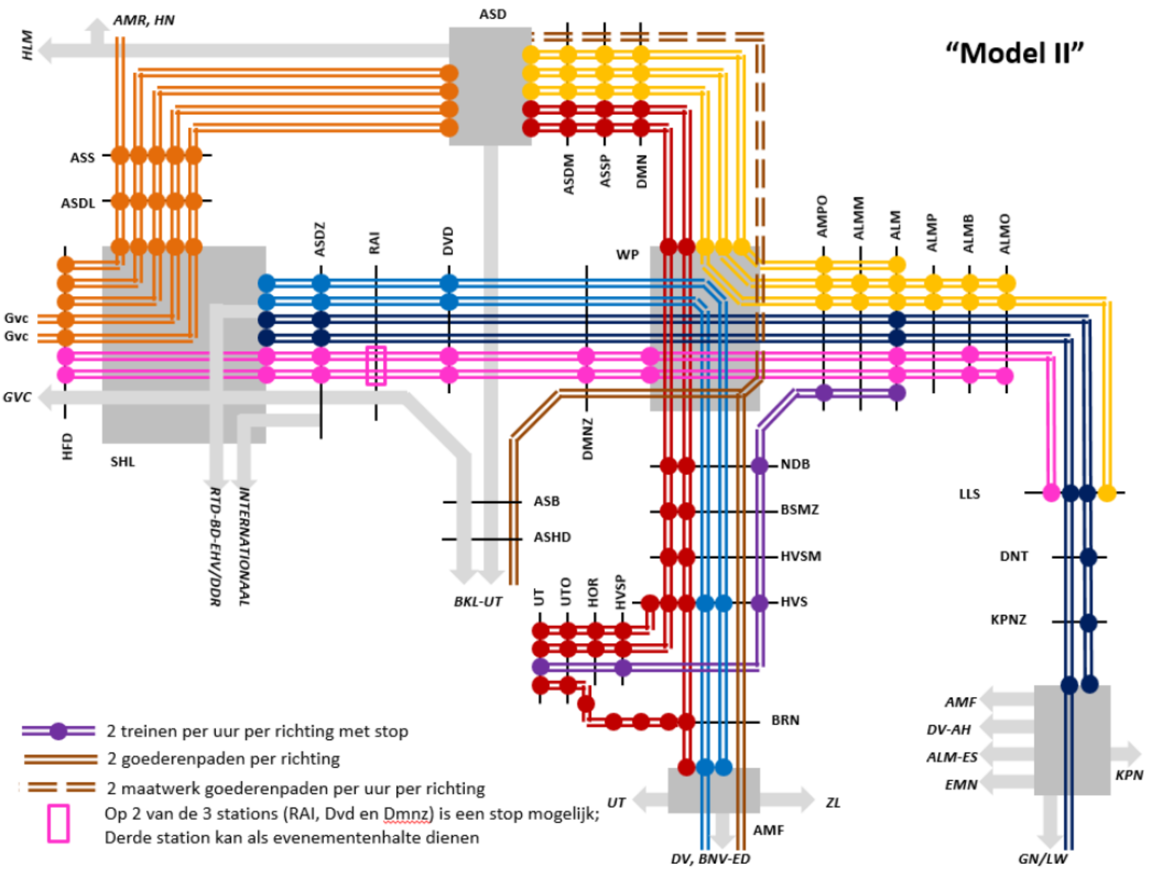


Figure 9: Proposed train paths and stops on the SAAL network for 2030 (van Wijk, 2020), edited

Table 7: Overview of the series of trains on the Gooi line between Hilversum and Weesp

Series number	Type of train	Between cities	Frequency	Rolling stock
140	IC international	Berlin and Schiphol	Simulated hourly instead of once every two hours	Talgo 16 carriages
1500	IC	Amersfoort and Schiphol	Hourly	ICNG 13 carriages
1600	IC	Eindhoven and Enschede	Hourly	ICNG 13 carriages
11600	IC	Eindhoven and Amersfoort	Hourly	ICNG 13 carriages
4900	Regional Express	Utrecht and Almere	Half hourly	SLT 6 carriages
5700	SP	Amsterdam and Utrecht	Half hourly	SLT 6 carriages
5800	SP	Amsterdam and Amersfoort Vathorst	Half hourly	SLT 6 carriages
BKG10	Freight	Oldenzaal Border and Kijfhoek	Half hourly	BR189 1400 ton

The Gooi line handles 12 trains an hour per direction, which are in four categories. Firstly, the sprinters and the intercities have four trains an hour in each direction, and two trains are scheduled for the freight and the regional express services. Table 7 gives the numbers of the series of trains on the Gooi line, the entire planned route, and what frequency of the train series are scheduled with their planned type for rolling stock. One train that differs slightly from the others is the 140 series between Amsterdam and Berlin. This train is scheduled two-hourly between the two capitals and is replaced by an NS intercity for each hour the train is not scheduled. Therefore, this train is scheduled hourly in timetable assessments.

In the line case, the intercity services only stop at Hilversum while slowly closing the distance and time intervals with the slower freight, sprinter and regional express trains in the network. For the regional express services, stops in Hilversum and Naarden-Bussum are scheduled, and they branch off towards Almere. The sprinter trains will stop at Hilversum, Hilversum Mediapark, Bussum Zuid, Naarden-Bussem and Weesp, thus calling at all stations on the line. The number of stops of these sprinter trains makes the performance increase of the measures at acceleration more significant. Lastly, the case has freight trains. These trains start at Amersfoort, as this is the last scheduled stop before the line case. The freight trains pass Hilversum at their scheduled time and do not stop there.

As for the data limitations introduced in Section 2.4, all rolling stock of the intercity trains is replaced with VIRM-6 rolling stock. The sprinter trains get SLT-6 rolling stock for their services. The BR189's performance with 3 kV DC overhead power is also available for the freight trains and therefore does not need to be changed. These three train types have performance curves for 3 kV DC overhead power, allowing for investigation of the effects of 3 kV DC on the network. To allow the investigation of the effects of the different measures, these scenarios without 3 kV DC use these three types of rolling stock as well.

For the safety margins of the Dutch assessment method, the passenger trains receive a 60-second buffer. The safety margin provides stability to the timetable in case of a delay. Next, the passenger trains get a performance reduction of 7% to provide some slack driving times. This results in a performance parameter for all passenger trains of 93% with a reservation buffer of 60 seconds. For Freight trains, the buffer and reduction in driving times are set to 0 as the additional weight of these trains provides the safety margins.

Table 8: Scenarios for the line case study

Scenario	Measures involved
1	NS’54/ATB-EG and 1,5 kV
2	NS’54/ATB-EG and 3 kV DC
3	NS’54/ATB-EG and ATO
4	ERTMS/ETCS and 1,5 kV
5	ERTMS/ETCS and 3 kV DC
6	ERTMS/ETCS, ATO and 1,5 kV
7	ERTMS/ETCS, ATO and 3 kV DC

Scenarios on the line study

In the line case study, seven scenarios will be conducted. The selected scenarios are designed to analyze the combined effect of ERTMS/ETCS, 3 kV DC overhead power and ATO. With a signalling and safety system required for train operations, the basis of a scenario is either NS'54/ATB-EG or ERTMS/ETCS.

Table 8 shows the seven scenarios to be simulated using the Hilversum to Weesp line. In this line case, the first scenario where the compression is executed is the base scenario with the current infrastructure situation and the proposed timetable composition of 2030. Afterwards, the timetable compression assessment for the other scenarios can be conducted to give insight into the capacity effects of the measures. The output of the different scenarios is the speed-distance graphs of trains (speed profile) and the travel times to check that the dispatching is conflict-free.

3.1.2 Network case study

The network case is the Gooi line, including expansions toward Amsterdam (central station and Zuid), Almere and Amersfoort. These boundaries for the case are chosen as trains will terminate at these stations after travelling over the Gooi line. Almere is the exception, as the trains to Almere often travel on towards Lelystad. The choice was made to end the case study at Almere as this is the first intercity station in this direction. To and from Almere, 16 trains per hour with many stopping patterns are present. Four of these trains will terminate at Almere Centrum while another four terminate at Almere Oostvaarders, and thus eight continue past the city of Almere.

The line from Weesp in the direction of Amersfoort has an additional major station with multiple directions southbound at Hilversum, where a line from Utrecht joins. The line from Utrecht is used by fewer trains than the other lines in the case study. One series terminates at Hilversum without interacting with the other trains considering a compressed timetable. Therefore, this train series is not included in the case study. A further four trains per hour, of which half is sprinter half regional express, arrive from Utrecht in Hilversum and are thus included in the study. Four trains with the same stopping pattern also travel towards Utrecht from Hilversum and the rest of the study area.

Each hour, from the direction of Amersfoort, four intercities, two sprinter and two freight trains arrive in Hilversum. These trains travel further towards either Amsterdam Zuid (intercity train), Amsterdam Central (Sprinter train) or travel onwards via Amsterdam Bijlmer Arena (Freight trains). At Weesp, all these trains interchange from Hilversum or Almere towards Amsterdam Zuid or Amsterdam Central station. With six tracks (3 in each direction, 2 with platforms), Weesp has the most options for trains to travel through the station.

Figure 10: Overview of the network case, blue lines give boundaries of the network (ProRail, 2020a), edited

After Weesp, ten sprinters an hour travel towards Amsterdam Central station. This whole line is mostly double-tracked (one in each direction). As these trains have the same scheduled stops, two tracks provide sufficient capacity for these ten trains an hour. When needed, a path for a freight train could be provided as a result of the freight train travelling from Amersfoort to Amsterdam Bijlmer Arena in both directions. As this path is not often used, the study will not include this train.

Twelve intercity and regional express trains with different stopping patterns occur towards Amsterdam Zuid every hour. Also, the freight path from Amersfoort continues shortly on this route before peeling off towards Amsterdam Blijmer Arena. After the junction near Weesp, this line is double-tracked until just after the station of Duivendrecht, where two tracks become available in both directions. Therefore, the bottleneck on this line is expected at Duivendrecht.

The route between Weesp and the switching lane towards Duivendrecht has two tracks in both directions for a total of four without stations for sprinters or intercities. Further, the blue lines in Figure 10 visualise the network boundaries. Also, the route between the switching lanes and Duivendrecht is shown as four tracks, while most stations on this route are only double-tracked. Trains enter or leave the simulation at the borders without considering rolling stock availability.

Proposed timetable structure

Figure 9 shows the proposed line structure for the case study network. Similar to the line case, the departure order of the scheduled train remains the same as the proposed timetable for 2030. A summary of the different trains and their frequencies is given in Table 9.

Table 9: Overview of the series of trains in the network case study

Series number	Type of train	Between cities	Frequency	Rolling stock
140	IC international	Berlin and Schiphol	Simulated hourly instead of once every two hours	Talgo 16 carriages
700	IC	Zwolle and Rotterdam	hourly	ICNG 13 carriages
1300	SP	The Hague and Zwolle	Half hourly	SLT 6 carriages
1400	SP	Amsterdam Central and Almere East	Half hourly	SLT 6 carriages
1500	IC	Amersfoort and Shiphol	Hourly	ICM 7 carriages
1600	IC	Enschede and Eindhoven	Hourly	ICNG 13 carriages
1800	IC	Rotterdam and Zwolle	Hourly	ICNG 13 carriages
2400	IC	Lelystad and Rotterdam	Hourly	ICNG 13 carriages
2600	SP	Amsterdam and Almere	Half hourly	SLT 6 carriages
4300	SP	Amsterdam and Lelystad	Half hourly	SLT 6 carriages
4900	Regional Express	Utrecht and Almere	Half hourly	SLT 6 carriages
5700	SP	Amsterdam and Utrecht	Half hourly	SLT 6 carriages
5800	SP	Amsterdam and Amfersfoort Vathorst	Half hourly	SLT 6 carriages
9200	High-speed train (IC)	Lelystad and Breda	Hourly	ICNG 13 carriages
11600	IC	Amfersfoort and Eindhoven	Hourly	ICNG 13 carriages
BKG10	Freight	Oldenzaal Border and Kijfhoek	Half hourly	BR189 1400 ton

Scenarios on the network study

The network study considers fewer scenarios than the line case study as most of the network case receives an upgrade towards ERTMS/ETCS level 2 due to the SAAL project. The signalling and safety systems on the network are ERTMS/ETCS and ETCS level 2. The effects of 3 kV DC and ATO will be compared on both individual levels with ERTMS/ETCS level 2 as combined. The selected scenarios provide sufficient possibilities to compare with the line case study to find the network interactions of the railway capacity. Table 10 shows the four different scenarios for the network case study.

Table 10: Scenarios for the network case study

Scenario	Measures involved
1	ERTMS/ETCS and 1,5 kV
2	ERTMS/ETCS and 3 kV DC
3	ERTMS/ETCS, ATO and 1,5 kV
4	ERTMS/ETCS, ATO and 3 kV DC

When the capacity consumption of the different scenarios under the proposed measures is found, the network case studies' effects are compared to those of the line case study. Whereafter the intercity between Amsterdam Central station and Amersfoort is reintroduced, and the timetable is compressed once more to find if the extra train path is possible. Otherwise, the found capacity gains help improve the current timetable's robustness.

3.2 ASSUMPTIONS AND LIMITATIONS

As the case study assumes the planned situation for the Dutch network, some assumptions were required to realize the final model. Further, during the research, some modelling and data limitations were found.

The first assumption is that the plans for the infrastructure for 2030 will be finished by then and not changed. Therefore, the stations of Amersfoort and Amsterdam are changed to their proposed 2030 versions, and the signal placement for the ERTMS/ETCS signalling system on the SAAL line is as designed for 2030. For the ERTMS/ETCS scenarios infrastructure without proposed signalling, the NS’54 signals are changed to virtual signals without changing their location

For the line and the network study, all train traffic outside the considered case does not influence the case traffic. In the actual network, there will be some interactions with the other trains, as there are, for example, trains to and from Utrecht from Amersfoort using the same platforms as the trains towards Hilversum. Therefore, the platform occupation at edge stations is not considered within the scope of the study during timetable compression. The platform occupation will be considered when inserting additional trains.

One of the limitations in data availability resulted in the third assumption. As 3 kV DC is not used on the Dutch network at the moment, only a few types of rolling stock have performance data for 3 kV DC overhead current as a result of a previous study. Therefore, all IC trains are assumed to use VIRM rolling stock, all sprinter and regional express trains are assumed to use SLT rolling stock, and all freight trains are assumed to use BR189 locomotives as tractive power.

Lastly, the nature of the capacity assessment method for railways is deterministic. Therefore, no delayed scenarios were considered. The Dutch assessment method introduced a buffer time and a slack driving time factor in the simulation to recover minor delays. This research used the same method to allow for delays to be recovered. Within UIC code 406, the method used is slightly different, as the timetable was compressed first and afterwards, a percentage of time represented in Table 4 was added.

4. RESULTS

This chapter discusses the results of the line and network case studies. For the results, the travel times and the capacity consumption of both the line case study (Section 4.1) and the network case study (Section 4.2) will be discussed. The line case provides the synergies between the measures in Section 4.1.1 with the capacity consumption results of these combinations in Section 4.1.2. The capacity results of Section 4.2.2 are used in 4.3 to line and network capacity results to find the interaction between line and network levels.

4.1 LINE CASE STUDY

The first section of the results discusses the smaller line case study of Hilversum-Weesp. First, the travel times on this route for the different trains are analyzed. After that, the different scenarios' capacity consumptions are given, and synergies are explored.

4.1.1 Travel times

Each measure affects the trains' travel time on the line network. These effects on the travel time differ per train type, as the travel times are related to the speed of the trains travelled over the route. For example, a sprinter has a lower average speed and stops more often than an intercity service. Figure 11 shows the speed-distance diagram with speed profiles of the NS'54/ATB-EG scenarios. The lines represent the base scenario (red), the scenarios with 3 kV DC (blue) and ATO (Green). Figure 12 shows the ERTMS/ETCS level 2 scenarios combined with 3 kV DC, ATO or 3 kV DC and ATO. The chosen train for the speed profile is a sprinter train between Hilversum and Weesp. In the ERTMS/ETCS scenario, the maximum speed allowed is higher at some points than the NS'54/ATB-EG scenario, while the sprinter will only shortly travel at this speed. Thus the travel time is more substantially affected by the measures on the network.

Figure 11 and Figure 12 show a sprinter train's speed (y-axis) over the distance between Hilversum and Weesp (x-axis), where Hilversum is at the base of the y-axis and Weesp roughly at the End of the x-axis. On x-axis also provides the placement of signals and the locations of the stations over the route. The mostly hidden red line provides the base scenario of NS’54/ATB-EG without any measures. The Figures show the speed at a given distance, and the acceleration and braking action are made visible by the change in speed. Therefore, this type of figure is helpful to visualize the effects of measures on the speed of trains and travel times.

