Justin Plasmeijer

# Virtual Coupling as an operational concept for Dutch railway corridors

TU Delft
ERTMS

# Virtual Coupling as an operational concept

## Analysis for the implementation of Virtual Coupling on Dutch main-line railway corridors

By

J. Plasmeijer (5188466)

in partial fulfilment of the requirements for the degree of

**Master of Science**
in Transport, Infrastructure and Logistics

at the Delft University of Technology,
to be defended publicly on December 5th 2024 at 3:00 P.M.

| | | |
|---|---|---|
| Thesis committee: | Prof. dr. R.M.P. Goverde, | TU Delft |
| | Dr. J.A. Annema, | TU Delft |
| | Ing. A. van Es, | PD ERTMS |



*Cover image: Main line railway corridor in the Netherlands (Den Haag – Utrecht) (Agro & Chemie, 2019)*

TU Delft

# Preface

This thesis was conducted as the final part of my Master of Science in Transport, Infrastructure and Logistics at Delft University of Technology and was carried out in cooperation with the Program Directorate ERTMS (PD ERTMS).

I would like to thank first of all Ing. A. van Es as my supervisor at PD ERTMS, for making this thesis possible, for his enthusiasm, vision and experience regarding the topic, and for his invaluable guidance and support throughout this project. I thoroughly enjoyed our many conversations and interactions, as well as the collegial atmosphere fostered by both A. van Es and my colleagues at PD ERTMS. I am thankful for their support, and for providing a pleasant and motivating work environment.

Next, I would like to offer special thanks to Prof. dr. R.M.P. Goverde, chair of my thesis committee, for his consistent guidance, detailed feedback, and clear instructions. His input was instrumental in shaping the direction of this research, and I greatly appreciated our bi-weekly sessions, where he consistently provided thoughtful and insightful feedback. His commitment to this project has been greatly appreciated, and I am truly thankful for his continuous support.

Additionally, I am grateful to Dr. J.A. Annema, who supervised my work on a broader level and offered valuable feedback on the process. His perspective and guidance helped ensure the overall progression and coherence of my work.

Finally, I would like to thank Joelle Aoun and Dr.ir. E. (Egidio) Quaglietta for their invaluable input, feedback, and the engaging conversations that enriched this thesis. Their expertise and advice were crucial in refining the final outcome of this project. (Quaglietta & Goverde, 2019) (Quaglietta, Spartalis, Wang, Goverde, & Koningsbruggen, 2022)

*Justin Plasmeijer*
*Delft, 2024*

# Executive summary

An increasing number of transportations means are moving towards the implementation of innovative platooning technology by introducing a Vehicle-To-Vehicle (V2V) communication layer between two consecutive vehicles. Research and real-life platooning implementations show promising results in terms of systems flexibility and frequency, leading to reduced operational costs and increased passenger satisfaction. A similar V2V-layer for railways is introduced within the concept of Virtual Coupling (VC), enabling consecutive trains to virtually couple to form platoons. Several analyses have demonstrated that VC could indeed lead to increased capacity and flexibility for railways, even when complex station layouts and safety margins are considered. However, its effective implementation in real-time operations remains unclear, particularly in terms of balancing benefits for passengers, infrastructure managers, and railway undertakings. Therefore, this research focuses on the development of operational concepts which apply VC to main-line railway corridors, and assessing them by considering factors such as user-friendliness, technical complexity, rolling stock circulation, and overall system efficiency (including frequency, infrastructure occupancy, and generalized travel times) within a real-world case study to test its effectiveness under realistic conditions.

To this end, a double diamond approach has been introduced, following the following steps:

1. Discovering similar concepts in other transport means;
2. Defining transport concepts specifically applicable to main line railway corridors;
3. Selecting most suitable concepts and developing specific operational patterns that train could be executed within a concept;
4. Evaluate operational patterns on frequencies, generalized travel times and infrastructure occupancy

Analysis on implementations and use cases of platooning and demand-driven concepts within other modes of transport provided valuable insights into the aspects on how flexible, demand-driven systems usually operate. It was found these critical design aspects are stopping plans, (de)coupling sequences, (de)coupling points, shunting, platooning, and timetables. These insights were supplemented by expert consultations with key stakeholders, such as ProRail, NS, and PD ERTMS, providing a comprehensive set of design aspects, building blocks, and objectives for the design of VC-tailored operational concepts.

Building on the insights gathered in the discover phase, the define phase aims to shape operational concepts tailored for mainline railway operations and identify the most promising concepts through a detailed SWOT analysis. Operational concepts were defined based on the extracted design aspects and building blocks using a morphological chart. By randomly combining the building blocks in the morphological chart, four distinct operational concepts were identified based on their contrasting characteristics and potential applications:

1. **Conventional pattern preserving full-stopping regional services**: This concept operates on a regular or fixed timetable, alternating IC-trains (serving only major station) and full-stopping trains (serving all regional and major stations). Additionally, a skip-stop service (skipping some regional stations while still serving all major stations) is added to create extra capacity and more direct connections from regional towards major stations. The full-stopping and skip-stop trains are allowed to virtually couple and enclosed by IC-trains. Since these regional trains are enclosed by IC-trains, the platoon structure is maintained throughout the journey and reunited at each major station.. Maintaining a more conventional pattern allows trains to operate over longer corridors within this concept, enabling shunting to occur at existing shunting facilities.
2. **Conventional pattern introducing skip-stop regional services**: Similar to the first concept, this approach follows a regular or fixed timetable, alternating IC trains with skip-stop trains. Consequently, regional stations are no longer directly connected to each other. However, train units reunite with their initially coupled units, preserving the platoon structure. Since the skip-stop trains are enclosed by IC trains, the platoon formation remains intact throughout the journey. By maintaining a more conventional pattern, this concept again enables trains to operate over longer corridors, allowing shunting to occur at existing shunting facilities.
3. **Skip-stop pattern without IC-trains**: This concept removes IC trains from the configuration in Concept 2, resulting in operations exclusively with skip-stop trains. Although it still follows a regular

or fixed timetable, major stations are no longer directly connected. All train units in this concept are homogeneous, allowing them to couple flexibly with other units along the route, which supports both random and coordinated platoon formations and enables more flexible scheduling. Operations can still be planned over longer corridors, allowing shunting to occur at dedicated depots. However, accommodating high-demand flows between major stations may require additional trains within this concept.

4. **Point-to-point pattern with only direct connections:** This concept replaces operations on longer corridors with a point-to-point pattern, differing from conventional patterns by focusing on direct connections between specific origin-destination pairs rather than continuous routes. Operations follow an on-demand timetable, with train units running exclusively between designated origin-destination pairs. Train platooning is entirely flexible, allowing units to couple and decouple as needed, without a fixed structure, to efficiently meet varying demand. Shunting will need to take place at stations to minimize response times and ensure timely operations.

To test performance under real-world conditions, demonstrate relevance, and gain practical decision-making insights, each operational concept was applied to the SAAL (Schiphol-Amsterdam-Almere-Lelystad) corridor, specifically focusing on the segment between the major stations Lelystad, Almere Centrum, and Weesp. The concepts were initially evaluated qualitatively through a SWOT analysis, which provided valuable insights into the applicability of each concept to the corridor based on criteria such as ease of implementation, user-friendliness, and technical complexity.

The first concept was found to strike the best balance between reliability and flexibility, offering fast, direct connections while maintaining accessibility for all passengers. The second concept worked well for high-demand routes but was less effective for low-demand stations. The third and fourth concepts were found to be less suited for implementation on the depicted case study due to infrastructure limitations and the complexity of real-time dispatching systems. A variant of concept 2, involving temporary skipping a station, was also considered, as this could be an effective strategy for specific peak hour demands and enhances the benefits of skip-stop patterns by eliminating the odd amount of regional stops between Lelystad and Almere Centrum.

For each concept, technical running times for each origin-destination (O-D) pair and headways between each consecutive train for the following five distinct maneuvers were calculated:

1. Plain line manoeuvres
    a. Plain line open track
    b. Simultaneously departing / arriving
    c. Sequentially departing arriving
2. Merge/ diverge manoeuvres
    a. Merge at a switch
    b. Diverge at a switch

The plain line open track manoeuvre (1a) refers to a case in which two consecutive trains run at open track at minimum separation distance. A sequential manoeuvre (1b) occurs when trains stop at a station one after the other, maintaining a consecutive sequence. In contrast, a simultaneously running case (1c) involves two trains stopping at the same platform track at the same time, allowing for more efficient use of track space. Merging (2a) and Diverging (2b) can solely take place around stations where switches are located.

Technical running times and headways were calculated based the corridors' infrastructure lay-out and real train motions. These running times and headways are used to assess the performance of certain operational patterns trains can perform within each of the selected concepts. Here, a pattern is referenced to a certain stopping plan (indicating which stations are served by each train) and operational plan (what is the sequence of trains and which maneuvers does it perform) a train executes. Since each train (either IC or Regional Train) within each of the depicted concepts have a permitted stop at Almere Centrum, patterns are compiled per corridor section: Lelystad → Almere Centrum and Almere Centrum → Weesp. Additionally, since only regional trains can vary in sequence and stopping patterns within each concept, the patterns were designed exclusively for regional services, while the IC remain serving major stations solely.

By combining all patterns between Lelystad and Almere Centrum with each pattern between Almere Centrum and Weesp, an initial selection of pattern combinations was made based on overall frequency and the number of non-direct OD pairs. To this end, a 5% time supplement was added to all technical running times to absorb minor deviations and reduce the risk of cascading delays. Additionally, a dwell time of 60 seconds was set for each station stop, along with buffer times to partially absorb deviations of the first train from its scheduled path and prevent delay propagation to the second train.

This process resulted in the selection of five pattern combinations (hereafter referred to as “variants”) that balanced frequency with a minimal number of non-direct OD pairs. Within Operational Concept 1, two variants were selected for final assessment:

1. **Variant 1**: This variant offers the highest possible frequency with no required transfers for any OD pairs, achieving a maximum frequency of 4 cycles per hour under both VC and ETCS Level 2 MB. Here, the leader train is a full-stopping regional train, and the follower is a skip-stop train.
2. **Variant 2**: This variant achieves a maximum frequency of 5 cycles per hour with VC and 4 cycles per hour with ETCS Level 2 MB, with one OD pair requiring a transfer. In this configuration, the skip-stop train skips two stations between Lelystad and Almere Centrum, then switches roles with the full-stopping train at Almere Centrum, skipping one station between Almere Centrum and Weesp.

Similarly, two variants were selected for final assessment within Operational Concept 2:

1. **Variant 3**: This variant minimizes the required number of OD-pair transfers, supporting 5 cycles per hour with VC and 4 cycles per hour with ETCS Level 2 MB. It requires transfers for only 2 OD-pairs, achieving nearly the same cycle frequency as Variant 3, with just 1 fewer cycle per hour.
2. **Variant 4**: This variant features simultaneous arrivals and departures at all major stations, minimizing non-direct OD pairs by having the skip-stop train skip two stations. Although the second train’s running times are longer, it still supports a frequency of 6 cycles per hour with VC and 5 with ETCS Level 2 MB.

The last selected variant (Variant 5) involves fully skipping a station between Lelystad and Almere Centrum during the morning rush hour, creating an even number of stops and enabling higher frequencies with optimal performance. This setup allows up to 7 cycles per hour under both ETCS Level 2 MB and VC, with four OD pairs requiring a transfer.

A final evaluation on infrastructure occupancy, frequency, and generalized travel times revealed that VC does provide benefits over ETCS Level 2 MB, particularly in reducing generalized travel times through synchronized stops. Implementing a skip-stop pattern creates more options for synchronized stops and has the potential to increase service frequency, enabling efficient and quick transfers within train platoons. Alternating these skip-stop services for regional stations with Intercity services ensures fast and direct connections between major stations are maintained. The variant that best strikes this characteristics is Variant 4. This approach aligns with existing infrastructure capabilities and service objectives, providing a well-balanced solution that optimizes operational efficiency and passenger convenience, facilitating the effective implementation of a platooning concept in mainline railway operations. Main recommendations are toward incorporating Passenger Volumes for Each OD Pair for a more accurate representation of impacts on various measures, and allowing adaptions in Mainline Layouts and Operations to create more coupling options.

# Contents

# 1. Introduction

In this section, an introduction in Virtual Coupling will be provided and the research problem, objective and scope of this thesis will be introduced.

## 1.1 Introduction in VC

The growing need to expand railway capacity has been highlighted by a growing number of studies. Many rail lines are currently operating at or near their maximum capacity, while the demand for passenger and freight transport continues to increase. At the same time, infrastructure managers face significant challenges in expanding networks due to the high costs and physical constraints, particularly in densely populated areas where available space is limited.

To address these capacity challenges, infrastructure managers often focus on optimizing block section layouts (Zhong, Xu, Yang, & Zhong, 2023). This approach aims to minimize line headways and energy consumption, but it comes with rapidly escalating investment costs (Quaglietta, 2014). Additionally, such optimizations have inherent limitations, as they rely on fixed track-based signaling systems. As a result, the railway industry is increasingly exploring the adoption of advanced signaling technologies that can enhance train separation, reliability, and operational safety (Quaglietta, Wang, & Goverde, 2020).

ETCS Level 2 and ETCS Level 2 Moving Block (MB) are two examples of advanced signaling systems aimed at improving railway capacity. ETCS Level 2 employs a radio-based fixed-block signaling system to reduce block lengths. Implementations of this system across Europe have demonstrated significant capacity improvements, largely due to its dynamic supervision of braking curves (Vlasenko, 2018). However, technological advancements are steering the industry toward moving-block signaling systems. Unlike fixed-block systems, moving-block signaling eliminates the need for track-side train vacancy detection by utilizing onboard Train Integrity Monitoring (TIM), as defined in ETCS Level 2 MB (Quaglietta, Wang, & Goverde, 2020). In this system, trains are separated by an absolute braking distance without relying on traditional track-side signaling.

Virtual Coupling (VC) represents an even more advanced approach, incorporating a vehicle-to-vehicle (V2V) communication layer into the signaling system. This layer allows trains to exchange real-time information about their kinematic states, such as the trains' speed and route (Quaglietta, Wang, & Goverde, 2020). Through this communication, trains can operate synchronously in platoon formations while maintaining a safe relative braking distance, as illustrated in Figure 1. By doing so, VC enables more efficient utilization of railway infrastructure.

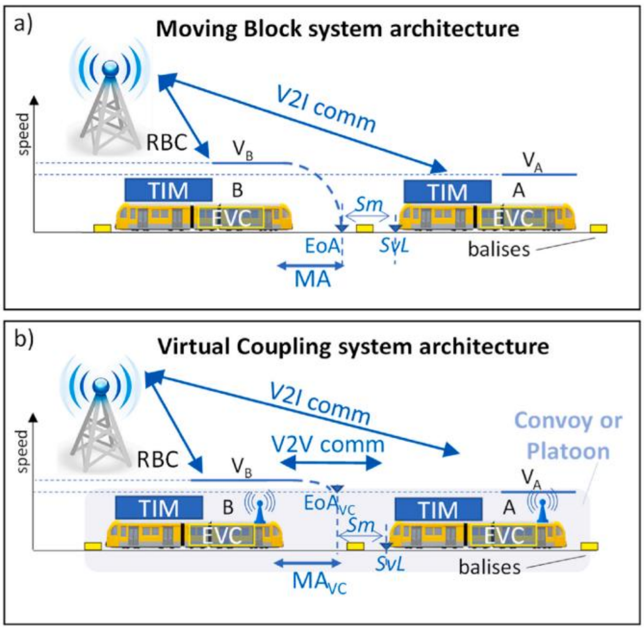



*Figure 1: Moving Block and Virtual Coupling architectures (Quaglietta, Spartalis, Wang, Goverde, & Koningsbruggen, 2022)*

Notably, VC introduces an unique coupling method that allows train units to split and merge automatically without relying on mechanical couplers. This flexibility enhances system efficiency. However, safety concerns arise when implementing VC, potentially limiting capacity improvements. While VC outperforms traditional moving-block systems on straight tracks, challenges persist at merging or diverging junctions. In such cases, trains within a convoy must be adequately spaced to ensure safe movement and proper switch locking.

To this end, Quaglietta, Wang, & Goverde (2020) dived deeper into operational states and corresponding transitions of trains running under Virtual Coupling and developed a multi-state train-following model for the analysis of virtual coupling railway operations. The states referred to by Quaglietta, Wang, & Goverde (2020) are:

1. ETCS L2 MB running
2. Coupling
3. Coupled running
4. Unintentional decoupling
5. Intentional decoupling

In the initial operational state (ETCS Level 2 MB running), Quaglietta, Wang, and Goverde (2020) specify that trains may only initiate virtual coupling if their upcoming route segment is shared with the train ahead. This restriction ensures efficiency, as coupling trains that are about to diverge at an imminent junction would be impractical.

The second state involves a transition from "ETCS Level 2 MB" to the "Coupling" operational state. During this phase, the trailing train closes the gap with the leading train, with the EVC system monitoring its speed relative to the leader. The trailing train approaches the End of Authority for Virtual Coupling (EoAVC), maintaining a safety margin from the rear of the leading train.

In the "intentional decoupling" state, the trailing train separates from the leader by maintaining a distance that includes the absolute braking distance and an additional margin to allow for the safe adjustment and locking of switches. The transition from coupled running to intentional decoupling is triggered when the distance between the head of the trailing train and the EoA falls to or below the absolute braking distance. After decoupling, the trailing train resumes independent operation under ETCS Level 2 MB until it encounters suitable conditions to couple with another train.

Several analysis on the capacity benefits and flexibility of the system were conducted and show the potentiality of VC, even when complex station lay-outs and safety margins were incorporated. Pan, Peng, Zhan, & Bai (2021) showed that even in complex station layouts train headways can be significantly reduced by 46% for a train arrival and 36% for a train departure case as compared to CTCS-3 (Chinese Train Control System), which is most comparable to ETCS Level 2 (Pan, Peng, Zhan, & Bai, 2021). Research by Gallo, Febbraro, Giglio, & Sacco (2020, 2021) aimed to gain more insight into increased flexibility by introducing VC. In their mathematical optimization model, the optimal number of carriages for each train and for each link were determined. It was found that VC can minimize the amount of missed connections while optimizing the amount of carriages in a path. In the case of 9 carriages per train, the amount of missed connections was 25% while a total of 198 carriages were used. After introducing flexible paths enabled by VC, the amount of carriages stayed almost the same (a total of 189), while the amount of missed connections dropped significantly to only 3% (Gallo, Febbraro, Giglio, & Sacco, 2020).

Besides an increment in capacity and flexibility, a SWOT performed by Aoun, Quaglietta, & Goverde (2020) indicated that VC can deliver even more advantages for the whole railway industry, such as an improved mitigation of delay propagation, reduced latency in communication with RBC, decreased OPEX and decreased energy consumption. Weaknesses for all market segments were found to be mostly associated with the safety risks and the need for investments and upgrades for trains and infrastructure. Opportunities of VC are mostly associated with the increased attractiveness of railways, potential profit increase for IMs and RUs, restructuring of the railway market, migration of current Control and Command systems and a maximization of capacity while reducing maintenance costs. Finally, threats were found to be mostly associated with the potential increase in ticket fees, increase in control complexity, additional costs of stakeholders and the partial redesign of policies, processes and engineering rules.

Lastly, the introduction of VC could increase research and developments in the industry, such as the implementation of ATO (Automatic Train Operation) and ETCS Level 2 MB. Given that trains operate with relatively short distances in VC, this necessitates automated driving through ATO for safe operations (Quaglietta, Wang, & Goverde, 2020). Therefore, gaining a deeper understanding of the feasibility and effectiveness of Virtual Coupling, could garner more support and expedite the implementation of ETCS Level 2 MB and ATO on current railway corridors.

## 1.2 Problem Description

ETCS Level 2 MB has the potential to increase capacity by shortening headways to absolute braking distance. VC allows platooning and demand-driven services over MB, which can even more increase capacities for railways. Moreover, since it allows to virtual couple units, instead of mechanically, VC has also the potential to increase the overall flexibility of the system. This way, VC could enhance the overall systems efficiency by optimizing the amount of resources, capacities and travel times.

While research exists on platooning and demand-driven service models, especially in other transportation sectors, studies that apply platooning as a concept specific to railway operations remain limited. Although several studies on VC implementation show promising results for capacity and flexibility, they often omit the influence of operational characteristics like varied stopping patterns, complex maneuvers, and coupling/decoupling sequences. These factors are likely to impact headways, generalized travel times, and resource allocation, which in turn affect VC's real-world benefits. Therefore, it remains unclear how VC could be effectively implemented as an operational transport concept for main-line railways market which could truly benefit passengers, railway undertakings and infrastructure managers.

## 1.3 Objective

The objective of this paper is to identify operational concepts that apply VC to mainline railway corridors, aiming to maximize benefits for railway undertakings, passengers, and infrastructure managers. This involves evaluating both qualitative factors, such as user-friendliness, technical complexity, and rolling stock circulation, and quantitative metrics, including generalized travel times, capacity utilization, and service frequency.

The main research question for this master thesis is:

*"Which operational concept(s) are most effective in terms of generalized travel times, infrastructure occupation and frequency for implementing Virtual Coupling on Dutch main-line passenger railway corridors?"*

The main research question will be answered jointly by the following sub-questions:

1. What are the characteristics of current platooning and demand-driven transport concepts that could be used with VC?
2. Which operational transport concepts can be defined specifically applicable for main-line railways operations?
3. What are the most promising transport concepts for implementation on a real-world case study under realistic conditions ?
4. How does each concept perform in terms of frequency, infrastructure occupation and generalized travel times for the selected corridor?

## 1.4 Limitations and scope

To narrow the scope of this study, the research is focused specifically on the implementation of VC for main-line railway markets. Moreover, the following assumptions have been made to limit the scope of the research:

- The reference level is set to ETCS Level 2 MB;
- All trains are assumed to be integer;
- Platoons can only be formed for a maximum of two train units;
- Only homogeneous trains can be virtually coupled;
- Infrastructure lay-outs and track speeds remain preserved.
- Concepts particularly focus on the implementation of VC on main-line railway corridors

## 1.5 Report structure

Chapter 2 contains a literature review, aiming to explore known implementations and/or use cases of platooning and demand-driven concepts that could be applicable to virtual coupling. This review aims to provide insights into the operational characteristics of flexible, demand-driven systems and how vehicle platooning can enhance capacities while reducing user and operating costs for the selected corridors.

Chapter 3 provides the requirements for the determination of transport concepts specifically applicable for virtual coupling operations. The requirements are divided into objectives and constraints, devised from literature and interviews with different stakeholdergroups. Based on this, building blocks are defined, from which the transport concepts specifically applicable for virtual coupling operations are extracted.

Chapter 4 involves the application of the extracted transport concepts on the case study. The transport concepts are first assessed through SWOT-analysis, after which different stopping plans (which stations are served by each train) and operational plans (what is the sequence of trains and which maneuvers will they perform) are extracted. Each stopping plan and each operational plan is combined into a pattern, and each pattern is simulated to obtain speed and running profiles.

Chapter 5 evaluates the performance of each combination of patterns based on infrastructure occupancy, frequencies, and generalized travel times.

Chapter 6 finally answers the main research question by providing conclusions and recommendations towards the implementation of VC on Dutch main-line passenger railways.

# 2. Methodology

This research follows a multi-step process aligned with the double diamond design approach, as illustrated in Figure 2.

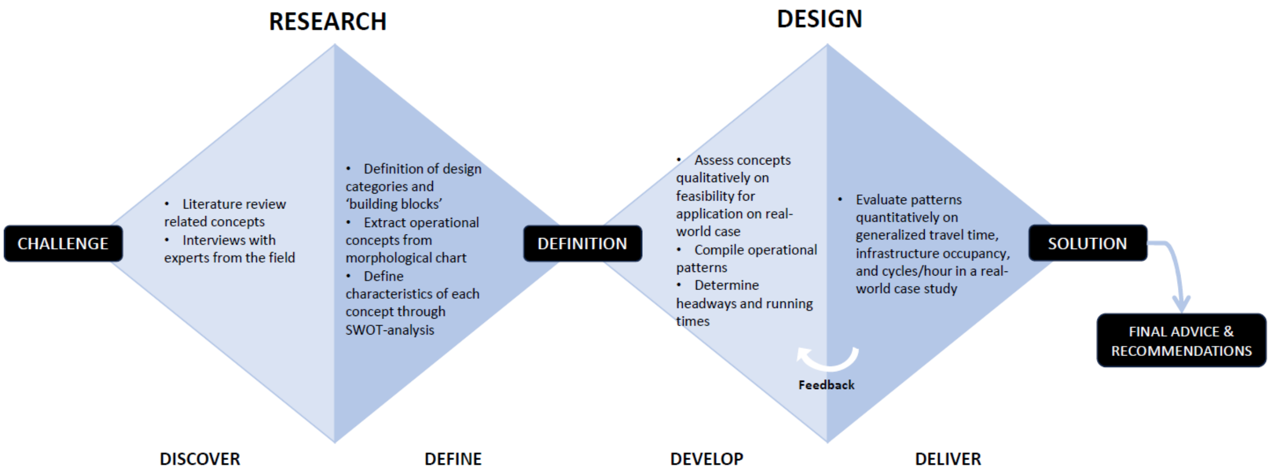



*Figure 2: Double diamond design approach*

## 2.1 Phase 1: Discover

The discover phase is the start of the research stage and involves discovering the challenge through literature review and expert interviews.

The literature review focuses on exploring known implementations and/or use cases of platooning and demand-driven concepts in other modes of transport that may be applicable to mainline VC operations. Based on this analysis, design categories are identified, specifically focused on identifying the characteristics of various stopping patterns, timetable structures, shunting strategies, and operational maneuvers relevant to VC implementation on mainline railway corridors. Additionally, the literature review was used to extract a set of objectives to evaluate the feasibility and effectiveness of these concepts in a later state.

The interviews are conducted to obtain a broader view on how VC could potentially be implemented on main-line railway corridor from the perspective of important stakeholders, including ProRail as the main infrastructure manager, NS as the main railway undertaking, and the PD ERTMS who oversees the planning, implementation, and coordination of ERTMS projects. These interviews focused on the potential benefits and challenges of VC within the mainline railway market and helped refining and expanding the objectives for designing operational concepts suitable for mainline corridors.

The combination of the literature review and expert interviews provided a comprehensive understanding of the challenge and identified potential building blocks for implementing VC on mainline railway corridors in the Netherlands.

## 2.2 Phase 2: Define

Building on the insights gathered in the discover phase, the define phase aims to shape operational concepts tailored for mainline railway operations and identify the most promising concepts through a detailed SWOT analysis.

First, a main user story for a virtual-coupled train traveling between stations was created. The primary findings from the literature review were integrated as design aspects and complemented with own insights. Each design aspect was then developed into "building blocks" for VC operations, representing specific events (e.g., coupling/decoupling at a station or during transit). The building blocks are extracted from literature research and again completed with own insights.

The building blocks were systematically combined using a morphological chart. This tool is particularly useful in the early stages of design and helps to generate new concepts by systematically exploring the design space with brainstorming (University of Cambridge, n.d.) (Börekçi, 2018). The design aspects form the rows, while the building blocks populate the cells. Certain design aspects may be ruled out if they conflict with the scope or depend on other factors, making them indistinguishable. Some design aspects could potentially be ruled out, for example when they are conflicting with the scope or depend on other design aspects, making them irrelevant. The operational concepts are developed based on the remaining aspects.

SWOT analyses were conducted to detail the characteristics of each concept, assessing strengths, operational challenges unique to VC, opportunities for VC implementation, and external threats that could impact feasibility on mainline railway corridors. For this, first the findings from literature review were used to identify widely recognized strengths, weaknesses, opportunities, and threats. Then, these point were elaborated by expert interviews with NS, ProRail, and PD ERTMS, capturing nuanced and context-specific points that may not be evident from the literature alone. The SWOTs were then complemented with own insight by leveraging AI tools for inspiration.

## 2.3 Phase 3: Develop

The develop phase marks the start of the design stage, where running times, headways, and frequencies are computed for one or more selected operational concepts. The selection of these concepts is based on qualitative evaluations from the SWOT analysis and the objectives defined in Phase 2, applied to a real-world case study. A real-world case study is valuable for assessing concepts as it provides practical context and helps evaluate their feasibility and performance under realistic conditions. To this end, the following assumptions have been made:

- The study case will be selected by the PD ERTMS and will involve a corridor comprising three major stations ($M1, M2, M3$) with at least one intermediate regional station between each major station.
- The operational performance under ETCS Level 2 Moving Block (MB) will serve as a benchmark.
- For standardization, two types of trains will be used in the assessment: the ICNG with 8 carriages for intercity services and the SNG with 4 carriages for regional services.
- In line with current railway operations and due to the absence of algorithms for cooperative traffic management under VC, a train running at scheduled track speeds will not be able to catch up to the one ahead unless the leading train is mandated to reduce speed or stop at a station.
- For trains operating under ETCS Level 2 MB or for two consecutive heterogeneous trains, a buffer time of 30 seconds will be applied.
- The dwell time for each type of station and train will be set at 60 seconds (Aoun, et al., 2020).
- A 3-second brake application time will be factored into all braking curve calculations.
- A minimum time supplement of 5% will be added to all technical running times to absorb minor deviations, reducing the risk of cascading delays, and contributing to more stable and resilient operations.
- For plain line running, a dynamic safety margin as introduced by (Quaglietta, Spartalis, Wang, Goverde, & Koningsbruggen, 2022) will be incorporated to ensure safe separation while considering operational hazards. For merging and diverging maneuvers, a fixed safety margin will be applied to prevent overshooting of danger points, as recommended by (Aoun, et al., 2020).
- The block length and turnout speeds of the switches are extracted from OVS00056-6.1-V009_Wissels en Kruisingen. The switch types and switch locations are extracted from OBE-sheets (Overzicht-Baan-Emplacement).
- For capacity reasons, both regional trains need to be able to stop simultaneously at each major station.
- The maximum amount of cycles are determined based on maximum infrastructure occupancy ratios of 85-90%. This ratio is higher than recommended by UIC of 60% during a daily period and 75% during peak hours for mixed traffic lines. However, it is expected that with the introduction of ATO, this recommended infrastructure occupancy limits can be extended. This assumption is based on the London Underground's Victoria Line, which operates with ATO and CBTC and can handle around 33 trains per

hour on a fully ATO system (Stacy, 2014). Although main line corridors infrastructure is often more complex and therefore still limits full occupancy use, it is expected that future systems will support infrastructure occupancy rates up to 85-90%.

- From current operations, it is assumed that all Intercity trains will always depart from a straight track to enhance fast direct connections.

### 2.3.1 Technical running times

The technical running times $r_{o,d,n}$ for train $n$ running from an origin $o$ to a certain destination $d$ are determined by calculating the speed $v$ and distance $d$ at every current time instant $k$, while taking into account infrastructure constraints, rolling stock specifications and operational characteristics. For each Origin-Destination (O-D) pair running times are calculated sequentially over the following sections:

1. Brake section
2. Acceleration section
3. Cruising section
4. Determine intersection point if cruising section < 0

#### Brake section

To compute the distance and time at each time instance $k$ during train braking, standard kinematic equations were applied.

| | **Distance** | **Time** |
|---|---|---|
| **Braking** | $d_{n+1} = \frac{\lvert v_{n+1}^2 - v_n^2 \rvert}{2 * b}$ | $t_{n+1} = \frac{\lvert v_n - v_{n+1} \rvert}{b}$ |

The braking rates $b$ are assumed to be constant parameters, to be constant for each type of train, with distinctions made between operational and emergency braking:

- $b_{operational,ICNG} = -0.66\ m/s^2$
- $b_{operational,SNG} = -0.8\ m/s^2$
- $b_{emergency} = -1.0\ m/s^2$

Using these parameters, the speed and distance at each time instant $t_k$ for the braking phase were calculated in Excel for every Origin-Destination (O-D) pair.

#### Acceleration section

The acceleration $a$ rates are computed based on the technical specifications of the ICNG and SNG trains using the equilibrium of forces acting on a moving train:

$$\rho m a = F_{Tr}(v) - R(v)$$

where:

- $\rho$ is the rotating mass factor
- $m$ the train mass
- $F_{Tr}(v)$ represents the tractive effort as a function of speed
- $R(v)$ is the total resistance as a function of speed.

The accelerate rate $a(v_n)$ varies with train speed, as the maximum tractive effort of a train engine follows a hyperbolic curve. This means that both maximum tractive effort and acceleration decrease non-linearly as speed increases. Acceleration rates were computed at one-second intervals.

Time and distance are then numerically solved from

$$t_{12} = \int_{v1}^{v2} \frac{\rho m}{F_{Tr}(v) - R(v)} dv \qquad and \qquad s_{12} = \int_{v1}^{v2} \frac{\rho m v}{F_{Tr}(v) - R(v)} dv$$

### Cruising section

The cruising section is calculated using standard kinematic equations for distance and time, where the train maintains a constant speed.

| | Distance | Time |
|---|---|---|
| **Cruising** | $d_{n+1} = v_n * (t_{n+1} - t_n)$ | $t_{n+1} = \frac{(d_{n+1} - d_n)}{v_n}$ |

### Intersection point

If the track section length constraints a train to accelerate to cruising speed, the intersection point have to be determined at which the acceleration curve and braking curve intersect. This intersection point is found iteratively by comparing the distances at which the acceleration phase transitions to cruising and the distance where braking begins.

## *2.3.2 Nominal running times*

After computing the technical running times, nominal running times are obtained by applying a 5% running time supplement to each technical running time for O-D pairs. This supplement accounts for minor deviations, improving schedule robustness and resilience.

To simplify this process, a single scheduled speed is determined for an entire track section (i.e. section between two major stations). The constraining O-D pair—typically the shortest segment—is selected first, as trains on this segment are unable to reach their maximum speed, making it the most restrictive case. Since nominal running times do not alter the acceleration and braking phases, using the shortest O-D pair ensures adding a minimum time supplement of 5% to all O-D pairs. Once the scheduled speed for the constraining O-D pair is established, running times for the remaining O-D pairs within the track section are computed based on this speed.

## *2.3.3 Headways*

Headways for each operational principle, as outlined by (Aoun, et al., 2020), were computed based on normative speed profiles at specific locations $l$ along the track between a follower train $n$ and leader a train $n-1$. The designated locations for each running principle are:

1. **Plain line manoeuvres**
    a. *Plain line open track*: At the point where the leader train reaches maximum scheduled speed
    b. *Simultaneously arriving*: At the point where the leader train begins operational braking or where the follower matches the leader's speed if the follower runs faster
    c. *Simultaneously departing*: At the point where the leader reaches maximum scheduled speed.
    d. *Sequentially departing / arriving*: At the point where the leader starts operational braking.
2. **Merge/ diverge manoeuvres**
    a. *Merge at a Switch*: At the point of merging.
    b. *Diverge at a Switch*: At the point of divergence.

Plain line open track maneuvers (1a) are obtained for each O-D pair. A sequential maneuver (1b) occurs when trains stop at a station one after the other, maintaining a consecutive sequence (Figure 3 left). In contrast, a simultaneously running case (1c) involves two trains stopping at the same platform track at the same time, allowing for more efficient use of track space (Figure 3 right).

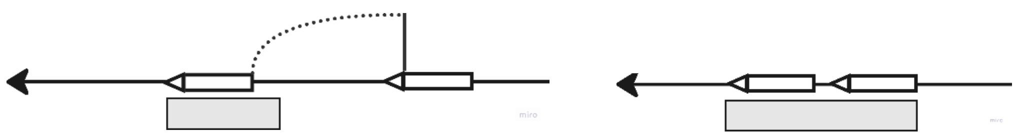


*Figure 3: Sequential running maneuver (left) and simultaneously running maneuver (right)*

For plain line maneuvers, a dynamic safety margin is included in line with  (E. Quaglietta, et al., 2022). This safety margin adds an additional layer of protection between the End of Authority for Virtual Coupling $EOA_{vc}$ (End Of Authority Virtual Coupling) of the follower train and the Supervised Location (SvL) of the leader. It prevents any unsafe overshooting of the $EOA_{vc}$ (or $EOA$) and a consequent collision with the danger point by accounting for any real time hazard that can occur during real time operations. Within the $dsm,$ a total of 5 potential hazards is included:

1. train position errors $sm_{pos_{k,n,n-1}}$
2. communication update delays $sm_{com_{k,n,n-1}}$,
3. train control delays $sm_{cont_{k,n,n-1}}$,
4. emergency braking applications of the leader train $sm_{emer_{k,n,n-1}}$
5. a constant term accounting for exogenous factors $sm_0$.

The dynamic safety margin $dsm_{k,n,n-1}$ is determined with a time interval $k$ = 1 second between the leader train $n-1$ and a follower train $n$ by summing all terms:

$$dsm_{k,n,n-1} = sm_{pos_{k,n,n-1}} + sm_{com_{k,n,n-1}} + sm_{cont_{k,n,n-1}} + sm_{emer_{k,n,n-1}} + sm_0$$

Next, headways for all headway locations are determined by accounting for the following headway elements:

- **The running time $t_{running}$** is the time needed to cross a block. In case of a merging or diverging maneuver, the running time is the time needed to cross the block of the switch:

$$t_{running}[s] = \frac{block\ length\ [m]}{speed\ [\frac{m}{s}]}$$

  When braking or accelerating, the clearing time is instead computed by determining the speed when entering and the speed when leaving the clearing point. For plain line maneuvers, the running time is equal to 0 seconds since no blocks are crossed.
- **The clearing time $t_{clear}$** is the time for the length of the train to pass a clearing point. When running at constant speed, this is calculated by:

$$t_{clearing}\ [s] = \frac{maximum\ train\ length\ [m]}{speed\ at\ release\ point\ [\frac{m}{s}]}$$

  When braking or accelerating, the clearing time is instead computed by determining the speed when entering and the speed when leaving the clearing point.
- **The release time $t_{release}$** is the time needed to release a block, which is equal to the communication time from/to the RBC in case of plain line and fixed to 4 seconds in the case where switches are considered. Also, for VC, an extra V2V communication latency is considered, which is extracted from *MovingRAIl Deliverable 4.2* and set equal to 0.02 seconds (Aoun, et al., 2020).
- **The setup time $t_{setup}$** is the time needed to setup the route, which is equal to 1 seconds for open track and equal to the time needed to move and lock a switch in an interlocking area. The time needed to move and lock a switch is extracted from *MovingRAIL Deliverable 4.2*, and set equal to 8 seconds for main line corridors (Aoun, et al., 2020). In VC scenarios where the follower shares the same route as the leader, the setup time for the follower is instead equal to 0 seconds.
- **The reaction time $t_{reaction}$** is extracted from *MovingRAIL Deliverable 4.2* and set equal to 6 seconds for MB and 1 second for VC to take the ATO-reaction time into account (Aoun, et al., 2020).
- **The approach time $t_{approach}$** for MB is determined by the time required for the follower train to cover the absolute braking distance to the preceding train, while for VC this time is based on the time required to cross a relative braking distance. Additionally, the approach time includes the time required to cross the $dsm_{k,n,n-1}$ for plain line maneuvers and instead a fixed safety margin around switches.

The minimum required headway for a specific maneuver between two consecutive trains 1-2 is calculated by summing all elements:

$$Headway_{train\ 1-2} = t_{running,1st\ train} + t_{clear,1st\ train} + t_{release,1st\ train} + t_{setup,2nd\ train} + t_{reaction,2nd\ train} + t_{approach,2nd\ train} \quad (1)$$

Note that headway calculations for merging, diverging, and sequential arrival maneuvers are based on technical running times. Instead, for plain line open track and simultaneous arrival/departure maneuvers, headway times are calculated using nominal speed, as lower speeds require more time for a follower train to pass the minimum headway distance.

### 2.3.4 Frequency

The final step in the develop phase involves calculating maximum frequencies $f_{max,p,q}$ for each train executing a specific stopping plan (which stations are served by each train) and operational plan (what is the sequence of trains and which maneuvers will they perform) on the selected case-study corridor. These stopping- and operational plans are merged into patterns, in which each pattern is distinguished by a sequence of numbers (corresponding with the amount of times a regional station is served by a regional train per cycle) and a letter (corresponding to particular sequence of trains and/or maneuvers trains perform). Patterns are developed separately for each track section (i.e. $M1$ to $M2$ and $M2$ to $M3$).

By combining each pattern for the first track section with a pattern for the second track section, combinations can be assessed on maximum applicable frequency along the entire corridor. Note that simply combining the best performing patterns (in terms of maximum frequency) for each track section does not guarantee an optimal solution for the entire corridor. This is because the difference in arrival times (delta arrival time) at $M2$ affects the initial conditions for trains departing from $M2$, potentially impacting the performance on the overall corridor. An algorithm evaluates each pattern combination to compute the maximum frequency for the corridor, considering arrival times and the minimum headway between consecutive trains. The indices, parameters and decision variables used in this algorithm are detailed in Tables 1, 2, and 3.

*Table 1: Indices and sets*

| Index | Description | Sets |
|---|---|---|
| n | Train index | n ∈ {1,2,…,N} |
| p | Pattern index for segment M1 to M2 | p ∈ {1,2,…,P} |
| q | Pattern index for segment M2 to M3 | q ∈ {1,2,…,Q} |
| o | Origin station index | o ∈ {1,2,…,O} |
| d | Destination station index | d ∈ {1,2,…,D} |
| l | Location index for computed headways along the corridor | l ∈ {1,2,…,L} |

*Table 2: Parameters*

| Index | Description | Units |
|---|---|---|
| $T$ | Considered time period | seconds |
| $r_{o,d,n}$ | Running time between $o$ and $d$ for train type $n$ | seconds |
| $dt_d$ | Dwell time at destination station $d$ | seconds |
| $bf_{n,n-1}$ | Buffer time between train $n$ and preceding train n-1 | seconds |
| $h_{l,n,n-1}$ | Minimum headway required at location $l$ between train $n$ and the preceding train $n-1$ | seconds |

*Table 3: Decision Variables (DV)*

| DV | Description | Units |
|---|---|---|
| $d_{M1,n,p}$ | Departure time of train $n$ from $M1$ for pattern $p$ | seconds |
| $d_{M2,n,p,q}$ | Departure time of train $n$ from $M2$ for patterns $p$ and $q$ | seconds |
| $a_{M2,n,p}$ | Arrival time of train $n$ at $M2$ for pattern $p$ | seconds |
| $a_{M3,n,p,q}$ | Arrival time of train $n$ at $M3$ for patterns $p$ and $q$ | seconds |

The objective of this algorithm is to find the maximum line frequency $f_{max,p,q}$ for a combination of patterns $p$ and $q$ by maximizing the number of cycles that fit within the time period $T$:

$$f_{max,p,q} = \frac{T}{\Delta T_{cycle}}$$

where $\Delta T_{cycle}$ is the time difference between the arrival of the last and the first train at $M3$ within one cycle. To this end, a seven-step algorithm is used which captures all constraints and considerations for scheduling trains and maximizing line frequency, taking into account patterns, headways, buffer times, and operational constraints:

1. **Calculate running times between $M_1$ $and$ $M_2$ for each train.**
   The running time $rt_{p,n}$ for each train $n$ for executing a certain pattern $p$ between M1 and M2 is determined by:

   $$rt_{p,n} = \sum_{(o,d)\in p} s_{o,d,n} * (r_{o,d,n} + dt_d)$$

   where $s_{o,d,n}$= 1 if train $n$ serves $(o,d) \in p$ , and 0 otherwise.

2. **Calculate (relative) arrival times at $M_2$ of $RE_1$ and $RE_2$.**
   The arrival times $a_{p1,w,s}$ of the first regional train $w = RE_1$ and the second regional train $w = RE_2$ at $s$ = $M_2$ are obtained by simulating a certain pattern $p$ between $M_1$ and $M_2$. The consequent relative arrival delay $q_{w2,w1,s}$ between $w_1 = RE_1$ and $w_2 = RE_2$ at $s$ = $M_2$ is obtained by taking the delta arrival times.

   For the first train (n=1) following pattern $p$, departing at t=0, the arrival time at M2 is:

   $$a_{M2,1,p} = rt_{p,1}$$

   For all subsequent trains performing pattern $p$, the departure time $d_{M1,n,p}$ is determined by the headway constraint relative to the previous train. For this, at each location $l$ associated with an origin-destination pair $(o,d) \in p$, a candidate departure time for train $n$ is computed:

   $$d_{M1,n,p,l} = d_{M1,n-1,p} + h_{l,n,n-1} - r_{M1,l,n}$$

   This calculation adjusts the departure time from $M1$ to ensure that the required headway $h_{l,n,n-1}$ at location $l$ is not violated. After calculating $d_{M1,n,p,l}$ for all relevant locations $l$ in the pattern $p$, the latest of these departure times is picked as actual departure time $d_{M1,n,p}$ for train $n$ from $M1$:

   $$d_{M1,n,p} = \max_{l\in(o,d)\in p} d_{M1,n,p,l}$$

   After determining the departure time from $M1$, the arrival times at $M2$ can be ultimately determined by:

   $$a_{M2,n,p} = d_{M1,n,p} + rt_{p,n}$$

3. **Calculate running times between $M_2$ $and$ $M_3$ for each train.**
   The running time $rt_{q,n}$ for each train $n$ following pattern $q$ between $M2$ and $M3$ is given by:

   $$rt_{q,n} = \sum_{(o,d)\in q} s_{o,d,n} * (r_{o,d,n} + dt_d)$$

   where $s_{o,d,n}$= 1 if train $n$ serves $(o,d) \in q$ , and 0 otherwise.

4. **Determine minimum required departure delays from $M_2$.**
In this step, train-type-specific and pattern-specific headways for determining the minimum required departure delay from $M2$ are incorporated. For the first train (n=1) following pattern $q$, departing at t=0, the departure time from M2 is:
$$d_{M2,1,q} = 0$$
For all subsequent trains performing pattern $q$, the departure delay relative to n=1 $dd_{M2,n,q}$ is determined by the headway constraint relative to the previous train. For this, at each location $l$ associated with an origin-destination pair $(o,d) \in q$, a candidate departure delay for train $n$ is calculated:
$$dd_{M2,n,q,l} = d_{M2,n-1,q} + h_{l,n,n-1} - a_{M2,n,q}$$
This calculation adjusts the departure time from $M2$ to ensure that the required headway $h_{l,n,n-1}$ at location $l$ is not violated. After calculating $dd_{M1,n,p,l}$ for all relevant locations $l$ in the pattern $q$, the maximum of these calculated departure delays is used for $dd_{M2,n,q}$:
$$dd_{M2,n,q} = \max_{l \in (o,d) \in q} dd_{M2,n,q,l}$$

5. **Determine real (relative) departure time from $M_2$.**
Having obtained the minimum required departure delay $dd_{M2,n,q}$ for train $n$ departing from $M2$, the actual departure time $d_{M2,n,q}$ can be computed. This time depends on the train's arrival time at $M2$, the necessary dwell time, and the headway constraints from Step 4.

If the arrival time $a_{M2,n,p}$ of train $n$ at $M2$ is greater than or equal to the minimum required departure delay $dd_{M2,n,q}$, then train $n$ can depart immediately after completing its dwell time $dt_{M2}$ at $M2$. Otherwise, train $n$ must wait until the required headway is satisfied. Consequently, the real departure time $d_{M2,n,p,q}$ for train $n$ departing from $M2$ following pattern $p$ and $q$ is given by:
$$d_{M2,n,p,q} = \max(a_{M2,n,p} + dt_{M2}, d_{M2,n-1,p,q} + dd_{M2,n,q})$$
Note that for the first train (n=1) following pattern $p$ and $q$, the departure time from M2 is:
$$d_{M2,1,p,q} = rt_{p,1}$$

6. **Calculate the arrival times for all trains at $M_3$.**
In this step, the arrival times at $M3$ for each train $n$ are determined based on its arrival time at $M2$ and its running time for executing pattern $q$. For the first train (n=1) following patterns $p$ from $M1$ to $M2$ and $q$ from $M2$ to $M3$, the arrival time at $M3$ is simply the sum of its running times from both segments:
$$a_{M3,1,p,q} = rt_{p,1} + rt_{q,1}$$
For each subsequent train $n$, the arrival time at $M3$ depends on its departure from $M2$ (which itself is influenced by pattern $p$), the running time from $M2$ to $M3$ for pattern $q$ and the buffer time $bf_{n,n-1}$ between train $n$ and the preceding train $n-1$:
$$a_{M3,n,p,q} = d_{M2,n,p,q} + rt_{q,n} + bf_{n,n-1}$$

7. **Calculate the maximum line frequency between $M_1$ and $M_3$.**
In this final step, the maximum line frequency is calculated. First, the arrival time at $M3$ of the last train in the current cycle has to be determined, which sets the basis for the beginning of the next cycle. Let $a_{M3,last,p,q}$ denote the arrival time at $M3$ of the first train and $a_{M3,last,p,q}$ denote the arrival time at $M3$ of the last train in the current cycle. The cycle time $\Delta T_{cycle}$ is the difference between the arrival time of the last and the arrival time of the first train at $M3$:
$$\Delta T_{cycle,p,q} = a_{M3,last,p,q} - a_{M3,1,p,q}$$

Given the total time period $T$, the maximum line frequency $f_{max,p,q}$, representing the maximum number of cycles that can be completed within $T$, is calculated by dividing $T$ by $\Delta T_{cycle}$:

$$f_{max,p,q} = \frac{T}{\Delta T_{cycle,p,q}}$$

From this, maximum frequencies $f_{max,p,q}$, along with the amount of non-direct O-D pairs are subtracted by implementing the algorithm in Python and used to select the most promising plans for final assessment in the deliver phase.

## 2.4 Phase 4: Deliver

In the deliver phase, the selected plans are assessed for frequency, infrastructure occupancy, and generalized travel times (GTT). Note that the frequency for each pattern has already been obtained in the develop phase. To encourage continuous improvement, a feedback loop is incorporated into this phase, allowing new insights gained during the assessment to inspire further development.

### *Infrastructure occupancy*

The infrastructure occupancy is computed by summing up the constraining headway times between consecutive trains within a cycle and dividing this sum by the total period $T$.

The infrastructure occupation time $T_{\min}$ of all trains in a period is the sum of all minimum line headways from the first train to the first train in the next cycle without buffer times. Since all trains were planned based on minimum line headways for a certain combination of patterns $p, q$, this can be obtained by:

$$T_{min,p,q} = \Delta T_{cycle,p,q} - \sum_{n=1}^{N-1} bf_{n,n-1}$$

The infrastructure occupancy percentage for a combination of patterns $C_{p,q}$ is then computed by:

$$C_{p,q} = 100 * \frac{T_{min,p,q}}{T}$$

### *Generalized travel time*

The GTT incorporates both linear time-dependent components and a fixed transfer penalty. The incorporated linear-time dependent components are as follows:

- **Bike time.** The bike time is only applied when a measure requires travelers to bike a longer distance to the next closest access point within a range of 3–5 kilometers from the origin. This assumption aligns with established behavior among train users in the Netherlands, where cycling is a common access mode for trips up to 3 kilometers, and the adoption of electric bikes extends this range to 5 kilometers (Jonkeren, Harms, Jorritsma, Huibregtse, & Bakker, 2018). Another study by Mil, Leferink, Annema, & van Oort (2021) supports this assumption, showing that cyclists are willing to travel longer distances to reach stops offering more direct transit options with fewer transfers, as these stations provide better integration into the overall transit network (Mil, Leferink, Annema, & van Oort, 2021). The additional biking time is calculated using a straight-line distance at a mean cycling speed of 15 km/h, which is then adjusted using a detour factor of 1.4 to reflect actual cycled distances (Jonkeren, Harms, Jorritsma, Huibregtse, & Bakker, 2018). To estimate the mean additional biking time for the entire affected area, half of this adjusted value is used.
- **Waiting time.** The waiting time is defined as the time a passenger waits when accessing a train. Under the assumption of random passenger arrivals, some passengers will arrive immediately after a train has departed (resulting in the maximum wait), while others will arrive just before the next train departs (resulting in minimal wait), with the average waiting time falling at the midpoint of these extremes. Consequently, if a station is served four times per hour, the mean waiting time would be 7.5 minutes. Note that in practice, this mean waiting time will often be shorter, as passengers tend to time their arrival just before a train departs. Note that the waiting time could differ for different OD-pairs, as some OD-pairs provide more options per hour than others.

- **In-vehicle time.** The in-vehicle time is the time travelers are traveling in the train, including dwell times. Note that in the case travelers cannot reach their desired destination from a given point of origin, travelers need to travel in opposite direction. The in-vehicle times of traveling to the opposite direction are assumed to be equal to the in-vehicle times as determined in this research and are added to the in-vehicle times to travel to a nearest major station.
- **Transfer time.** Whenever a passenger needs to transfer to a train traveling in the opposite direction, the transfer time is calculated as the average interval between train arrivals. For certain OD-pairs, passengers do not need to travel in the opposite direction, as they can transfer at an intermediate station along their journey. In these cases, the transfer time is defined as the interval between the arrival of their first train and the departure of their connecting train. Note that the transfer time does not include the dwell time at the station, as the dwell time is already included in the in-vehicle time.

It is important to note that additional factors, such as the increased likelihood of finding a seat in the skip-stop variant, are not considered within this research due to the absence of reliable demand data.

Each component has a disutility value $\beta$ representing its disutility, as extracted from (Arentze & Molin, 2013):

*Table 4: Considered GTT-components with associated disutility value*

| **Parameter** | **$\beta$ values** |
|---|---|
| **access_bike (BT)** | -0.095 |
| **wait_access (WT)** | -0.073 |
| **in-vehicle_train (IVT)** | -0.049 |
| **Transfer (TT)** | -0.097 |
| **transfer penalty (PY)** | -0.113 |

The equivalent in-vehicle time for a specific transfer time is calculated using:

$$transfer\ time * \beta_T + P = equavalent\ in\ vehicle\ time * \beta_{IVT}$$

To express all components in terms of equivalent in-vehicle time, the linear components are normalized relative to in-vehicle time. The transfer penalty is normalized by assuming a mean transfer time and using the above formula to compute the equivalent in-vehicle time. The absolute penalty value $PY$ while normalizing the linear $\beta$ values towards in-vehicle time can be obtained by:

$$mean\ transfer\ time * \frac{\beta_T}{\beta_{IVT}} + PY = equavalent\ in\ vehicle\ time * \frac{\beta_{IVT}}{\beta_{IVT}}$$

The GTT can be computed as follows:

$$GTT = \frac{\beta_{BT}}{\beta_{IVT}} * BT + \frac{\beta_{WT}}{\beta_{IVT}} * WT + IVT + \frac{\beta_T}{\beta_{IVT}} * TT + PY \qquad (2)$$

Due to the absence of demand-data, the GTT for a certain pattern treats all O-D pairs equally. Although this might give some bias, the obtained GTTs provide valuable insights into the relative impact of each variant, allowing to compare the relative performance of different stopping and operational plans. These GTTs should hence be treated as comparative indicators rather than absolute values which would require the inclusion of demand-weighted factors. Moreover, the inclusion of additional bike time offers some insight into the disutility of temporarily fully skipping a station. However, it does not account for all potential negative impacts or the number of affected travelers. As such, it should be treated only as a comparative penalty factor of the variant's impact rather than an absolute value.

# 3. Definition of operational concepts

This section outlines the definition of operational concepts. It begins with an analysis of existing platooning implementations, followed by the identification of design aspects, objectives, and building blocks specifically tailored for the implementation of VC on mainline railway corridors. Based on the extracted design aspects and building blocks, transport concepts are defined. The section concludes with detailed SWOT analysis for each defined concept, providing a comprehensive understanding of the feasibility of each approach towards the obtained objectives.

## 3.1 Analysis on current platooning implementations

In this Section, a literature review is conducted to explore known implementations and/or use cases of platooning and demand-driven concepts that could be applicable to VC. As the literature review is mainly used for the deviation of design aspects and building blocks, the focus is particularly concentrated on extracting operational characteristics. Modes of transport considered within this research are busses, hyperloop, trucks, rail, and automated people movers (APM).

### *Busses*

Different concepts of platooning and/or demand-driven services for busses are found in literature, such as Modular Autonomous Vehicles (MAV), Dynamic Autonomous Road Transit (DART), SSaBRT (Slim Semi-autonomous Bus Rapid Transit) and on-demand autonomous shuttle bus service (ASBS). For these concepts, literature describes various ways for possible operations, including vehicle design, (de)coupling points, platoon sizes, and station configurations.

The SSaBRT and DART systems dynamically adjust to passenger demand by employing electronically connected platoons of vehicles or modules, which travel together along shared route sections and detach when the routes diverge (Ginn, et al., 2017) (Nguyen, et al., 2019). The DART-system dynamically adjust the number of modules in a platoon based on actual demand, while maintaining a constant frequency to enhance a reliable and regular service (Tian, Lin, Wang, & Liu, 2022). Moreover, by allowing to drive in platoons, "indirect – direct" trips are provided to the passengers, in which a traveler do not need to wait for the next module to arrive since it is already a part of the platoon (Raua, et al., 2019). Schedules are synchronized by the DART decision-making system at transfer stations to allow the vehicles to create platoons (Ginn, et al., 2017). Whereas the DART system provides a service based on a constant rate, SSaBRT services are completely smartphone demand-based.

The Modular Autonomous Vehicle (MAV), developed by Next Future Transportation and trialed in Dubai, introduces an innovative approach to flexible, on-demand service. Although its capacity adjustments require mechanical assembling and disassembling of modular transport units, the concept still allows for efficient operation (Ji, Liu, Shen, & Du, 2020). n this system, passengers board modular units prior to their docking with the main modular vehicle at stations, while alighting passengers move to designated units before undocking occurs (Ji, Liu, Shen, & Du, 2020) (Tian, Lin, Wang, & Liu, 2022). This approach significantly reduces boarding and alighting times.

Within this framework, Zhang, Ge, Tang, and Zhong (2024) propose a skip-stop strategy for MAV services on fixed bus routes. This strategy prioritizes higher service frequency at stops with greater demand while minimizing stops at lower-demand locations. By optimizing the headway, the number of MAVs per trip, and the coupling and decoupling schemes at intermediate stops, the system adapts to spatial and temporal variations in demand. The skip-stop approach enhances flexibility and operational efficiency, as illustrated in a dynamic coupling and decoupling scheme depicted in scenario 2, which provides tailored service levels based on stop-specific demand (Zhang, Ge, Tang, & Zhong, 2024).