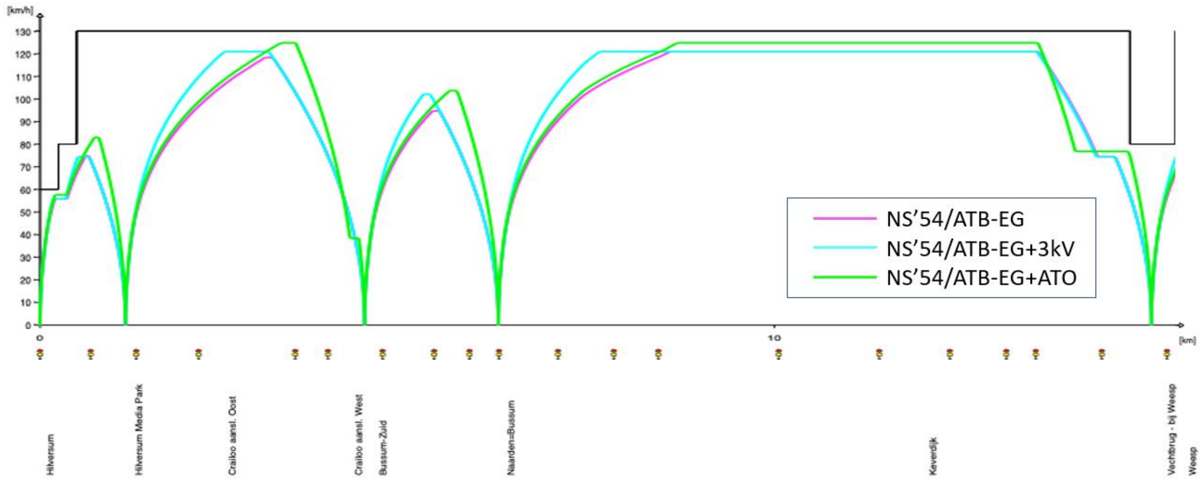


Figure 11: Speed-distance graph of NS'54/ATB-EG scenarios of the 5700 series sprinter

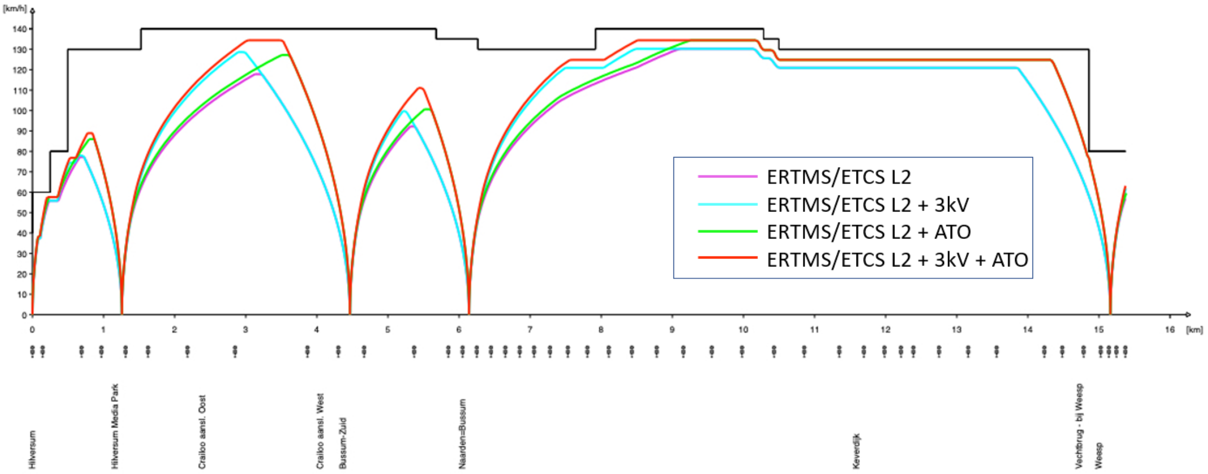


Figure 12: Speed-distance graph of ERTMS/ETCS level 2 scenarios of the 5700 series sprinter

Figure 11 shows that the 3 kV DC and ATO scenarios have improved performance in different areas under NS'54/ATB-EG. Where the performance gain with 3 kV DC is in the acceleration over the standard scenario, the advantage of ATO systems is at deceleration. Therefore, the opportunity for the systems to synergize together and further improve the efficiency of the trains. Sprinter trains in the 5700 and 5800 series have the highest decrease in travel time of 42 and 53 seconds, respectively. This difference is found in the departure platform in Weesp, therefore having a slightly different route. Intercity trains of 1500, 140, 1600 and 11600 series have negligible travel time decreases of 14 seconds under ATO. In the middle is the 4900 series, with a 41-second decrease.

In Figure 11, near Weesp, the speed profile of the ATO rolling stock reaches the speed given by the signalling aspect quicker than the standard scenario and 3 kV DC rolling stock. This faster reduction in speed explains why the 1500 series has a roughly equal absolute travel time decrease in a shorter route, as some travel time advantage is unused. This situation differs between NS'54/ATB-EG and ERTMS/ETCS level 2, as the signalling is in the cabin instead of trackside, so ATO is faster at roughly 80 km/h in Figure 11.

Under NS'54/ATB-EG, Table 11 shows that the decrease in travel time is most significant with the ATO trains, with a possible advantage for the passengers of 10 seconds per stop, reducing the travel time of a sprinter between Amsterdam and Amersfoort by roughly 2 minutes. Therefore the advantage for the passengers considering the travel time of ATO would be significant without considering network connections at stations.

Table 11: Travel times Hilversum-Weesp for the NS'54/ATB-EG scenarios (percentage in brackets is the difference from the base scenario NS'54/ATB-EG)

	5700 serie	1500 serie	4900 serie	5800 serie	11600 serie	Freight
NS'54/ATB-EG	00:14:48	00:08:25	00:08:50	00:14:49	00:08:25	00:11:40
NS'54/ATB-EG + 3 kV DC	00:14:30 (-2,0%)	00:08:18 (-1,4%)	00:08:37 (-2,5%)	00:14:31 (-2,0%)	00:08:18 (-1,4%)	00:11:18 (-3,1%)
NS'54/ATB-EG ATO	00:14:06 (-4,7%)	00:08:11 (-2,8%)	00:08:09 (-7,7%)	00:13:56 (-2,6%)	00:08:11 (-2,8%)	00:11:18 (-3,1%)

Table 12: Travel times Hilversum-Weesp for the ERTMS/ETCS scenarios (percentage in brackets is the difference from the base scenario of NS’54/ATB-EG)

	5700 serie	1500 serie	4900 serie	5800 serie	11600 serie	Freight
ERTMS/ETCS L2	00:14:15 (-3,7%)	00:08:21 (-0,8%)	00:08:36 (-2,6%)	00:14:15 (-3,8%)	00:08:21 (-0,8%)	00:11:22 (-2,6%)
ERTMS/ETCS L2 + 3 kV DC	00:13:54 (-6,1%)	00:08:11 (-2,8%)	00:08:21 (-5,5%)	00:13:54 (-6,2%)	00:08:11 (-2,8%)	00:11:20 (-2,9%)
ERTMS/ETCS L2 + ATO	00:13:12 (-10,8%)	00:08:12 (-2,6%)	00:08:12 (-7,2%)	00:13:12 (-10,9%)	00:08:12 (-2,6%)	00:11:22 (-2,6%)
ERTMS/ETCS L2 + 3 kV DC + ATO	00:12:48 (-13,5%)	00:08:02 (-4,6%)	00:07:56 (-10,2%)	00:12:48 (-13,6%)	00:08:02 (-3,8)	00:11:20 (-2,9%)

The second set of scenarios considers ERTMS/ETCS as the signalling and safety systems. When comparing Figure 11 and Figure 12, the ERTMS/ETCS scenarios' maximum track speed is higher than the NS'54/ATB-EG infrastructure. In some areas of the infrastructure, the speed is increased to 140 km/h over the current 130 km/h. This increase in maximum speed gives the ERTMS/ETCS-equipped trains a slight travel time improvement over the current NS'54/ATB-equipped trains. The advantage is again most prominent in the sprinters, indicating that the stop-start behaviour of these trains provides a larger benefit than the increased top speed used mainly by intercity services.

When comparing the different travel times of the scenarios in Table 12, the travel time decrease of a measure combined with ERTMS/ETCS is not a summation of travel times of the effect under NS’54/ATB-EG to the travel time reduction of ERTMS/ETCS over the base scenario of Table 11. 3 kV DC provides a similar step in travel time reduction under ERTMS/ETCS and NS’54/ATB-EG (3 seconds difference), indicating that the acceleration under ERTMS/ETCS is a little more efficient than NS’54/ATB-EG to decrease travel times. For ATO, the travel time improvement combined with ERTMS/ETCS is more significant than when ATO is combined with NS’54/ATB-EG. Figure 11 explains this, with the lower travelled speed around kilometre 14, due to the interaction of ATB-EG and ATO.

The combination of ERTMS/ETCS, 3 kV DC and ATO provides the best travel time of the investigated scenarios. The improved braking of ATO and acceleration of 3 kV DC synergize by providing a longer time at track speed. This advantage is most considerable for the sprinter trains, as these trains have the most scheduled stops. The intercity trains mainly profit from the improved performance within the model. The reached speed in the model is closer to the track speed in scenarios including ATO, which is expected as the performance reduction with ATO is lower at 4% over the other scenarios at 7%.

The most optimal scenario for the passengers is the complete package of measures, reducing the travel time of a sprinter train by 2 minutes and 22 seconds for an intercity train. Considering the total travel time of 15 minutes under NS’54/ATB-EG for a sprinter train, this advantage is very significant. Most of this travel time decrease is found in ATO, with improved speed and braking.

Table 13: Capacity consumption Hilversum-Weesp for the timetable of one hour

	Blocking time	Capacity consumption
NS’54/ATB-EG	55 min 08 sec	91,9%
NS’54/ATB-EG + 3 kV DC	53 min 36 sec	89,8%
NS’54/ATB-EG + ATO	53 min 00 sec	88,3%
ERTMS/ETCS level 2	51 min 42 sec	86,2%
ERTMS/ETCS level 2 + 3 kV DC	50 min 58 sec	84,9%
ERTMS/ETCS level 2 + ATO	44 min 00 sec	73,3%
ERTMS/ETCS level 2 + ATO + 3 kV DC	43 min 04 sec	71,8%

4.1.2 Capacity consumption

The second performance indicator of the measures is the capacity consumption of the lines. As introduced in Section 2.2, capacity consumption is the lowest time possible for all scheduled trains to pass without conflicts, divided by the initially scheduled period. The result is a percentage describing the time used to execute the compressed timetable compared to the original period. The results found after the compression of an hour of scheduled trains on the Hilversum-Weesp route result in the values provided in Table 13.

The first observation from this table is the 5.7% point improvement of ERTMS/ETCS level 2 over NS'54/ATB-EG. The change of the signalling system, including some signalling placement adaptations. This change allows for more efficient dispatching of trains due to quicker block release. Under both systems, the effects of the reduced speed at stations increase the track occupation at these locations. With the adaptations in the signalling placement under ERTMS/ETCS level 2, the total occupation time of the tracks near stations reduces. Next to the change of signal placement and the resulting increase in the number of signals, ERTMS/ETCS level 2 needs less distance headway in front of the train to continue at track speed due to the braking curves determining the needed track length in front. This distance headway reduction allows trains to follow quicker and reduces occupation time.

A further observation is a reduction in the effectiveness of 3 kV DC under ERTMS/ETCS compared to NS'54/ATB-EG. Where 3 kV DC has a reduction capacity consumption of 2,1% points under NS'54/ATB-EG, this is reduced to a 1,3% point reduction under ERTMS/ETCS level 2. The explanation for this difference in effectiveness is found in the braking curves. A higher speed requires a longer track distance to allow for free acceleration due to the braking-based movement authority of ERTMS/ETCS. With 3 kV DC improving the acceleration of the rolling stock, the ETCS braking curves will also require more distance, reducing the capacity effect compared to the entrance-based trackside signalling of NS'54. Therefore, the promising effects of 3 kV DC for the travel time do not convert into capacity consumption reductions.

The other side of the spectrum is ATO, as ATO provides a more significant improvement in capacity consumption under ERTMS/ETCS level 2 compared to NS’54/ATB-EG,3,6% point against 12,9% point. The 12,9% point does not include the reduction of ERTMS/ETCS level 2 over NS’54/ATB-EG. This improvement is due to the braking curve-based movement authority over the trackside entrance-based signalling. With Ns’54/ATB-EG, trains need to slow to the indicated speed as fast as possible, thus travelling at a reduced speed for a more extended period than when they are required to brake by the ERTMS/ETCS braking curves. This braking-based signalling increases the effect of ATO, with an effect of an enlarged capacity consumption reduction over the situation with NS’54/ATB-EG. With this 12,9% point decrease in capacity consumption, a large portion of the scheduled hour can be considered slack times to catch delays and increase the overall reliability of the timetable. The time left over after the compression of the timetable for the ERTMS/ETCS level 2 and ATO scenario is 26,7% or 16 minutes.

Still, the combination of ERTMS/ETCS level 2, 3 kV DC and ATO gives the most significant capacity consumption reduction. The total capacity consumption of this scenario for the line case study is 71,8% providing a 20,1% point reduction in capacity consumption compared to NS'54/ATB-EG case study. This provides a theoretical increase in scheduling slack time of 12 minutes and 4 seconds over the scheduled trains on the line case study. For this scenario, the addition of the individual capacity effects of the measures is possible. The effect of 3 kV DC overhead power and ATO under ERTMS/ETCS level 2 combined are only 0,2% point less compared to the reduction in capacity consumption from the combined scenario over the ERTMS/ETCS level 2 scenario.

With a track occupancy of 71,8% in the final scenario, the unoccupied time of the tracks equals almost 17 minutes. This spare time allows for an additional minute of buffer per train over the current Dutch scheduling norms. The increase in slack time in the schedule provides further reliability advantages, as the recovery capability of the schedule is increased due to the lower track occupation due to a passing train.

The Appendix shows the conflict-free time distance graphs to visualise the simulated trains on the line case study. For the line case study, only the northbound trains are visualised.

4.2 NETWORK CASE STUDY

This second section of the results describes the travel times and network capacity consumption. The network is from Amsterdam to Amersfoort and From Almere to Amsterdam Zuid, intersecting near Weesp.

4.2.1 Travel times

For the passengers, Section 4.1.1 shows the reduction in travel time over the line case study. These results had quite a variance in the travel time reductions of the sprinter and intercity trains. While this indication of travel time reduction is promising, the network contains some almost complete sprinter routes, providing further insights into the travel time reductions due to the different measures. The network case does not consider the NS'54/ATB-EG scenarios, as a large portion of the network infrastructure has ERTMS/ETCS level 2 planned in 2030. Therefore, this section considers the ERTMS/ETCS level 2 scenario as the base scenario and the travel time reductions are calculated from this scenario. Which, according to the results in Section 4.1.1, already has a reduced travel time compared to NS'54/ATB-EG.

With a large variety of stopping patterns in the case study, the reduction in travel time over the ERTMS/ETCS level 2 scenario varies from just 56 seconds for the 1800 series to 3 minutes and 23 seconds for the 5800 series (Table 14). This correlates with the findings on the line case study as the 1800 series goes straight from Almere to Amsterdam Zuid while the 5800 travels from Amersfoort to Amsterdam with ten stops in between. On average, the combination of ERTMS/ETCS level 2, 3 kV DC and ATO reduced the travel time on the network by 6% over the scenario with just ERTMS/ETCS level 2. When comparing this reduction in travel time with the percentual travel time reduction of the line case study between the same measure sets, the effect of the network study is 1% point lower than the network study. The longer distance between some stops explains this difference. For example, the travel time of the 5800 series in the network study reduces by 3 minutes and 13 seconds after 3 kV DC and ATO are implemented to 39:09 from Amersfoort to Amsterdam, while the reduction on the line case study for this train is 1 minute and 27 seconds to 12:48

from Hilversum to Weesp. Therefore, a significant part of the travel time gain was present in the line case study. The distance between the stops for this sprinter service is provided in Figure 10.

The results found in the network study once again show that the sprinters profit most from the performance advantages provided by the measures. This advantage is mainly realised by ATO, as the performance of the trains is increased, and the stops without end-of-movement authority have a faster deceleration than the scenarios without ATO. The overall gain is larger than the line case study as the length of the track on the network case study is over three times the length of the track in the line case study.

4.2.2 Capacity consumption

In the second case study, the focus is on the effects of network interactions on capacity consumption. A measurement of the capacity usage is taken at a central location of the case study network to evaluate the capacity consumption. At Weesp (Wp), there are six tracks, where all but four trains of the network simulated period pass. Four of the six tracks have a platform, allowing sprinter trains to stop there, while intercity and freight trains can pass without hinder. As all tracks have a different service pattern, slight differences in capacity consumption are present. Therefore, Table 15 shows the capacity consumption on the six tracks at Weesp, with the last column showing the average. The distance time diagrams for these scenarios are provided in the Appendix. For each scenario, the conflict-free train paths are shown on the routes Amsterdam-Amersfoort and Amsterdam Zuid-Almere.

With the ERTMS/ETCS level 2 scenario, the capacity consumption at all tracks of Weesp had higher capacity consumption than the line study. An explanation for this is the combination of a larger number of trains, and the route of the trains became longer without overtaking opportunities. The longer routes will move conflicts between trains towards the start and end of the routes, increasing the time needed between trains on the non-conflict side.

Table 14: Travel times of the different train series on the network case study

	ERTMS/ETCS level 2	ERTMS/ETCS level 2 + 3 kV DC	ERTMS/ETCS level 2 + ATO	ERTMS/ETCS level 2 + 3 kV DC + ATO
1800	0:17:20	0:17:04 (-1,5%)	0:16:39 (-3,4%)	0:16:24 (-5,4%)
5800	0:42:32	0:41:50 (-1,6%)	0:39:55 (-6,2%)	0:39:09 (-8,0%)
1600	0:31:36	0:31:00 (-1,9%)	0:29:56 (-5,3%)	0:29:33 (-6,5%)
4300	0:21:03	0:20:37 (-2,1%)	0:20:18 (-3,6%)	0:19:53 (-5,4%)
BGK10	0:32:08	0:31:54 (-0,7%)	0:32:03 (-0,3%)	0:30:58 (-3,6%)
1400	0:26:42	0:26:10 (- 2,0%)	0:25:25 (-4,8%)	0:24:49 (-7,1%)
2400	0:17:20	0:17:04 (-1,5%)	0:16:39 (-3,9%)	0:16:24 (-5,4%)
5700	0:28:09	0:27:38 (-1,8%)	0:26:50 (-4,7%)	0:26:17 (-6,6%)
1500	0:31:33	0:31:07 (-1,4%)	0:30:04 (-4,7%)	0:29:38 (-6,1%)
2600	0:24:53	0:24:24 (-1,9%)	0:23:49 (-4,3%)	0:23:18 (-6,4%)
1300	0:20:45	0:20:22 (-1,8%)	0:19:54 (-4,1%)	0:19:33 (-5,8%)
4600	0:26:38	0:26:10 (-1,8%)	0:25:34 (-4,0%)	0:24:49 (-6,8%)

Table 15: Capacity consumption for the network case at Weesp.

Scenario	Weesp track 1	Weesp track 2	Weesp track 3	Weesp track 4	Weesp track 5	Weesp track 6	Average
ERTMS/ETCS level 2	90,5%	96,6%	96,6%	98,8%	98,6%	98,6%	96,6%
ERTMS/ETCS level 2 + 3 kV DC	90,2%	93,2%	93,2%	95,6%	95,2%	95,2%	93,8%
ERTMS/ETCS level 2 + ATO	82,0%	84,8%	84,8%	88,1%	85,7%	85,7%	85,2%
ERTMS/ETCS level 2 + 3 kV DC + ATO	79,4%	82,0%	82,0%	83,5%	84,0%	83,9%	82,5%

At Weesp, the northbound sprinters trains stop at platforms per direction. All trains for Amsterdam central station use track 6, while the sprinters and regional expresses for Amsterdam Zuid use track 5, and the intercities and freight trains pass on track 4. This arrangement is also used for the southbound direction, with platform 1 for Almere and 2 for direction Hilversum.

For the network, the ERTMS/ETCS level 2 scenario is the base for the evaluation. In this scenario, the average capacity consumption is 14% points higher than the line study. If only the Northbound tracks, the capacity consumption is, on average, another 2,1% higher. Compared to the average of the first network scenario. This difference in track occupation rates results from the different traffic compositions in combination with the length of the routes.

The capacity consumption for the ERTMS/ETCS level 2 scenarios on the line study, given in Table 13, can be compared to the averages of the network case. This comparison shows that the steps provided by implementing measures over ERTMS/ETCS level 2 on the network case study are comparable to the line case results. The comparable capacity steps provide that the network interactions on the track capacity are insignificant when comparing similar traffic compositions. While capacity consumptions are heightened in the network case study, the conflicts of the trains were either at the stations at the edges of the case study or near Weesp, where the trains will split into different tracks per direction. Indicating that the bottleneck of the network shifts from the edges of the network to switching lanes centrally located in the network.

4.3 LINE AND NETWORK CAPACITY EFFECTS

Considering the results in Sections 4.1 and 4.2, the most obvious difference is the increased capacity consumption over the whole network case study. The length of track in the case study explains the increase in capacity consumption. Table 16 shows the reduction in capacity consumption in both the network and line case studies.

Table 16: Percent point reduction in capacity consumption over ERTSM/ETCS level 2

Scenario	Line capacity consumption	Average network capacity consumption
ERTMS/ETCS level 2 + 3 kV DC	-1,3% point	-2,8% point
ERTMS/ETCS level 2 + ATO	-12,9% point	-11,4% point
ERTMS/ETCS level 2 + 3 kV DC + ATO	-14,4% point	-14,1% point

Comparing the capacity consumption reductions for the ERTMS/ETCS level 2 scenarios that include measures to the ERTMS/ETCS level 2 scenarios. The reduction in capacity consumption is comparable for the network and the line case studies, where the advantage of 3 kV DC overhead power is more significant in the network case study with a 2,8% point over the base network scenario with ERTMS/ETCS level 2. For the line study, the reduction is roughly half this at 1,3% point. While this could be considered a significant difference in capacity consumption reduction, the extra slack time in the network is 54 seconds. This extra slack time in the line case study is 1,6% of the occupied time under the ERTMS/ETCS level 2 scenario. This difference in capacity consumption effects is due to the longer routes of trains in the network and the resulting higher initial capacity consumption, as the values found in the line case study are the minimum capacity consumption possible for this small network area.

For the scenario of ATO under ERTMS, the average capacity consumption reduction is 1,5% point less compared with the line case study. The presence of more stations in the network study explains this result. At stations, trains can brake towards the end of authority without it being a conflict. Under ERTMS/ETCS level 2, the supervised curve has a lower deceleration than the -0,8 m/s^2 for a free braking action from the ATO trains. Still, with a difference of 1,5% point, the effects of the network, for the Dutch situation, are not significant. The capacity consumption reduction resulting from 3 kV DC and ATO is comparable for the line and network case studies being 14,4% point and 14,1% point, respectively. As the line case study found, these capacity consumption under the ERTMS/ETCS level 2 signalling are comparable to the individual effects of 3 kV DC, and ATO summed.

An explanation of the almost equal reduction in capacity consumption is the case study selection. The Gooi line receives 12 trains per hour in each direction and handles many trains with diverse service patterns. This high number of trains can result in one of the network's bottlenecks. As slow freight trains, the regular sprinter, and the intercity trains are all present on the Gooi line, high capacity requirements between trains are common to see (e.g. intercity behind a freight train). As described in Section 2.2, a way to evaluate a more extensive network in detail is first to identify and investigate the bottlenecks. In this network study, the network bottlenecks were found at the switching lane at Weesp and the entrances at the stations at the network's edges.

For a future study, it can be interesting to investigate a case over the entire length of an intercity train with network interactions. This study contains the almost complete routes of some sprinter trains, with the remaining route being less than 10 minutes of travel time. These relatively small tail sections of the sprinter services do not contain the bottleneck for the services after considering the bottleneck in the network case study. When considering the longer routes travelled by intercity services, there are more train series with further interactions, possibly introducing a different dynamic to the capacity consumption reductions found in this case study.

5. ADDITIONAL TRAINS PATHS

With the capacity consumption of the line and network known, the robustness of the timetable increases by implementing the proposed measures. An example of robustness on the railway is the buffer time between trains. Another use for this additional buffer time is adding an extra train path. As Section 1.1 already introduced the desire for an intercity path between Amsterdam Central station and Amersfoort, this Chapter explores the opportunity of trading the robustness created by the measures for an additional train path. After the design of the train path is explained, the capacity consumption effects for the different network scenarios, introduced in Section 3.1.2, are provided.

The additional train path must be created twice hourly in both directions, which is standard in the Dutch railway timetable. The proposed intercities get paths which run directly behind the freight trains on the route between Amersfoort and Weesp, with a stop at Hilversum. The decision to introduce the intercity paths behind the freight train is due to the room in the timetable from Weesp to Amsterdam Central station and the high capacity requirement of the intercity behind the freight train. The stop at Hilversum is advantageous for capacity consumption, as the average speed difference between the intercity and freight trains reduces. A further advantage of this intercity is the more consistent service pattern to Amsterdam Central station, as the gap in the sprinter services is filled. The train paths are also inserted behind the freight train from Weesp to Amersfoort for the route from Amsterdam Central station to Amersfoort.

Table 17 provides the capacity consumption for the tracks in Weesp for the additional train scenarios. Compared to the network case study, the first observation is the increase in the capacity consumption by 12,3% point on average. When comparing this to the average capacity consumption of the trains on the network scenario for ERTMS/ETCS level 2, at the track between Hilversum and Weesp, each train averages a required capacity consumption of 7,2%. Therefore, the new train consumed some of the buffer times, which provided robustness to the timetable in the network.

For the scenarios of ERTMS/ETCS level 2 with and without 3 kV DC, the capacity consumption is over 100%. Therefore, becoming unstable and introducing the risk of unrecoverable delays in the day-to-day operations, with a sidenote that in the simulation, each train has a 60-second time buffer and a performance reduction to recover minor delays.

For the scenarios containing ATO, the capacity consumption at all tracks in Weesp is under 100%, indicating a stable situation. With the ERTMS/ETCS level 2 and ATO scenario, the capacity at Weesp 4 is 99,6%, which shows that the proposed additional trains just fit within the scheduled period. While this is a stable situation, the small amount of slack time to recover delays is undesirable for the operators. The average capacity consumption of this scenario provides a more desirable value of 97,6%. This provides 1 minute and 26 seconds, which are not required per the capacity consumption of the scheduled timetable.

The best capacity consumption in this set of scenarios is with ERTMS/ETCS level 2, 3 kV DC and ATO combined. Compared to the line case study, this scenario provides an average capacity consumption over all the tracks at Weesp of 95,3%, 12,8% points more. With, on average, 4,7% of the scheduled time still available for the recovery of delays, this equates to 2 minutes and 49 seconds of conflict-free scheduling. In this scenario, track four at Weesp has the highest capacity consumption at 97,5%, including the normative buffers for the Dutch assessment method. Thus delays can be recovered with this scenario, which includes the additional intercities.

Table 17: Capacity consumption for the network case with two additional intercities in both directions at Weesp.

	Weesp track 1	Weesp track 2	Weesp track 3	Weesp track 4	Weesp track 5	Weesp track 6	Average
ERTMS/ETCS level 2	109,4%	109,4%	109,1%	106,2%	106,2%	106,2%	107,7%
ERTMS/ETCS level 2 + 3 kV DC	107,2%	107,2%	107,5%	105,6%	105,6%	105,9%	106,5%
ERTMS/ETCS level 2 + ATO	97,1%	97,6%	97,6%	99,6%	96,9%	96,9%	97,6%
ERTMS/ETCS level 2 + 3 kV DC + ATO	94,8%	94,7%	94,7%	97,5%	95,1%	95,0%	95,3%

From this analysis, it can be concluded that the introduction of ERTMS/ETCS level 2 in combination with ATO provide sufficient capacity to the Gooi line to allow for the reintroduction of an intercity between Amsterdam Central station and Amersfoort. However, this intercity service requires 12,8% points of capacity consumption, which brings the capacity consumption close to an unstable situation.

6. DISCUSSION

Within the research, some assumptions and alterations made the research possible. For the model, some assumptions were required. Within this Chapter, the possible implications of these assumptions are discussed. Some of the provided information is already provided in Section 3.2

6.1 ASSUMPTIONS FOR THE MODEL

The first limitation was the quality of the model used. The model used was a copy of the NL model of RHDHV. Therefore, the assumption is made that the model's results correctly represent the current and future situation on the Dutch network, and no calibration or validation was conducted during the research. This model included the rolling stock performance and all infrastructure data. ProRail regularly checks this model against counterparts of other companies, and therefore the correctness was not doubted.

The model's infrastructure represents the currently correct 2030 situation. The infrastructure situation includes the renovation of Amsterdam Central Station (to be realized in 2028), the west side of Amersfoort Central station (to be realized in 2024) and SAAL (planned for 2029). This assumption is made as the 2030 hourly pattern considers these construction works finished. For the renovation at Amersfoort, the alterations should be finished before 2030. However, as the construction at Amsterdam Central Station and the SAAL route are still in the planning phase, these are prone to delays pushing the delivery date past 2030, which results in the infrastructure being a mixture of the current and planned version in 2030.

Within the 2030 timetable, the sprinter trains on the SAAL line received a reduction in buffer time of 30 seconds and a performance reduction of 4%. The trains on the SAAL line received this buffer in the Report of Van Wijk (2020). This buffer was required to create the regular timetable for the SAAL line, and the studies base scenario includes the same reduced buffer for these trains.

A further assumption is the used railway traffic as all train traffic outside the considered area was not considered to influence the case traffic. In the actual network, traffic between Amersfoort and Utrecht uses the same platforms as the trains in the case study. Therefore the platform occupation was not considered in the scope of the line and network cases. For the implementation of the new intercities, the platforms used by the trains were chosen so they would not conflict with the other train traffic.

The last limitation of the model was its deterministic nature of the model, which meant that the train paths were simulated without variance. A buffer was inserted to accommodate the operation variance, and the trains' performance was reduced to create some slack driving times.

6.2 ASSUMPTIONS FOR THE MEASURES

With the different measures, some uncertainties are introduced to the model. These uncertainties result from data limitations and estimations of the effects of measures.

6.2.1 ERTMS/ETCS level 2

OpenTrack mentions that their software correctly implements the signalling system of ERTMS/ETCS level 2. The signalling was changed towards a virtual block for parts of the model where no infrastructure change for 2030 was present. A more optimized signalling placement in these areas can provide further capacity effects. The involved areas are

Amsterdam Central station towards the connection of Diemen and Amfersfoort to Hilversum, as the other network parts already received the ERTMS/ETCS level 2 design. Therefore the capacity effects can change if the design of these areas changes to a more optimized signalling placement.

6.2.2 3 kV DC overhead current

The 3 kV DC overhead current provides the most significant data limitation in the research. The performance of trains changes with the increase in overhead current and available voltage. As most of the trains on the Dutch network only have the option to use a 1,5 kV DC overhead current, the performance with a different electric current is not sure. In the research of Paulussen et al. (2017), the performance of the VIRM, SLT and BR189 was mentioned. These same performance curves are included in the OpenTrack model of RHDHV and used for the simulations, including the 3 kV DC overhead power.

Not all trains in the proposed timetable used these three rolling stock types. To ensure a good comparison between the different scenarios, all intercity trains were converted to VIRM trains. This replacement of trains had unintended advantages over the planned ICNG trains, as the acceleration of the VIRM was lower and allowed for an earlier departure behind sprinter trains compared to the ICNG rolling stock. The SLT replaced all other train types in the original sprinter and regional express trains schedule. For the freight trains, no change was needed as these trains already used the BR189 locomotives.

While these train types are some of the older trains on the network, the expectation is that their presence on the Dutch network will not end before 2030. Therefore, some inaccuracy in the rolling stock performance for the network is introduced as the VIRM train can not travel over the HSL and in Germany. With the replacement of the intercities, the model does assume this as true. Also, the performance of the VRIM is different compared to the ICNG or the new international train to Germany. The newer rolling stock has an overall better acceleration than the VIRM, which allows the VIRM to be dispatched quicker behind the other trains and will require some extra time to reach the track speed.

6.2.3 Automatic train operations

The effects of Automatic Train Operations are based on previous research and conversations with experts. Previous in-situation tests provided the basis for these effects, and these values are often conceived as accurate. Still, reducing the buffer of ATO trains hurts the system's capacity to recover from delays. In contrast, ATO trains are expected to have fewer delays, as human error in driving them is eliminated from the system. Therefore ATO needs to provide sufficient certainty in further in-situation tests that this performance is reached before becoming a serious option for NS.

Another implication of ATO is the combination with ERTMS/ETCS level 2. For now, the Dutch vision is to enrol baseline 3 of ERTMS/ETCS on the network. This baseline is not compatible yet with ATO systems. Currently, baseline four is being developed, which should allow ATO operations. It is uncertain if the Dutch network operator and NS will consider this a future upgrade on the network.

7. CONCLUSION

With the results found in Chapters 4 and 5, first, the subquestions are answered, leading to the answer to the main research question. Afterwards, Section 7.2 reflects on the research goal, and Section 7.4 provides some recommendations for future research.

7.1 ANSWERING THE RESEARCH QUESTIONS

The first sub-question was:

What are the capacity effects of ERTMS/ETCS level 2, the increase to 3 kV DC overhead current and ATO?

The effects of each measure over the NS’54/ATB-EG base scenario are described to answer this sub-question. First, the change to ERTMS/ETCS level 2 was investigated. While this safety and signalling system is designed to improve the safety and operation of the railway, there is some capacity benefit when comparing the system with the legacy system on the Dutch network. As ERTMS/ETCS improves communication between the train and the trackside, more information about the train is known. Therefore, a proactive braking curve-based signalling system is possible instead of a reactive, block entrance-based signalling system like NS’54. As the movement authority now depends on the required braking distance of the train, the needed free track length in front of the trains reduces compared to NS’54. This results in a decrease in time headway between trains, thus increasing the railway's capacity.

The second measure is a 3 kV DC overhead current. With more overhead power available to the trains, the trains can accelerate faster. This increased acceleration allows for faster clearance of signalling blocks just behind a station. Under NS’54/ATB-EG, this results in a larger capacity consumption effect than with ERTMC/ETCS level 2. The increased acceleration by 3 kV DC results in a faster-growing braking distance. The larger braking distance results under ERTMS/ETCS in a larger track reservation requirement for track speed movement authority. NS’54/ATB-EG does not consider the braking distance in the same way and provides track speed as soon as the required track length is available, decreasing the time headway required for conflict-free dispatching of trains.

Lastly, ATO has the most significant impact on the capacity of a network, as ATO improves the trains in multiple areas, including the required buffer time used in the assessment method. This buffer time reduces by 15 seconds when an ATO GoA 2 system is used in the train. With this travel time reduction, the estimated braking increases to -0,8m/s^2 and the performance reductions of the Dutch scheduling conditions (Table 5) become 4%. These three improvements drop the scheduled time headway most significantly compared to the other measures. Another benefit of ATO is its synergy with the 3 kV DC overhead current. The braking improvement of ATO provides a reduced braking distance. It thus reduces the track reservation requirement for track speed under ERTMS/ETCS, further reducing the time headway under 3 kV DC overhead power.

The second sub-question was:

What is the (combined) line capacity effect of ERTMS/ETCS level 2, the increase to 3 kV DC overhead current and ATO?

In the case study from Hilversum to Weesp, 3 kV DC overhead current and ATO are combined with the legacy signalling and safety system. The 3 kV DC overhead current reduced the capacity consumption by a 2,1% point, whereas ATO managed a 3,6% point reduction. The safety and signalling system ERTMS/ETCS level 2 alters the effects found for the measures. ERTMS/ETCS level 2 improves the capacity consumption with a 5,7% point over NS’54/ATB-EG. While the combination of ERTMS/ETCS and 3 kV DC improves the capacity consumption over the individual measures, the effect was reduced to 1,3% point.

The combination of ATO and ERTMS/ETCS level 2 improved the capacity effect of implementing ATO. The 5,9% point found under ATB-EG was converted to a 12,9% point reduction under ERTMS/ETCS level 2. This increase is due to the braking curve-based movement authority. With NS’54/ATB-EG, the ATO trains reduced speed quicker than the standard trains as the braking would happen at the signal as required by the signalling system, which caused the ATO train to travel at reduced speed for a longer distance and consume more track capacity.

The final scenario found the best result. Combined with all measures, the capacity effect of 3 kV DC overhead performance managed a further 1,5% point reduction over ERTMS/ETCS level 2, and ATO was realized to a 71,8% capacity consumption in the line case study.

From these numbers, it can be concluded that the signalling system is an important factor in the effects of different measures regarding capacity. With NS’54/ATB-EG, increasing the acceleration of trains is generally a direct decrease in capacity consumption in capacity consumption where braking performance increase from ATO is the major contributor under ERTMS/ETCS.ETCS level 2.

Sub-question three was:

What are the differences in effects of the individual and combined measures when considering line and network capacity?

The case study of the Gooi line and part of the SAAL line was used to investigate the network effects of the different measures. ERTMS/ETCS level 2 was these scenarios' signalling and safety system. The reduction of capacity consumption after implementing 3 kV DC overhead power is 1,3% point for the line case and -2,8% point for the network case study over only ERTMS/ETCS. The slight difference in these capacity consumption reductions can be explained by the size of the cases and the number of stops included. In the network case study, these longer routes provide both the sprinter and Intercity trains with more moments of acceleration. On average, the time headway between trains is more significant than in the line case study.

The comparable reduction in capacity consumption seems not a coincidence, as the reduction in capacity consumption of ATO under ERTMS/ETCS level 2 is an 11,4% point average of the six tracks at Weesp for the network case. This is again comparable to the line case study results at 12,9% points. The lower network capacity reduction results from more extreme braking actions towards the end of movement at stations. Still, the complete package of measures is close to the summation of the found capacity consumption reductions found in both case studies at 14,4% points and 14,1% points for the line and network case studies, respectively.