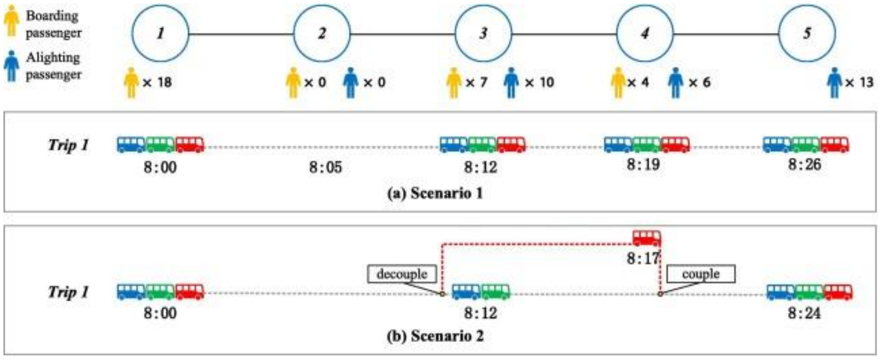


*Figure 4: skip-stop strategy on fixed bus routes (Zhang, Ge, Tang & Zhong, 2024)*

Zhang, Ge, Tang, & Zhong (2024) acknowledge that scenario 2 offers two advantages over Scenario 1. Firstly, Scenario 2 improves the alignment between Modular Autonomous Vehicle (MAV) availability and passenger demand by optimizing supply to meet demand at individual bus stops, unlike Scenario 1, which focuses on the broader bus-route level. This leads to enhanced operational efficiency and time savings. Additionally, Scenario 2 demonstrates a shorter operational time compared to Scenario 1. Secondly, while Scenario 1 assumes all passengers are waiting at stops prior to MAV arrivals, Scenario 2 minimizes both passenger waiting time and in-vehicle time (Zhang, Ge, Tang, & Zhong, 2024).

## *Hyperloop*

The Hyperloop concept was first introduced by Elon Musk in 2013, who outlined a vision for a transportation system that could transport people and goods at speeds exceeding those of traditional high-speed trains (Doppelbauer, 2023). The hyperloop operates on the principle of reduced air pressure within the tube, allowing the pods to travel with minimal air resistance. This reduction in air resistance enables the pods to achieve speeds comparable to or even exceeding the speed of sound (Delft Hperloop, 2024). The passenger pod would be designed to hold up to 40 passengers and drive fully autonomous (VLAIO, n.d.)

Hyperloop networks can function as either point-to-point services or all-stops services (Hardt Hyperloop, 2023). Point-to-point services are tailored for high-speed, long-distance journeys. These services closely resemble the Dutch Intercity trains, bypassing intermediate stops. However, the pods' high speed of up to 700 km/h enables them to cover even longer distances between larger cities. When approaching its destination station, a vehicle moves through a switch to diverge from a mainline onto an off-ramp tube. Here, the vehicle gradually decelerates and switch lanes automatically, without the need of mechanical parts in the infrastructure (Hardt Hyperloop, 2023) (Delft Hperloop, 2024). Figure 5 shows a conceptual representation of a hyperloop network and its stations. Close to each station, depots are located, facilitating for the storage and maintenance of hyperloop vehicles (Hardt Hyperloop, 2023).

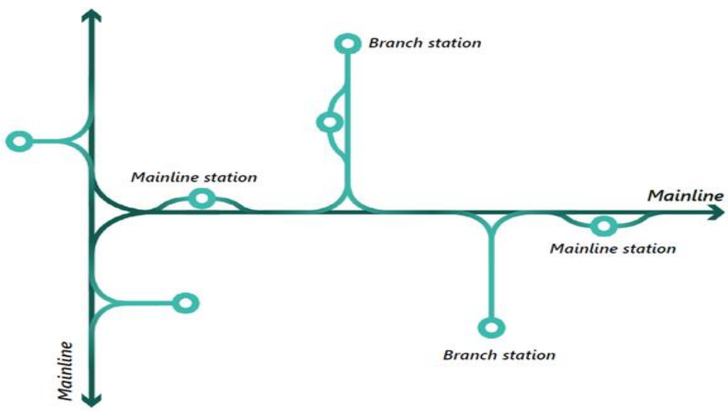


*Figure 5: Conceptual representation of a hyperloop network (Hardt Hyperloop, 2023).*

In addition to a point-to-point service, the hyperloop can also offer an all-stop service, akin to a metro-style service with a predetermined stopping pattern (Hardt Hyperloop, 2023).

Virtual Coupling principles could similarly be applied to the hyperloop system, where pods could operate at reduced distances shorter than the absolute braking distance. This would allow them to move in synchronized, radio-linked platoons, effectively functioning as a single unit (Borges & Quaglietta, 2021). Due to the increased flexibility by the introduction of Virtual Coupling, Pawlik, Kycko, & Zakrzewski (2021) acknowlidge that the amount of pods could be dynamically adjusted to real-time demand (Pawlik, Kycko, & Zakrzewski, 2021). The Virtual Coupling of pods is here referenced to as hypertrains, in which the last pods could decouple at intermediate stations “on-the-fly” without disrupting the journey of the rest of the hypertrain (Pawlik, Kycko, & Zakrzewski, 2021). Eichelberger et al. (2020) suggest that the number of pods required in the system can be minimized through efficient redistribution of available pods. However, this redistribution process necessitates sending partially filled pods at times. To address this, they introduce a straightforward yet effective mechanism called "symmetric redistribution," where for every pod departing from station A to station B, another pod is simultaneously dispatched from station B to station A.

To address potential challenges for passengers in navigating on-demand services, Eichelberger et al. (2020) propose ensuring that pods are always available at each station. They recommend assigning a virtual departure bin to each pod, where departure is triggered once the bin is filled, based on a combination of maximum waiting time for the first passenger and the pod’s capacity. To reduce operational complexity, pod allocation to stations can be based on historical demand data, with adjustments made periodically as real-time demand patterns emerge.

### *Trucks*

Most of the research on truck platooning has concentrated on technical feasibility (Balador et al., 2022) and safety considerations (Kaiser et al., 2022). Additionally, it has been observed that a significant portion of the research emphasizes the potential for fuel savings and reduced emissions.

Given that trucks are primarily used for cargo transportation, the feasibility of concepts towards passenger satisfaction are not considered. Instead, the focus for truck platooning and on-demand concepts is on operational scenarios for efficient transportation. Liatsos, Golias, Hourdos, and Mishra (2024) classify operational scenarios on truck platooning coordination into three main categories: scheduled platoon planning, real-time platooning, and opportunistic planning.

**Scheduled platoon planning**
In scheduled platoon planning, departure times are predetermined before a trip starts. Liatsos, Golias, Hourdos, and Mishra (2024) propose a model to identify optimal (de)coupling locations for truck platooning. The model allows for a flexible number of trucks to form platoons, constrained by a predefined maximum. It also permits trucks to bypass platoons, allowing to travel directly from their origin to destination following the shortest route. Additionally, the model accounts for both single-driver and dual-driver platoons, incorporating adjustments to travel time to ensure compliance with Hours of Service (HOS) regulations. For the introduction of this concept, three noticeable assumptions were made (Liatsos, Golias, Hourdos, & Mishra, 2024):

1. Drivers are stationed at decoupling nodes to individually drive trucks to their respective destinations.
2. Origin and destination points are excluded from being used as (de)coupling locations.
3. Only the lead truck requires a driver

In contrast, other models, such as the one proposed by Xue, Lin, and You (2021), adopt a semi-autonomous fixed platooning approach. In this mode, trucks are restricted to forming platoons only with other trucks departing from the same terminal simultaneously. Consequently, trucks drive to all customers and decouple one unit at each customer node (Xue, Lin, & You, 2021). Larsen, Rich, and Rasmussen (2019) focused their research on Hub-Based Platooning, highlighting two key points: (1) implementing on-the-fly platooning significantly enhances efficiency, and (2) when drivers can rest while operating as followers in a platoon, the potential for increased profitability grows substantially (Larsen, Rich, & Rasmussen, 2019).

**Real-time platoon planning**
In real-time platooning, all trip information (like desired arrival times) is communicated just before or during the trip. Real-time platooning coordination primarily relies on the truck catch-up strategy, in which the following truck accelerates to join and form a platoon with the leading truck. Zhang, Jenelius, & Ma (2017) examined the coordination of truck platoons and departure time scheduling while accounting for the impact of travel time uncertainty on platooning efficiency and revealed that real-time platooning may increase schedule deviations as trucks might have to wait to couple to another truck (Zhang, Jenelius, & Ma, 2017). Additionally, the study revealed that platooning on converging routes causes higher schedule deviations and increased driving costs compared to diverging routes, as this required vehicles to synchronize at merging points.

**Opportunistic platoon planning**
Finally, in opportunistic planning, trucks in neighboring locations opportunistically join existing traveling convoys. Liang, Martensson, and Johansson (2013) determined that for opportunistic platooning to be fuel-efficient, the distance the following truck needs to travel to its destination should be at least 16.5 times greater than the inter-vehicle distance required for it to catch up with the leading truck. Additionally, Noruzoliaee, Zou, & Zhou (2021) observed that for trucks to group with neighboring platoonable vehicles, deviations from their original driving profiles are necessary, potentially causing delays (Noruzoliaee, Zou, & Zhou, 2021).

### *Rail*

In general, it was found that many studies focus on the passenger demand orientated scheduling and optimization of line capacity under Virtual Coupling / platooning in metro services, mainly focused on all-stop patterns (Wu, Chunhai, & Tao, 2021), (Chai S. , Yin, D'ariano, Samà, & Tang, 2023) (Chai S. , et al., 2024). For a clear overview of all results, the findings are divided in 4 parts: (1) Maneuvers and train sequences, (2) service and station characteristics, and (3) timetables.

**Maneuvers and train sequences**
The multi-state-train-following model as introduced by (Quaglietta, Wang, & Goverde, 2020) analyzed the capacity gains towards different operational maneuvers and train sequences. To this end, four scenarios were considered:
1. non-stopping trains having the same route
2. non-stopping trains having different routes
3. stopping trains having the same route
4. stopping trains having different routes

Capacity was assessed based on both space separation and time headway between successive trains, in which it was assumed that The train behind will catch up with the leading train to virtual couple. The scenario showing the most significant improvements in both space separation and time headway was found to be the "stopping trains having different routes" scenario.

Ning et al. (2023) highlighted the challenges of implementing the speed-up scenario proposed by Quaglietta, Wang, & Goverde (2020) due to speed restrictions near switch areas and the tendency of trains to operate at maximum track speeds. To address these limitations, Ning et al. introduced the following convoy coordination strategy based on a waiting mode that accounts for switching time constraints and speed reductions at junctions:

- The last train accelerates to cruising speed following an optimal speed curve based on traction acceleration.
- Preceding trains maintain a constant speed and delay acceleration to align with the coupling process.
- All trains achieve a coupled state once the last train reaches cruising speed.

This approach increases coupling opportunities, supports flexible convoy structures while preserving train order, and minimizes bottleneck conflicts. Simulations showed that this strategy enhanced capacity by 30.7% on regional railway lines.

Nold & Corman (2021) analyzed different train sequences in which trains are coupled and found that this  also significantly affect the capacity. To this end, two potential sequences were evaluated:

- Coupling the regional train behind the IC in the direction of travel;
- Coupling the regional train before the IC in the direction of travel.

Sequence 1 is technically simpler to implement, as it involves the trailing regional train passing the switch and starting its journey after the switch is set (Nold & Corman, 2021). This sequence minimizes the impact on IC train's travel time, providing passengers with the shortest in-vehicle travel times between cities 1 and 2.

Specifically, in this configuration the regional train waits on a side track at the final station within the agglomeration of city 1. Once the track vacancy detection system confirms that the IC train has cleared the switch, the route and switch are set for the regional train. The regional train then accelerates, catches up to, and couples with the IC train, allowing both to travel at high speeds toward city 2. This approach is feasible because Regional trains used in such scenarios typically have strong dynamic performance, as they are designed for frequent stops, and their standardized maximum speeds are often comparable to those of IC services.

Shortly before the first station of the agglomeration 2, the regional train decouples from the IC to stop at the next station, from where the trains will have an absolute braking distance once approaching the diverging switch. Since the IC remains on its track, its speed is unaffected and therefore optimized travel times for the IC.

Additionally, Nold & Corman (2021) suggested that operations under sequence 1 can even be further optimized with the use of a trailable switch at the converging point K1 (see Figure 6-c). With the use of a trailable swith, the regional train can pass (or force) the switch into the right direction. However, they argue that trailable swithes significantly reduce speed limits and therefore can only be applied in and around station areas. According to Maschek (2015), the speed of trailable switches is limited to 40 km/h due to the risk of excessive forces that could cause derailments at higher speeds.

Pan, Peng, Zhan, & Bai (2021) focused on station-related train-following maneuvers and analyzed two scenarios: "Two Trains Arriving at a Station" and "Two Stationary Trains Departing from the Station." The results revealed that that the reduction in headways are more pronounced in the train arrival case, with a 46% decrease, compared to a 36% reduction in the train departure case, suggesting that it is more favored to arrive virtually coupled (Pan, Peng, Zhan, & Bai, 2021).

Schumann (2017) acknowledge that virtual coupling of two merging train units “on-the-fly”, as proposed by Ning, et al. (2023), Quaglietta, Wang & Goverde (2020) and Nold & Corman (2021) can be challenging, because a decrease in speed of the leading train shortly before passing the switch could potentially lead to a side-on collision, necessitating the regulation of the second train's speed before the coupling procedure. Therefore, they argue that to avoid such safety risks, a trailable switch that can be safely traversed in any situation and state should be implemented around station areas. Additionally, Schumann (2017) propose that coupling should occur near stopping stations where speeds are lower, resulting in shorter braking distances and safer operations, or solely in stations at standstill. The latter is technical less difficult to implement and may already lead to significant line capacity benefits, as the main handicap of the mechanical coupling procedure are currently the long coupling times, resulting in large buffer times and negative effects on the overall travel time (Schumann, 2017).

**Service and station characteristics**
Aoun et al. (2020) proposed recommendations on service and station characteristics to ensure the safe operation of Virtual Coupling train services while enhancing the market appeal of each railway segment from both stakeholder and passenger perspectives. These recommendations were developed based on expert surveys and stated travel preference analyses under Virtual Coupling, supplemented by brainstorming sessions with European railway experts as part of the *MOVINGRAIL* framework (Aoun et al., 2020). The findings highlighted the following key operational service characteristics:

- Service headways between 7 and 20 minutes for a specific O-D pair and train category (IC or regional) are considered optimal for both stakeholders and passengers;
- Mainline trains should include a minimum of six carriages to ensure enough seating capacity;
- Given the frequencies and lengths, platforms will need to be dedicated to a certain group of destinations. Instead, platforms can allow for trains going to different destinations to stop at the same platform track when having low-frequent regional trains;
- Platforms will need to be extended and divided into distinct sections, which can be clearly marked with signage, physical barriers, or a combination of both;
- Platform doors will be required to ensure safety and efficiency in fully automated operations. Additionally, crew may be limited to platforms only.

**Timetable**
Nold & Corman (2021) focused on how timetables should be designed for Virtual Coupling operations. They analyzed three distinct network planning scenarios for connecting two major agglomerations, each with four intermediate suburban stations. In the depicted network configuration below, InterCity (IC) trains are denoted in pink, while regional trains, linking the smaller suburban stations, are represented in green and blue.

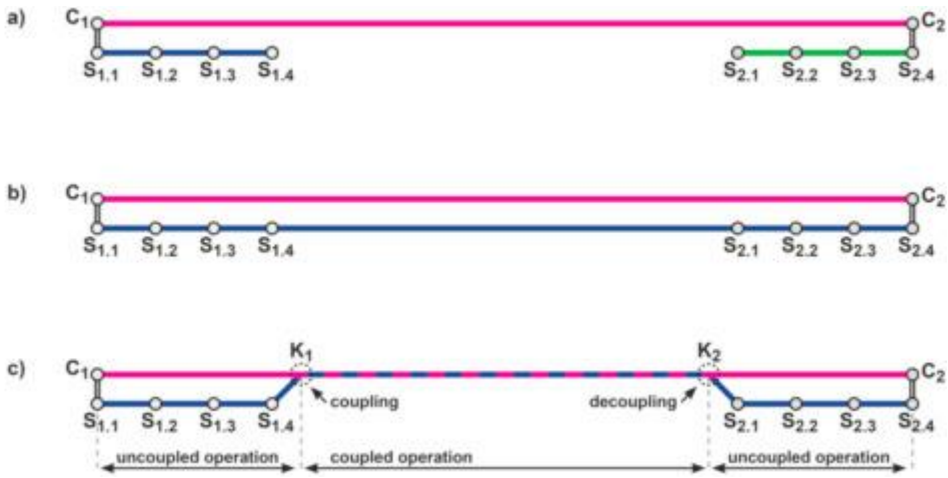


*Figure 6: Three scenarios for connecting two agglomeration station and eight suburban station (Nold & Corman, 2021)*

The concept illustrated in Figure 6-c was identified as the most favorable, as it allows linked commuter train networks to provide direct connections between major and minor stations without significantly impacting the line capacity between K1 and K2. Bart Sigger, a consulted expert from NS, acknowledged this benefits also, offering passengers more direct connections with longer distance trains (Sigger, 2024).

Chai S., Yin, Tang, D'Ariano, & Samà (2023) proposed another planning configuration. They analyzed train scheduling and rolling stock circulations for virtual coupling scenarios in metro networks and proposed a network in which each corridor is is divided in smaller line sections. The vehicle units are pre-allocated across different depots at the start and end of each line where vehicle units can be virtually (de)coupled. Consequenlly, the platooning length might be flexibly adapted based on the demand of a line. Various other studies used a comparable approach, allowing rolling stock to change compositions via (de)coupling operations at both ends of the rail transit line Wang, et al. (2018), Zhou, et al. (2022) and Pan, Yang, & Liang (2023).

Ning et al. (2023) highlight that hybrid cyclic timetables, which combine the regularity of cyclic timetables with the flexibility of non-cyclic schedules, allows trains to deviate within specified departure time windows, enhancing the adaptability of VC. Hybrid cyclic timetables retain the accessibility and predictable service patterns of cyclic timetables, which are easy for passengers to remember, while also accommodating fluctuations in passenger demand, a strength typically associated with non-cyclic timetables (Robenek, Azadeh, Maknoon, & Bierlaire, 2017). This balance improves both operational flexibility and passenger convenience.

## *Automated People Mover*

The Automated People Mover (APM) is defined in the APM Standards as a system of automated vehicles configured with APM systems range from "ride-hailing" AV services to shared public vehicles with a capacity up to 25 passengers (Lott, Young, Duvall, & Henao, 2022). A APM for secondary railways was proposed by Sebron, Gol-Hashem, Krebs, & Tschürtz (2021). They argued that the primary challenge of implementing such a specialized system is in single-track scenarios, where multiple autonomous railcars operate on-demand within a 24/7 service framework. Managing efficient and safe operations under these conditions requires innovative solutions to ensure smooth coordination and minimize delays on limited infrastructure (Sebron, Gol-Hashem, Krebs, & Tschürtz, 2021).

Lott, Young, Duvall, & Henao (2022) explored various station configurations for APM-systems. They proposed a Serial Berth Station Configuration and Parallel Berth Station Configuration as depicted in the Figure below.

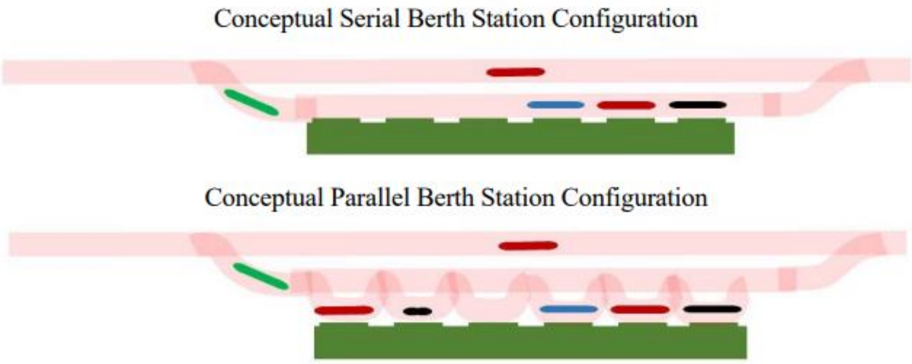



*Figure 7: Comparison of station serial berth and parallel berth configurations (Lott, Young, Duvall, & Henao, 2022)*

At the moment, most station layouts are comparable with the Serial Berth Station Configuration. However, Lott, Young, Duvall, & Henao (2022) argue that despite the bigger footprint, the Parallel Berth Station Configuration can provide many benefits related to the flexibility and capacity of the system. In the Parallel Berth Station Configuration, vehicles have the ability to enter a station lane, navigate directly to an available berth, and dock independently. This configuration eliminates the need for other vehicles to queue, allowing for seamless operations and reducing delays.

Although there are some current implementations know for APM systems, such as the ParkShuttle operating between Kralingse Zoom in Rotterdam and Rivium in Capelle a/d Ijssel, no further applicable results were found for implementing virtual coupling (VC) technology in railway operations, as these systems typically serve specific urban and airport contexts, where demand and operational models differ significantly from the needs of high-capacity, frequent railway services.

## *Summary of findings*

The table below shows the main findings from each of the considered modes in the previous subsections. As the literature review is mainly used for the deviation of an operational transport concept applicable for main-line railway corridors, the main findings are particularly concentrated on operational characteristics, including stopping patterns, timetables, station usage, network layout, and operational maneuvers.

*Table 5: Summary of main findings literature review*

| **Transport mode** | **Operational characteristic** | **Main findings** |
|---|---|---|
| **Bus** | Stopping pattern | Studies by (Ginn, et al., 2017) (Nguyen, et al., 2019) (Zhang, Ge, Tang, & Zhong, 2024) propose skip-stop pattern while maintaining regular pattern, while (Cao & Ceder, 2019) (Ji, Liu, Shen, & Du, 2020) (Tian, Lin, Wang, & Liu, 2022) propose fully on-demand. Skip-stop pattern may increase efficiency (Zhang, Ge, Tang, & Zhong, 2024). By allowing to drive in platoons, "indirect – direct" trips are provided to the passengers, in which a traveler do not need to wait for the next module to arrive since it is already a part of the platoon (Raua, et al., 2019). |
| | Timetable | Schedules are synchronized beforehand to allow the vehicles to create platoons (Ginn, et al., 2017). A constant frequency to enhance a reliable and regular service is favored (Tian, Lin, Wang, & Liu, 2022). |
| | Shunting | Passengers are permitted to board modular units while they are still separate from the main modular vehicle at the station. Simultaneously, alighting passengers are directed to designated modular units in preparation for their detachment from the main vehicle (Tian, Lin, Wang, & Liu, 2022). |
| | Manoeuvres | (De)coupling both at stations and on-the-fly (Ginn, et al., 2017) (Zhang, Ge, Tang, & Zhong, 2024). |
| **Hyperloop** | Stopping pattern | Full-stop or point-to-point pattern (Hardt Hyperloop, 2023). |
| | Timetable | On-demand (Eichelberger, Geiter, Schmid, & Wattenhofer, 2020) (Pawlik, Kycko, & Zakrzewski, 2021). Departure is initiated once the departure bin reaches its capacity (Eichelberger, Geiter, Schmid, & Wattenhofer, 2020). Amount of pods could be dynamically adjusted to real-time demand (Pawlik, Kycko, & Zakrzewski, 2021). |
| | Shunting | Network consist of mainline and branch lines. Pods are always available near or at a stations. Pods are symmetricly distributed by dispatching a pod from B → A whenever one departs from A → B. (Eichelberger, Geiter, Schmid, & Wattenhofer, 2020). |
| | Manoeuvres | (De)coupling mainly "on-the-fly" to form hypertrains (Pawlik, Kycko, & Zakrzewski, 2021) |
| **Trucks** | Stopping pattern | Research proposed methods for decoupling trucks at each customer node and on the way back pulling back all uncoupled trucks (Liatsos, Golias, Hourdos, & Mishra, 2024). Alternatively, stop at each customer node (Xue, Lin, & You, 2021). |
| | Timetable | Research reveals that real-time and opportunistic planning might cause delays, while scheduled platooning can enhance more efficient operations (Zhang, Jenelius, & Ma, 2017) (Noruzoliaee, Zou, & Zhou, 2021). Platooning preferably not on converging routes, as this leads to increased schedule mismatches and increased driving costs compared to diverging routes (Zhang, Jenelius, & Ma, 2017). |
| | Shunting | Special (de)coupling locations are predefined where trucks shunt, in which trucks might also not form a platoon (Liatsos, Golias, Hourdos, & Mishra, 2024) |
| | Manoeuvres | Results tend to recommend for (de)coupling at nodes (Xue, Lin, & You, 2021) (Liatsos, Golias, Hourdos, & Mishra, 2024), although also |

| | | |
|---|---|---|
| | | acknowledge that on-the-fly platooning will lead to more efficiency (Larsen, Rich, & Rasmussen, 2019). Truck drivers are stationed at decoupling nodes to individually operate the trucks to their designated destinations (Liatsos, Golias, Hourdos, & Mishra, 2024). |
| **(Light)rail** | Stopping pattern | Most studies analysed full-stopping patterns (Quaglietta, Wang, & Goverde, 2020) (Nold & Corman, 2021), only some studies suggest implementing a skip-stop pattern (Wu, Chunhai, & Tao, 2021) (Chai S. , Yin, D'ariano, Samà, & Tang, 2023) (Chai S. , et al., 2024). |
| | Timetable | Most studies recommend fixed or alternatively hybrid timetable,. Frequency of 7-20 minutes (Aoun, et al., 2020). Current main-line operations (mixed regional and IC stop pattern) rarely studied. Combination of IC and RE trains favoured, as this enables direct connections between major and minor station without major effects on the line capacity (Nold & Corman, 2021) (Sigger, 2024) . Operations either performed by a Hybrid or fixed cyclic timetable (Robenek, Azadeh, Maknoon, & Bierlaire, 2017) (Ning, et al., 2023). |
| | Shunting | Platforms preferably need to be dedicated to a certain group of destinations, segregated into sections (Aoun, et al., 2020). Additionally, because of the limited amount of space, trains are not allowed to shunt at a platform (Aoun, et al., 2020). |
| | Manoeuvres | (De)coupling either on still-stand or "on-the-fly" (Quaglietta, Wang, & Goverde, 2020) (Nold & Corman, 2021) (Ning, et al., 2023), around stations or around junctions (Schumann, 2017). Although literature tend to recommend around stations, (de)coupling at junctions can also provide benefits. IC should preferably precede regional train (Nold & Corman, 2021). Since trains frequently operate at maximum track speeds, platooning coordination should involve the leader train accelerating to its cruising speed while the following trains maintain a constant speed and delay their acceleration to synchronize for coupling (Ning, et al., 2023). VC tend to provide most benefits for stopping trains having different routes (Quaglietta, Wang, & Goverde, 2020). (De)coupling on the fly is found to be more challenging, because a decrease in speed of the leading for merging junction train shortly before passing the switch could potentially lead to a side-on collision (Schumann, 2017). Therefore, Virtual Coupling could also be solely applied in stations, in which it could already provide significant capacity benefits due to decreased buffer times. |
| **Automated People Mover** | Stopping pattern | On-demand direct O-D connections (Sebron, Gol-Hashem, Krebs, & Tschürtz, 2021) |
| | Timetable | No notable results were found on timetables |
| | Shunting | The Parallel Berth Station Configuration allows vehicles to independently enter a station lane, maneuver to an available berth, and dock without requiring other vehicles to move or be dispatched beforehand (Lott, Young, Duvall, & Henao, 2022) |
| | Manoeuvres | (De)coupling mainly "on-the-fly" (Sebron, Gol-Hashem, Krebs, & Tschürtz, 2021) |

## 3.2 Objectives

A set of 8 objectives was established based on key findings from the literature and insights from interviews with experts at ProRail, NS, and the ERTMS Program Directorate:

O.1. The concept should provide a reliable service as much as possible
O.2. The concept should minimize the generalized travel times
O.3. The concept should minimize the infrastructure occupancy
O.4. The concept should maximize user-friendliness

O.5. The concept should minimize the amount of required rolling stock
O.6. The concept should minimize rolling stock circulation complexity
O.7. As for the convenience of passengers, trains should preferably stop simultaneously to allow travelers to transfer to other directions within the same platoon.
O.8. The concept should minimize shunting at stations, as this affects station capacity and throughput

Key points from interviews with NS, which informed objectives 1 to 5, emphasized the importance of a reliable and user-friendly service. Current operations clearly distinguish regional and intercity services, effectively meeting high demand from and to major and lower demand streams between regional stations, which should preferably be preserved. Additionally, NS highlighted the need for rolling stock circulation that is not overly complex and closely resembles current operations. This approach would facilitate the use of existing rolling stock, allowing for a smoother implementation and testing phase during regular operations. This perspective was also strongly supported by experts from the PD ERTMS. From the viewpoint of the main infrastructure manager, minimizing infrastructure occupancy was highlighted as a key objective (objective 6). The final two objectives (objectives 7 and 8) were derived from the literature review.

## 3.3 Design aspects

From the analysis as performed in Section 3.1, a couple design aspects, along with possible implementations which are later used as building blocks, can already be extracted:

1. **Different Stopping Plans**: Different stopping plans are identified, such as point-to-point, full-stopping patterns, skip-stop patterns, and conventional IC-RE pattern.
2. **(De)coupling Locations**: (De)coupling of train units is found to occur at various locations, including at stations, dedicated points along the route, or "on-the-fly".
3. **(De)coupling Sequences**: When accounting for heterogeneous vehicles, a intercity train could decouple before slower regional service or vice versa. When having homogeneous trains, (de)couple sequence does not matter.
4. **Shunting**: Deport locations could be positioned near or within stations to ensure flexible operations. However, limited space in and around stations makes it challenging to place depots in optimal locations for efficient operations, and therefore could also take place at shunting areas.
5. **Timetable Models**: Different timetable modes were identified. Transport modes like hyperloops and APM systems tend to implement on-demand timetables. However, railways and buses generally favor fixed or hybrid timetables, particularly in virtual coupling operations. Additionally, in on-demand systems, various dispatching methods help ensure efficient use of rolling stock and improve user experience by optimizing scheduling and resource allocation.
6. **Route:** Platoons can be formed with non-stopping trains having the same route, non-stopping trains having different routes, stopping trains having the same route, stopping trains having different routes
7. **Station lay-out**: A possible station configuration could be Parallel Berth, where multiple trains operate efficiently within the same station. Another configuration enables passengers to egress at a different location, such that boarding and alighting is smoother. Lastly, platforms can be stretched, enabling platoons to stop simultaneously, such that passengers can transfer to other directions within the same platoon.