The conclusion that could be drawn from these results is that while the capacity consumption effects of measures are comparable between a line and network case study, the results are not the same. Therefore, a method where first the network bottlenecks are identified and, afterwards, the capacity consumption of this bottleneck could provide insight into the minimum capacity effects of different measures. Within this report, the network case provided five bottlenecks for the network: Amfersfoort, Amsterdam Zuid, Amsterdam Central Station, Almere and Weesp. Weesp is the only bottleneck in the middle of the network and was expected as multiple busy routes converge there.

The final sub-question sounded like this:

Is there an opportunity to increase the number of trains on a network using the combined effects of the different measures when looking at the Gooi line?

An intercity was introduced to investigate the opportunity of adding an extra train from Amersfoort to Amsterdam, which only stopped in Hilversum on the way. The order of other trains was not altered in the process, and the capacity consumption remained under 100% for the scenarios with ATO. Unfortunately, individually and combined, ERTMS/ETCS level 2 and 3 kV DC did not achieve a capacity consumption under 100% with an additional intercity.

The location of the new intercity was behind a freight train. Thus, the capacity consumption of this combination of trains is on the higher side of the possible combinations due to the average speed difference. Implementing the extra train increased the capacity consumption with an average of 12% points over the different scenarios, reducing the trains' capabilities on the network to recover from delays due to other trains.

The answers to these subquestions can be combined to answer the main research question:

What are the differences in capacity effects when comparing the individual capacity effects of the implementation of ERTMS/ETCS level 2, increasing the overhead current to 3 kV DC and ATO with combinations of the measures on a line and network level?

After comparing the effect of ERTMS/ETCS level 2, the increase of current to 3 kV DC and ATO between a line and a network study. The total consumption is case-dependent, but the effects of the measures remain comparable. Further, the signalling system is a crucial system for the operations of the network and the effects of different performance-increasing measures. When matching the advantages of a measure with the optimal type of signalling system, the effects on capacity can improve.

The increase to 3 kV DC was less effective when combined with ERTMS/ETCS level 2 than Ns’54/ATB-EG. In contrast, the effect of ATO under ERTMS/ETCS level 2 is significantly higher than with NS’54/ATB-EG as ERTMS/ETCS utilizes the increased braking of trains more efficiently than NS’54/ATB-EG.

The network case study found minor differences in the effects compared to the line case study. These differences are due to the movement of bottlenecks of trains, increasing the required time headway between trains. The overall additive effects of the measures are within 0,3% point. Therefore, the indicative role of a line case study is beneficial.

Therefore, it is suggested that the research on ERTMS/ETCS in combination with ATO receives further attention if no train paths are changed. Implementing 3 kV DC overhead power only increases capacity when combined with ATO. Thus the priority should be on the ATO implementation, both for more in-situ tests under ERTMS/ETCS for goods and passenger train operations and for developing a supporting signalling system.

7.2 REFLECTION ON THE RESEARCH GOAL

In Section 1.3, the research goal was defined. The aim was to investigate to what extent the combination of ERTMS/ETCS level 2, 3 kV DC overhead current and ATO could increase the capacity of the Dutch railway network. Also, the possibility of providing new train paths with the found capacity consumption reduction was mentioned.

This research combined the different measures mentioned in the research goal, and with the analysis of the speed-distance graphs, the capacity effects of the measures were explained. Further, the different capacity consumptions of the sets of measures provided insight into a network's effects on the capacity consumption compared to a line.

Finally, an extension of the main research question found that ERTMS/ETCS level 2 combined with ATO can facilitate an intercity service over the Gooi line. 3 kV DC overhead current decreases capacity consumption, thus providing some robustness to the schedule. These findings provide a sufficient basis to conclude that the research completed the goal

7.3 REFLECTION ON THE RESEARCH GAP

The research gap was defined as the lack of research on the combined capacity effects of measures on a highly used railway network, including the difference in line and network capacities. With the answers to the research questions, the study results mostly reach the closure of the gap.

With the consistent results between the different measures over the line and network case studies, the effects of a network on capacity consumption are minimal. The main effect was the increased capacity consumption due to the number of trains and the length of their routes. The network interactions did not affect the capacity reductions of the combination of measures on the network.

The goal of investigating the different synergies of the measures was found, with, for example, the difference in the effect of 3 kV DC under NS’54/ATB-EG, ERTMS level 2 and the combination of ERTMS/ETCS level 2 and ATO. The effect of 3 kV DC was reduced to an insignificant effect under ERTMS/ETCS level 2 compared to NS’54/ATB-EG. In contrast, ATO combined with ERTMS/ETCS level 2 again provided the capacity reduction.

While the research gap is not closed entirely for the network interactions, the research provides insight into the interactions of the three selected measures. Further research on other network locations could be considered for network interactions to confirm the findings.

7.4 FUTURE RESEARCH RECOMMENDATIONS

As with most research, during research, some further areas for interesting research were found.

Costs vs capacity gain

While all the measures investigated in the research are planned to be implemented on the network, the projected costs for each measure are uncertain. Therefore, future research could investigate the cost-effectiveness of the measures. The possibility of this research depends on the availability of the (development) costs of the different measures.

Robustness of the timetable

During the research, the ability to recover from delays was not considered. To allow for the consideration of possible delays, the simulated trains received a performance decrease to allow for slack driving times and a 60-second buffer for each of the trains following the Dutch timetable assessment method. For ATO trains, the performance was increased, and the buffer was reduced, thus affecting the robustness. These robustness-reducing changes are made due to the more predictable nature of ATO's computer-controlled trains. With tests already being conducted by ProRail and partners (ProRail, 2021c).

Confirmation of line and network interactions

The final area of further investigation could be the study to either confirm or disprove the found effects of the line and network interactions. This could be done by increasing the network elements in a case study or taking a network case study and investigating the effects of the investigated measures on a line within that study area.

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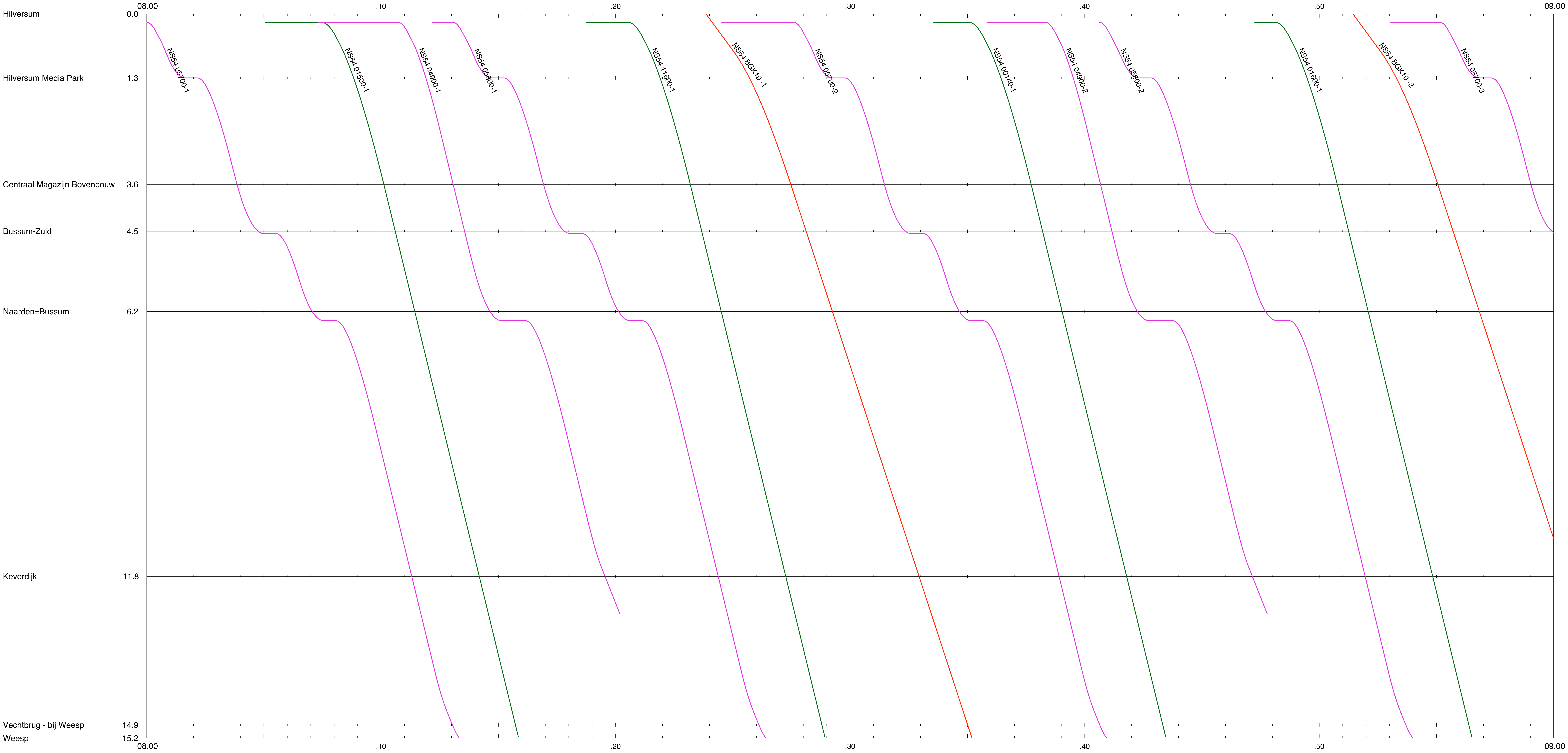
9. APPENDIX

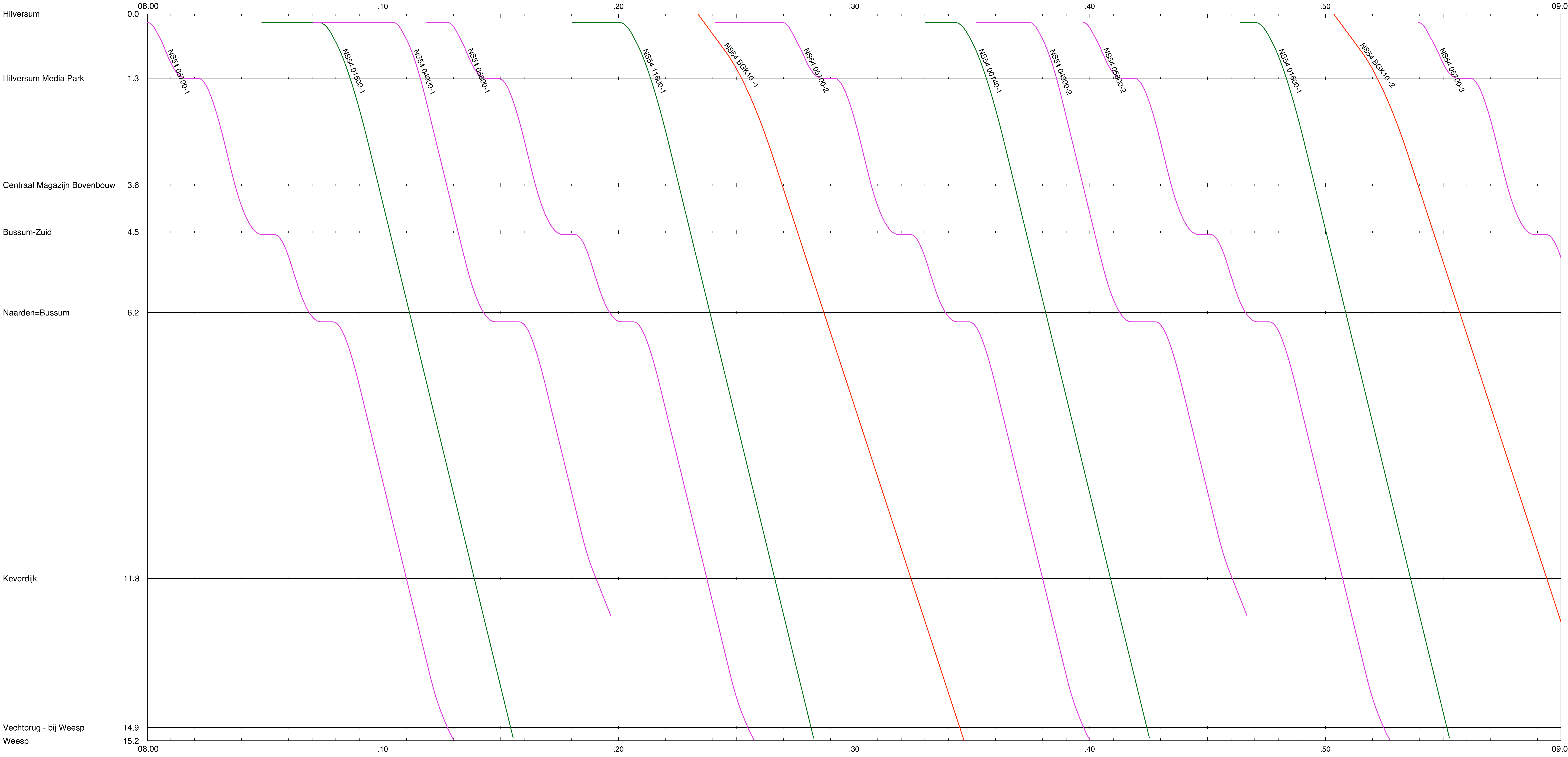
In the Appendix, the different distance time diagrams are given. The following list gives the scenario of each of the distance time graphs

a. Line: NS’54/ATB-EG, 1,5 kV DC
b. Line: NS’54/ATB-EG, 3 kV DC
c. Line: NS’54/ABT-EG, 1,5 kV DC, ATO
d. Line: ERTMS/ETCS level 2, 1,5 kV DC
e. Line: ERTMS/ETCS level 2, 3 kV DC
f. Line: ERTMS/ETCS level 2, 1,5 kV DC, ATO
g. Line: ERTMS/ETCS level 2, 3 kV DC ATO
h. Network: ERTMS/ETCS level 2, 1,5 kV DC (Asd-Amf)
i. Network: ERTMS/ETCS level 2, 1,5 kV DC (Asdz-Alm)
j. Network: ERTMS/ETCS level 2, 3 kV DC (Asd-Amf)
k. Network: ERTMS/ETCS level 2, 3 kV DC (Asdz-Alm)
l. Network: ERTMS/ETCS level 2, 1,5 kV DC, ATO (Asd-Amf)
m. Network: ERTMS/ETCS level 2, 1,5 kV DC, ATO (Asdz-Alm)
n. Network: ERTMS/ETCS level 2, 3 kV DC, ATO (Asd-Amf)
o. Network: ERTMS/ETCS level 2, 3 kV DC, ATO (Asdz-Alm)
p. Additional train: ERTMS/ETCS level 2, 1,5 kV DC (Asd-Amf)
q. Additional train: ERTMS/ETCS level 2, 1,5 kV DC (Asdz-Alm)
r. Additional train: ERTMS/ETCS level 2, 3 kV DC (Asd-Amf)
s. Additional train: ERTMS/ETCS level 2, 3 kV DC (Asdz-Alm)
t. Additional train: ERTMS/ETCS level 2, 1,5 kV DC, ATO (Asd-Amf)
u. Additional train: ERTMS/ETCS level 2, 1,5 kV DC, ATO (Asdz-Alm)
v. Additional train: ERTMS/ETCS level 2, 3 kV DC, ATO (Asd-Amf)
w. Additional train: ERTMS/ETCS level 2, 3 kV DC, ATO (Asdz-Alm)

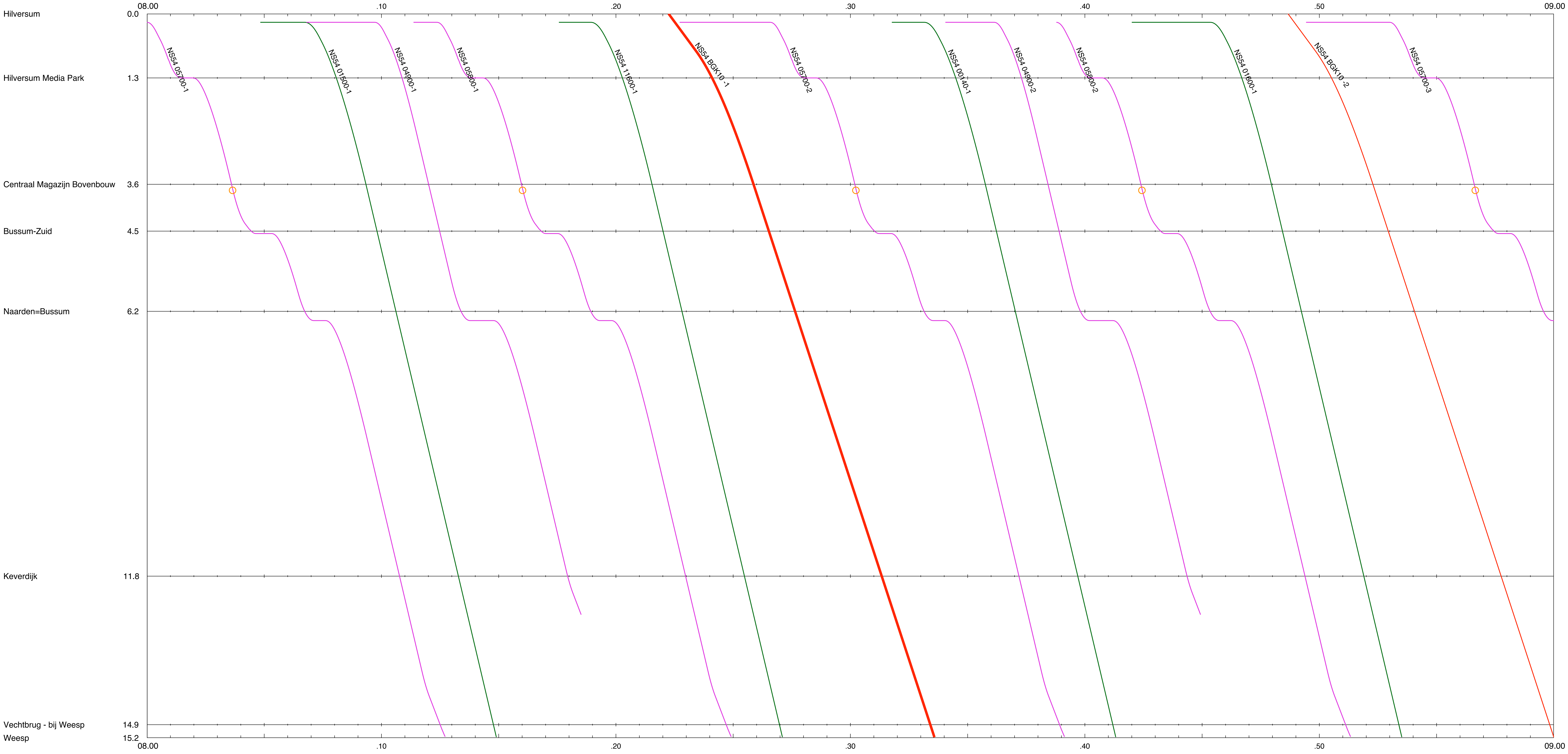
A. Line: NS'54/ATB-EG, 1,5 kV DC: Hilversum - Weesp



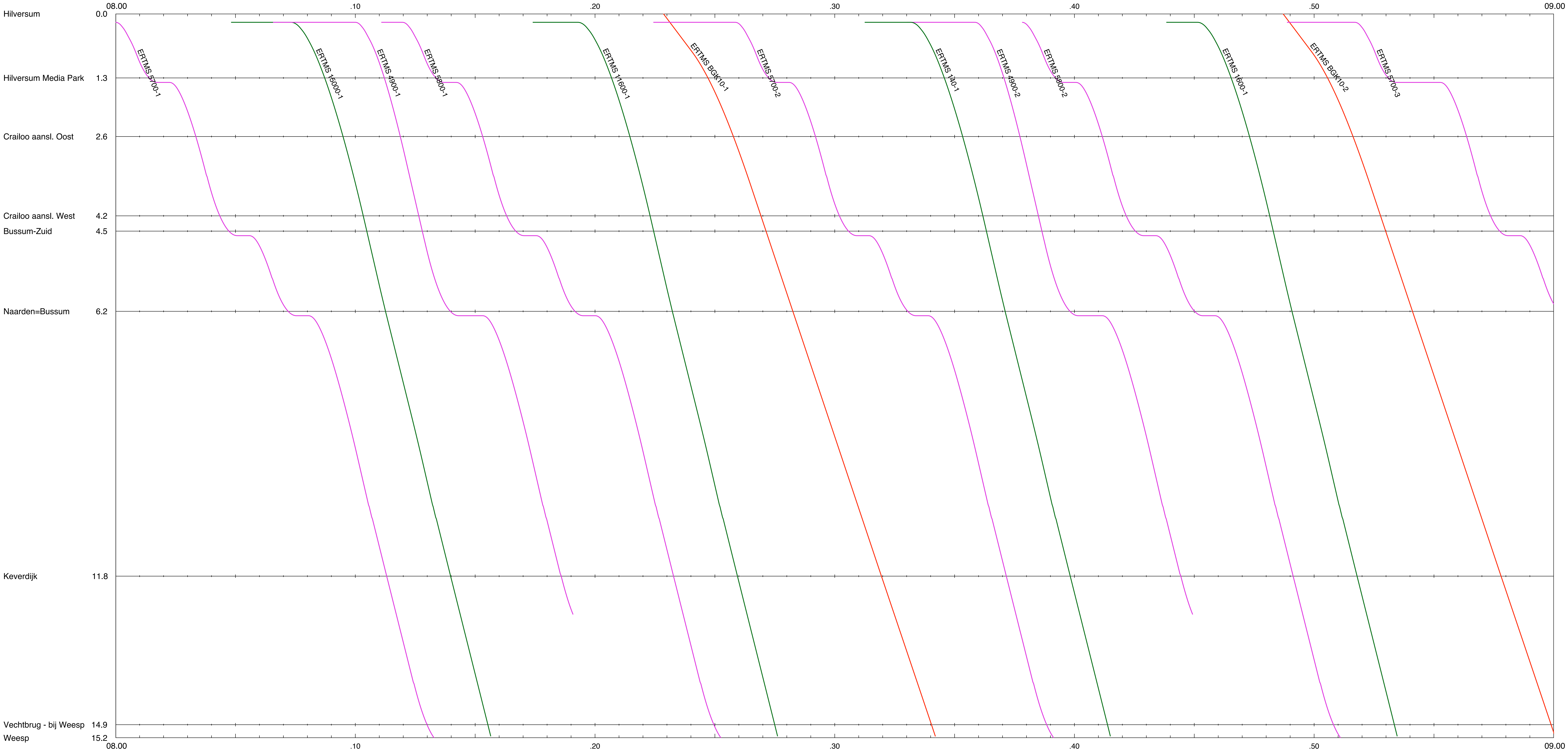
B. Line: NS'54/ATB-EG, 3 kV DC: Hilversum - Weesp



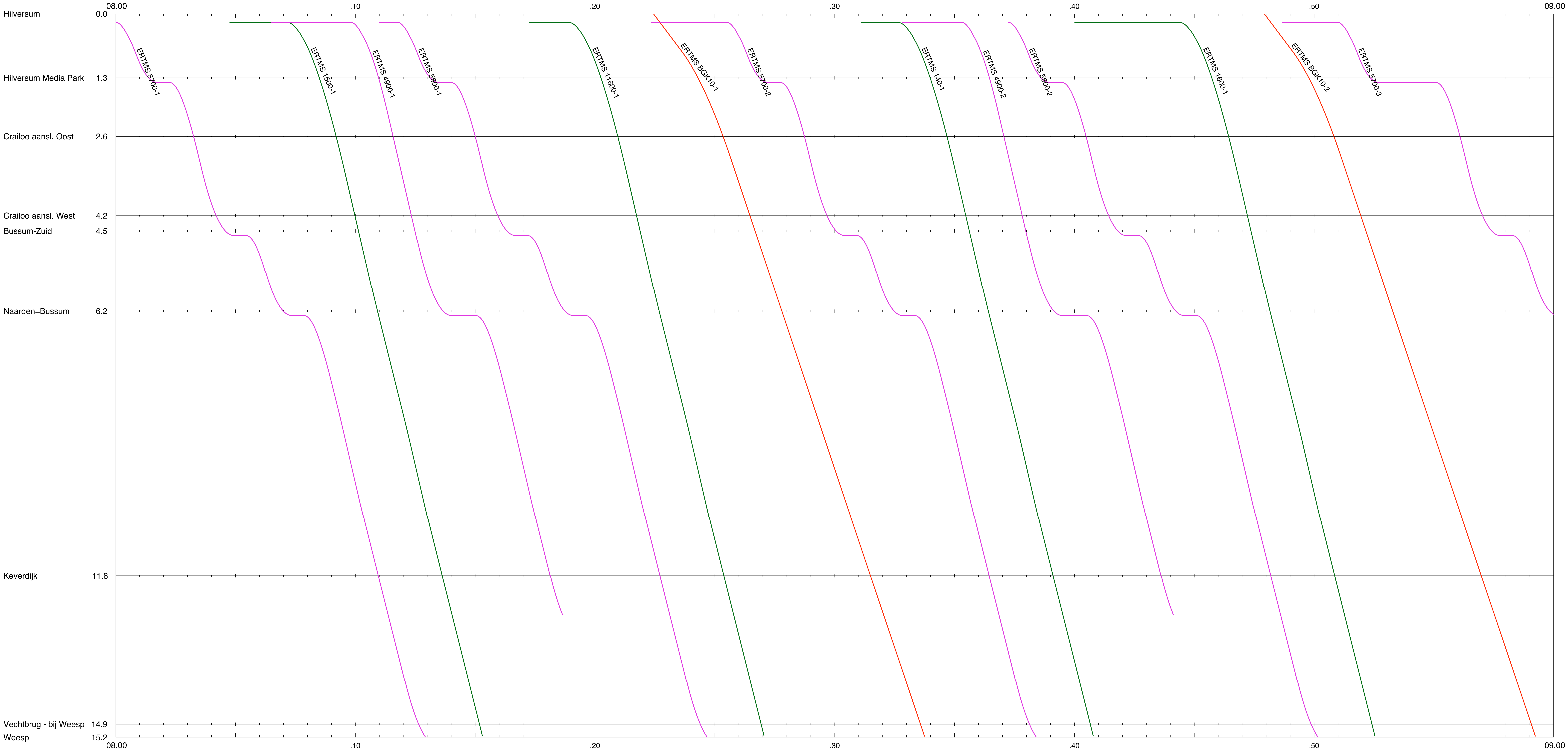
C. Line: NS'54/ATB-EG, 1,5 kV DC, ATO: Hilversum - Weesp



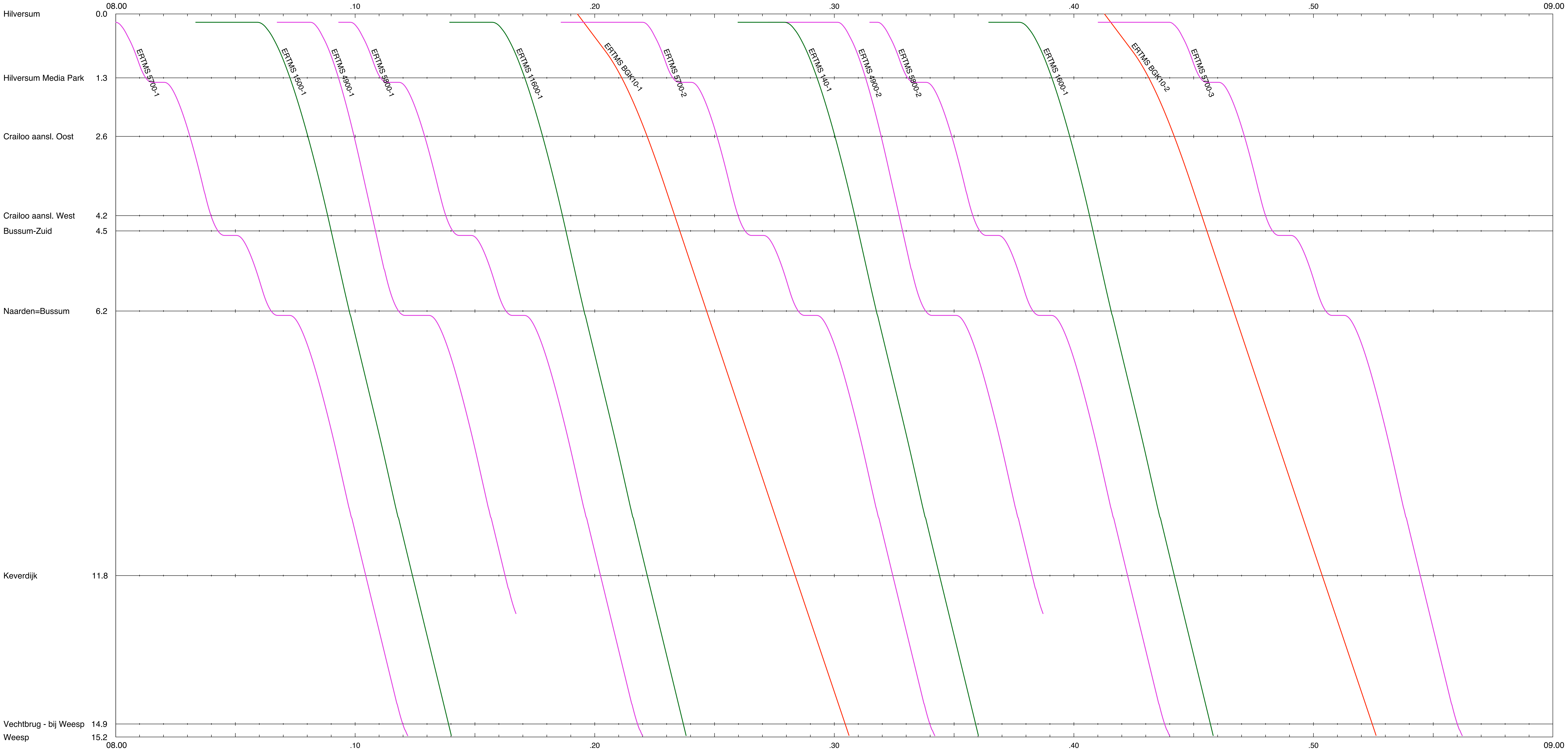
D. Line: ERTMS/ETCS level 2, 1,5 kV DC: Hilversum - Weesp



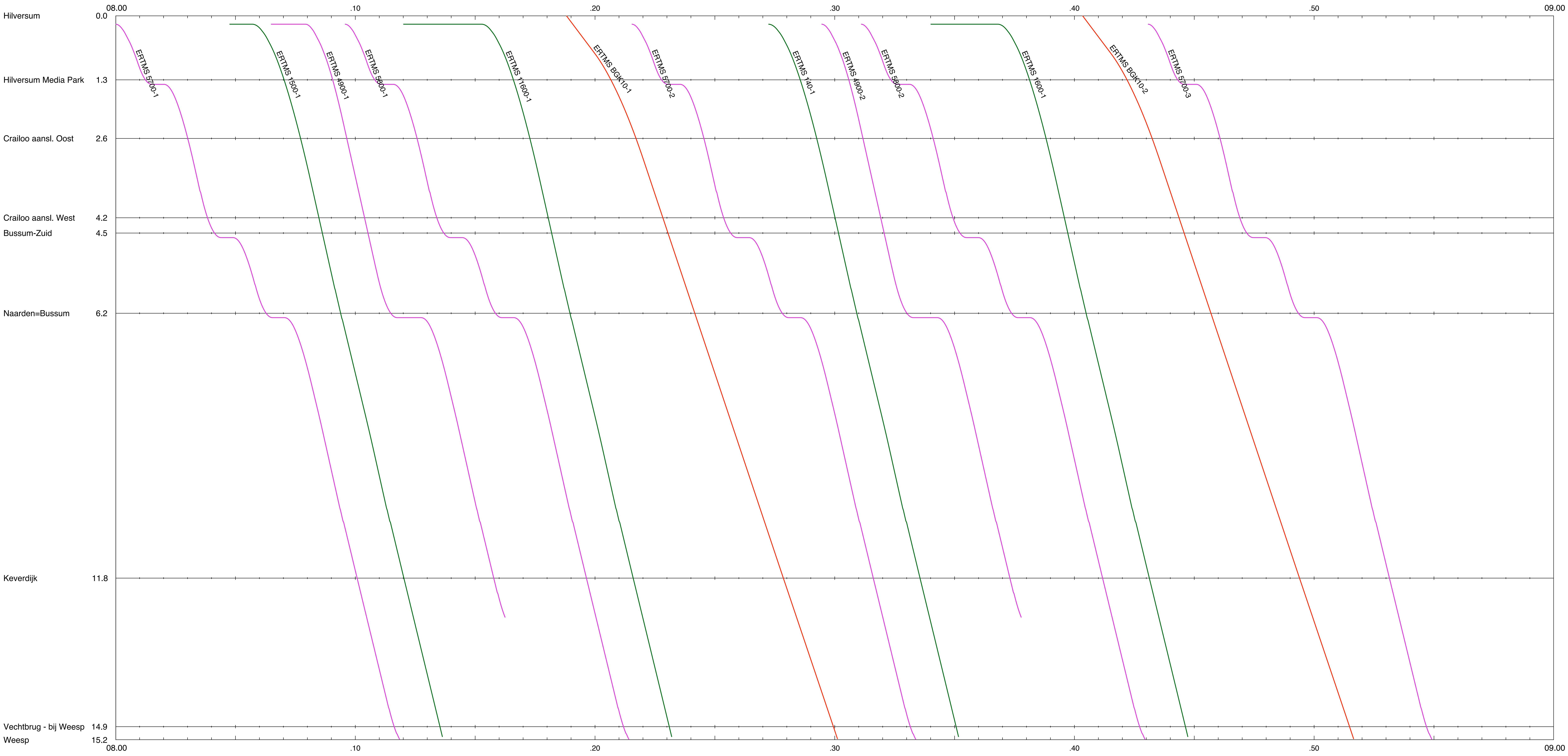
E. Line: ERTMS/ETCS level 2, 3 kV DC: Hilversum - Weesp



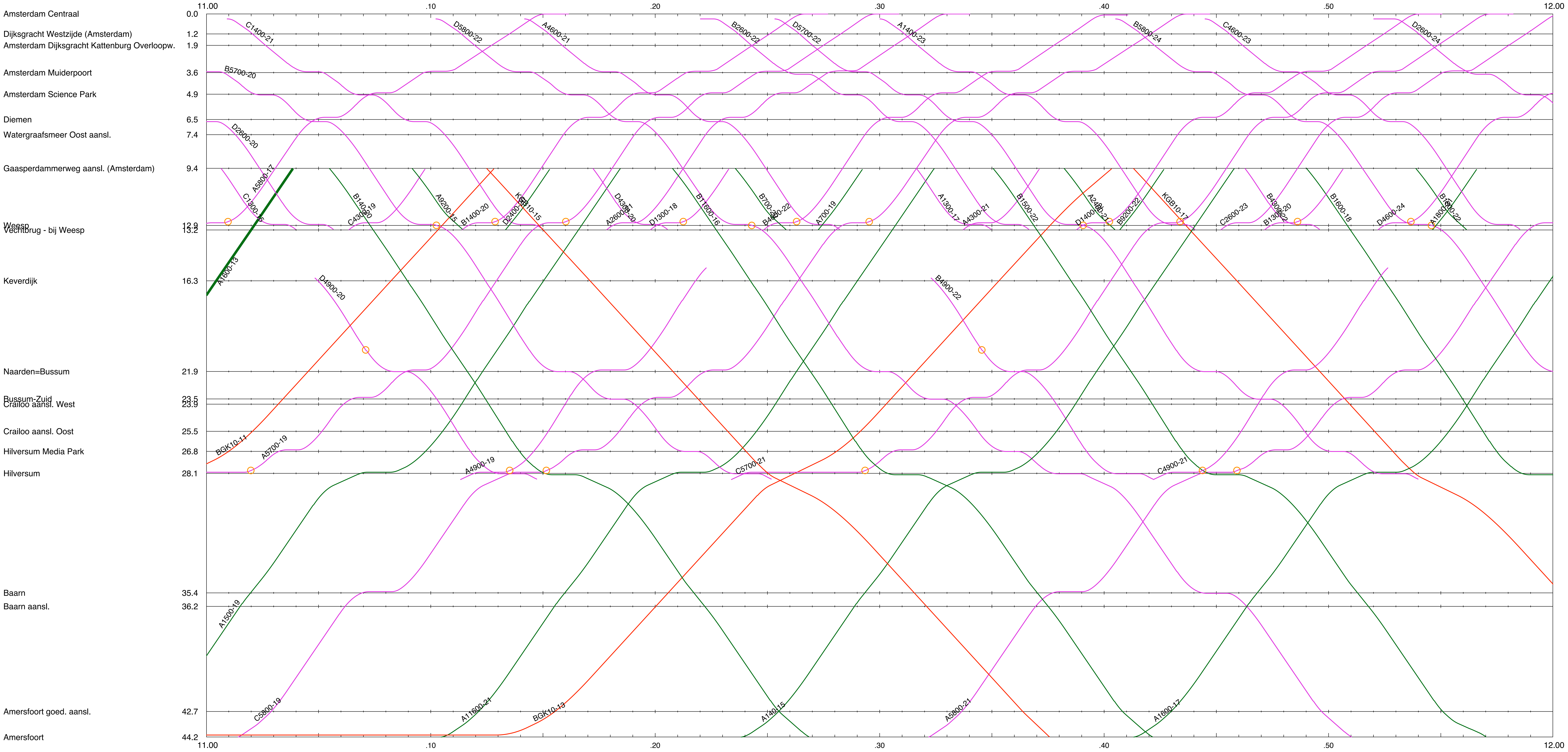
F. Line: ERTMS/ETCS level 2, 1,5 kV DC, ATO: Hilversum - Weesp