To test and further refine these design aspects, a main user story was developed (see Figure 8) to illustrate an operational scenario in which a train connects two stations. In total, 5 different stages were obtained from the user story, being the arrival/depart from the deport, the train arrival at a station, the stop at a station, the train departure at a station, and the ride between to the next station or a junction. Note that a direct arrow is drawn between depot and station, because the depot could also be located within a station.

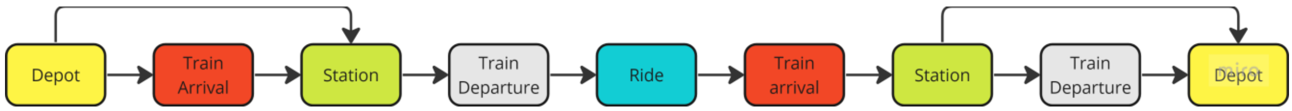



*Figure 8: Main user story for a virtual coupling operational scenario*

For each stage, the design aspects are matched with the associated stage and supplemented based on own insights. Table 6 illustrates an overview of all obtained design aspects.

*Table 6: Design aspects for a virtual coupling operational scenario*

| Depot | Train Arrival | Station | Train Departure | Ride |
|---|---|---|---|---|
| (De)coupling sequence<br>Shunting<br>(De)coupling points | (De)coupling sequence<br>(De)coupling points<br>Platooning | (De)coupling sequence<br>Platooning<br>Timetable<br>Shunting<br>~~Station lay-out~~ | (De)coupling sequence<br>(De)coupling points<br>Platooning | (De)coupling sequence<br>(De)couple points<br>Platooning<br>Route<br>Stopping pattern |

The station layout was excluded from consideration, as it falls outside the scope of this research. Additionally, as shown in Table 6, one design aspect was added: **platooning**. Definitions for this newly added design aspect, along with definitions for the previously identified aspects, are as follows:

- **Shunting**: Refers to the location where train units perform shunting operations. Note that the scope of this research limits trains to only shunt at existing infrastructure, i.e. at stations or depots.
- **Route**: Specifies the destination a unit follows throughout its journey.
- **Timetable**: Specifies the scheduling model followed by the units, such as on-demand, fixed, or regular patterns.
- **Stopping pattern**: Describes the sequence of stations at which a unit stops during its route.
- **(De)coupling sequence**: The order in which units with different service patterns (e.g., stopping or direct services) couple or decouple.
- **(De)coupling points**: The specific locations along the track where units (de)couple. Note that this also influences station and network utilization.
- **Platooning**: The ways in which platoons can be formed, such as reuniting with initial coupled units or coupling with other units.

## 3.4 Operational concepts

Most of building blocks associated with each design aspect were already extracted in Section 3.3. For the two newly added design aspects, building blocks are compiled with own insights. These building blocks can be found in the columns, while the design aspects can be found in the rows.

*Table 7: Morphological chart containing design categories and building blocks*

| Design categories | Building blocks | | | | | |
|---|---|---|---|---|---|---|
| **Stopping patterns** | Skipping units only | Direct units only (point-to-point) | Stopping units only | Skipping and stopping units | Skipping and direct units | Direct and stopping units |
| | Skipping, stopping and direct units | | | | | |
| **Timetable** | On-demand, no threshold | On-demand, bin threshold | Regular pattern | Fixed timetable | | |
| **Platooning** | Units original platoon preserved | Units are exchangend coordinated along platoons | Platoons are formed randomly | | | |
| **Routes** | Trains share same destination, both during ride and stop | Trains share same destination group, both during ride and stop | Trains from/to different destination groups, only during ride | Trains from/to different destination groups, both during ride and stop | Trains from/to different routes, only during ride | Trains from different routes, both during ride and stop |
| **Shunting** | Shunt in stations | Shunt at depots | | | | |
| **Coupling points** | Coupling at standstill | Coupling at departure | Coupling at open track | Coupling at arrival | | |
| **Decoupling points** | Decoupling at standstill | Decoupling at departure | Decoupling at open track | Decoupling at arrival | | |
| **Coupling sequences** | Stopping unit couples before through unit | Stopping couples after through unit | | | | |
| **Decoupling sequences** | Stopping unit decouples before through unit | Stopping decouples after through unit | Stopping unit decouples in between through units | | | |

Since this study focuses on analyzing an operational concept in a single direction, all trains are assumed to share the same destination group. As a result, the design category “route” is omitted as a potential distinguishing factor. Additionally, the exact points and sequences for coupling and decoupling are shaped by the stopping patterns and timetable followed by trains within this operational model. Consequently, these categories have also been excluded from the morphological chart.

The operational concepts are developed based on the remaining four design categories: stopping patterns, timetable, platooning, and shunting. By randomly combining the building blocks within each of these design categories, a total of four operational concepts are obtained:

1. **Conventional pattern preserving full-stopping regional services**: This concept operates on a regular or fixed timetable, alternating IC-trains (serving only major station) and full-stopping trains (serving all regional and major stations). Additionally, a skip-stop service (skipping some regional stations while still serving all major stations) is added to create extra capacity and more direct connections from regional towards major stations. The full-stopping and skip-stop trains are allowed to virtually couple and enclosed by IC-trains. Since these regional trains are enclosed by IC-trains, the platoon structure is maintained throughout the journey and reunited at each major station.. Maintaining a more conventional pattern allows trains to operate over longer corridors within this concept, enabling shunting to occur at existing shunting facilities.

2. **Conventional pattern introducing skip-stop regional services:** Similar to the first concept, this approach follows a regular or fixed timetable, alternating IC trains with skip-stop trains. Consequently, regional stations are no longer directly connected. However, train units reunite with their initially coupled units, preserving the platoon structure. Since the skip-stop trains are enclosed by IC trains, the platoon formation remains intact throughout the journey. By maintaining a more conventional pattern, this concept again enables trains to operate over longer corridors, allowing shunting to occur at existing shunting facilities.
3. **Skip-stop pattern without IC-trains**: This concept removes IC trains from the configuration in Concept 2, resulting in operations exclusively with skip-stop trains. Although it still follows a regular or fixed timetable, major stations are no longer directly connected. All train units in this concept are homogeneous, allowing them to couple flexibly with other units along the route, which supports both random and coordinated platoon formations and enables more flexible scheduling. Operations can still be planned over longer corridors, allowing shunting to occur at dedicated depots. However, accommodating high-demand flows between major stations may require additional trains within this concept.
4. **Point-to-point pattern with only direct connections:** This concept replaces operations on longer corridors with a point-to-point pattern, differing from conventional patterns by focusing on direct connections between specific origin-destination pairs rather than continuous routes. Operations follow an on-demand timetable, with train units running exclusively between designated origin-destination pairs. Train platooning is entirely flexible, allowing units to couple and decouple as needed, without a fixed structure, to efficiently meet varying demand. Shunting will need to take place at stations to minimize response times and ensure timely operations.

These operational concepts may include multiple building blocks from the same design category, reflecting potential variations within each concept. While other operational concepts could be developed from the morphological chart, the four outlined here are identified as the most distinct and relevant for further analysis due to their contrasting characteristics.

## 3.5 SWOT-analysis

To gain a deeper insight in the effectiveness of each operational concept towards the obtained objectives, SWOT analysis are conducted, highlighting each concept's strengths, operational challenges specific to VC, opportunities for VC integration, and (external) threats that could affect feasibility. The SWOT analysis evaluates each concept within a standardized mainline configuration featuring two major stations (M1 and M2) and two intermediate regional stations (R1 and R2), see Figure 9.


*Figure 9: Theoretical configuration used for SWOT-analysis*

Below, strengths, weaknesses, opportunities, and threats of each concept are obtained by applying qualitatively each concept to this standard configuration.

### *Concept 1: Conventional pattern preserving full-stopping regional services*

In a conventional patten, intercity (IC) trains are alternated with stopping (regional) trains. The IC trains typically serve as the  backbone of the network, connecting major cities directly with non- or limiting amount of stops. Regional trains (RE), on the other hand, complement the IC service by serving smaller towns, suburban areas, and intermediate stations along the route. By alternating IC's and RE's, major stations serve as interchanging points, where passengers can transfer between IC and RE trains, facilitating travel across different regions and catering to various travel needs.

Within this concept, one IC-train is alternated with two regional trains. The latter trains are homogeneous and therefore can virtually couple and decouple. Since this concept requires planned (de)coupling points, a good planning and coordination of train units is necessary to enhance a reliable service (Objective O.1.). Therefore, trains will have to follow a fixed or regular timetable within this concept. A potential variation of this concept when applicated on the section Almere centrum → Weesp is shown in Figure 10.

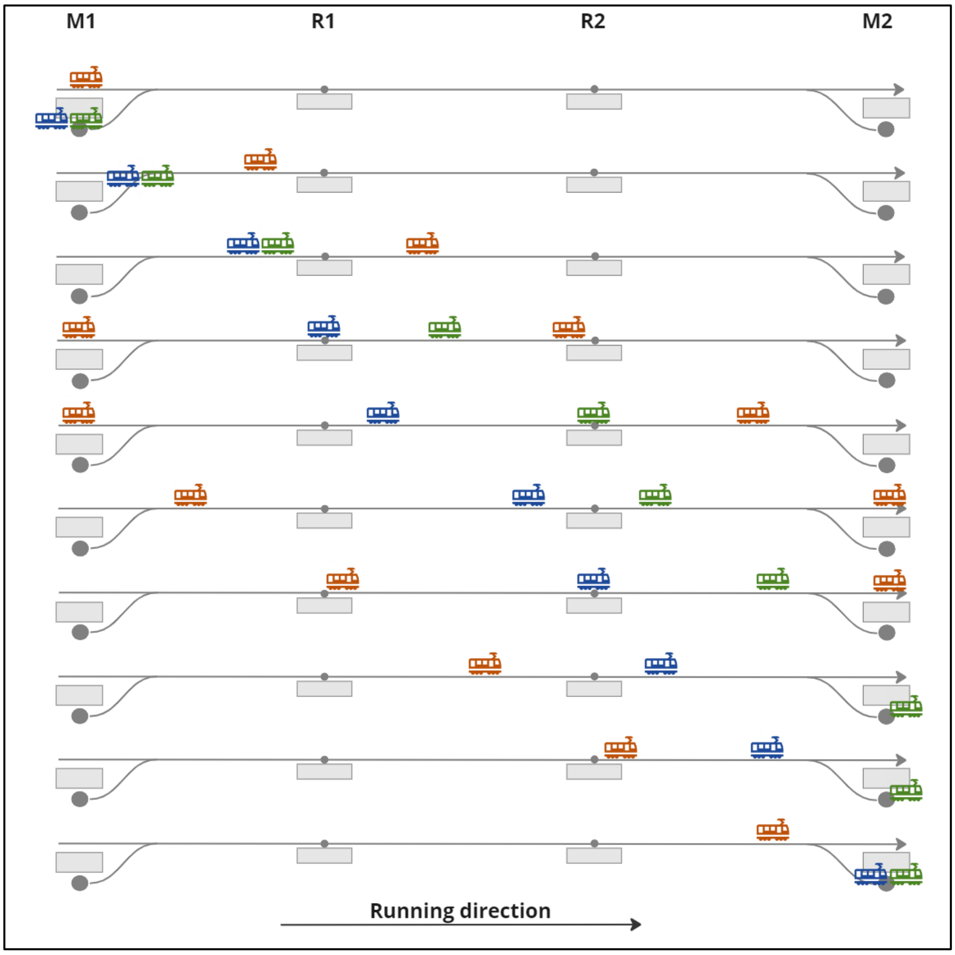



*Figure 10: Visualization of a Conventional pattern preserving full-stopping regional services*

In this variant of the concept, the IC-train (orange) departs from station M1 and runs directly to M2 without intermediate stops. The green and blue trains function both as regional services, with the green train functioning as a skip-stop service, stopping only at R2, and the blue train serving as a full stopping train, stopping at both R1 and R2.

Specifically, both regional trains depart simultaneously from M1. At R1, the blue train decouples from the green train to stop at the station, while the green train runs straight to R2, where it makes a scheduled stop. After stopping at R1, the blue train proceeds to R2, making another stop, before continuing to M2 to again reunite with the green train. After the blue train has cleared the track, the next IC train departs from Almere Centrum. In this configuration, the blue and green train units "virtually couple" between Almere Centrum and Almere Muziekwijk and again when stationary at Weesp. Importantly, the original train sequence (IC-RE-RE-IC) remains unchanged upon arrival at Weesp. Additionally, if routes diverge beyond Weesp, decoupling can be done either while stationary or "on-the-fly," reducing technical complexity.

Table 8 outlines all strengths, weaknesses, opportunities, and threats, providing deeper understanding into the feasibility of this concept.

*Table 8: SWOT-analysis on a Conventional pattern preserving full-stopping regional services*

| **Strengths** | **Opportunities** |
|---|---|
| • Provides a non-stopping connection between stations M1 and M2<br>• Provides a direct connection between each regional station<br>• Clear concept for passengers, since concept is comparable to traditional IC / RE service<br>• Requires comparable amount of rolling stock as compared to current services<br>• Skip-stop train increases capacity and reduces travel times for high-demand OD-pairs, improving overall network efficiency<br>• The concept maintains the original train sequence (IC-RE-RE-IC), ensuring minimal disruption to the established timetable and passenger expectations.<br>• Since this pattern allows trains to serve longer lines, shunting can take place at depot locations, enhancing higher station capacities<br>• In line with literature, this specific variant only requires "on-the-fly" decoupling, which requires less advanced timing and coordination issues | • When a platoon simultaneously stops at one platforms, a passenger can easily transfer to the another carriage corresponding to his/her desired destination within a platoon<br>• In line with literature, this specific variant only requires "on-the-fly" decoupling, which can enhance a faster implementation<br>• Depending on the frequency, passengers may transfer at M2 to another train to reach the desired destination faster, potentially improving customer satisfaction.<br>• In line with literature, it enables the possibility to depart synchronously, which again enhances greater line capacity after M2.<br>• In line with literature, skip-stop can be coupled before full-stopping train for optimal line-throughput<br>• In line with literature, platforms could be segregated into designated sections, reducing potential confusion for passengers.<br>• In line with literature, skipping train could be planned before non-skipping train |
| **Weaknesses** | **Threats** |
| • The preceding train will have to wait at M2 until the rest of the platoon have caught up, this can become extensively long as the amount of stops between major stations M1 and M2 increase<br>• Still long travel times for stations only served by the full stopping train<br>• Lower line capacity because trains have more stops<br>• Passengers at stations served by skip-stop and full stopping trains may find the concept confusing, since the services differ in stopping patterns.<br>• Success relies heavily on the synchronization of trains at key stations. Any delays in one train could affect the operation of both, leading to a ripple effect of delays across the network.<br>• Coupling options are limited | • Since the preceding train will have to wait until the rest of the platoon have caught up, this can cause a decrease in passenger satisfaction and increment of generalized travel time, potentially causing a negative modal shift<br>• The blue train, functioning as a full stopping service, still occupies valuable track space, restricting overall line capacity and consequently potentially limiting service frequency. |

## *Concept 2: Conventional pattern introducing skip-stop regional services*

In this operational concept, a conventional patten is again preserved in which one intercity (IC) train is alternated with two regional trains (RE). The IC trains again connect major cities directly with non-stopping services, whereas the RE-trains serve regional stations. The two regional trains perform a skip-stop pattern, in which each train at least skips one regional station. Note that since conventional pattern is preserved, the regional train still stops at each major station. Since such a pattern requires planned (de)coupling points, a good planning and coordination of train units is necessary to enhance a reliable service (Objective O1). Therefore, trains will have to follow a fixed timetable within this concept. A potential variation of this concept when applicated on the section Almere centrum → Weesp is shown Figure 11.

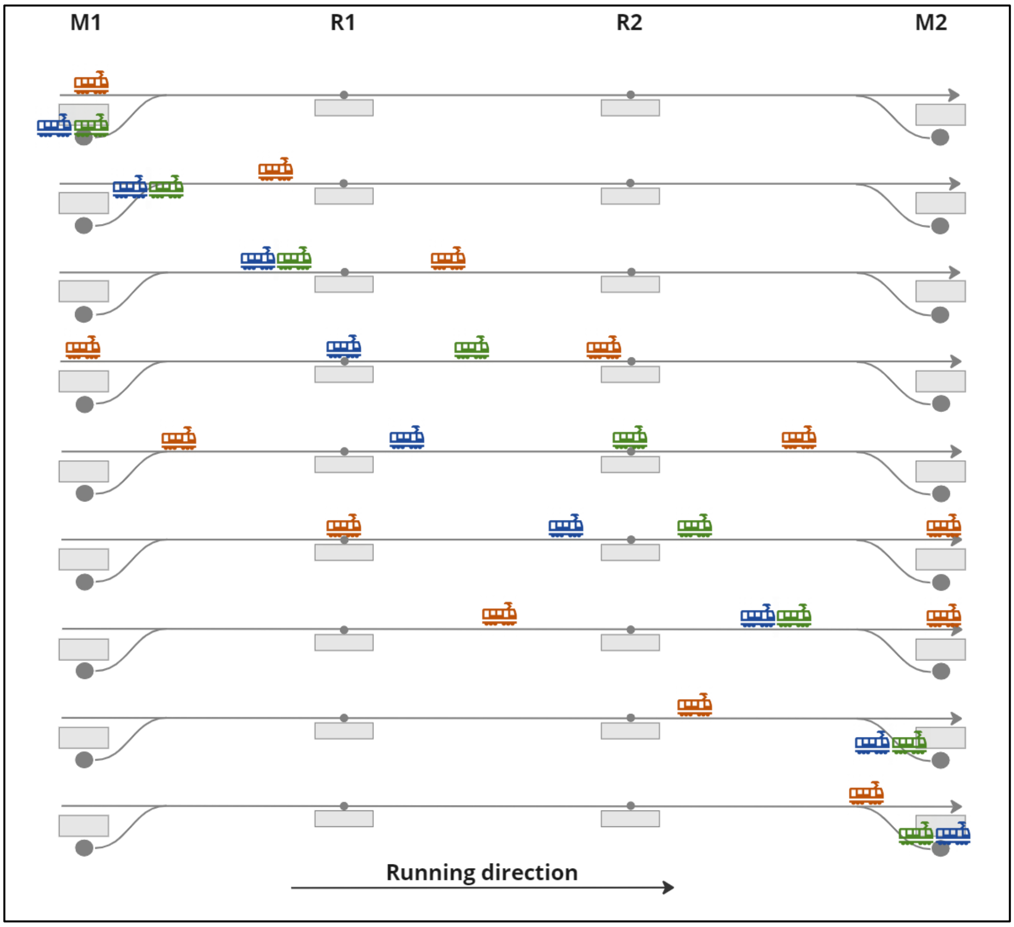


*Figure 11: Visualization of a Conventional pattern introducing skip-stop regional services*

In this variant, the direct IC train (orange) departs from station M1 and runs directly to M2. The green and blue regional trains, both operating as skip-stop services, depart simultaneously from M1. At station R1, the blue train decouples to make a stop, while the green train continues directly to R2, where it makes its scheduled stop. After completing its stop at R1, the blue train proceeds to R2, where it will virtually couple with the green train "on-the-fly". Both trains then continue to M2 in a virtually coupled formation.

Following the regional trains, another direct IC train departs from M1. In this configuration, the blue and green trains virtual couple between M1 and R1 and again between R2 and M2, requiring precise coordination for smooth operation. Notably, the original train sequence (IC-RE-RE-IC) at M1 is again maintained upon arrival at M2.

The SWOT-analysis in Table 9 summarizes strengths, opportunities, weaknesses and threats of this concept.

*Table 9: SWOT-analysis of a Conventional pattern introducing skip-stop regional services*

| Strengths | Opportunities |
| --- | --- |
| • Provides a non-stopping connection between stations M1 and M2<br>• Initial platoon are reunited at next major station<br>• Since the blue and green unit reunite before entering M2, the preceding train will not have to wait until the rest of the platoon have caught up<br>• Requires comparable amount of rolling stock as compared to current services<br>• By skipping certain stations, travel times for high-demand origin-destination pairs are reduced, enhancing overall network efficiency and better serving long-haul passengers with faster journeys to key destinations.<br>• Skipping stations increases line capacity by reducing the number of stops, allowing for more efficient use of track infrastructure as compared to concept 1.<br>• The concept maintains the original train sequence (IC-RE-RE-IC), ensuring minimal disruption to the established timetable and passenger expectations.<br>• Since this pattern allows trains to serve longer lines, shunting can take place at depot locations, enhancing higher station capacities | • In line with literature, when a platoon simultaneously stops at one platforms, a passenger can easily transfer to the another carriage corresponding to his/her desired destination within a platoon<br>• Depending on the frequency, passengers may transfer at M2 to another train to reach the desired destination faster, potentially improving customer satisfaction.<br>• Since platoons are reunited, it enables the possibility to depart synchronously, which again enhances greater line capacity beyond M2<br>• By reducing travel times and providing more efficient services, this concept has the potential to improve the passenger experience, especially for those traveling longer distances.<br>• In line with literature, platforms could be segregated into designated sections, reducing potential confusion for passengers.<br>• In line with literature, skipping train could be planned before non-skipping train |
| **Weaknesses** | **Threats** |
| • No direct connection between (low-demand) regional stations R1 and R2, passengers will need to transfer<br>• The virtual coupling and decoupling of the green and blue trains at multiple points along the route require more precise timing and coordination. In line with literature, this could cause delays and operational challenges, risking disruptions and reliability issues.<br>• Passengers might find it confusing to navigate two skip-stop services operating on the same route, especially if they are not familiar with which train stops at which station.<br>• The skip-stop pattern is most effective when there is an even number of stations, as this allows for a balanced distribution of stops between the two services. With an even number of stations, the benefits of introducing a skip-stop pattern could be diminished, as one train may need to stop at more stations than the other, leading to unbalanced travel times and reduced efficiency.<br>• Coupling options are limited | • (de)Coupling "on-the-fly" requires advanced techniques<br>• Since passengers traveling between R1 and R2 will need to transfer, this can cause a modal shift towards other modes for the regional market<br>• There is a risk of passenger dissatisfaction, particularly if passengers are unsure which train will stop at their destination. |

### *Concept 3: Skip-stop pattern without direct trains*

In this concept, the current service is redesigned to operate exclusively homogeneous train units, eliminating the distinction between IC and RE trains. All services still follow a fixed pattern, with trains running as skip-stop services based on demand streams. This allows for more flexible operations where trains adjust stopping patterns to cater to the varying passenger flows between different stations. For instance, trains can skip lower-demand stations while still ensuring direct connections between major stations, improving travel times for longer trips without needing dedicated express trains. A key feature of this system is the ability for trains to virtually couple with each other train, creating a more flexible system and enhancing the features of virtual coupling.

An alternative variant of this concept would be to eliminate direct services entirely, with all trains stopping at each station. While this variant sacrifices the faster journeys between major stations, it offers a more uniform and predictable service across the network, ensuring that all passengers, regardless of their origin or destination, experience a consistent level of service. This approach maximizes accessibility, similar to the operation of metro systems in urban areas, where frequent stopping is a core feature. The SWOT-analysis in Table 10 summarizes strengths, opportunities, weaknesses and threats of this concept.

*Table 10: SWOT-analysis of a Skip-stop pattern without direct trains*

| **Strengths** | **Opportunities** |
|---|---|
| • By operating homogeneous units, the system allows for more flexible skip-stop patterns that can be better optimized to demand streams, offering faster travel times for passengers traveling between high-demand stations.<br>• More options to virtual couple with other trains can enhance network efficiency<br>• The use of a single type of train unit reduces operational complexity, as there are no distinctions between intercity and regional trains. This could lower maintenance costs and simplify scheduling.<br>• In the variant where all trains stop at each station, passengers benefit from consistent service, ensuring that all stations are regularly served, much like a metro system, improving accessibility for all passengers regardless of station size.<br>• According to literature, this concept works well in metro-like environments with a high density of stops, where it enhances frequent services and more flexible operations, particularly for growing city suburbs or high-density regions. | • This concept offers a modernized approach to rail travel by adopting flexible, metro-like operations on main-line services, which could appeal to growing urban corridors or areas with increasingly dense populations.<br>• Operating homogeneous units across the entire network could reduce headways when implementing MB or VC (Knutsen, Olsson, & Fu, 2024)<br>• Might still provide a non-stopping connection between stations M1 and M2 |
| **Weaknesses** | **Threats** |
| • In line with literature, the elimination of IC trains and the focus on skip-stop services could negatively impact long-distance passengers, as travel times may increase without dedicated direct services.<br>• Skip-stop services based on demand streams may disadvantage passengers using lower-demand stations, leading to reduced service frequency and longer travel times for those passengers.<br>• With no dedicated IC-trains, high-demand routes between major stations could face overcrowding if skip-stop services alone cannot adequately handle the demand, especially during peak hours.<br>• Increment of technical and operational complexity, since this this concept now requires "on-the-fly" coupling and decoupling with more than 1 train.<br>• Introduces increased timetable complexity, as the train does not reassemble with its initial units<br>• Passengers may find it difficult to navigate the system, particularly if trains stop inconsistently at certain stations | • The exchange of units can increase complexity for planners and travelers, which may cause dissatisfaction or delays<br>• Main-line services spanning long distances are typically served by faster, direct trains with high capacities like IC double-deck services. Adopting a metro-like system with skip-stop services may lead to dissatisfaction among passengers traveling between cities, as it increases journey times<br>• Without dedicated IC-services, there is a risk that capacity on major routes could decrease, especially if the skip-stop services are not frequent enough to handle peak demand.<br>• Main-line rail infrastructure is typically designed for distinct types of services (express and local), and adapting it to a metro-like system could require significant changes or upgrades to accommodate the new operational structure, which may be costly and time-consuming. |

### *Concept 4: Point-to-point pattern with only direct connections*

A point-to-point train pattern refers to a system where trains operate directly between specific origin-destination (O-D) pairs without intermediate stops. Traditionally used for high-speed, long-distance routes—similar to how aviation links major airports—this service model can now be applied to shorter distances within the mainline rail market, due to the increased line capacity enabled by introducing VC. The primary advantage of this pattern is its efficient, direct connection, which minimizes travel time and maximizes convenience for passengers traveling between designated points.

In this concept, the existing service would be redesigned to operate with homogeneous train units, removing the distinction between IC and RE trains. High-demand O-D pairs can be served more frequently, while low-demand pairs would see less frequent service, optimizing the overall system. A notable feature is the ability for train units to virtually couple, allowing for greater flexibility and enhancing the potential benefits of VC technology.

Trains could follow either a fixed schedule or be dispatched based on real-time demand. The latter option introduces increased system complexity, as flexible circulation patterns may conflict with current railway safety regulations. Train units would couple and decouple occasionally, either around station areas, during stops, or on open track, similar to freeway merging.

Departures could be organized similarly to hyperloop systems, where a train departs once there is at least one request for a specific O-D pair or when a predetermined capacity threshold (e.g., 60%) is reached. Alternatively, a bin-threshold concept could be employed, where departures are based on a combination of the waiting time of the first passenger and the number of requests for that O-D pair.

The SWOT-analysis in Table 11 summarizes strengths, opportunities, weaknesses and threats of this concept.

*Table 11: SWOT-analysis of a Point-to-point pattern with only direct trains*

| **Strengths** | **Opportunities** |
|---|---|
| • Provides a direct non-stopping connection between each OD-pair minimizing in-vehicle times<br>• Adjusting service frequency based on demand means high-demand O-D pairs receive more frequent service, while low-demand pairs are served less often, improving operational efficiency and resource allocation.<br>• Flexibility that virtual coupling could provide is enhanced by a point-to-point pattern | • Can be combined with a fixed timetable in which high-demand OD-pairs have a fixed cycle and low-demand OD-pairs are on-demand<br>• The system could dynamically adjust to fluctuating passenger volumes, offering faster service where needed and reducing operational inefficiencies on less-traveled sections. |
| **Weaknesses** | **Threats** |
| • Managing a flexible system where trains are dispatched based on real-time demand increases operational complexity. Dynamic routing and scheduling might conflict with existing safety regulations and infrastructure limitations.<br>• Increment of technical and operational complexity, since this this concept now requires “on-the-fly” coupling and decoupling with more than one train.<br>• Passengers may find it difficult to navigate the system, particularly if trains stop inconsistently at certain stations<br>• Passengers traveling to or from regional stations could be underserved, as the point-to-point pattern eliminates intermediate stops, potentially causing inconvenience for these users.<br>• Depending on threshold, requires a lot of rolling stock. As a consequence, low-demand or long-haul routes may not be possible, causing the need for passengers to transfer<br>• Depending on threshold, waiting times at smaller regional stations may increase significantly<br>• Complex rolling stock circulation because of real-time requests increasing amount of routes<br>• Stopping trains may precede direct trains in junctions, which potentially could impact speed and line throughput<br>• Requires lot of depots close to stations (or in stations) for short response time<br>• As thins concept requires a higher line throughput to implemented effectively, significant infrastructure upgrades may be needed, particularly around station areas and technology for managing virtual coupling and flexible train dispatch. | • In line with literature, on-demand railway systems might lead to inefficient use of track space, which could potentially lower the total throughput of the rail line.<br>• May not be beneficial as trains may not operate at full capacity.<br>• Main-line rail infrastructure is typically designed for distinct types of services (express and local), and adapting it to a metro-like system could require significant changes or upgrades to accommodate the new operational structure, which may be costly and time-consuming.<br>• Smaller regional stations may receive significantly less service, potentially leading to dissatisfaction among passengers in these areas. |

# 4. Application

To test performance under real-world conditions, demonstrate relevance, and gain practical decision-making insights, each operational concept was applied to a real-word case study.