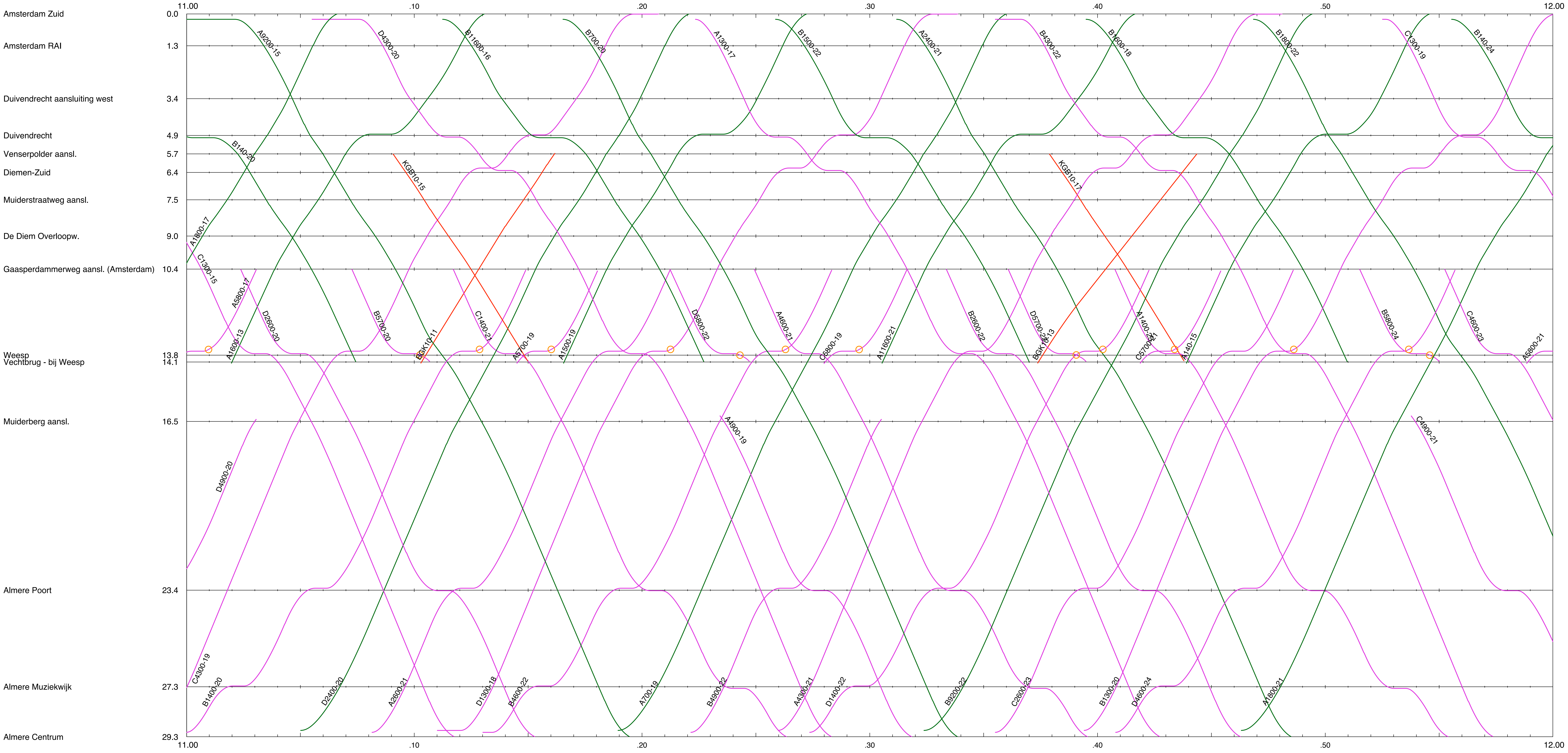
G. Line: ERTMS/ETCS level 2, 3 kV DC, ATO: Hilversum - Weesp



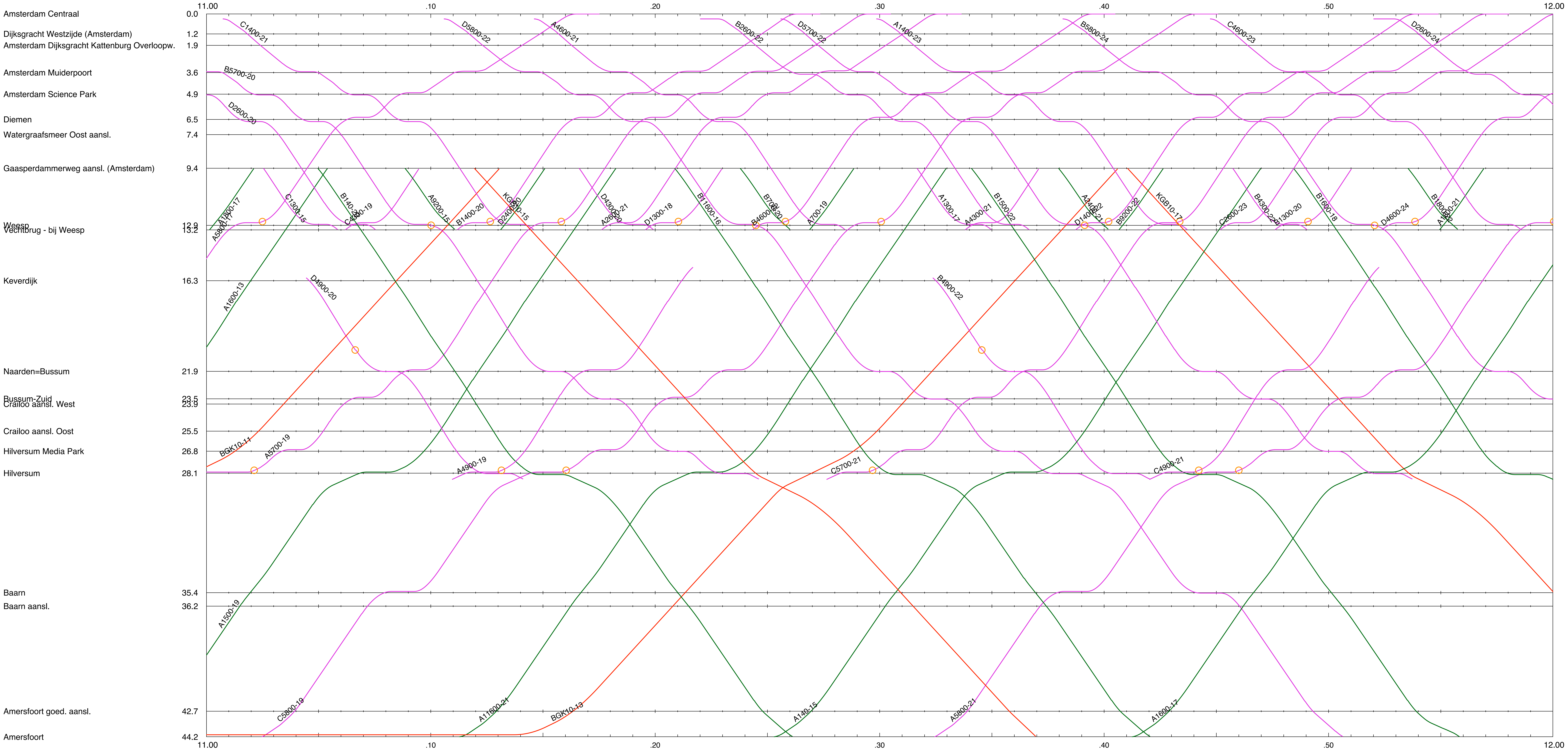
H. Network: ERTMS/ETCS level 2, 1,5 kV DC: Amsterdam Centraal - Amersfoort



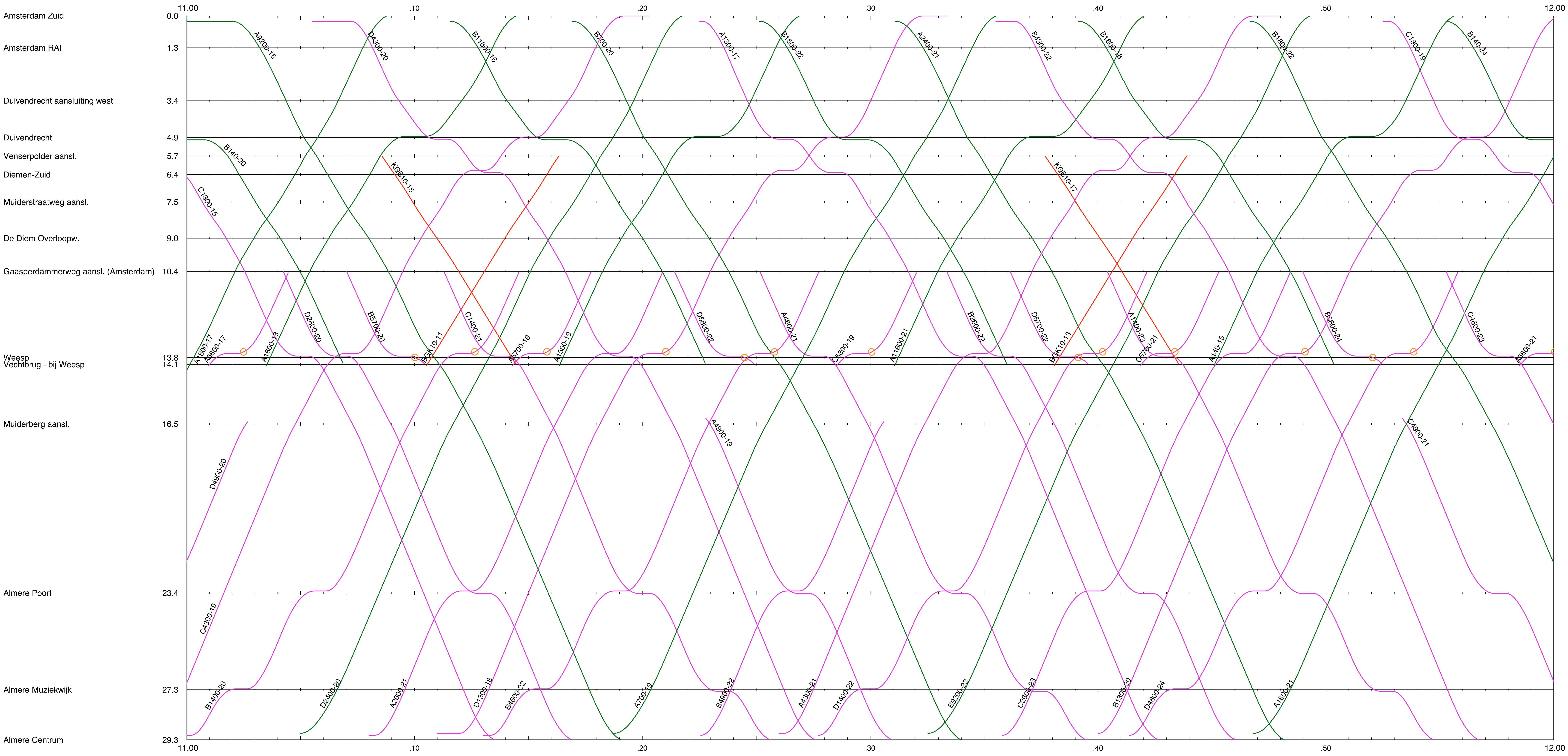
I. Network: ERTMS/ETCS level 2, 1,5 kV DC: Amsterdam Zuid - Almere Centrum



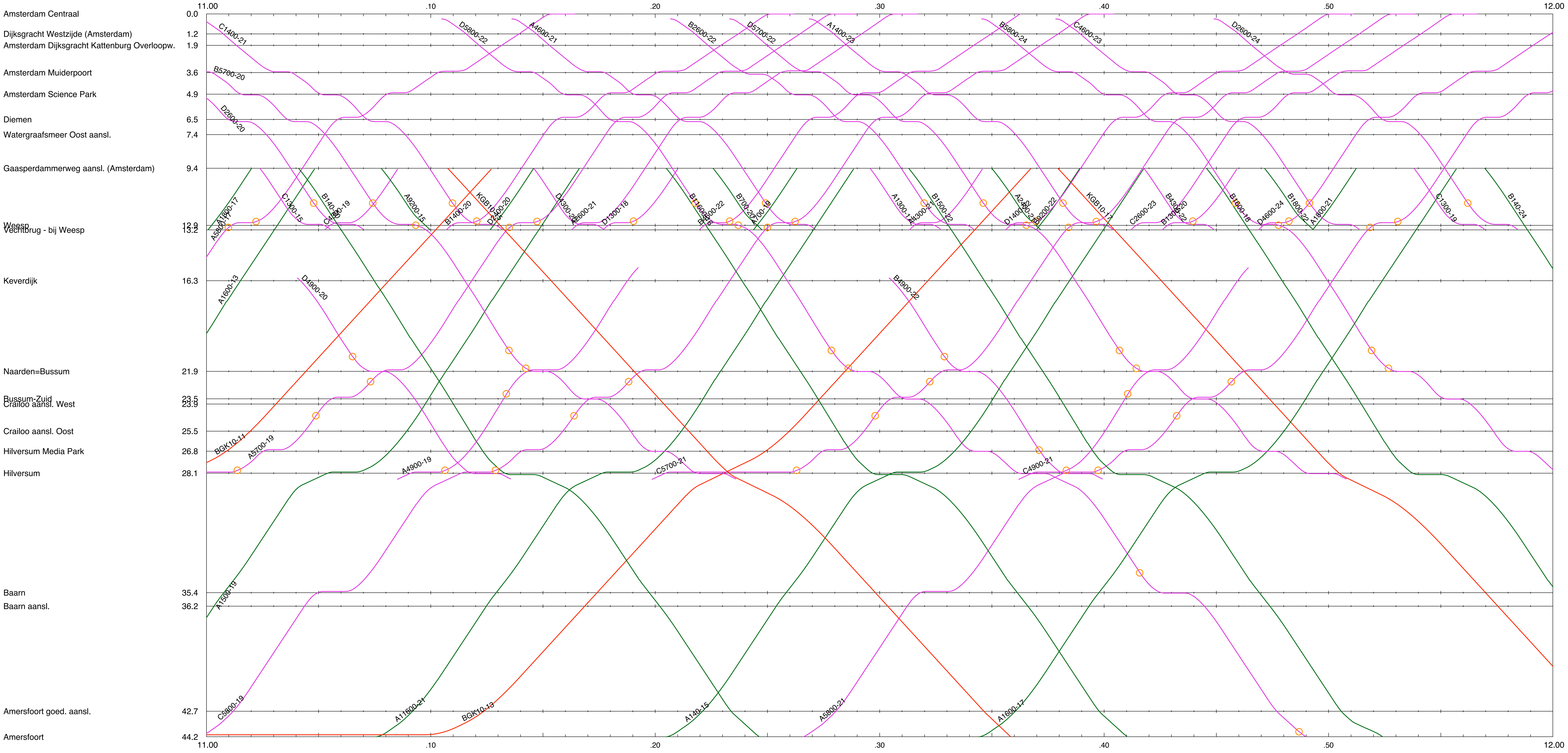
J. Network: ERTMS/ETCS level 2, 3 kV DC: Amsterdam Centraal - Amersfoort



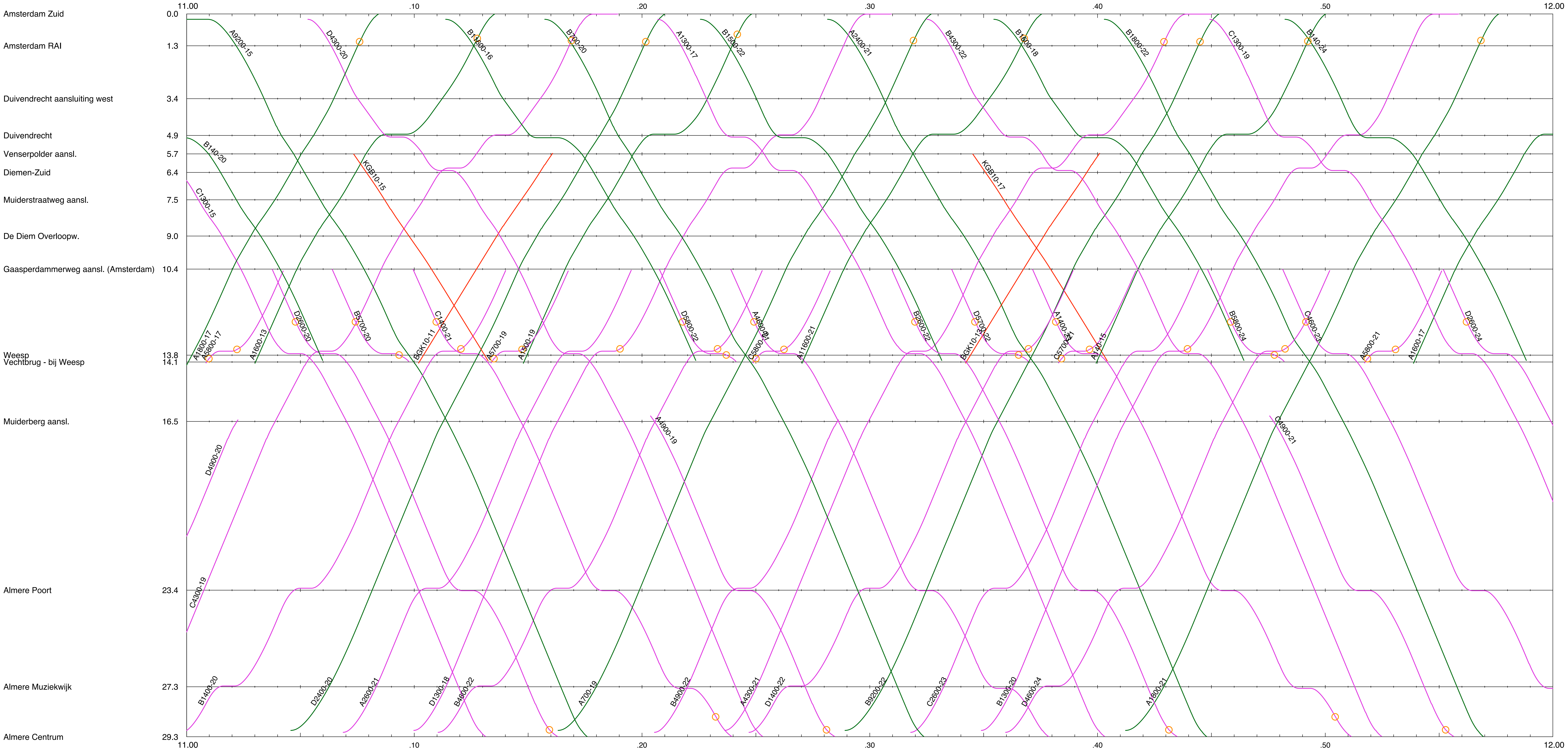
K. Network: ERTMS/ETCS level 2, 3 kV DC: Amsterdam Zuid - Almere Centrum



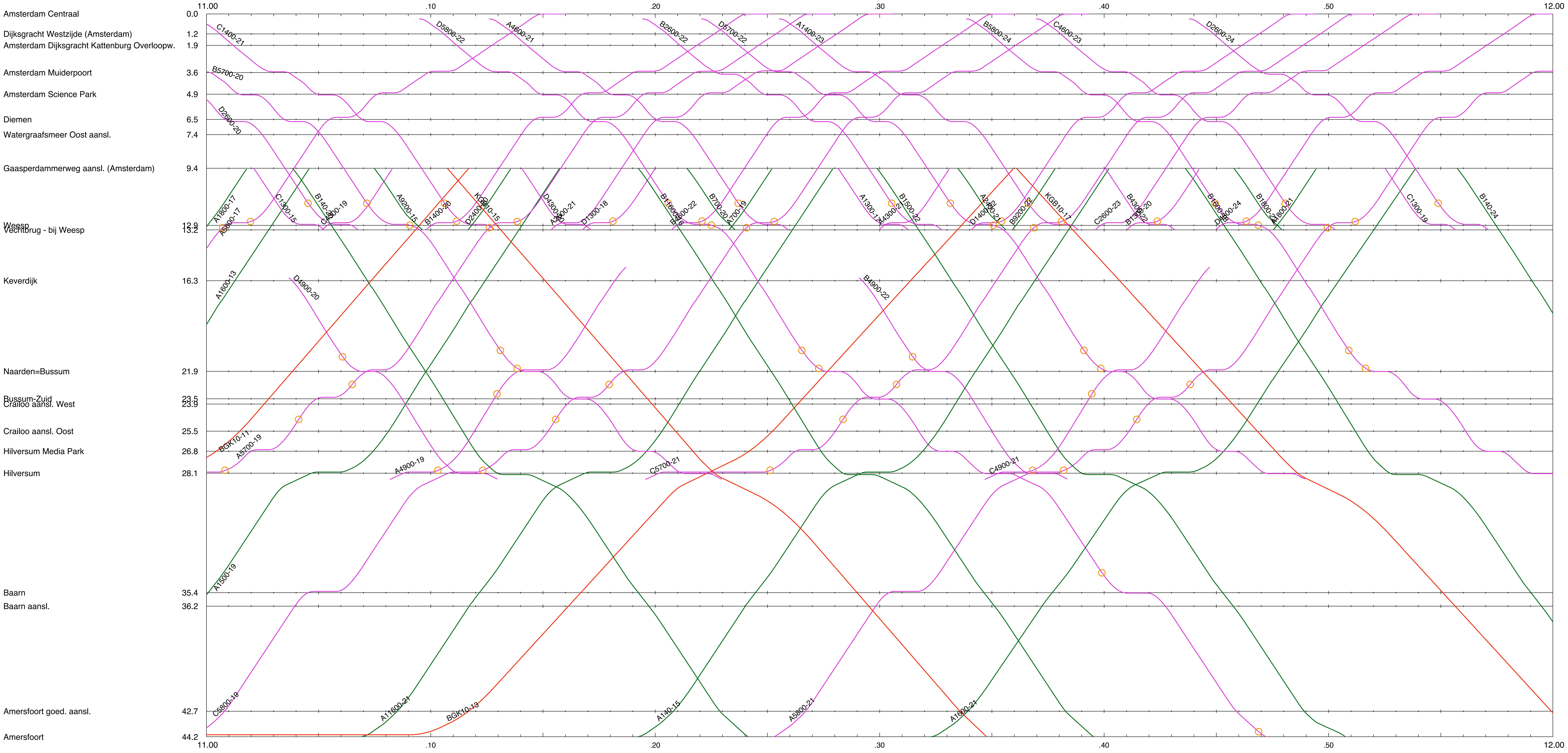
L. Network: ERTMS/ETCS level 2, 1,5 kV DC, ATO: Amsterdam Centraal - Amersfoort



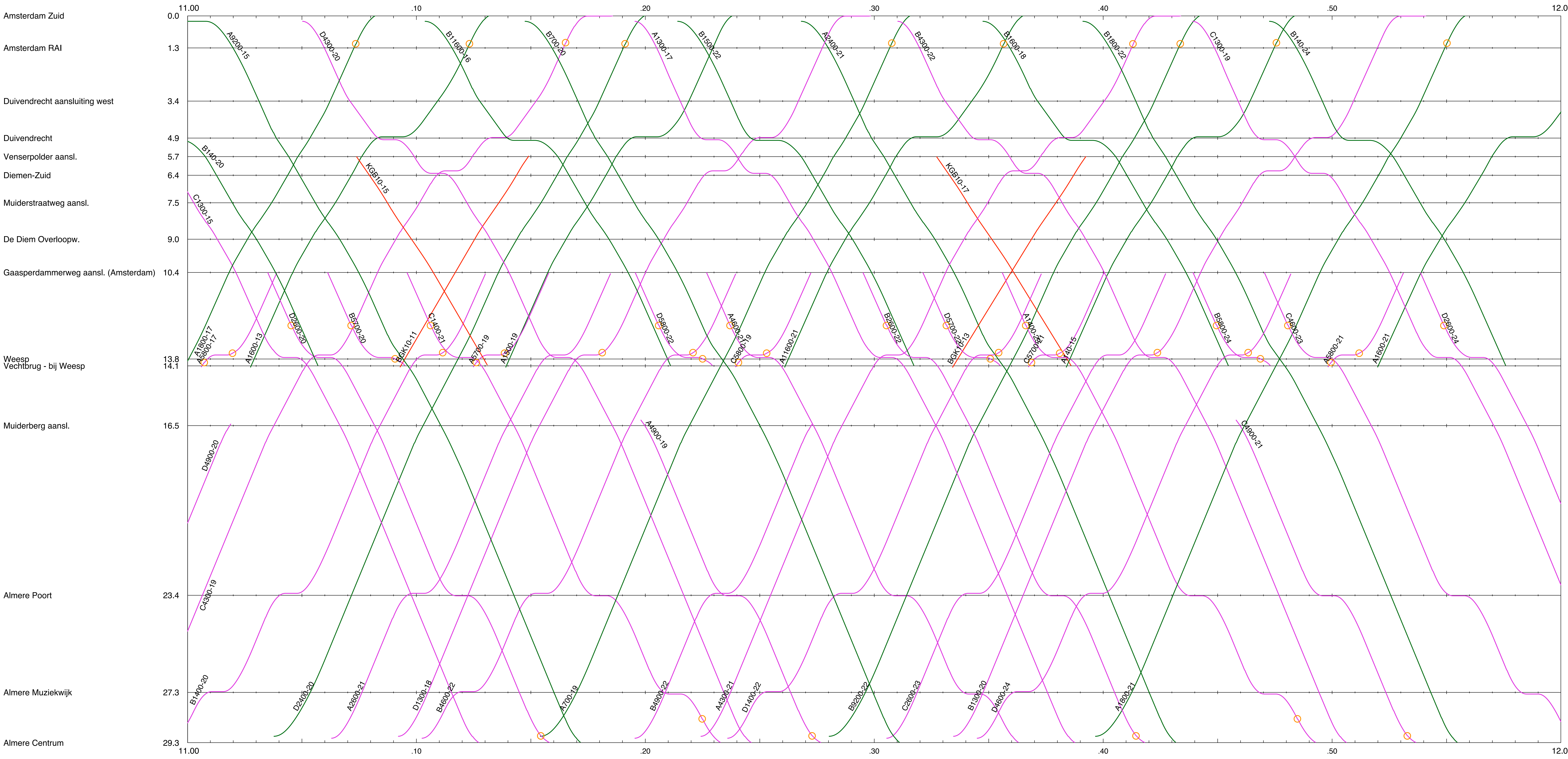
M. Network: ERTMS/ETCS level 2, 1,5 kV DC, ATO: Amsterdam Zuid - Almere Centrum



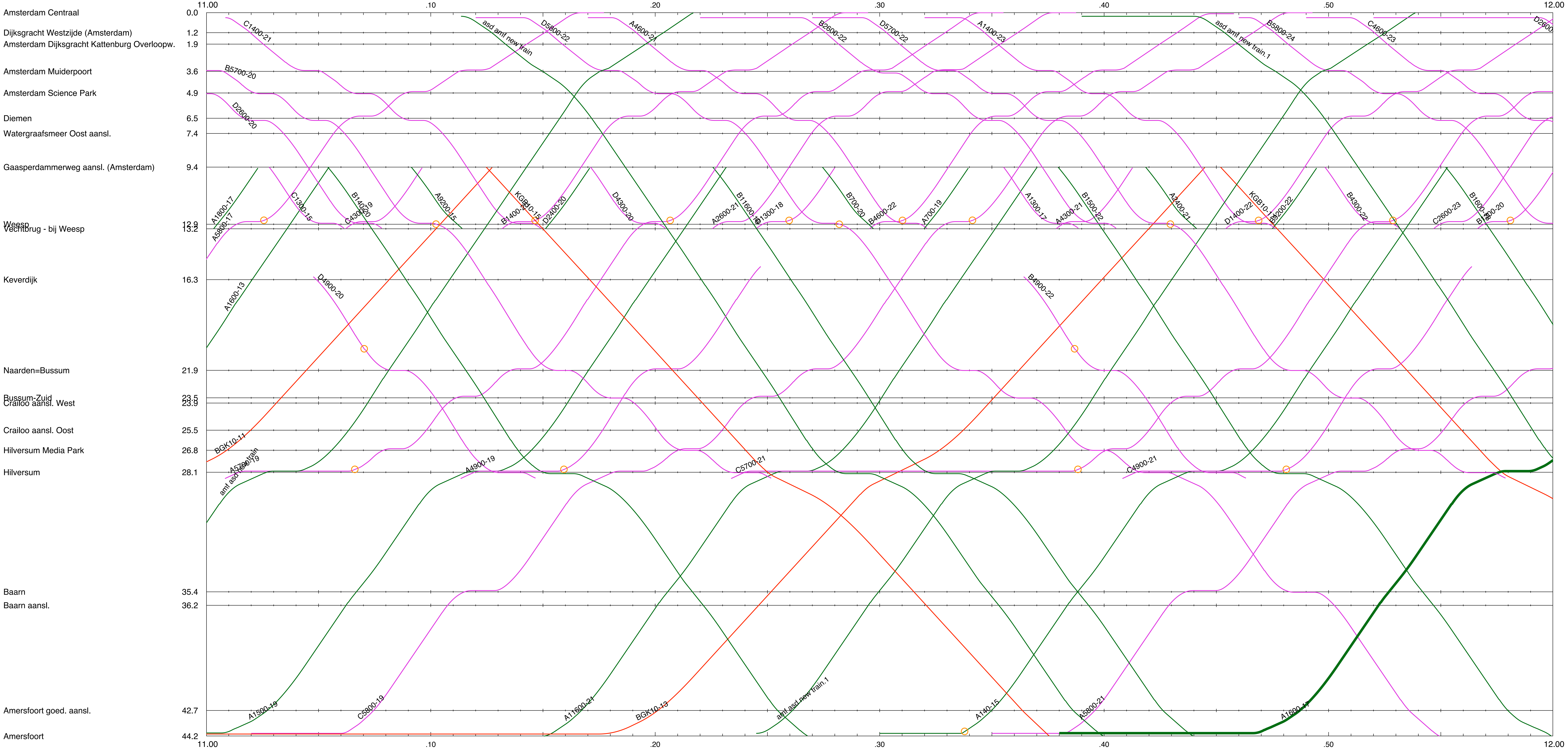
N. Network: ERTMS/ETCS level 2, 3 kV DC, ATO: Amsterdam Centraal - Amersfoort



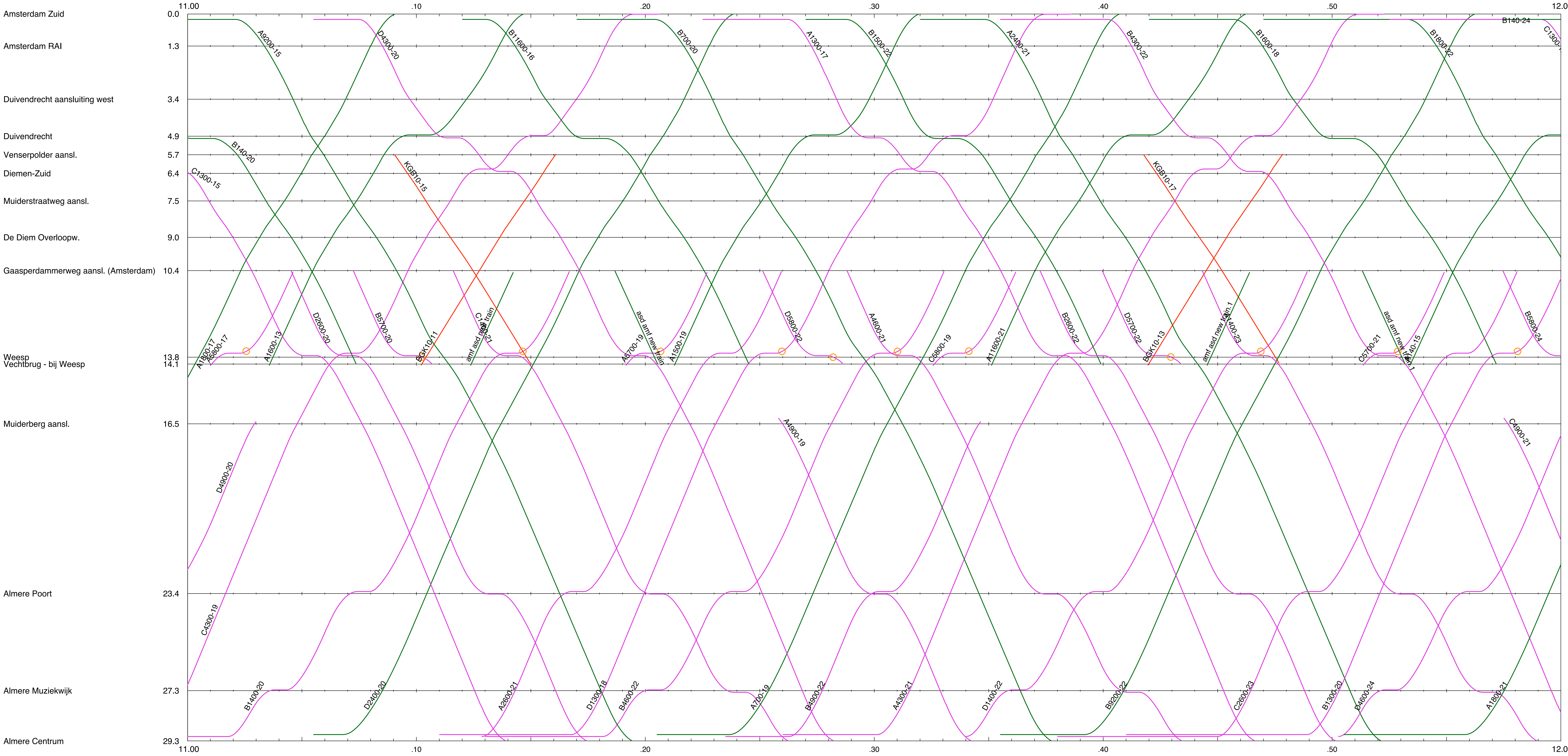
O. Network: ERTMS/ETCS level 2, 3 kV DC, ATO: Amsterdam Zuid - Almere Centrum