First, the case-study will be introduced, after which a selection of the defined concepts from Section 3 will be made by considering the depicted case study's infrastructure layout. For the selected concepts, running times, headways and frequencies are computed by applying different operational patterns.

## 4.1 State-of-the-art

The SAAL-corridor - specifically between Lelystad and Weesp in the direction towards Amsterdam during the morning rush hour - is depicted as case study because of its central position in the Netherlands, its growing demand and persistent stability problems (Ministerie van Infrastructuur en Waterstaat, 2022) (Programma Directie ERTMS, 2024).

The SAAL is one of the busiest rail corridors in the country, serving a vital connection between the densely populated Randstad area and the growing cities of Almere and Lelystad. It accommodates both commuter and long-distance train services, handling a high volume of passengers daily. The corridor is expected to transport between 69.650 and 76.900 travelers per day, reflecting its critical role in the Dutch transportation network (Ministerie van Infrastructuur en Waterstaat, 2022). Consequently, the SAAL corridor has undergone significant infrastructure upgrades in recent years, including the addition of tracks and improvements to stations. However, as notified in the 20th progress report for the implementation of ERTMS in the Netherlands, the SAAL-corridor still suffers from issues of track stability, passenger forecasts and timetable feasibility (Programma Directie ERTMS, 2024).

The decision was made to specifically focus on the section between Lelystad and Weesp, particularly in the direction toward Amsterdam during the morning rush hour, as this is where most capacity issues are expected. The current infrastructure lay-out between Lelystad and Weesp is illustrated in Figure 12 and Figure 13, including track speeds and stop locations for each station. Note that since the trains drive towards the west (towards Amsterdam), the direction of travel is from the right to the left. All regional stations are labelled with small dots and all major stations with large dots.

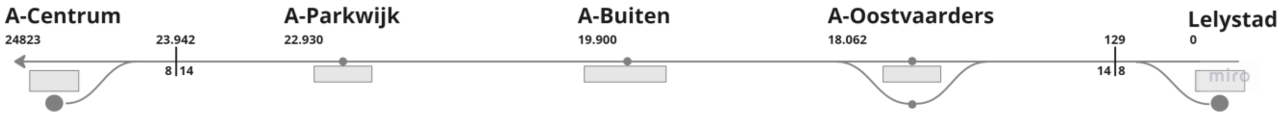



*Figure 12: Current infrastructure lay-out between Lelystad and Almere Centrum in the direction of Amsterdam*


*Figure 13: Current infrastructure lay-out between Almere Centrum and Weesp*

The platform lengths of each station are as follows:

- Lelystad: 340 meter
- Almere Oostvaarders: 276 meter
- Almere Buiten: 341 meter
- Almere Parkwijk: 278 meter
- Almere Centrum: 331 meter
- Almere Muziekwijk: 257 meter
- Almere Poort: 274 meter
- Weesp: 318 meter

For standardization purposes, the types of trains that operate on the SAAL-corridor are set to an ICNG with 8 carriages for IC-services and a SNG with 4 carriages for regional services. An overview of the characteristics of both train types can be found in Table 12.

*Table 12: Technical specifications SNG / ICNG*

| **Name** | **SNG** | **ICNG** |
|---|---|---|
| **Series** | 4 carriages | 8 carriages |
| $v_{max}$ | 160 km/h | 200 km/h |
| **Length / unit** | 75.7 m | 164 m |
| $b_{operational}$ | -0.8 m/s^2 | -0.66 m/s^2 |
| $b_{emergency}$ | -1.0 m/s^2 | -1.0 m/s^2 |
| **Empty mass** | 128,383 kg | 282,375 kg |
| **Nominal load** | 14,210 kg | 31,010 kg |
| **Rotating mass factor** $\rho$ | 6.74 % | 4.82 % |
| **Tractive effort** | 132 kN | 266 kN |
| **Roling resistance** | 0.00522 N/kg + 7.005 N/(m/s) + 1.1244 N/(m/s)^2 | 0.00282 N/kg + 84.61 N/(m/s) |
| **Air resistance** | 4.6008 N/(m/s)^2 | 1.6446 N/(m/s)^2 |

Using these specifications and the equilibrium of forces acting on a moving train, acceleration and deceleration rates are computed at a one second interval. The consequent acceleration curves of each train can be found in Figure 14 and Figure 15.

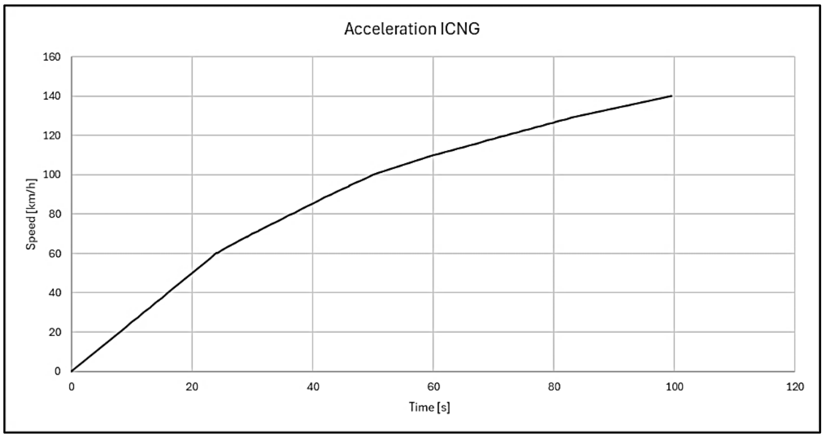



*Figure 14: Acceleration curve ICNG*

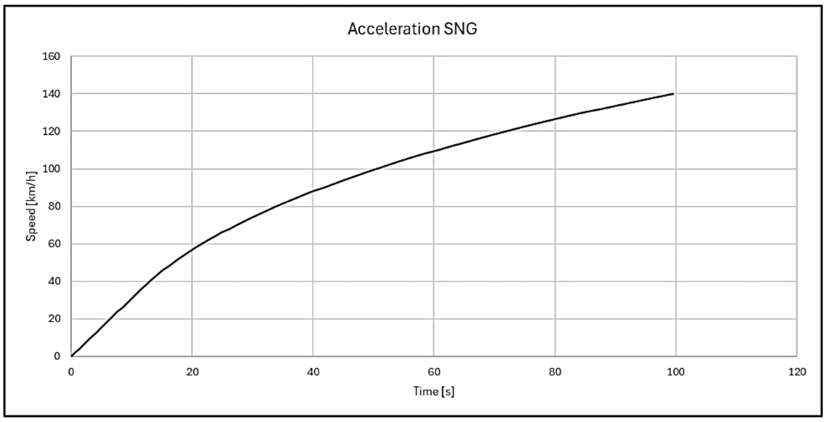



*Figure 15: Acceleration curve SNG*

Note that the platform lengths of the regional stations restrict the length of regional trains to a maximum of 257 meter, i.e. 3 units of 4 carriages each with a total combined length of 227.1 meters (train type SNG). Besides, the current platform lengths of the major stations (Lelystad and Almere Centrum) restrict the length of IC trains to a maximum of 331 meter, i.e. 2 units containing 8 carriages with a total length of 328 meter (train type ICNG).

For simplicity, SNG-trains are hereafter referred to as RE-trains, and ICNG-trains to as IC-trains.

## 4.2 Qualitative selection

Considering the SAAL corridor's infrastructure layout, train characteristics, and the performed SWOT-analysis, the first concept emerged as the most suitable option for achieving the objectives outlined in Section 3.2. This approach enables fast connections between major stations while preserving direct connections between all regional stations. The skip-stop service allows quicker travel for long-distance passengers, while the full-stop service ensures complete network coverage. Minimal infrastructure or regulatory adjustments are required, as a similar model currently operates on the SAAL corridor, benefiting passengers, infrastructure managers, and railway undertakings by offering a familiar structure.

The second concept enhances travel times on high-demand routes from regional stations (e.g., from Almere Buiten) and offers efficient service for passengers traveling from major stations in the direction of Amsterdam. However, it lacks direct connections between low-demand regional stations, limiting its applicability. As such, this concept could be implemented during peak hours when demand is highest for routes from regional stations to Amsterdam rather than between regional stations. The skip-stop pattern allows for higher frequencies on high-demand OD pairs from regional stations toward Amsterdam, thus increasing peak-time capacity. While some passengers for lower-demand routes may need to transfer, the increased frequency could reduce overall travel times. Given the short travel distances between regional stations, many passengers may opt for cycling or car travel for convenience, especially for shorter trips under 10-15 km (Loop, 1997). Therefore, this concept represents a viable alternative for increasing efficiency with moderate infrastructure adjustments.

One potential drawback derived extracted from the SWOT-analysis is that with an odd number of stations, increased frequency may be compromised, as seen between Lelystad and Almere Centrum. To address this, an alternative concept could involve fully skipping or adding one station between Lelystad and Almere Centrum during the morning rush hour, creating an even number of stations. This modification could enhance synchronized arrivals, facilitating quick transfers within platoons. Given the high density of stations, particularly between Almere Oostvaarders and Almere Centrum, temporarily skipping one station is a more feasible option than adding an additional stop.

In contrast, the third and fourth concepts are found less suitable for the SAAL-corridor. Although potentially effective in urban settings, these concepts would require substantial infrastructure changes, regulatory adjustments, and complex real-time dispatching systems, making them impractical for current mainline corridors.

Based on these considerations, the first and second concept were considered as most feasible, as they strike an optimal balance between reliability and flexibility, providing fast, direct connections while maintaining accessibility. Additionally, to address the challenges of an odd number of stations, a variant of the second concept (referred to as concept 2b) is included, in which one station is fully skipped during the morning rush hour.

## 4.3 Patterns

To evaluate the performance of each selected concept under realistic operations, operational patterns are identified based on the corridors' infrastructure lay-out. Each pattern is distinguished by a sequence of numbers (corresponding with the amount of times a regional station is served by a regional train per cycle) and a letter (corresponding to particular sequence of trains and/or maneuvers trains perform). Patterns are developed separately for each track section (i.e. Lelystad to Almere Centrum and Almere Centrum to Weesp).

### *4.3.1 Concept 1*

To develop a set of patterns for Concept 1 (Conventional Pattern Preserving Full-Stopping Regional Services), morphological charts were utilized to combine various building blocks, incorporating diverse stopping and operational plans. As this concept limits variations to regional trains only, the patterns are exclusively focused on the stopping and operational plans of regional trains.

**Lelystad → Almere Centrum**

Table 13 provides the morphological used to extract patterns for the section between Lelystad and Almere Centrum. The major stations are labelled with a 'M', in which a M1 refers to the starting station (Lelystad) and M2 to the Almere Centrum. The intermediate regional stations are labeled R1, R2, and R3, corresponding to Almere Oostvaarders, Almere Buiten, and Almere Parkwijk, respectively. Since Almere Oostvaarders allows trains to pass one another, a category titled 'Passing at R1' is included in the chart as well.

*Table 13: Morphological chart for composing patterns between Lelystad and Almere Centrum*

| **Category** | **Building Blocks** | | | |
|---|---|---|---|---|
| **Depart from M1** | Blue and green depart from the same platform | Blue and green depart from different platforms | | |
| **Arrival at M2** | Blue and green arrive at the same platform | Blue and green arrive at different platforms | | |
| **Stopping plan** | ~~Blue stops at R1 and R2, Green at R3~~ | Blue stops at R1 and R2, Blue & Green at R3 | ~~Blue stops at R1 and R3, Green at R2~~ | ~~Blue stops at R1, Green at R2 and R3~~ |
| | ~~Blue stops at R1, Green at R2 and Blue & Green at R3~~ | Blue stops at R1 and R3, Blue & Green at R2 | ~~Blue stops at R1, Blue & Green at R2 and Green at R3~~ | Blue stops at R1, Blue & Green at R2 and R3 |
| | ~~Green stops at R1, Blue at R2 and R3~~ | ~~Green stops at R1 and R3, Blue at R2~~ | ~~Green stops at R1, Blue at R2 and Blue & Green at R3~~ | ~~Green stops at R1 and R2, Blue at R3~~ |
| | Green stops at R1 and R2, Blue & Green at R3 | ~~Green stops at R1, Blue & Green at R2 and Blue at R3~~ | Green stops at R1 and R3, Blue & Green at R2 | Green stops at R1, Blue & Green at R2 and R3 |
| | Blue & Green stop at R1, Blue at R2 and R3 | ~~Blue & Green stop at R1, Blue at R2, Green at R3~~ | Blue & Green stop at R1 and R3, blue at R2 | ~~Blue & Green stop at R1, Green at R2, Blue at R3~~ |
| | Blue & Green stop at R1, Green at R2 and R3 | Blue & Green stop at R1 and R3, Green at R2 | Blue & Green stop at R1 and R2, Blue at R3 | Blue & Green stop at R1 and R2, Green at R3 |
| | Blue & Green stop at R1, R2 and R3 | | | |
| **Passing at R1** | Tailing train passes | Tailing train does not pass | | |

Note that some of the building blocks are ruled out because they do not provide a direct connection between each regional station and therefore does not comply with the concepts' principles. To clearly distinguish all patterns, each one is identified by a sequence of numbers that corresponds to the amount of times a regional station is served by a regional train per cycle in the direction of Amsterdam (corresponding to the applicated stopping plan). For example, a 1-1-2 stopping plan means that one regional train stops at Almere Oostvaarders, one at Almere Buiten, and two regional trains at Almere Parkwijk. Note that since Lelystad and Almere Centrum are served by all trains, these stations are not distinctive for identifying different stopping plans and excluded from the sequence used to distinguish the various stopping plans.

While serving a specific stopping plan within the first concept, train sequences can be adjusted at M1 (Lelystad) and R1 (Almere Oostvaarders), allowing trains to optimally perform their stopping plan in order to optimize line capacity and operational efficiency. These adjustments are referred to as operational plans. For this particular section, a total of five distinct variations can be identified:

- a.1: Leader train operates as a full stopping train, while the follower operates as a skip-stop train.
- a.2: Leader train operates as a full stopping train, passed by the follower train at Almere Oostvaarders operating as a skip-stop train. This plan is only considered when only one regional train has a scheduled stop at Almere Oostvaarders.
- b.1: Leader operates as a skip-stop regional train, while the follower operates as a full stopping train. At Almere Oostvaarders, the follower stops at the straight platform track.
- b.2: Leader operates as a skip-stop regional train, while the follower operates as a full stopping train. At Almere Oostvaarders, the follower stops on the deflecting track. This plan is only considered when the leader has a scheduled stop at Almere Oostvaarders.
- c: Until Almere Buiten, the leader operates as a full stopping train, while the follower functions as a skip-stop train. After Almere Buiten, the roles reverse. This plan is only feasible if both trains have a scheduled stop at Almere Buiten with enough overlap time to allow passengers to transfer. Note that in a 1-2-2 pattern, both regional trains follow a full stopping schedule after stopping at Almere Buiten, making them indistinguishable from a.

A pattern is now formed by combining a letter corresponding to a specific operational variation with a certain stopping plan. So, a 1-1-2 stopping plan in which the leader stops at each regional station and the follower functions as a skip-stop train by only serving the Almere Parkwijk is referred to as pattern 1-1-2a1. This way, a total of 21 patterns is extracted in Table 14, specifically for the section between Lelystad and Almere Centrum. A ‘1’ is assigned to each train when it stops at the corresponding station.

*Table 14: Overview of all extracted patterns between Lelystad and Almere Centrum for concept 1*

| Stopping plan | Operational plan reference | Regional Unit | Almere Oostvaarders | Almere Buiten | Almere Parkwijk |
|---|---|---|---|---|---|
| **1-1-2** | **a1/a2** | Green | 1 | 1 | 1 |
| | | Blue | | | 1 |
| | **b** | Green | | | 1 |
| | | Blue | 1 | 1 | 1 |
| **1-2-1** | **a1/a2** | Green | 1 | 1 | 1 |
| | | Blue | | 1 | |
| | **b** | Green | | 1 | |
| | | Blue | 1 | 1 | 1 |
| | **c** | Green | 1 | 1 | |
| | | Blue | | 1 | 1 |
| **1-2-2** | **a1/a2** | Green | 1 | 1 | 1 |
| | | Blue | | 1 | 1 |
| | **b** | Green | | 1 | 1 |
| | | Blue | 1 | 1 | 1 |
| | **c** | Green | 1 | 1 | 1 |
| | | Blue | | 1 | 1 |
| **2-1-2** | **a1/a2** | Green | 1 | 1 | 1 |
| | | Blue | 1 | | 1 |
| | **b1/b2** | Green | 1 | | 1 |
| | | Blue | 1 | 1 | 1 |
| **2-1-1** | **a1/a2** | Green | 1 | 1 | 1 |
| | | Blue | 1 | | |
| | **b1/b2** | Green | 1 | | |
| | | Blue | 1 | 1 | 1 |
| **2-2-1** | **a1/a2** | Green | 1 | 1 | 1 |
| | | Blue | 1 | 1 | |
| | **b1/b2** | Green | 1 | 1 | |
| | | Blue | 1 | 1 | 1 |

**Almere Centrum → Weesp**
Similarly, a morphological chart is used to extract patterns for the section between Almere Centrum and Weesp in Table 15. Here, M1 refers to the starting station Almere Centrum, and M2 to Weesp. The intermediate regional stations are labeled R1 and R2, corresponding to Almere Muziekwijk and Almere Parkwijk respectively.

*Table 15: Morphological chart for composing patterns between Almere Centrum and Weesp*

| **Category** | **Building Blocks** | | | |
|---|---|---|---|---|
| **Depart from M1** | Blue and green depart from the same platform | Blue and green depart from different platforms | | |
| **Arrival at M2** | Blue and green arrive at the same platform | Blue and green arrive at different platforms | | |
| **Stopping plan** | ~~Blue stops at R1, Green at R2~~ | Blue stops at R1, Blue & Green at R2 | ~~Green stops at R1, Blue at R2~~ | Green stops at R1, Blue & Green at R2 |
| | Blue & Green stop at R1, Blue at R2 | Blue & Green stop at R1, Green at R2 | Blue & Green stop at R1 and R2 | |
| **Platoon length** | Longer than platform length | Equal or shorter than platform length | | |

Some building blocks are ruled out as they do not provide direct connections between all regional stations. Additionally, since trains cannot pass each other in this section, the departure order will always match the arrival order at M2. Furthermore, platform constraints prevent trains from stopping simultaneously, eliminating the possibility of passenger transfers or switching roles (e.g., between full-stopping and skip-stop services). Consequently, only two operational variations can be identified for this specific section:

a. Leader train operates as a full stopping train, while the follower operates as a skip-stop train.
b. Leader operates as a skip-stop regional train, while the follower operates as a full stopping train.

Now, a 1-2 stopping plan in which the leader stops at each regional station and the follower functions as a skip-stop train by only serving the Almere Parkwijk is referred to as pattern 1-2a. This way, a total of 5 patterns can be extracted specifically for the section between Almere Centrum and Weesp.

*Table 16: Overview of all extracted patterns between Almere Centrum and Weesp for concept 1*

| **Stopping plan** | **Operational plan reference** | **Regional Unit** | **Almere Muziekwijk** | **Almere Poort** |
|---|---|---|---|---|
| **1-2** | **a** | Green | 1 | 1 |
| | | Blue | | 1 |
| | **b** | Green | | 1 |
| | | Blue | 1 | 1 |
| **2-1** | **a** | Green | 1 | 1 |
| | | Blue | 1 | |
| | **b** | Green | 1 | |
| | | Blue | 1 | 1 |
| **2-2** | **-** | Green | 1 | 1 |
| | | Blue | 1 | 1 |

## *4.3.2 Concept 2a*

For Concept 2a – A Conventional pattern introducing skip-stop regional services – a total of 11 patterns can be extracted. Table 17 provides an overview of all these patterns, specifically for the section between Lelystad and Almere Centrum. These patterns are based on the morphological chart in Section 4.3.1, in which all the crossed building blocks have now been considered.

*Table 17: Overview of all extracted patterns between Lelystad and Almere Centrum  for concept 2a*

| Stopping plan | Operational plan reference | Regional Unit | Almere Oostvaarders | Almere Buiten | Almere Parkwijk |
|---|---|---|---|---|---|
| **1-1-1** | **a** | Green | | 1 | |
| | | Blue | 1 | | 1 |
| | **b** | Green | | 1 | 1 |
| | | Blue | 1 | | |
| | **c1/c2** | Green | 1 | | 1 |
| | | Blue | | 1 | |
| | **d1/d2** | Green | 1 | | |
| | | Blue | | 1 | 1 |
| | **e1/e2** | Green | 1 | 1 | |
| | | Blue | | | 1 |
| | **f** | Green | | | 1 |
| | | Blue | 1 | 1 | |
| **1-2-1** | **a** | Green | | 1 | 1 |
| | | Blue | 1 | 1 | |
| | **b** | Green | 1 | 1 | |
| | | Blue | | 1 | 1 |

Note that operational reference letters c, d and e include two sub-plans, referred to as ‘1’ and ‘2’. For these operational plans, the follower train could pass the leader train at Almere Oostvaarders. Each ‘2’ (i.e. c2, d2 and e2) sub-plan stands for the situation in which the follower train passes the leader train. Similarly, using the crossed building blocks from Table 15, two patterns were obtained between Almere Centrum and Weesp. See Table 18.

*Table 18: Overview of all extracted patterns between Almere Centrum and Weesp  for concept 2a*

| Stopping plan | Operational plan reference | Regional Unit | Almere Muziekwijk | Almere Buiten |
|---|---|---|---|---|
| **1-1** | **a** | Green | | 1 |
| | | Blue | 1 | |
| | **b** | Green | 1 | |
| | | Blue | | 1 |

### *4.3.3 Concept 2b*

In Concept 2b, two scenarios are examined: one where Almere Buiten is closed (Scenario 1) and another where Almere Parkwijk is closed (Scenario 2). Closing Almere Oostvaarders was not considered, as residents living between Lelystad and Almere Oostvaarders may already face long cycling distances to reach the nearest station. Additionally, closing more than one station is not deemed favorable, as it would result in an odd number of stations, which would again reduce the efficiency fully skipping a station.

For both scenarios, each regional train running between Lelystad and Almere Centrum now performs only one stop (as it still utilizes a skip-stop pattern). Table 19 provides an overview of all possible patterns for the section between Lelystad and Almere Centrum when either Almere Buiten or Almere Parkwijk is closed, based on the morphological chart in Section 4.3.1.

*Table 19: Overview of all extracted patterns between Lelystad and Almere Centrum for concept 2b*

| Scenario | Stopping plan | Operational plan reference | Unit | Almere Oostvaarders | Almere Buiten | Almere Parkwijk |
|---|---|---|---|---|---|---|
| Fully skipping Almere Buiten | 1-1 | a | Green | | | 1 |
| | | | Blue | 1 | | |
| | 1-1 | b1/b2 | Green | 1 | | |
| | | | Blue | | | 1 |
| Fully skipping Almere Parkwijk | 1-1 | c | Green | | 1 | |
| | | | Blue | 1 | | |
| | 1-1 | d1/d2 | Green | 1 | | |
| | | | Blue | | 1 | |

Note that operational reference letters b and d for both scenarios include two sub-plans, referred to as ‘1’ and ‘2’. For these operational plans, the follower train could pass the leader train at Almere Oostvaarders. Each ‘2’ (i.e. b2 and d2) sub-plan stands for the situation in which the follower train passes the leader train.

Patterns between Almere Centrum and Weesp are similar to those extracted in Table 18.

## 4.4 Running times

To ultimately quantitively test each patterns’ performance, running times are determined for each O-D pair. For this, first technical running times are computed based on technical maximum track speed using the acceleration and deceleration characteristics for each train from Section 4.1.

Normative running times (and associated speeds) for each OD-pair are determined by applying a minimum time supplement of 5% to all OD-pairs. Normative speeds are established per section (i.e. one maximum normative speed is set between Lelystad and Almere Centrum and another between Almere Centrum and Weesp). It was found that Almere Buiten – Almere Centrum was the restricting O-D pair between Lelystad and Almere Centrum and Almere Centrum – Almere Poort between Almere Centrum and Weesp, with a consequent maximum scheduled speed of 32.78 m/s and 33.33 m/s respectively. The consequent normative speed for each OD-pair can be found in Tables 21 and 22. The associated applicated time supplements to each OD-pair can be found in Table 20 en Table 21. Note that since a single maximum normative speed is determined for all OD-pairs within a given section, some OD-pairs receive a time supplement percentage significantly higher than the required 5%.

*Table 20: Applied running time supplements for each OD-pair between Lelystad and Almere Centrum*

| From / To | Lelystad | Almere Oostvaarders | Almere Buiten | Almere Parkwijk | Almere Centrum |
|---|---|---|---|---|---|
| **Lelystad** | | 14.05% | 14.43% | 14.94% | 11.10% |
| **Almere Oostvaarders** | | | 5.21% | 5.61% | 7.80% |
| **Almere Buiten** | | | | 5.11% | 5.20% |
| **Almere Parkwijk** | | | | | 5.86% |
| **Almere Centrum** | | | | | |

Table 21: Applied running time supplements for each OD-pair between Almere Centrum and Weesp

| From / To | Almere Centrum | Almere Muziekwijk | Almere Poort | Weesp |
|---|---|---|---|---|
| **Almere Centrum** | | 5.22% | 6.48% | 12.19% |
| **Almere Muziekwijk** | | | 5.32% | 7.59% |
| **Almere Poort** | | | | 5.03% |
| **Weesp** | | | | |

## 4.5 Headway computations

Minimum technical headways are determined between consecutive regional trains (RE-RE) and intercity and regional trains (IC-RE) based on the SAAL-corridors' infrastructure lay-out and train characteristics. To meet the requirement of simultaneously stopping at each major station, the normative regional train configuration was earlier set to three mechanically coupled train units with a total length of 227.1 meters. Although Almere Buiten is classified as a regional station, its platform length of 341 meters allows trains to stop simultaneously as well. In contrast, platform lengths at all other stations along this section of the SAAL corridor restrict trains to sequential stops only.

Headways are calculated at each predefined maneuver (being plain line open track, simultaneously arriving/departing, sequentially arriving/departing, merging and diverging maneuver) using Formula (1) for both ETCS Level 2 MB and VC operations. The following paragraphs include solely headway calculations specifically for two consecutive regional trains. Headways for scenarios where an IC train follows a regional train or vice versa can be computed following the same method. Section 4.6 provides a complete overview of all computed headways at each location, along with the associated running speeds.

### *4.4.1 Plain line Open Track (Moving Block)*

For two consecutive trains running on open track under ETCS Level 2 Moving Block (MB), the dynamic safety margin excludes the terms accounting for emergency braking applications of the leader train, as the separation is already based on the absolute braking distance. Additionally, the margin does not account for V2V communication delays, as only the train-to-RBC communication delay is relevant in this operational context. Moreover, the approach time is replaced by an absolute braking distance for train $n$. Since the absolute braking distance is assumed to be the most constraining element, the largest headway times for a plain running case is found when two consecutive trains run at maximum speed. Following this, the dynamic safety margin for two consecutive Regional Train running under ETCS Level 2 MB between the leader train $n-1$ and a follower train $n$ contains the following elements:

$$sm_{pos_{k,n,n-1}} = 10.00\ m$$
$$sm_{com_{k,n,n-1}} = \max\left(0, 2.0 * \left(\frac{140}{3.6}\right) - 2.0 * 0\right) = 77.78\ m$$
$$sm_{cont_{k,n,n-1}} = \max\left(0, 1.0 * \left(\frac{140}{3.6}\right) - 1.0 * 0\right) = 38.89\ m$$
$$sm_{emer_{k,n,n-1}} = 0\ m$$
$$sm_0 = 12.85\ m$$

The total minimum dynamic safety margin $dsm\_sim_{k,n,n-1}$ between train $n$ and $n-1$ is now obtained by summing these values:

$$dsm\_MB_{n,n-1} = sm_{pos_{k,n,n-1}} + sm_{com_{k,n,n-1}} + sm_{cont_{k,n,n-1}} + sm_{emer_{k,n,n-1}} + sm_0$$
$$= 10.0 + 77.78 + 38.89 + 0 + 12.9 = 139.51\ m$$

Using Formula (1), the minimum headway between two consecutive trains can be determined. The absolute braking distance at maximum speed is 1061.88 meter, or 48.61 seconds (including a 3 seconds brake application time). Since in Moving Block trains no longer exchange data, a setup time for the follower train should be included. This setup time is equal to the communication from/to RBC (2.0 seconds). Adopting each element and combining the time to cross the safety margin $dsm\_MB_{k,n,n-1}$ with the absolute braking time, the minimum MB-headway in meters between two regional trains running at maximum track speed is computed by the following elements:

$$l_{run} = 0\ m$$
$$l_{clear} = 227.1\ m$$
$$l_{release} = 2.0 * 38.89 = 77.78\ m$$
$$l_{setup} = 2.00 * 38.89 = 77.78\ m$$
$$l_{reaction} = 1.00 * 38.89 = 38.89\ m$$
$$l_{b,absolute} = \frac{\left(v_{k,n}\right)^2}{2b_n} = \frac{(38.89)^2}{2 * 0.8} + 3 * 38.89 = 1061.88\ m$$
$$l_{approach} = l_{b,absolute} + dsm_{n,n-1} = 1061.88 + 139.51 = 1201.40\ m$$

The minimum headway distance is now obtained by summing all headway elements using Formula (1):

$$Headway\ train\ 1_{\text{3units}} \rightarrow 2_{\text{1unit}} = \ 0\ + 227.1 + 77.78 + 77.78 + 38.89 + 1201.40 = 1622.94\ m$$

The minimum headway time can now be determined by dividing the headway distance by the maximum track speed:

$$Headway\ train\ 1_{\text{3units}} \rightarrow 2_{\text{1unit}} = \frac{1622.94}{38.89} = 41.73\ s$$

When running at a lower nominal speed, the consequent headway time is longer and can be calculated by dividing the required distance for two consecutive trains at maximum track speed by the normative speed. Following this, the headway time for two regional trains at open track is found to be equal to 49.51 seconds between Lelystad and Almere Centrum, and 48.69 seconds between Almere Centrum and Weesp.

### *4.4.2 Plain line Open Track (Virtual Coupling)*

Similarly, the minimum required headway for two consecutive regional trains running at VC is determined. Note that all error terms for calculating the $dsm$ are now included:

$$sm_{pos_{k,n,n-1}} = 10.00\ m$$
$$sm_{com_{k,n,n-1}} = \max\left(0, 2.02 * \left(\frac{140}{3.6}\right) - 2.02 * \left(\frac{140}{3.6}\right)\right) = 0\ m$$
$$sm_{cont_{k,n,n-1}} = \max\left(0, 1.0 * \left(\frac{140}{3.6}\right) - 1.0 * \left(\frac{140}{3.6}\right)\right) = 0\ m$$
$$sm_{emer_{k,n,n-1}} = \max\left(0, \frac{(38,89)^2}{2 * 0,8} - \frac{(38,89)^2}{2 * 1,0}\right) = 189.04\ m$$
$$sm_0 = 12.85\ m$$

The total minimum dynamic safety margin $dsm\_sim_{k,n,n-1}$ between train $n$ and $n-1$ is now obtained by summing these values:

$$dsm_{n,n-1} = \ sm_{pos_{k,n,n-1}} + sm_{com_{k,n,n-1}} + \ sm_{cont_{k,n,n-1}} + sm_{emer_{k,n,n-1}} + sm_0 = 10.00 + 0 + 0 + 189.04 + 12.85 = 211.89\ m$$

Having obtained the minimum length of the dynamic safety margin, the minimum headway distance can now be computed as well:

$$l_{run} = 0\ m$$
$$l_{clear} = 227.1\ m$$

$$l_{release} = 2.02 * 38.89 = 78.56\ m$$
$$l_{setup} = 0\ m$$
$$l_{reaction} = 1.00 * 38.89 = 38.89\ m$$
$$l_{b,relative} = \frac{(v_{k,n})^2}{2b_n} - \frac{(v_{n-1})^2}{2b_{n-1}} = \frac{(38.89)^2}{2 * 0.8} - \frac{(38.89)^2}{2 * 0.8} = 0\ m$$
$$l_{approach} = l_{b,relative} + dsm_{n,n-1} = 0 + 211.89 = 211.89\ m$$

The minimum headway distance is now obtained by summing all headway elements using Formula (1):

$$Headway\ train\ 1_{\text{3units}} \rightarrow 2_{\text{1unit}} = 0 + 227.1 + 78.56 + 0 + 38.89 + 0 + 211.89 = 556.43\ m$$

The minimum headway time can now be determined by dividing the headway distance by the maximum track speed:

$$Headway\ train\ 1_{\text{3units}} \rightarrow 2_{\text{1unit}} = \frac{556.43}{38.89} = 14.31\ s$$

Similar to Section 4.4.1, the headway time for two consecutive regional trains running at nominal speed is calculated by dividing the required distance by the normative speed for each section. This way, the headway between Lelystad and Almere Centrum is found to be 16.98 seconds, and 16.69 seconds between Almere Centrum and Weesp respectively.

## *4.4.3 Plain line Simultaneously arriving / departing (Moving Block)*

**Simultaneously departing**

For any case in which two regional trains simultaneously depart from the same platform when running at moving block supervision, it is assumed that the follower train $n$ can depart at the moment the leader is at least at the minimum required distance for two consecutive trains running at moving block at maximum track speed. For this, it is assumed that the follower will accelerate to the same speed as the leader train. Consequently, the dynamic safety margin between the leader train $n-1$ and a follower train $n$ contains the following elements:

$$sm_{pos_{k,n,n-1}} = 10.00\ m$$
$$sm_{com_{k,n,n-1}} = \max\left(0, 2.0 * \left(\frac{140}{3.6}\right) - 2.0 * \left(\frac{140}{3.6}\right)\right) = 0\ m$$
$$sm_{cont_{k,n,n-1}} = \max\left(0, 1.0 * \left(\frac{140}{3.6}\right) - 1.0 * \left(\frac{140}{3.6}\right)\right) = 0\ m$$
$$sm_{emer_{k,n,n-1}} = 0\ m$$
$$sm_0 = 12.85\ m$$

The total minimum dynamic safety margin $dsm\_sim_{k,n,n-1}$ between train $n$ and $n-1$ is now obtained by summing these values:

$$dsm\_MB_{n,n-1} = sm_{pos_{k,n,n-1}} + sm_{com_{k,n,n-1}} + sm_{cont_{k,n,n-1}} + sm_{emer_{k,n,n-1}} + sm_0 = 10.0 + 0 + 0 + 0 + 12.9 = 22.85\ m$$

Except for the approach length, all other headway elements can be extracted from section 4.1.1. The approach length for the simultaneously running case is calculated with the new computed dynamic safety margin:

$$l_{approach} = l_{b,absolute} + dsm_{n,n-1} = 1061.88 + 22.85 = 1084.73\ m$$

The total minimum required headway for two consecutive trains running at the same speed now becomes:

$$Headway\ train\ 1_{\text{3units}} \rightarrow 2_{\text{1unit}} = 0 + 227.1 + 77.78 + 77.78 + 38.89 + 1084.73 = 1506.27\ m$$

The minimum headway time can now be determined by dividing the headway distance by the maximum track speed:

$$Headway\ train\ 1_{3\text{units}} \rightarrow 2_{1\text{unit}} = \frac{1506.27}{38.89} = 38.73\ s$$

For track sections where the maximum speed is lower or the train cannot accelerate to full speed, headway time is adjusted to reflect these constraints. Given that the follower train already starts 255 meters behind the leader train, it can depart 32.20 seconds after the leader train has departed, ensuring safe separation while optimizing departure intervals:

$$\frac{1506.27 - 255.00}{38.89} = 32.20\ s$$

**Simultaneously arriving**

For any case in which two regional trains simultaneously arrive at the same platform at moving block, they must maintain a separation equivalent to the minimum required headway time at open track. Therefore, the headway time for two regional trains arriving simultaneously is set equivalent to the obtained value from Section 4.1.1 (41.73 seconds).

When running at nominal speed, the headway time for two consecutive trains running at ETCS Level 2 MB is calculated in a similar manner and equal to 49.51 seconds between Lelystad and Almere Centrum. See the time-distance diagram in Figure 16. The leader train is visualized in green, while the follower in visualized in blue. Note that the separation distance remains consistent until the follower train comes to a stop 255 meters behind the leader train.

Figure 17 shows the speed profile of the follower train (in blue) as it approaches Almere Centrum. Initially, the train runs at 32.78 m/s (the maximum scheduled speed for open track) before starting an operational braking, reducing its speed to 20.83 m/s due to a restricted speed limit around Almere Centrum.

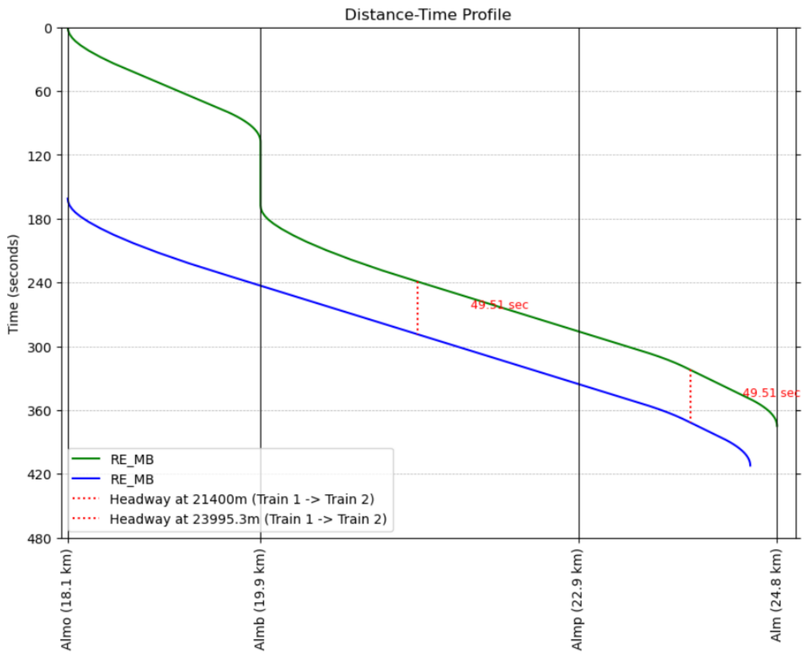



*Figure 16:Time-distance profile for simultaneously arriving at Almere Centrum (Alm) under MB*

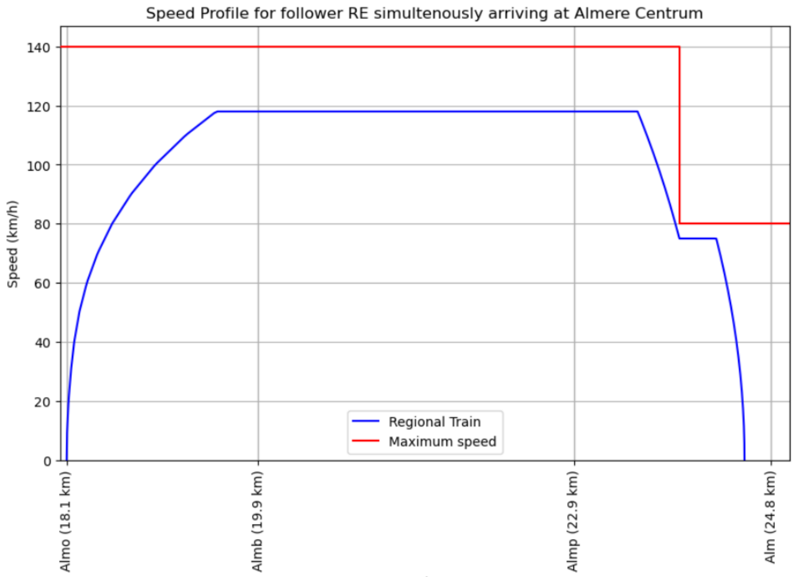



*Figure 17: Speed profile for simultaneously arriving at Almere Centrum (Alm) under MB*

### *4.4.4 Plain line Simultaneously arriving / departing (Virtual Coupling)*

**Simultaneously departing**

For any case in which two regional trains simultaneously depart from the same platform when running at VC, the follower train $n$ can depart at the moment the leader is at least at the minimum required distance for two virtually coupled consecutive trains running at maximum speed at open track. Recall that the minimum required distance for a maximum track speed of 38.89 m/s was 556.43 meters. Since the follower train already starts 255 meter behind the leader train, the follower can depart 7.75 seconds after the leader train have been departed:

$$\frac{556.43 - 255}{38.89} = 7.75\ s$$

Note that for track sections where the maximum speed is lower or the train cannot accelerate to full speed, the headway time is calculated accordingly.

**Simultaneously arriving**

For cases where two regional trains simultaneously arrive at the same platform, the follower train is assumed to stop 255 meters behind the front of the leader train. Since the minimum required distance for two consecutive trains running at maximum track speed is 556.43 meters, the follower train must cover the difference of 301.43 meters (i.e., 556.43 meters - 255 meters) to align correctly and stop at 255 meters behind the leader train.

For this, the follower train should decouple at a certain time instant $t_k$ and speed $v_{decouple}$ when approaching a station, while not violating the minimum required headway up to the critical safety point. The critical safety point is the moment at which the tail of the leader train fully passed the stopping point of the follower (which is 255 meters behind the stopping point of the leader train), as from that moment the trains does not share the same route anymore. The speed at the moment the leader train (length 227.1 meters) fully passes the critical safety point is calculated by equalizing the remaining required distance with the leader train's braking curve:

$$255 - 227.1 = \frac{v_{leader}^2}{1.6}$$

The consequent $v_{leader}$ is found equal to 6.68 m/s at the moment the tail passes the critical safety point.

The optimal $v_{decouple}$ for a follower regional train which simultaneously arrives with a leader train can now be computed for each major station by minimizing the real distance between both trains subtracted with the required minimum headway at the critical safety point. Recall that each major station, it is assumed that regional trains always depart from the deflecting track. Consequently, regional trains approach Almere Centrum on the straight track, as this becomes the deflecting track for departure. Instead, at Weesp, regional trains arrive directly at the deflecting track. The optimal $v_{decouple}$ for both locations is iteratively solved at speed intervals of 1 km/h.

*Simultaneous arriving at Almere Centrum*

After performing several iterations, it was found that the optimal $v_{decouple}$ for a follower train arriving at Almere Centrum is 54 km/h or 15.00 m/s. The associated minimum required dynamic safety margin $dsm_c$ at the critical safety point is found for a $v_{decouple} = v_{follower}$ of 15.00 m/s and a $v_{leader}$ of 6.68 m/s. Note that after decoupling, the trains run at moving block supervision, and therefore $sm_{emer_{k,n,n-1}}$ is set equal to 0 meters. Moreover, note that $v_{k,n}$ is the current speed of the follower train, and $v_{k-c,n-1}$ the speed of the leader train before the communication update delay.

$$sm_{pos_{k,n,n-1}} = 10.00\ m$$
$$sm_{com_{k,n,n-1}} = \max(0,\ \tau_{com}v_{k,n} - \tau_{com}v_{k-c,n-1}) = 2.02 * 15.00 - 2.02 * 8.27 = 13.59\ m$$
$$sm_{cont_{k,n,n-1}} = \max(0,\ \tau_{c,n}v_{k,n} - \tau_{c,n-1}v_{k-c,n-1}) = 1.00 * 15.00 - 1.00 * 8.27 = 6.73\ m$$
$$sm_{emer_{k,n,n-1}} = 0\ m$$
$$sm_0 = 12.85\ m$$
$$dsm_c = 10.00 + 13.59 + 6.73 + 0 + 12.85 = 43.17\ m$$

The minimum headway distance at the critical safety point can now be calculated by using Formula (1) and substituting $dsm_c$ in the approach length of the follower train:

$$l_{run} = 0\ m$$
$$l_{clear} = 227.10\ m$$
$$l_{release} = 2.00 * 15.00 = 30.00\ m$$
$$l_{setup} = 2.00 * 15.00 = 30.00\ m$$
$$l_{reaction} = 1.00 * 15.00 = 15.00\ m$$
$$l_{b,absolute} = \frac{(v_{k,n})^2}{2b_{emerg,n}} = \frac{(15.00)^2}{2 * 1.0} + 3 * 15.00 = 157.50\ m$$
$$l_{approach,sim} = 43.17 + 157.50 = 200.67\ m$$

Adding these headway elements, the minimum required headway distance between the leader and follower is found to be:

$$Headway\ 1 \rightarrow 2 = 0 + 227.1 + 30.30 + 30.00 + 15.00 + 200.67 = 503.07\ m$$

The required minimum headway distance can now be compared to the real distance between the leader and follower train. Recall that at the moment the trains reached 54 km/h (or 15.00 m/s), the trains are still 556.43 meters separated and that at the critical point the leader has a speed of 6.68 m/s. To brake from 15.00 m/s to 6.68 m/s, the leader needs 112.82 meters, or 10.41 seconds. In this time, the follower runs a distance of 156.19 meters, meaning the trains close up another 43.37 meters. Consequently, at the critical point, both trains are 513.08 meters separated, while 503.07 meters was minimal required. From this, it can be concluded that a $v_{decouple}$ of 15.00 m/s does not violate the minimum headway constraint.

Note that since trains are initially virtually coupled, they enter the station at minimum open track plain line headway. When running at normative speed, this means that the trains are 16.98 seconds or 556.53 meters separated, see the time-distance diagram in Figure 18. The leader train is visualized in green, while the follower in visualized in blue.

Figure 19 shows the speed profile of the follower train when approach Almere Centrum. First, the trains runs at 32.78 m/s (maximum scheduled speed at open track), after which it start performing an operational braking to 20.83 m/s because of the restricted speed limit. When approaching Almere Centrum, the follower decouples at 15.00 m/s for 301.43 meters, after which it brakes to stillstand and stops 255 meters behind the follower train.

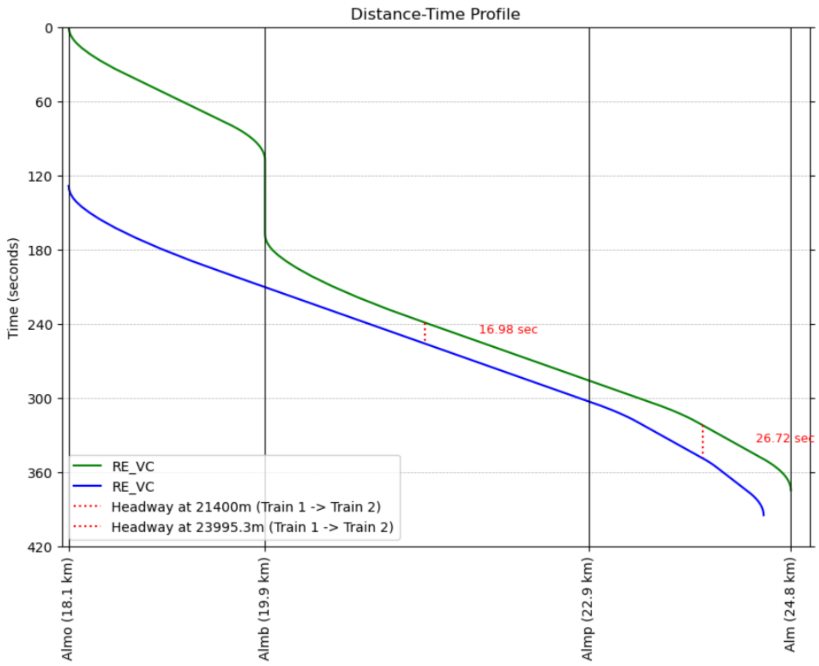



*Figure 18: Time-distance profile for simultaneously arriving at Almere Centrum (Alm) under VC*

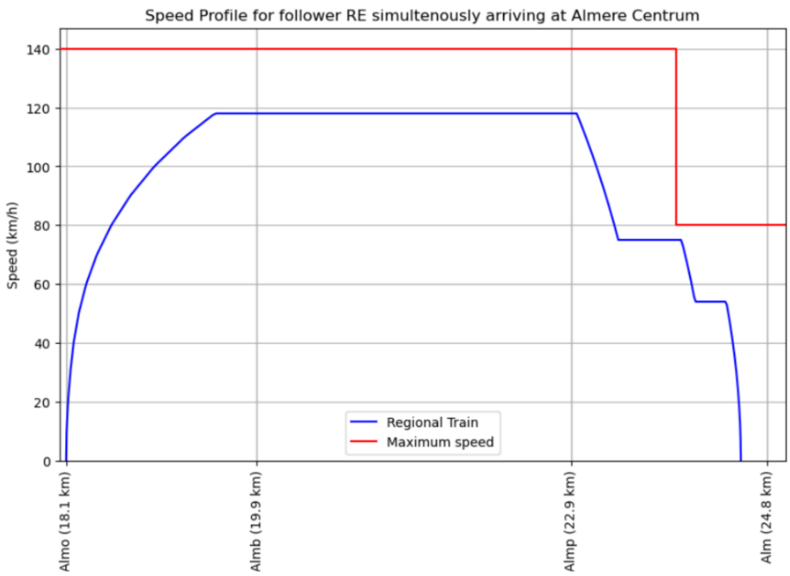



*Figure 19: Speed profile for simultaneously arriving at Almere Centrum (Alm) under VC*

*Simultaneously arriving at Almere Buiten and Weesp*

For simultaneous arrivals at Almere Buiten, the trains also stop at the straight track, as this station does not have a deflecting track. Consequently, the same decoupling speed $v_{decouple}$ and speed profile determined for simultaneous arrivals at Almere Centrum can be applied here as well.

Instead, the optimal $v_{decouple}$ at Weesp is determined for trains simultaneously arriving at a deflecting track. To allow the follower to catch up a maximum distance, the leader and follower decouple before reaching the switch. After decoupling, the leader will continue braking to the maximum turnout speed for the switch, which for all deflecting tracks is equal to 40 km/h. At a certain moment, the follower train stops braking at

$v_{decouple}$ to allow it to catch up with the leader train. It was found that the optimal $v_{decouple}$ when for simultaneously arriving at Weesp is at 52 km/h or 14.44 m/s.

*Simultaneously arriving when not initially virtual coupled*
The situation becomes more complex when two trains simultaneously arrive at a station, but are not initially virtually coupled. This typically occurs when the leader is accelerating from a stop and cannot reach maximum speed due to limited track length, while the follower is cruising at maximum track speed. When approaching the station, the trains running state will transform from 'Decoupled' running into a 'Coupling' running state. The follower will need to start braking earlier (as it has a higher speed), while it is still catching up with the leader train. When the follower reaches the same speed as the leader train (which is at the exact moment the leader starts braking), the trains' state will transition from a 'Coupling' into a 'Virtual Coupled' running state. From that point, both trains operate virtually coupled and brake simultaneously, maintaining a safe separation of 556.43 meters until the follower reaches $v_{decouple}$.

This case will be further detailed using the example of simultaneous arrivals at Almere Centrum, illustrating how the follower train adjusts its speed and position to achieve the required stopping distance of 255 meters behind the leader train. In this scenario, a leader train running between Almere Parkwijk and Almere Centrum accelerates to a maximum technical speed of 26.98 m/s, while a follower train approaches the leader train at a maximum technical speed of 38.89 m/s. At point $s_3$, the follower train already started braking while the leader is still running at 26.98 m/s (Figure 20-1). By the time the follower reaches $s_2$ and the leader reaches $s_1$, both trains are traveling at the same speed at a safe separation of 556.43 meters (Figure 20-2). At $s_1$ (455.10 meters before the stop), the leader has to start braking from 26.98 m/s to stillstand to perform a planned stop at Almere Centrum. At the moment the follower reaches $s_1$, the follower will need to continue to brake until it reaches $v_{decouple}$, allowing to catchup with the leader train and stop right behind the leader train at Almere Centrum (Figure 20-3).

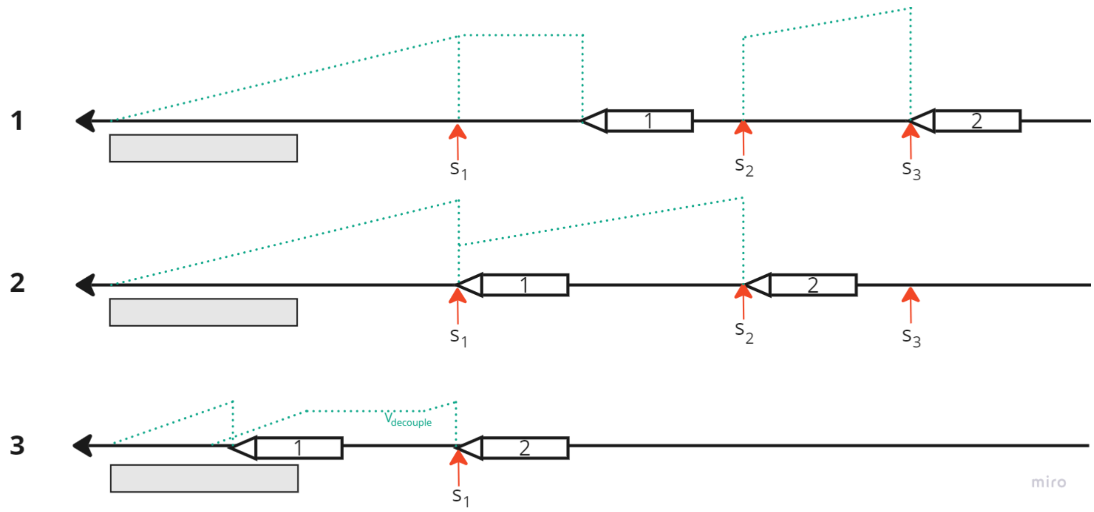



*Figure 20: Detailed visualization for a simultaneously arrival maneuver*

The consequent headway time is measured at point $s_2$ and is the time it takes for the follower to cross the distance from $s_2$ to $s_1$, which in this case is 20.62 seconds:

$$Headway\ train\ 1,2 = \frac{556.43}{26.98} = 20.62\ s$$

When running at nominal speed, the follower approaches the leader train at 32.78 m/s, while the leader runs at a normative speed of 20.83 m/s. At point $s_3$ (see Figure 20), the follower train again has to start braking while the leader continues to run at 20.83 m/s. By the time the follower reaches $s_2$ and the leader reaches $s_1$, both trains are traveling at the same speed at a safe separation of again 556.43 meters. At $s_1$ (271.27 meters before the stop), the leader has to start braking from 20.83 m/s to stillstand to perform a planned stop at Almere

Centrum. At the moment the follower reaches $s_1$, the follower will need to continue to brake until it reaches $v_{decouple}$, allowing to catchup with the leader train and stop right behind the leader train at Almere Centrum. The consequent headway time is again measured at point $s_2$ and is the time it takes for the leader to cross the distance from $s_2$ to $s_1$ for running at normative speed:

$$Headway\ train\ 1,2 = \frac{556.43}{20.83} = 26.72\ s$$

The corresponding running profile for both trains and speed profile for the follower train for a simultaneous arrival maneuver at Almere Centrum can be found in Figure 21 and Figure 22. The leader train is again visualized in green, while the follower in visualized in blue.

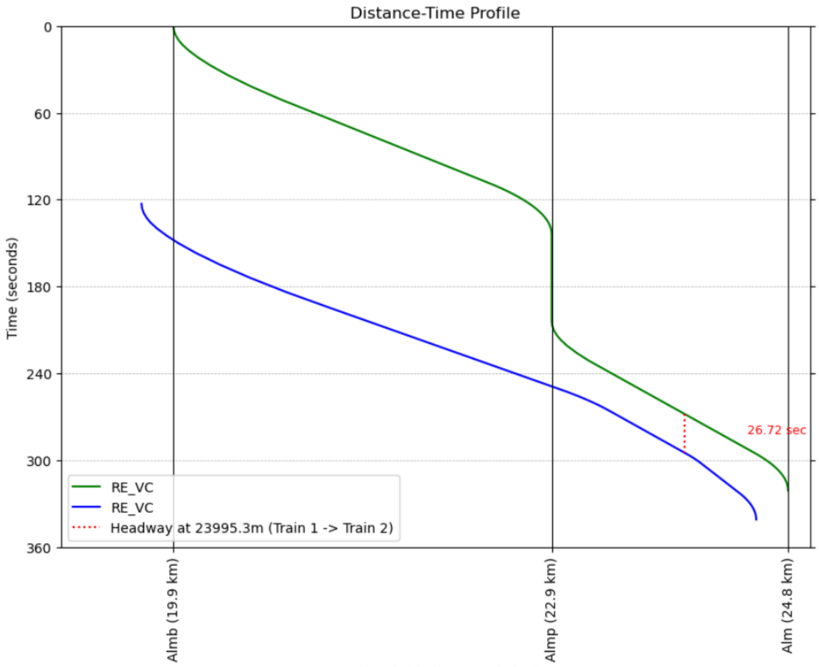



*Figure 21: Time-distance profile for simultaneously arriving when the follower has a higher approach speed*

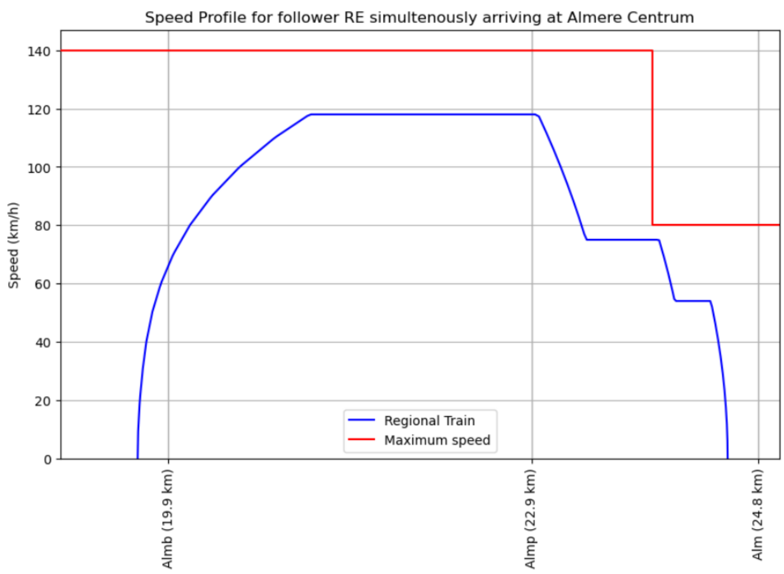



*Figure 22: Speed profile for simultaneously arriving at Almere Centrum (Alm) under VC*

### *4.4.5 Plain line Sequentially arriving / departing (Moving Block)*

For two consecutive regional trains sequentially stopping at a certain station when running at ETCS Level 2 MB supervision, the critical safety point $MB_c$ is found at the point the tail of the leader train fully passed the stopping point of the follower train. Since the maximum train length of a regional train was set to 227.1 meters, this critical safety point is at 227.1 meters behind the stopping point (end of the platform) of the follower train. When the leader has not still passed $MB_c$ and performs an emergency braking, the leader and follower train need to be separated by a safety margin $sm$ and coordination distance $Cd$ to guarantee safe separation. See the illustration below.