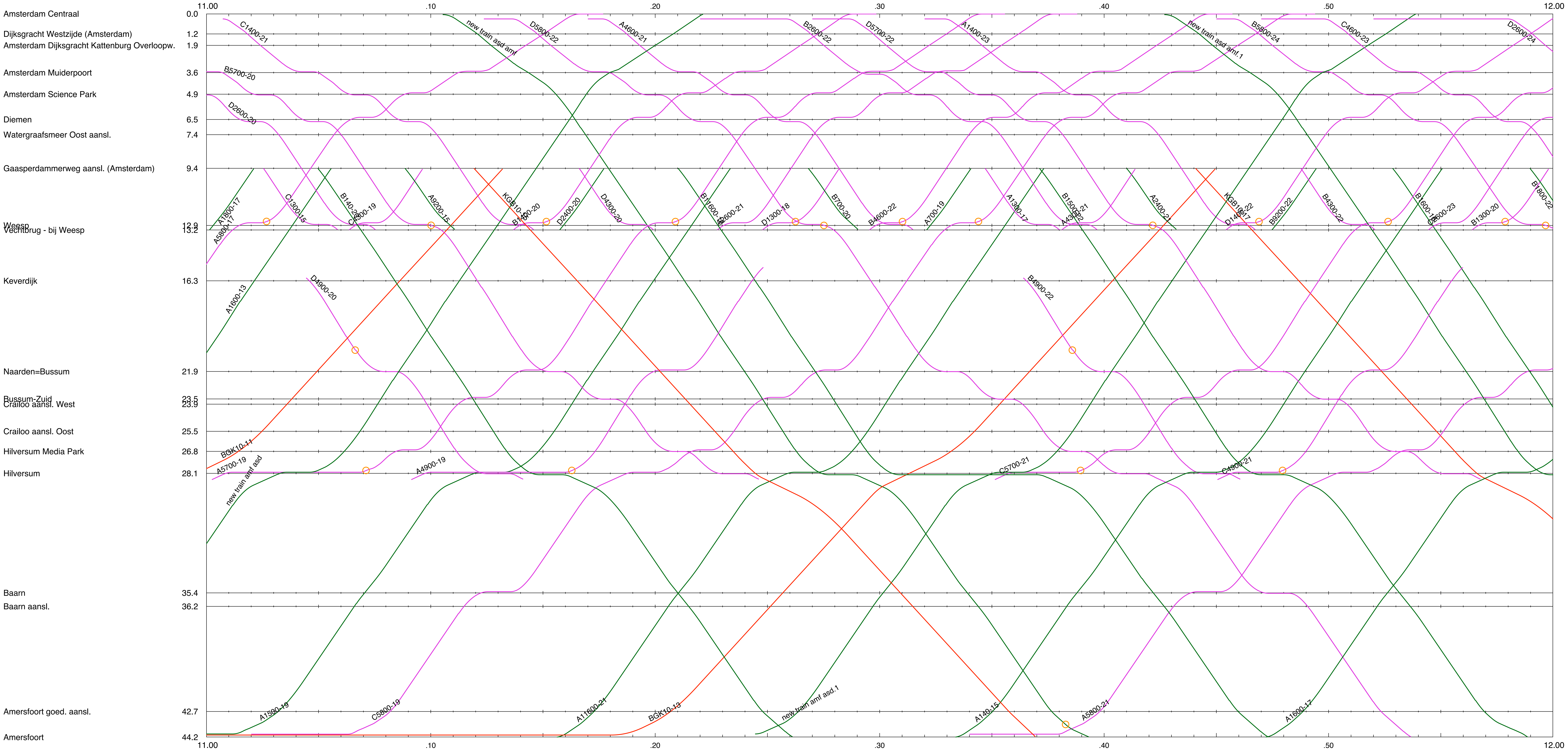
P. Additional train: ERTMS/ETCS level 2, 1,5 kV DC: Amsterdam Centraal - Amersfoort



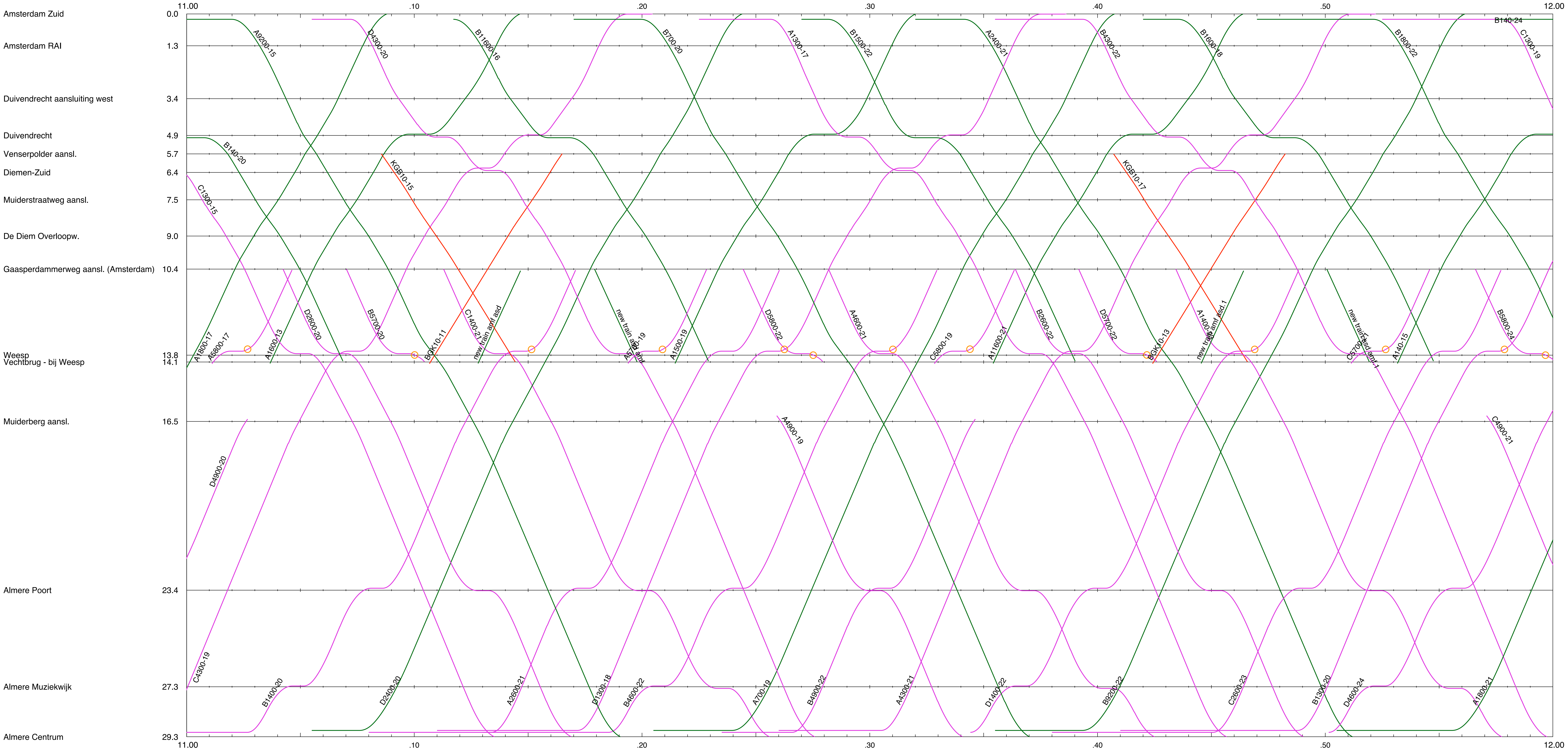
Q. Additional train: ERTMS/ETCS level 2, 1,5 kV DC: Amsterdam Zuid - Almere Centrum



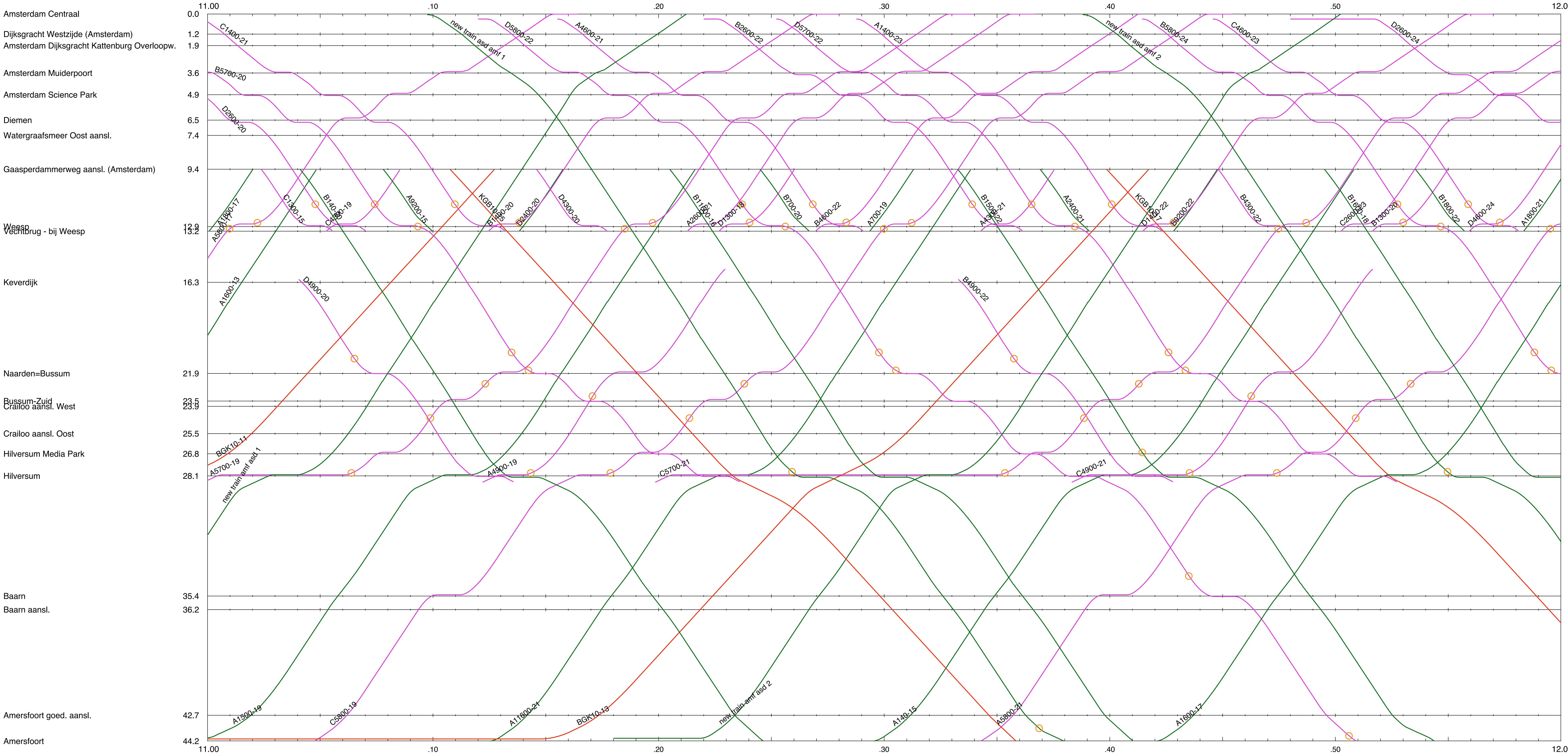
R. Additional train: ERTMS/ETCS level 2, 3 kV DC: Amsterdam Centraal - Amersfoort



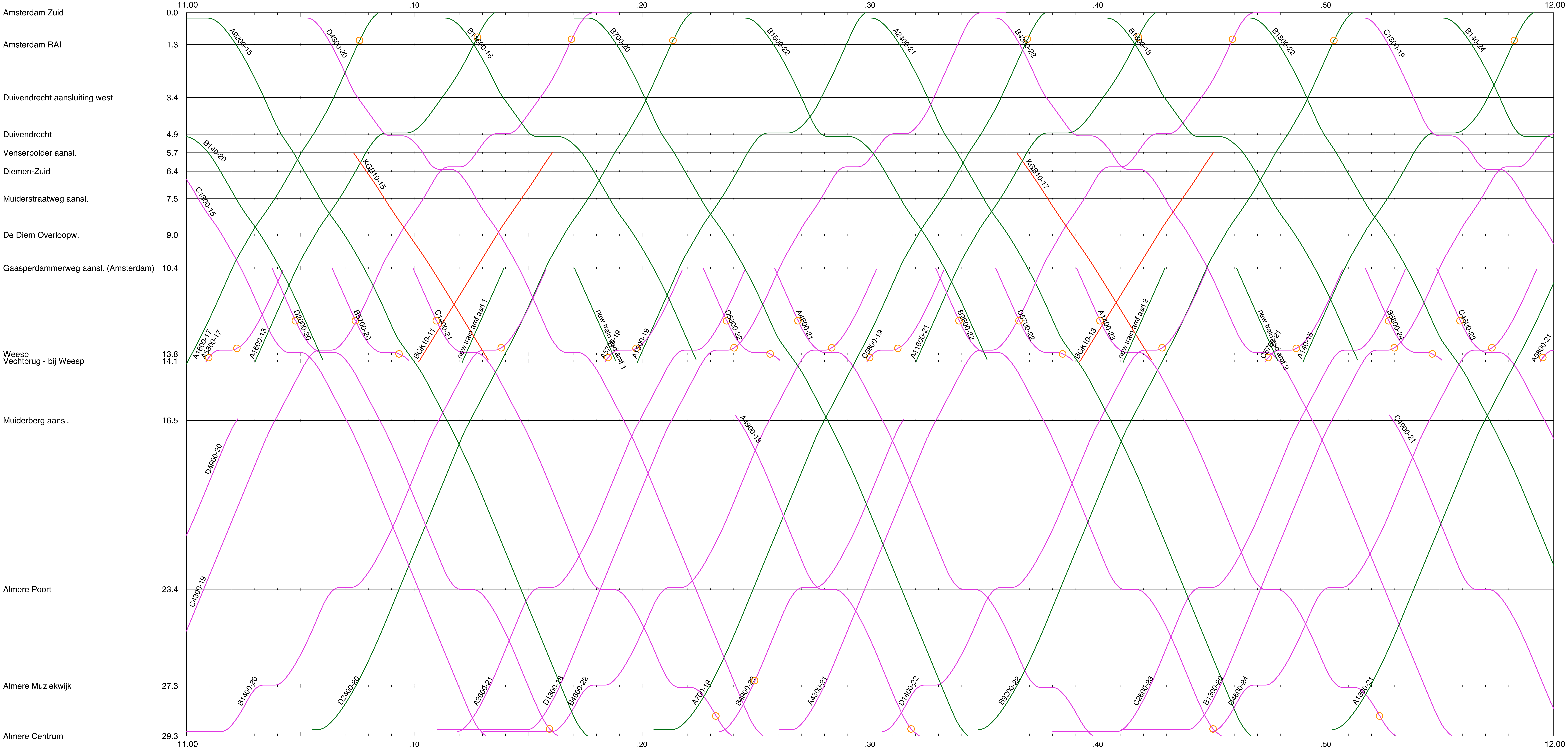
S. Additional train: ERTMS/ETCS level 2, 3 kV DC: Amsterdam Zuid - Almere Centrum



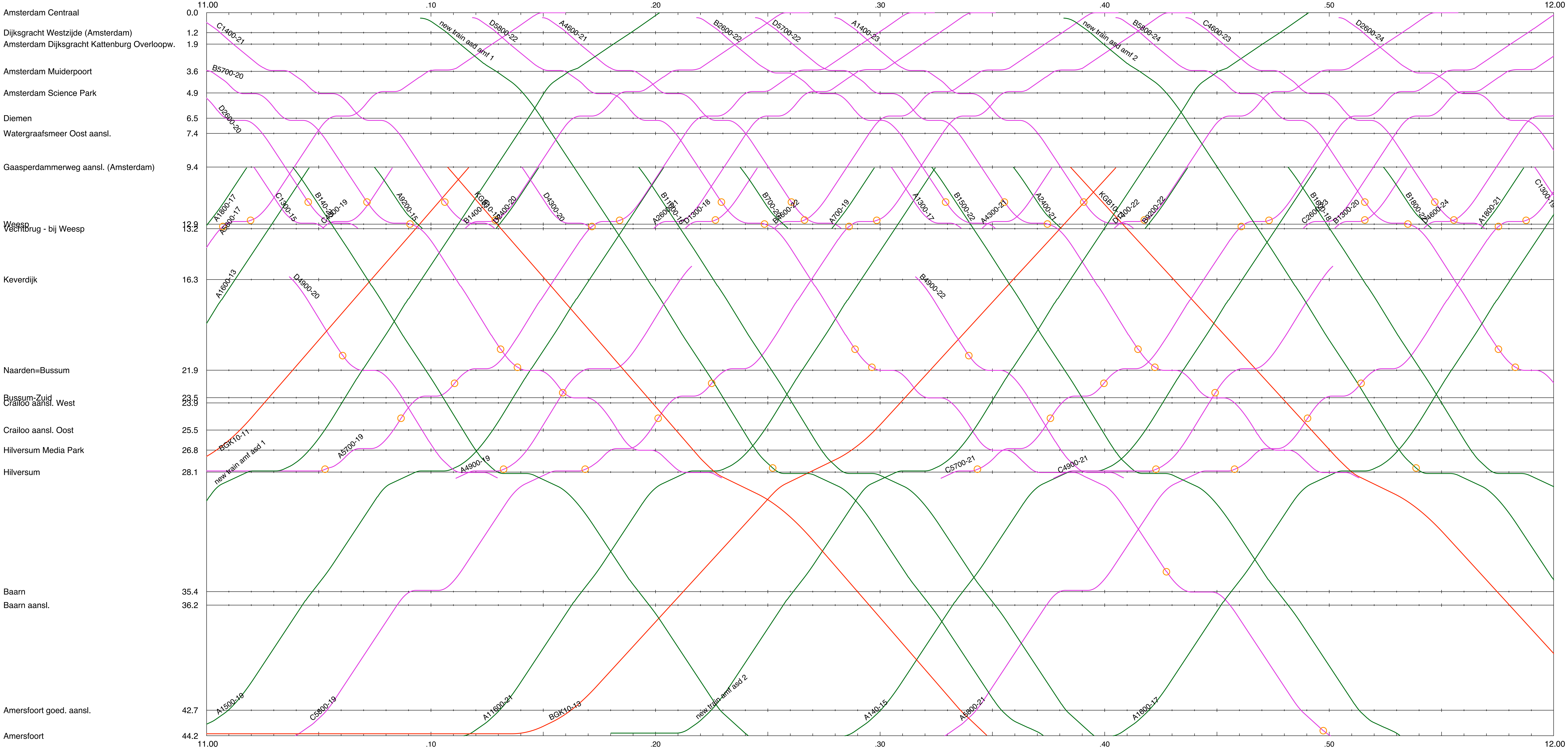
T. Additional train: ERTMS/ETCS level 2, 1,5 kV DC, ATO: Amsterdam Centraal - Amersfoort



U. Additional train: ERTMS/ETCS level 2, 1,5 kV DC, ATO: Amsterdam Zuid - Almere Centrum



V. Additional train: ERTMS/ETCS level 2, 3 kV DC, ATO: Amsterdam Centraal - Amersfoort



W. Additional train: ERTMS/ETCS level 2, 3 kV DC, ATO: Amsterdam Zuid - Almere Centrum