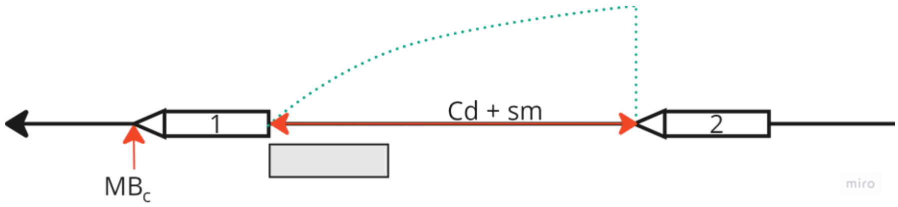



*Figure 23: Detailed visualization of a sequential arrival maneuver under MB*

The running time to $MB_c$ can be obtained by extrapolating acceleration rates from section 4.1. It was found that the leader train reaches $MB_c$ after 23.44 seconds at a speed of 17.57 m/s. Below, the safety margin $sm$ is computed at $MB_c$, for which again a dynamic safety margin $dsm_{seq}$ is used for a $v_{follower}$ of 38.89 m/s and a $v_{leader}$ of 17.57 m/s. Since both trains run at absolute braking distance, $sm_{emer_{k,n,n-1}}$ is set equal to 0 meters. Moreover, note that $v_{k,n}$ is the current speed of the follower train, and $v_{k-c,n-1}$ the speed of the leader train before the communication update delay.

$$sm_{pos_{k,n,n-1}} = 10.00\ meter$$
$$sm_{com_{k,n,n-1}} = \max\left(0,\ \tau_{com}v_{k,n} -\ \tau_{com}v_{k-c,n-1}\right) = 2.00 * 38.89 - 2.00 * 16.56 = 44.66\ \ m$$
$$sm_{cont_{k,n,n-1}} = \max\left(0,\ \tau_{c,n}v_{k,n} -\ \tau_{c,n-1}v_{k-c,n-1}\right) = 1.00 * 38.89 - 1.00 * 16.56 = 22.33\ m$$
$$sm_{emer_{k,n,n-1}} = 0\ m$$
$$sm_0 = 12.85\ m$$
$$dsm_{seq} = 10.00 + 44.66 + 22.33 + 0 + 12.85 = 89.83\ m$$

The minimum headway distance at $MB_c$ can now be obtained by calculating the Coordination distance $Cd$, for which Formula (1) is used. Note that $dsm_{seq}$ is substituted in the approach length of the follower train:

$$l_{run} = 0\ m$$
$$l_{clear} = 227.1\ m$$
$$l_{release} = 2.00 * 38.89 = 77.78\ m$$
$$l_{setup} = 2.00 * 38.89 = 77.78\ m$$
$$l_{reaction} = 1.00 * 38.89 = 38.89\ m$$
$$l_{b,absolute} = \frac{\left(v_{k,n}\right)^2}{2b_{emerg,n}} = \frac{(38.89)^2}{2 * 1.0} + 3 * 38.89 = 872.84\ m$$
$$l_{approach,sim} = 89.83 + 872.84 = 962.67\ m$$

The consequent headway in seconds between train 1 and 2 should at least be equal to:

$$Headway\ train\ 1_{3\text{units}} \rightarrow 2_{1\text{unit}} =\ 0\ +\ 227.1 + 77.78 + 77.78 + 38.89 + 962.67 = 1384.22\ m$$

Consequently, at $MB_c$ the trains should at least 1384.22 meters separated. For comparison purposes, the corresponding headway time on open track has also been calculated. For this, the obtained separation distance at $MB_c$ has to be supplemented with:

- An additional headway distance accounting for the distance the second train catches up with the leader train when the leader train brakes;
- An additional headway account for the dwell time for the leader train;
- A time accounting for the difference between the emergency braking of the second train and an operational braking of the first train for stopping at the station.

The first time supplement is determined by computing how much time the follower train catches up with the leader train when the leader train accelerates to $VC_c$. The leader train needs 23.44 seconds or 227.1 meter to accelerate to $VC_c$. In that time, the follower runs 833.86 meters, meaning that the follower will catch up 911.63-227.1 = 684.53 meters or 17.60 seconds with the leader train.

The dwell time is obtained from Aoun, et al. (2020) and fixed to 60 seconds for both main line and regional market segments. The dwell time starts at the moment the leader train stops. In this time, the follower catches 2333.33 meters up with the leader train.

The last headway supplement is the time or distance loss to perform an operational braking for the first train. The first train needs 945.22 meter to complete an operational braking, in which the follower catches 4.86 seconds up with the leader train. Note that a 3 second brake application time was already included in the absolute braking distance.

Having obtained all headway elements, the minimum required headway for two trains performing a sequential stop at open track is determined with Formula (1):

$$Headway\ train\ 1_{3\text{units}} \rightarrow 2_{1\text{unit}} = 1384.22 + 684.53 + 2333.33 + 945.22 = 5347.30\ m$$

The corresponding headway time at open track is found to be 137.50 seconds. Note that, that this headway time, derived from the acceleration phase of the leader train and the braking phase of the follower train, represents the maximum headway times and is therefore greater than those based on nominal running speeds. A time-distance diagram and a speed profile for sequentially arriving are presented in Figures 24 and Figure 25. Although these diagrams specifically reflect operations under VC, they offer insights into the general execution of such maneuver.

### *4.4.6 Plain line Sequentially arriving / departing (Virtual Coupling)*

For two consecutive regional trains sequentially stopping at a certain station running at VC supervision, the critical safety point is found at the point moment the leader train passes a certain point such that when the leader train has to perform an emergency stop, the tail will always pass the stopping point of the follower train (end of the platform). This point is referred to as the Virtual Coupling Critical ($VC_c$) point. When the leader has not still passed $VC_c$ and has to perform an emergency braking, the leader and follower train need in any case to be separated by a $sm$ (again computed using a dynamic safety margin $dsm_{seq}$) and coordination distance $Cd$ to guarantee safe separation. See the illustration below.

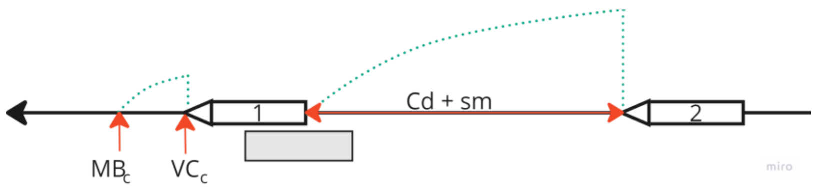


*Figure 23: Detailed visualization for a sequential arrival maneuver under VC*

In other words, at $VC_c$ the distance $D_{acc,v_{max}}$ to accelerate ($acc$) to a certain maximum speed $v_{max}$ for the leader train plus the distance $D_{emerg,v_{max}}$ it takes to apply an emergency braking ($emerg$) from $v_{max}$ to standstill must at least exceed the length of the leader train (227.1 meters):

$$D_{acc,v_{max}} + D_{emerg,v_{max}} \geq 227.1$$

Note that the $D_{acc,v_{max}}$ is equal to $VC_c$, determined by extrapolating the acceleration and braking rates of the leader train:

*Table 22: Extrapolating the Virtual Coupling Critical point*

| **Speed [km/h]** | **Speed [m/s]** | **d_acc** | **d_emerg** | **d_total** | **t_acc** |
|---|---|---|---|---|---|
| **46** | 12.78 | 101.31 | 119.97 | 221.28 | 15.29 |
| ***46.63*** | *12.95* | *104.35* | *122.74* | *227.09* | *15.53* |
| **47** | 13.06 | 106.16 | 124.39 | 230.55 | 15.67 |

The critical point $VC_c$ is found at 104.45 meters behind the stopping point, or 15.53 seconds after departure from the stopping point (middle row Table 22).

Note that since the speed difference between the leader and follower train is relatively high (follower runs at 38.89 while the leader runs at 12.95 m/s), both trains are separated by an absolute braking distance. Running at relative braking distance would hence require larger safety margins, resulting in a longer headway between the leader and follower train. Note that although the headways are determined based on an absolute braking distance, $VC_c$ is determined using relative braking distance between the leader and follower train. This safety risk is deemed acceptable since the second train will always need to stop at the fixed stopping point.

Below, first $dsm_{seq}$ is determined at the critical safety point for a $v_{follower}$ of 38.89 m/s and a $v_{leader}$ of 46.63 km/h or 12.95 m/s. Since both trains run at absolute braking distance, $sm_{emer_{k,n,n-1}}$ is set equal to 0 meters. Moreover, note that $v_{k,n}$ is the current speed of the follower train, and $v_{k-c,n-1}$ the speed of the leader train before the communication update delay.

$$sm_{pos_{k,n,n-1}} = 10.00\, meter$$
$$sm_{com_{k,n,n-1}} = \max\left(0,\ \tau_{com} v_{k,n} - \ \tau_{com} v_{k-c,n-1}\right) = 2.02 * 38.89 - 2.02 * 12.95 = 55.30\ m$$
$$sm_{cont_{k,n,n-1}} = \max\left(0,\ \tau_{c,n} v_{k,n} - \ \tau_{c,n-1} v_{k-c,n-1}\right) = 1.00 * 38.89 - 1.00 * 12.95 = 27.37\ m$$
$$sm_{emer_{k,n,n-1}} = 0\ m$$
$$sm_0 = 12.85\ m$$
$$dsm_{seq} = 10.00 + 55.30 + 27.37 + 0 + 12.85 = 105.52\ m$$

The minimum headway distance at $VC_c$ can now be obtained by calculating the Coordination distance $Cd$, for which Formula (1) is used. Note that $dsm_{seq}$ is substituted in $l_{approach,sim}$ of the follower train:

$$l_{run} = 0\ m$$
$$l_{clear} = 227.1\ m$$
$$l_{release} = 2.02 * 38.89 = 78.56\ m$$
$$l_{setup} = 2.00 * 38.89 = 77.78\ m$$
$$l_{reaction} = 1.00 * 38.89 = 38.89\ m$$
$$l_{b,absolute} = \frac{\left(v_{k,n}\right)^2}{2 b_{emerg,n}} = \frac{(38.89)^2}{2 * 1.0} + 3 * 38.89 = 872.84\ m$$
$$l_{approach,sim} = 105.52 + 872.84 = 978.36\ m$$

The consequent headway in seconds between train 1 and 2 is obtained using Formula (1):

$$Headway\ train\ 1_{\text{3units}} \rightarrow 2_{\text{1unit}} = \ 0\ +\ 227.1 + 78.56 + 77.78 + 38.89 + 978.36 = 1400.68\ m$$

Consequently, at $VC_c$, the trains should at least be 1400.68 meters separated. For clarity and comparison purposes, the associated headway time on open track for two consecutive trains that sequentially stop at a station is calculated. For this, the obtained separation distance at $VC_c$ is again supplemented with three additional headway distances, similar as those from the sequential moving block maneuver (Section 4.4.5).

The first time supplement is determined by computing how much time the follower train catches up with the leader train when the leader train accelerates to $VC_c$. The leader train needs 15.53 or 104.36 meter to accelerate to $VC_c$. In that time, the follower runs 603.89 meters, meaning that the follower will catch up 603.89-104.36 = 499.53 meters or 12.85 seconds with the leader train.

The dwell time is again 60 seconds. In this time, the follower catches 2333.33 meters up with the leader train.

The last headway supplement is the time or distance loss to perform an operational braking for the first train. The first train needs 945.22 meter to complete an operational braking, in which the follower catches 4.89 seconds up with the leader train. Note that a 3 second brake application time was already included in the absolute braking distance.

Having obtained all headway elements, the headway while running at open track is:

$$Headway = 1400.68 + 499.53 + 2333.33 + 945.22 = 5178.76\ m$$

The corresponding headway time is found to be 133.17 seconds. The associated running and speed profile for two consecutive trains arriving at Almere Parkwijk can be found in Figure 24 and Figure 25 respectively.

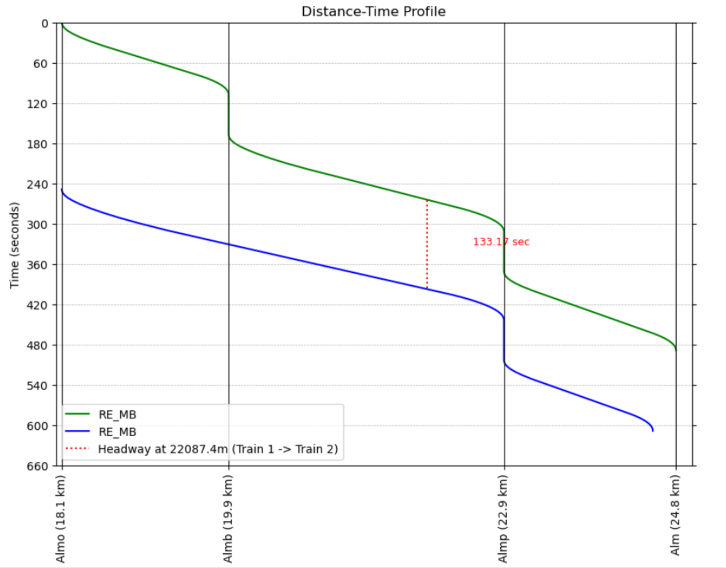



*Figure 24: Time-distance profile for sequentially arriving at Almere Centrum (Alm) under VC*

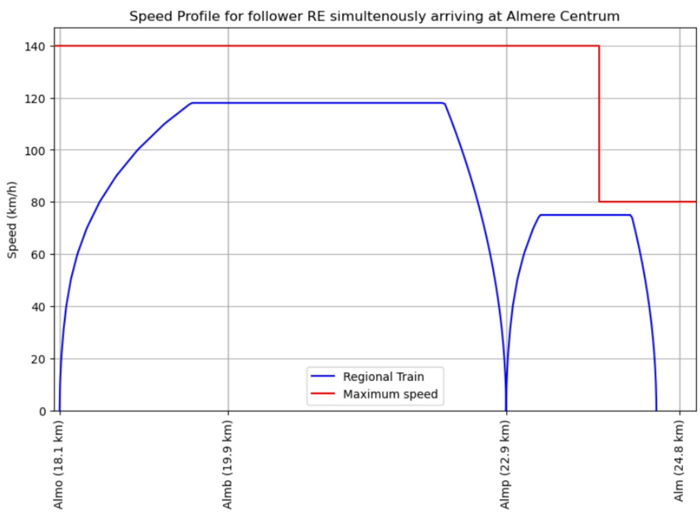



*Figure 25: Speed profile for sequentially arriving at Almere Poort (Almp) and Almere Centrum (Alm) under VC*

## *4.4.7 Merging switch headways*

A merging maneuver is observed at the following locations between Lelystad and Weesp:

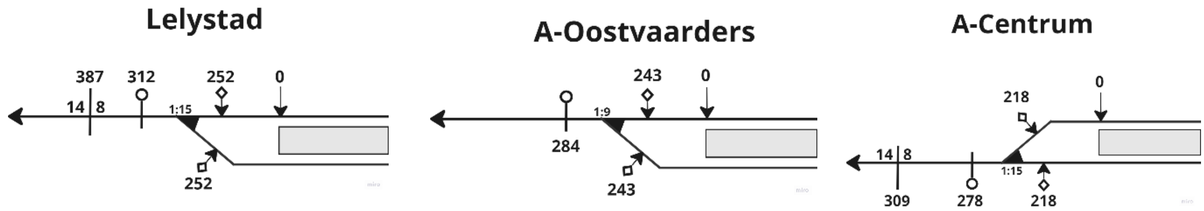



*Figure 26: Overview of considered merging locations*

The sign indicates the release point for a merging maneuver at the front of a switch. When a train passes this point, the switch can be released, moved into the right direction and again used by a follower train. The sign indicates the back of a switch, which for two consequent trains is considered as the danger point. This point may never be passed before the switch is moved and locked into the right position. The 14|8 sign indicates the speed track speed limits divided by 10 (i.e. 14 indicates a speed limit of 140 km/h). The numbers directly above or beneath the signs indicate the location of the point relative to the start point (location 0), which is considered to be at the end of a platform indicated by an arrow. The back of the switch is protected by a safety margin, preventing any unsafe overshooting of the $EOA$ and a consequent collision with the danger point. This safety margin replaces the dynamic safety margin and is set to 50 meters from the back of the switch.

At Lelystad and Almere Centrum, Regional and Intercity Trains must have a planned stop and must have the opportunity to stop next to each other. Moreover, it is assumed that at these locations Regional Trains will always depart from the deflecting track, while Intercity Trains will always depart from the straight track. Almere Oostvaarders is only served by Regional trains, in which they can either stop next to each other or pass each other. In the latter case, the passing unit will always follow the straight track.

From this, the following specific merge maneuvers (location,sequence) can be derived:

- Lelystad,IC-RE: RE departs from deflecting track after IC departed from straight track
- Lelystad,RE-IC: IC departs from straight track after RE departed from deflecting track
- A-Oostvaarders,straight: RE departs from straight track after RE departed from deflecting track
- A-Oostvaarders,branch: RE departs from deflecting track after RE departed from straight track
- A-Oostvaarders,pass: RE departs from deflecting track after RE passed through straight track
- A-Oostvaarders,IC-RE: RE departs from deflecting track after IC passed through straight track
- A-Oostvaarders,RE-IC: IC passes through straight track after RE departed from deflecting track
- A-Centrum,IC-RE: RE departs from deflecting track after IC departed from straight track
- A-Centrum,RE-IC: IC departs from straight track after RE departed from deflecting track

For all maneuvers, the minimum headway times are computed using Formula (1) and a static safety margin of 50 meters from the back of the switch. The consequent headways are found to be:

$$H_{Lelystad,IC-RE} = 7.03 + 16.41 + 4.00 + 1.00 + 8.00 + 7.58 = 44.02\ s$$
$$H_{Lelystad,RE-IC} = 5.97 + 10.58 + 4.00 + 1.00 + 8.00 + 7.33 = 36.88\ s$$
$$H_{A-oostvaarders,straight} = 8.19 + 20.44 + 4.00 + 1.00 + 8.00 + 7.46 = 49.09\ s$$
$$H_{A-oostvaarders,branch} = 5.04 + 10.55 + 4.00 + 1.00 + 8.00 + 9.94 = 38.53\ s$$
$$H_{A-oostvaarders,pass} = 2.34 + 5.84 + 4.00 + 1.00 + 8.00 + 9.94 = 38.43\ s$$
$$H_{A-oostvaarders,IC-RE} = 2.34 + 8.43 + 4.00 + 1.00 + 8.00 + 9.94 = 33.72\ s$$
$$H_{A-oostvaarders,RE-IC} = 8.19 + 20.44 + 4.00 + 8.00 + 1.00 + 22.44 = 64.07\ s$$
$$H_{A-Centrum,IC-RE} = 7.20 + 16.95 + 4.00 + 1.00 + 8.00 + 6.92 = 44.07\ s$$
$$H_{A-Centrum,RE-IC} = 6.34 + 10.82 + 4.00 + 1.00 + 8.00 + 6.73 = 36.89\ s$$

The release time, set-up time and reaction times are extracted from Section 2.3. The running times, clearing times, and approach times are computed in the sub-sections below. The running times, clearing times, and approach times are calculated in the subsections below. Note that at all merging locations, the follower train must brake to a standstill if the switch is not properly locked. As a result, the trains must maintain an absolute braking distance at the switch point location, meaning that the local headway times are identical for both VC and ETCS Level 2 MB operations.

### Running time

The running time of the first train $t_{run}$ is calculated as the time required to cross the switch block section and safety margin. The diagrams below illustrate the determination of running times for departures from either the straight track or the deflecting track. Departures from deflecting tracks are constrained by the maximum turnout speeds $v_{turnout}$ dictated by the switch angular ratio:

- At Lelystad and Almere Centrum, the switch angular ratio is 1:15, restricting the train's speed on the branching track to 80 km/h (22.22 m/s).
- At Almere Oostvaarders, the switch angular ratio is 1:9, limiting the speed on the branching track to 40 km/h (11.11 m/s).

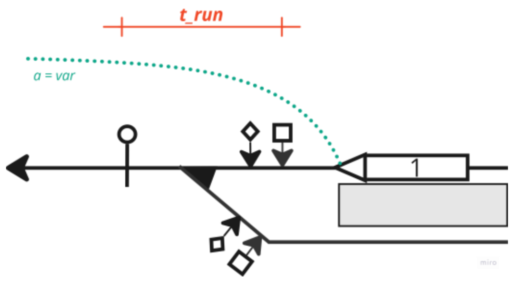



*Figure 27: Visualization on determination of running time for departure from straight track*

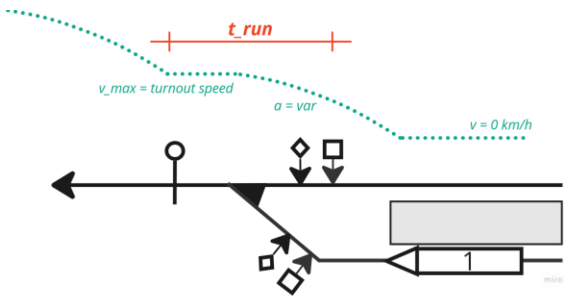



*Figure 28: Visualization on determination of running time for departure from deflecting track*

In Figure 27 and Figure 28, the start of the safety margin is indicated by a sign. The Table below shows for each location the distance (relative to the start point), time and speed at which the 1st train enters the safety margin (sm) and the distance, time and speed at which the first train leaves the switch block section at . The speeds and times are obtained by extrapolating the acceleration rates from Section 4.1.

*Table 23: Overview of distance, time and speed for leader train to determine running times*

| Location | Track | Maneuver | Type of train | Entering sm point [m] | Entering sm time [s] | Entering sm speed [m/s] | Release point [m] | Release time [s] | Release speed [m/s] |
|---|---|---|---|---|---|---|---|---|---|
| **Lelystad** | Straight | Stopping | IC | 202 | 24.13 | 16.73 | 312 | 31.16 | 19.94 |
| | Branch | Stopping | RE | 202 | 22.05 | 16.89 | 312 | 28.02 | 19.75 |
| **Almere Oostvaarders** | Straight | Stopping | RE | 193 | 21.55 | 16.64 | 284 | 26.59 | 19.10 |
| | | Passing | RE | 193 | 4.96 | 38.89 | 284 | 7.30 | 38.89 |
| | | | IC | 193 | 4.96 | 38.89 | 284 | 7.30 | 38.89 |
| | Branch | Stopping | RE | 193 | 23.84 | 11.11 | 284 | 32.03 | 11.11 |
| **Almere Centrum** | Straight | Stopping | IC | 168 | 19.92 | 15.69 | 278 | 26.26 | 18.94 |
| | Branch | Stopping | RE | 168 | 21.91 | 15.21 | 278 | 29.11 | 19.03 |

It is important to note that at both Lelystad and Almere Centrum, trains departing from deflecting tracks do not exceed the restricted turnout speeds at the release points. At Almere Oostvaarders, the RE train departing from the deflecting track reaches its turnout speed before it crosses the safety margin point. This allows trains departing from the branching track at Almere Oostvaarders to accelerate to 40 km/h, maintaining this speed while traversing the switch section.

The running times $Trun_{location,track,maneuver,type}$ in seconds can now be observed by subtracting the *entering sm time* from the *release time* in Table 23:

$$Trun_{Lelystad,straight,stopping,IC} = 31.16 - 24.13 = 7.03\ s$$
$$Trun_{Lelystad,branch,stopping,RE} = 28.02 - 22.05 = 5.97\ s$$
$$Trun_{A-oostvaarders,straight,stopping,RE} = 26.59 - 21.55 = 5.04\ s$$
$$Trun_{A-oostvaarders,straight,passing,RE} = 7.30 - 4.96 = 2.34\ s$$
$$Trun_{A-oostvaarders,straight,passing,IC} = 7.30 - 4.96 = 2.34\ s$$
$$Trun_{A-oostvaarders,branch,stopping,RE} = 32.03 - 23.84 = 8.19\ s$$
$$Trun_{A-Centrum,straight,stopping,IC} = 29.11 - 21.91 = 7.20\ s$$
$$Trun_{A-Centrum,branch,stopping,RE} = 26.26 - 19.92 = 6.34\ s$$

## Clearing time

For a merging maneuver, the clearing time is the time needed for the full length of a train to pass the release point of a switch. For an accelerating train, the clearing time is the running time from the release point to the clearing point. The clearing point for each location is determined with the following formula:

$$Clearing\ point = Release\ point + Train\ length$$

Following this, the clearing point relative to the starting point at each location for each type of train is as follows:

$$Clearing\ point_{Lelystad,RE} = 312 + 227.1 = 539.1\ m$$
$$Clearing\ point_{Lelystad,IC} = 312 + 328 = 640\ m$$
$$Clearing\ point_{A-Oostvaarders,RE} = 284 + 227.1 = 511.1\ m$$
$$Clearing\ point_{A-Oostvaarders,IC} = 284 + 328 = 612\ m$$
$$Clearing\ point_{A-Centrum,RE} = 278 + 227.1 = 505.1\ m$$
$$Clearing\ point_{A-Centrum,IC} = 278 + 328 = 606\ m$$

Table 24 presents the distances of the release point and of the clearing point relative to starting point (which is located at the end of a platform), and associating relative running times and speed.

*Table 24: Computation of Clearing times*

| Location | Track | Maneuver | Type of train | Distance to release point [m] | Running time [s] | Speed [m/s] | Distance to clearing point [m] | Running time [s] | Speed [m/s] |
|---|---|---|---|---|---|---|---|---|---|
| **Lelystad** | Straight | Stopping | IC | 312 | 31.16 | 19.94 | 640.0 | 47.57 | 26.81 |
| | Branch | Stopping | RE | 312 | 28.02 | 19.75 | 539.1 | 38.60 | 22.22 |
| **Almere Oostvaarders** | Straight | Stopping | RE | 284 | 26.59 | 19.10 | 511.1 | 37.14 | 23.37 |
| | | Passing | RE | 284 | 7.30 | 38.89 | 511.1 | 13.14 | 38.89 |
| | | | IC | 284 | 7.30 | 38.89 | 612.0 | 15.74 | 38.89 |
| | Branch | Stopping | RE | 284 | 32.03 | 11.11 | 511.1 | 52.47 | 11.11 |
| **Almere Centrum** | Straight | Stopping | IC | 278 | 26.26 | 18.94 | 606.0 | 43.21 | 26.21 |
| | Branch | Stopping | RE | 278 | 29.11 | 19.03 | 505.1 | 39.93 | 22.22 |

For trains departing from the deflecting track at Almere Oostvaarders, trains are restricted by the maximum turnout speed until reaching the clearing point. For trains departing from the straight track at Almere Oostvaarders, trains are not restricted by any turnout speeds. For a passing train at Almere Oostvaarders, the clearing time is determined by dividing the length of the Regional train by the maximum track speed. At Lelystad and Almere Centrum, the turnout speed is reached after 435.99 meters, or 33.96 seconds. Consequently, the clearing time can be determined by adding the acceleration time from the release point to turnout point with the remaining time to run at constant turnout speed to the clearing point.

The clearing times $Tclear_{location,track,maneuver,type}$ in seconds can now be observed by subtracting the running times to the release point from running time to the clearing point from Table 24:

$$Tclear_{Lelystad,straight,stopping,IC} = 47.57 - 31.16 = 16.41\ s$$
$$Tclear_{Lelystad,branch,stopping,RE} = 38.60 - 28.02 = 10.58\ s$$
$$Tclear_{A-Oostvaarders,straight,stopping,RE} = 37.14 - 26.59 = 10.55\ s$$
$$Tclear_{A-Oostvaarders,straight,passing,RE} = 13.14 - 7.30 = 5.84\ s$$
$$Tclear_{A-Oostvaarders,straight,passing,IC} = 15.74 - 7.30 = 8.43\ s$$
$$Tclear_{A-Oostvaarders,branch,stopping.RE} = 52.47 - 32.03 = 20.44\ s$$
$$Tclear_{A-Centrum,straight,stopping,IC} = 43.21 - 26.26 = 16.95\ s$$
$$Tclear_{A-Centrum,branch,stopping,RE} = 39.93 - 29.11 = 10.82\ s$$

## Approach time

The approach time for merging switches is the time needed for the follower train to brake in the case the switch is not locked into the right direction correctly. The follower train $n$ receives an $EoA$ to the start of the safety margin point, even if the switch has not been already locked. This means that a train can accelerate to a certain maximum speed $v_{max}$ while still being able to safely brake to standstill if the switch is not properly locked.

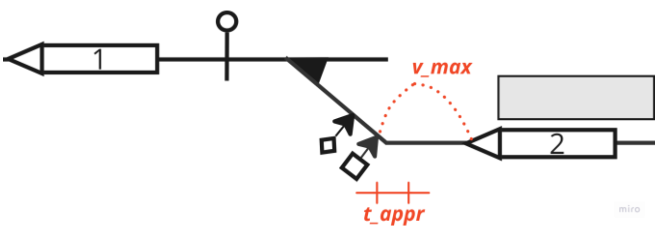



*Figure 23: Visualization of approach time*

In other words, the distance $D_{acc,v_{max}}$ to accelerate $(acc)$ to a certain maximum speed $v_{max}$ plus the distance $D_{emerg,v_{max}}$ it takes to apply an emergency braking $(emerg)$ from $v_{max}$ to standstill may never exceed the $EoA$ given to train $n$ to the safety margin:

$$D_{acc,v_{max}} + D_{emerg,v_{max}} \leq EoA$$

Table 25 presents the maximum speed $v_{max}$ and associated acceleration $D_{acc,v_{max}}$ and braking $D_{emerg,v_{max}}$ distances to the $EoA$ for each of the three merging locations. The approach time for each location is the time needed to brake from $v_{max}$ to standstill and can be obtained from the outmost right column. Note that within the emergency brake distances and times, an additional brake build-up time of 3 seconds is included to account for the period it takes for the braking system to fully engage and produce the desired deceleration once a braking command is issued.

*Table 25: Computation of Approach times*

| Location | Track | Maneuver | Type of train | Max. Speed follower [m/s] | Accele-ration distance [m] | Braking distance [m] | EoA (safety margin point) [m] | Braking time [s] | Time over braking distance [s] |
|---|---|---|---|---|---|---|---|---|---|
| **Lelystad** | Straight | Stopping | IC | 11.67 | 98.89 | 103.06 | 202 | 14.67 | 7.33 |
| | Branch | Stopping | RE | 12.19 | 91.09 | 110.91 | 202 | 15.19 | 7.58 |
| **Almere Oostvaarders** | Straight | Stopping | RE | 11.92 | 86.26 | 106.74 | 193 | 14.94 | 7.46 |
| | | Passing | RE | 38.89 | - | 872.84 | 193 | 41.89 | 22.44 |
| | | | IC | 38.89 | - | 872.84 | 193 | 41.89 | 22.44 |
| | Branch | Stopping | RE | 11.11 | 72.71 | 110.48 | 193 | 14.11 | 9.94 |
| **Almere Centrum** | Straight | Stopping | IC | 10.54 | 80.85 | 87.12 | 168 | 13.54 | 6.73 |
| | Branch | Stopping | RE | 11.13 | 72.61 | 95.39 | 168 | 14.13 | 6.92 |

The $v_{max}$ at Almere Oostvaarders branch is set to 11.11 m/s, as this is the maximum turnout speed.

## *4.4.8 Diverging switch headways*

A diverging maneuver is observed at the following locations along the SAAL-corridor between Lelystad and Weesp:

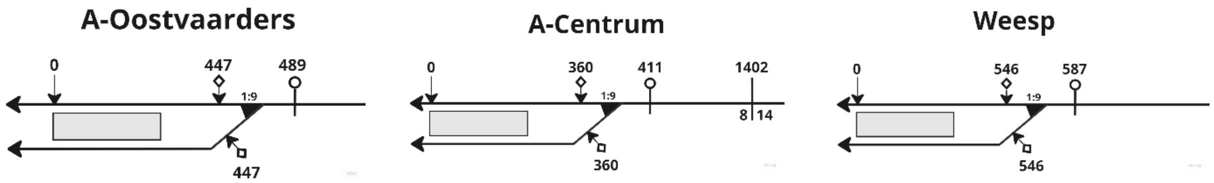



*Figure 4: Overview of considered diverging locations*

The sign indicates the front of a switch, which for two consequent trains is considered as the danger point and in any case may not be passed before the switch is moved and locked into the right position. The sign indicates the back of a switch, which for diverging cases is considered as the release point. When a leader train passes this point, the switch can be released, moved into the right direction and again used by a follower train. The numbers directly above or beneath the signs indicate the location of the points relative to the stopping point, which is assumed to be at the end of a platform (indicated by an arrow). The front of a switch is protected by a safety margin, preventing any unsafe overshooting of the $EOA$ and a consequent collision with the danger point. This safety margin is equal to the merging maneuver, fixed to 50 meters from the front of the switch. For each of the three locations, it is assumed that the leader train stops at the straight track while the follower will stop at the deflecting track.

At Almere Centrum, Regional and Intercity Trains must have a planned stop and must have the opportunity to stop next to each other. Here, it is assumed that Regional Trains will always arrive at the straight track, while Intercity Trains will always arrive at the deflecting track. Recall that Almere Oostvaarders is only served by Regional trains, in which they can either stop next to each other or pass each other. At Weesp, IC-trains are allowed to pass Regional Trains. Therefore, Regional Trains will always use the deflecting track.

From this, the following specific merge maneuvers (location,sequence) can be derived:

- A-Oostvaarders,straight: RE arrives at straight track after RE arrived at deflecting track

- A-Oostvaarders,branch: RE arrives at deflecting track after RE arrived at straight track
- A-Oostvaarders,pass: RE passes through straight track after RE arrived at deflecting track
- A-Oostvaarders,IC-RE: RE arrives at deflecting track after IC passed through straight track
- A-Oostvaarders,RE-IC: IC passes through straight track after RE arrived at deflecting track
- A-Centrum,IC-RE: RE arrives at straight track after IC arrived at deflecting track
- A-Centrum,RE-IC: IC arrives at deflecting track after RE arrived at straight track
- Weesp,IC-RE: RE arrives at deflecting track after IC passed through straight track
- Weesp,RE-IC: IC passes through straight track after RE arrived at deflecting track

For all maneuvers, the minimum headway times are computed using Formula (1) and a static safety margin of 50 meters from the back of the switch. The consequent headways in seconds are found to be:

$$Headway\ train\ 1,2_{\mathrm{A-Oostvaarders,branch}} = 3.16 + 9.63 + 4.00 + 8.00 + 1.00 + 34.75 = 60.55\ \mathrm{s}$$
$$Headway\ train\ 1,2_{\mathrm{A-Oostvaarders,branch}} = 8.19 + 20.44 + 4.00 + 8.00 + 1.00 + 23.75 = 65.38\ \mathrm{s}$$
$$Headway\ train\ 1,2_{\mathrm{A-Oostvaarders,pass}} = 8.19 + 20.44 + 4.00 + 8.00 + 1.00 + 22.44 = 64.07\ \mathrm{s}$$
$$Headway\ train\ 1,2_{\mathrm{A-Oostvaarders,IC-RE}} = 2.34 + 8.43 + 4.00 + 8.00 + 1.00 + 34.75 = 58.53\ \mathrm{s}$$
$$Headway\ train\ 1,2_{\mathrm{A-Oostvaarders,RE-IC}} = 8.19 + 20.44 + 4.00 + 8.00 + 1.00 + 22.44 = 64.07\ \mathrm{s}$$
$$Headway\ train\ 1,2_{\mathrm{A-Centrum,IC-RE}} = 9.09 + 23.18 + 4.00 + 8.00 + 1.00 + 14.11 = 59.38\ \mathrm{s}$$
$$Headway\ train\ 1,2_{\mathrm{A-Centrum,RE-IC}} = 3.96 + 11.79 + 4.00 + 8.00 + 1.00 + 18.28 = 45.52\ \mathrm{s}$$
$$Headway\ train\ 1,2_{\mathrm{Weesp,IC-RE}} = 2.98 + 10.74 + 4.00 + 8.00 + 1.00 + 33.56 = 52.61\ \mathrm{s}$$
$$Headway\ train\ 1,2_{\mathrm{Weesp,RE-IC}} = 8.19 + 20.44 + 4.00 + 8.00 + 1.00 + 18.28 = 59.91\ \mathrm{s}$$

The release time, set-up time and reaction times are extracted from Section 2.3. The running times, clearing times, and approach times are computed in the subsections below. The running times, clearing times, and approach times are calculated in the subsections below. Note that at all merging locations, the follower train must brake to a standstill if the switch is not properly locked. As a result, the trains must maintain an absolute braking distance at the switch point location, meaning that the local headway times are identical for both VC and ETCS Level 2 MB operations.

## Running time

The Running time 1st train is the time to cross the switch block section for junctions plus the safety margin. Recall that at Almere Centrum, it is assumed that the Regional Trains will always arrive at the straight track and that at Weesp Regional Trains will always arrive at the deflecting track. At Almere Oostvaarders, Regional Trains can either arrive at the straight or deflecting track or can be passed by another Regional Train.

The illustrations below show the determination of the running times $t_{run}$ of either an arrival case at a straight track or branching track. Arrivals at branching tracks are restricted by maximum turnout speeds following from the switch angular ratios. At all diverge locations, the switch angular ratio is 1:9, restricting a train to cross the switch at only 40 km/h or 11.11 m/s. When a Regional Train passes its follower at Almere Oostvaarders, it is always assumed that the passing train will follow the straight track. See the illustrations below.

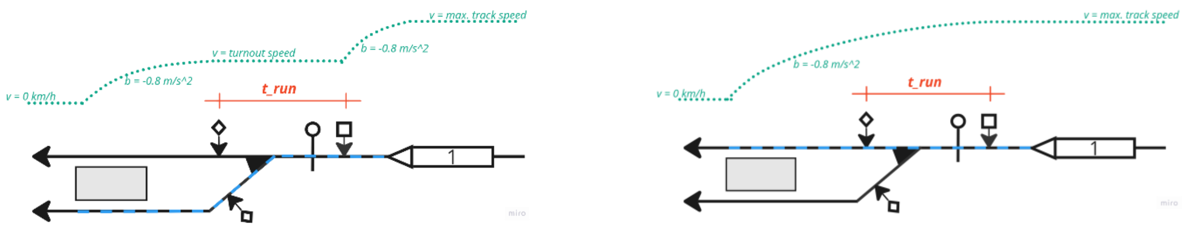



*Figure 31: Visualization for determination of running time when arriving at a deflecting track (left) and straight track (right)*

The start of the safety margin is indicated by a sign. The Table below presents for each location the distance, time and speed at which the 1st train enters the safety margin (sm) and at which the 1st train leaves the switch block section at the release point. All times and distances are relative to the stopping point at location 0. For instance, a train approaching the straight track at Almere Oostvaarders begins operational braking from 140 km/h at 51.61 seconds, enters the safety margin 37.42 seconds before stopping, clears the switch at 34.26 seconds, and comes to a complete stop at time 0 and location 0, positioned at the end of the platform on the straight track.

*Table 26: Switch section entering and release distance, speed and time*

| Location | Track | Maneuver | Type of train | Entering sm point [m] | Entering sm time [s] | Entering sm speed [m/s] | Release point [m] | Release time [s] | Release speed [m/s] |
|---|---|---|---|---|---|---|---|---|---|
| **Almere Oostvaar-ders** | Straight | Stopping | RE | 561 | 37.42 | 29.94 | 470 | 34.26 | 27.41 |
| | | Passing | RE | 561 | 14.43 | 38.89 | 470 | 12.09 | 38.89 |
| | | | IC | 561 | 14.43 | 38.89 | 470 | 12.09 | 38.89 |
| | Branch | Stopping | RE | 561 | 57.43 | 11.11 | 470 | 49.24 | 11.11 |
| **Almere Centrum** | Straight | Stopping | IC | 461 | 41.49 | 11.11 | 360 | 32.40 | 11.11 |
| | Branch | Stopping | RE | 461 | 33.92 | 27.13 | 360 | 29.96 | 23.96 |
| **Weesp** | Straight | Passing | IC | 637 | 20.85 | 30.56 | 546 | 17.87 | 30.56 |
| | Branch | Stopping | RE | 637 | 57.33 | 11.11 | 546 | 49.14 | 11.11 |

The running times $Trun_{location,track,maneuver,type}$ in seconds can now be observed by subtracting the *entering sm time* from the *release time* in Table 26:

$$Trun_{A-Oostvaarders,straight,stopping,RE} = 37.42 - 34.26 = 3.16\ s$$
$$Trun_{A-Oostvaarders,straight,passing,RE} = 14.43 - 12.09 = 2.34\ s$$
$$Trun_{A-Oostvaarders,straight,passing,IC} = 14.43 - 12.09 = 2.34\ s$$
$$Trun_{A-Oostvaarders,branch,stopping,RE} = 57.43 - 49.24 = 8.19\ s$$
$$Trun_{A-Centrum,straight,stopping,IC} = 41.49 - 32.40 = 9.09\ s$$
$$Trun_{A-Centrum,branch,stopping,RE} = 33.92 - 29.95 = 3.96\ s$$
$$Trun_{Weesp,straight,passing,IC} = 20.85 - 17.87 = 2.98\ s$$
$$Trun_{Weesp,branch,stopping,RE} = 57.33 - 49.14 = 8.19\ s$$

## Clearing time

For a train approaching a diverging switch while braking, the clearing time is the running time from the back of the switch to the clearing point. The clearing point for each location is determined by:

$$Clearing\ point = Back\ of\ the\ switch - Train\ length$$

Following this, the clearing point in meters relative to the back of the switch for each type of train is:

$$Clearing\ point_{A-Oostvaarders,RE} = 470.0 - 227.1 = 242.9\ m$$
$$Clearing\ point_{A-Oostvaarders,IC} = 470.0 - 328.0 = 142.0\ m$$
$$Clearing\ point_{A-Centrum,RE} = 360.0 - 227.1 = 132.9\ m$$
$$Clearing\ point_{A-Centrum,IC} = 360.0 - 328.0 = 32.0\ m$$
$$Clearing\ point_{Weesp,RE} = 546 - 227.1 = 318.9\ m$$
$$Clearing\ point_{Weesp,IC} = 546 - 328 = 218.0\ m$$

Table 27 shows the distances of the back of the switch and of the clearing point relative to the end of the platform, and associating relative running times and speed. Note that for all trains arriving at a branching track, the clearing time is influenced by the turnout speed. Recall that the turnout speed for all diverging locations is 40 km/h.

*Table 27: Distances of the back of the switch and clearing points relative to end of the platforms*

| **Location** | **Track** | **Maneuver** | **Type of train** | **Distance to back of switch [m]** | **Running time [s]** | **Speed [m/s]** | **Distance to clearing point [m]** | **Running time [s]** | **Speed [m/s]** |
|---|---|---|---|---|---|---|---|---|---|
| **Almere Oostvaar-ders** | Straight | Stopping | RE | 470 | 34.26 | 27.41 | 242.9 | 24.63 | 19.70 |
| | | Passing | RE | 470 | 12.09 | 38.89 | 242.9 | 6.25 | 38.89 |
| | | | IC | 470 | 12.09 | 38.89 | 142.0 | 3.65 | 38.89 |
| | Branch | Stopping | RE | 470 | 49.24 | 11.11 | 242.9 | 28.81 | 11.11 |
| **Almere Centrum** | Straight | Stopping | IC | 360 | 33.03 | 11.11 | 32.0 | 9.84 | 6.49 |
| | Branch | Stopping | RE | 360 | 29.96 | 23.96 | 132.9 | 18.17 | 14.54 |
| **Weesp** | Straight | Passing | IC | 546 | 17.87 | 30.56 | 218.0 | 7.13 | 16.96 |
| | Branch | Stopping | RE | 546 | 56.08 | 11.11 | 318.9 | 35.65 | 11.11 |

The clearing times $Tclear_{location,track,maneuver,type}$ in seconds can now be observed by subtracting the running time at the clearing point from the running time at the back of the switch in the table:

$$Tclear_{A-Oostvaarders,straight,stopping,RE} = 34.26 - 24.63 = 9.63\ s$$
$$Tclear_{A-Oostvaarders,straight,passing,RE} = 12.09 - 6.25 = 5.84\ s$$
$$Tclear_{A-Oostvaarders,straight,passing,IC} = 12.09 - 3.65 = 8.43\ s$$
$$Tclear_{A-Oostvaarders,branch,stopping,RE} = 49.24 - 28.81 = 20.44\ s$$
$$Tclear_{A-Centrum,branch,stopping,IC} = 33.03 - 9.84 = 23.18\ s$$
$$Tclear_{A-Centrum,straight,stopping,RE} = 29.96 - 18.17 = 11.79\ s$$
$$Tclear_{Weesp,straight,passing,IC} = 17.87 - 7.13 = 10.74\ s$$
$$Tclear_{Weesp,branch,stopping,RE} = 46.08 - 35.65 = 20.44\ s$$

## Approach time

The approach time is the time needed for the follower train to brake for the switch and differ for trains running to a straight and for trains running towards a deflecting track. In both cases, the follower train $n$ receives an $EoA$ to the start of the safety margin point, even if the switch has not been already locked. To ensure the train stops on time and does not overshoot the $EoA$, the approach time for a deflecting track is the largest of an operational braking from maximum track speed $v_{track}$ to the turnout speed $v_{turnout}$ or an emergency braking from maximum $v_{track}$ to the front of the switch. For a certain train type aiming to stop at a straight track, the approach time is instead the largest of an operational braking from maximum track speed to the stopping location at the platform or an emergency braking to the front of the switch in the case the switch is not locked properly.

Recall from Section 4.1 that the $v_{track}$ is equal to 140 km/h around Almere Oostvaarders, 80 km/h around Almere Centrum and 110 km/h around Weesp. Also, recall that $v_{turnout}$ for each location is 40 km/h. To compute the braking curves, the braking rates from Section 2.3.1 are used.

Below, the calculations can be found for a Regional Train approaching the deflecting and straight track at Almere Oostvaarders.

<u>Almere Oostvaarders – Regional Train stopping at deflecting track</u>

A Regional Train approaching the diverging switch at Almere Oostvaarders has to perform either an emergency braking in the case the switch is not locked properly or an operational braking from 140 km/h to 40 km/h to safely pass the switch:

$$t_{emergency,A-Oostvaarders} = \frac{\frac{140}{3.6}}{b_{emerg}} = 38.89\ s = 756.17\ m$$

$$t_{operational,A-Oostvaarders,deflecting} = \frac{\frac{140}{3.6}}{b_{oper,RE}} - \frac{\frac{40}{3.6}}{b_{oper,RE}} = 48.61 - 13.89 = 34.72\ s = 868.06\ m$$

As the distance required for an operational braking is greater than the required distance for an emergency braking, the approach time is defined as the time required to travel from the point where the train's speed corresponds to the emergency braking distance to the switch. In other words, the speed has to be determined at which the emergency braking distance is equal to the operational braking distance:

$$l_{emergency,A-Oostvaarders} = l_{operational,A-Oostvaarders,deflecting}$$

$$\frac{\left(\frac{140}{3.6}\right)^2}{2 * b_{emerg}} = \frac{x^2}{2 * b_{oper,RE}} - \frac{\left(\frac{40}{3.6}\right)^2}{2 * b_{oper,RE}}$$

It is found that $x$ is equal to 36.51 m/s. The approach time is now the time it takes for the Regional Train to perform an operational braking from 36.51 m/s to 11.11 m/s:

$$t_{approach} = \frac{36.51 - 11.11}{0.8} = 31.75\ s$$

Accounting for a 3 second brake application time, the consequent approach time is 34.75 seconds:

$$Tapproach_{A-Oostvaarders,branch} = 31.75\ s + 3\ s = 34.75\ s$$

Similarly, the approach times for all other locations are where a regional train can stop at the diverging track are computed (including a 3 second brake application delay)::

$$Tapproach_{A-Centrum,bramch} = 15.28\ s + 3 = 18.28\ s$$
$$Tapproach_{Weesp,branch} = 22.90\ s + 3 = 25.90\ s$$

Almere Oostvaarders – Regional Train stopping at straight track

For train approaching the straight track, the operational braking times are relative to the safety margin point . Therefore, the operational braking distance for trains running straight have to be reduced with the distance from the safety margin point to the stopping point, which can be adopted from Table 27. The consequent operational braking distance for a Regional Train aiming to the straight track at Almere Oostvaarders is:

$$l_{operational,A-Oostvaarders,straight} = \frac{\left(\frac{140}{3.6}\right)^2}{2 * b_{oper,RE}} - l_{run,sm} = 945.22 - 561 = 384.22\ m$$

So, a train starts performing an operational braking at 384.22 meters before the start of the switch, while it needs 756.17 meter to perform an emergency stop. Recall from Table 26 that when performing an operational braking to stop at the platform, the train has a speed of 29.94 m/s at the safety margin point .

The approach time is now the time it takes to run 756.17 meters to the safety margin point . Over this distance, the train first runs 756.17-384.22 = 371.96 meters at 140 km/h, after it will perform an operational braking for 384.22 meters from 38.89 to 29.94 m/s to the safety margin point . The consequent approach time is found to be 20.75 seconds:

$$t_{approach} = \frac{371.96}{38.89} + \frac{38.89 - 29.94}{0.8} = 9.56 + 11.19 = 20.75\ s$$

Accounting for a 3 second brake application time, the consequent approach time is 23.75 seconds:

$$Tapproach_{A-Oostvaarders,straight,stop} = 20.75\ s + 3\ s = 23.75\ s$$

Similarly, the approach times for all other locations are where a regional train can stop at a straight track are computed (including a 3 second brake application delay):

$$Tapproach_{A-Oostvaarders,straight,pass} = 19.44\ s + 3 = 22.44\ s$$
$$Tapproach_{A-Centrum,straight} = 11.11\ s + 3 = 14.11\ s$$
$$Tapproach_{Weesp,straight} = 15.28\ s + 3 = 18.28\ s$$

## 4.6 Overview of computations

Table 28 provides an overview of all headways between two consecutive regional trains at each predefined location, along with the technical and nominal speeds for each O-D pair.

*Table 28: Technical and normative speeds, along with headway time and locations for two consecutive Regional Trains*

| OD-pair | Maneuver | Head-way Location $l$ (m) | Tech. Speed (m/s) | Norm. Speed (m/s) | Sequence | Head-way MB (s) | Head-way VC (s) |
|---|---|---|---|---|---|---|---|
| Lelystad -Almere Oostvaarders | Simultaneously departing | 2509.0 | 38.89 | 32.78 | RE following RE | 45.95 | 16.98 |
| | Plain line open track | 2509.0 | 38.89 | 32.78 | RE following RE | 49.51 | 16.98 |
| | Sequentially arriving | 17116.8 | 38.89 | 32.78 | RE following RE | 137.50 | 133.17 |
| | Diverge at Almere Oostvaarders | 17501.0 | 11.11 | 11.11 | RE to deflecting track followed by RE to straight track | 65.38 | 65.38 |
| | | 17501.0 | 11.11 | 11.11 | RE to straight track followed by RE to deflecting track | 60.55 | 60.55 |
| | | 17501.0 | 11.11 | 11.11 | RE to deflecting track followed by a passing RE through straight track | 64.07 | 64.07 |
| Lelystad – Almere Buiten | Simultaneously departing | 2509.0 | 38.89 | 32.78 | RE following RE | 45.95 | 16.98 |
| | Open track | 2509.0 | 38.89 | 32.78 | RE following RE | 49.51 | 16.98 |
| | simultaneously arriving | 18398.4 | 38.89 | 32.78 | RE following RE | 49.51 | 16.98 |
| Lelystad – Almere Parkwijk | Simultaneously departing | 2509.0 | 38.89 | 32.78 | RE following RE | 45.95 | 16.98 |
| | Plain line open track | 2509.0 | 38.89 | 32.78 | RE following RE | 49.51 | 16.98 |
| | Sequetially ariving | 21984.8 | 38.89 | 32.78 | RE following RE | 137.50 | 133.17 |
| Almere Oostvaarders – Almere Buiten | Merge at Almere Oostvaarders | 18255.0 | 11.11 | 11.11 | RE from deflecting track followed by RE from straight track | 49.09 | 49.09 |
| | | 18255.0 | 11.11 | 11.11 | RE from straight track followed by RE from deflecting track | 38.53 | 38.53 |
| | | 18255.0 | 11.11 | 11.11 | RE passing through straight track followed by RE from deflecting track | 38.43 | 38.43 |
| | Plain line open track | 19252.0 | 30.66 | 23.89 | RE following RE | 67.94 | |
| | Simultaneously arriving | 19543.33 | 30.66 | 23.89 | RE following RE | 68.07 | 34.03 |
| Almere Oostvaarders – Almere Parkwijk | Merge at Almere Oostvaarders | 18255.0 | 11.11 | 11.11 | RE from deflecting track followed by RE from straight track | 49.09 | 49.09 |
| | | 18255.0 | 11.11 | 11.11 | RE from straight track followed by RE from deflecting track | 38.53 | 38.53 |
| | | 18255.0 | 11.11 | 11.11 | RE passing through straight track followed by RE from deflecting track | 38.43 | 38.43 |
| | Plain line open track | 21009.9 | 38.89 | 32.78 | RE following RE | 49.51 | 16.98 |
| | Sequetially ariving | 21984.8 | 38.89 | 32.78 | RE following RE | 137.50 | 133.17 |
| Almere Oostvaar | Merge at Almere Oostvaarders | 18255.0 | 11.11 | 11.11 | RE from deflecting track followed by RE from straight track | 49.09 | 49.09 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ders – Almere Centrum | | 18255.0 | 11.11 | 11.11 | RE from straight track followed by RE from deflecting track | 38.53 | 38.53 |
| | | 18255.0 | 11.11 | 11.11 | RE passing through straight track followed by RE from deflecting track | 38.43 | 38.43 |
| | Plain line open track | 21009.9 | 38.89 | 32.78 | RE following RE | 49.51 | 16.98 |
| | Simultaneously arriving | 22749.0 | 38.89 | 32.78 | RE following RE | 49.51 | 16.98 |
| Almere Buiten – Almere Parkwijk | Simultaneously departing | 21977.3 | 36.72 | 28.89 | RE following RE | 51.80 | 18.32 |
| | Open track | 21977.3 | 36.72 | 28.89 | RE following RE | 56.18 | X |
| | Sequetially ariving | 22087.4 | 36.72 | 28.89 | RE following RE | 137.50 | 133.17 |
| Almere Buiten – Almere Centrum | Simultaneously departing | 22409.0 | 38.89 | 32.78 | RE following RE | 45.95 | 16.98 |
| | Plain line open track | 22409.0 | 38.89 | 32.78 | RE following RE | 49.51 | 16.98 |
| | Simultaneously arriving | 22749.0 | 38.89 | 32.78 | RE following RE | 49.51 | 16.98 |
| Almere Parkwijk – Almere Centrum | Sequentially departing | 23714.6 | 26.68 | 20.83 | RE following RE | 47.44 | 20.14 |
| | Plain line open track | 23714.6 | 26.68 | 20.83 | RE following RE | 77.90 | X |
| | Simultaneously arriving | 23995.2 | 26.98 | 20.83 | RE following RE | 77.90 | 26.71 |
| Almere Centrum – Almere Muziek wijk | Simultaneously departing | 26245.9 | 28.63 | 22.78 | RE following RE | 47.29 | 19.27 |
| | Plain line open track | 26245.9 | 28.63 | 22.78 | RE following RE | 71.25 | X |
| | Sequetially ariving | 26331.8 | 28.63 | 22.78 | RE following RE | 137.50 | 133.17 |
| Almere Centrum – Almere Poort | Simultaneously departing | 27814.0 | 38.89 | 33.33 | RE following RE | 45.19 | 16.69 |
| | Plain line open track | 27814.0 | 38.89 | 33.33 | RE following RE | 48.69 | 16.69 |
| | Sequetially ariving | 29845.8 | 38.89 | 33.33 | RE following RE | 137.50 | 133.17 |
| Almere Muziek wijk – Almere Poort | Sequentially departing | 29353.0 | 38.89 | 33.33 | RE following RE | 45.19 | 16.69 |
| | Plain line open track | 29353.0 | 38.89 | 33.33 | RE following RE | 48.69 | 16.69 |
| | Sequetially ariving | 29845.8 | 38.89 | 33.33 | RE following RE | 137.50 | 133.17 |
| Almere Muziek wijk – Weesp | Sequentially departing | 29353.0 | 38.89 | 33.33 | RE following RE | 45.19 | 16.69 |
| | Plain line open track | 29353.0 | 38.89 | 33.33 | RE following RE | 48.69 | 16.69 |
| | simultaneously arriving | 36287.9 | 38.89 | 33.33 | RE following RE | 48.69 | 16.69 |
| Almere Poort - Weesp | Sequentially departing | 33300.0 | 38.89 | 33.33 | RE following RE | 45.19 | 16.69 |
| | Plain line open track | 33300.0 | 38.89 | 33.33 | RE following RE | 48.69 | 16.69 |
| | Simultaneously arriving | 36287.9 | 38.89 | 33.33 | RE following RE | 48.69 | 16.69 |

Some cells are marked with an "X" instead of a value, indicating that the track section is too short to allow trains to virtually couple. However, virtual coupling remains feasible during simultaneous arrivals as trains approach the station.

Similarly, Table 29 provides an overview of all headway locations, technical speeds and normative speeds for a regional train following an Intercity train and vice versa.

*Table 29: Technical and normative speeds, along with headway time and locations between Regional trains and Intercity Trains*

| Headways between Regional (RE) and Intercity (IC) train | | | | | | | |
|---|---|---|---|---|---|---|---|
| **OD-pair** | **Maneuver** | **Head-way Location $l$ (m)** | **Tech Speed (m/s)** | **Norm Speed (m/s)** | **Sequence** | **Head-way MB (s)** | **Head-way VC (s)** |
| Lelystad – Almere Centrum | Merge at Lelystad | 202.0 | 38.89 | 36.11 | IC from straight track followed by RE from deflecting track | 44.02 | 44.02 |
| | | 202.0 | 38.89 | 36.11 | RE from deflecting track followed by IC from straight track | 36.88 | 36.88 |
| | Plain line Open track | 23170.4 | 38.89 | 36.11 | IC followed by RE | 50.50 | 18.20 |
| | | 23170.4 | 38.89 | 36.11 | RE followed by IC | 53.29 | 26.51 |
| | Diverge at Almere Centrum | 24362.0 | 11.11 | 11.11 | IC to deflecting track followed by RE to straight track | 59.38 | 59.38 |
| | | 24362.0 | 11.11 | 11.11 | RE to straight track followed by IC to deflecting track | 45.52 | 45.52 |
| Almere Centrum - Weesp | Merge at Almere Centrum | 24991.0 | 38.89 | 36.11 | IC from straight track followed by RE from deflecting track | 44.07 | 44.07 |
| | | 24991.0 | 38.89 | 36.11 | RE from deflecting track followed by IC from straight track | 36.89 | 36.89 |
| | Plain line Open track | 36767.5881 | 38.89 | 36.11 | IC followed by RE | 50.50 | 18.20 |
| | | 36767.5881 | 38.89 | 36.11 | RE followed by IC | 53.29 | 26.51 |
| | Diverge at Weesp | 39890.0 | 38.89 | 36.11 | IC to straight track followed by RE to deflecting track | 52.61 | 52.61 |
| | | 39890.0 | 38.89 | 36.11 | RE to deflecting track followed by IC to straight track | 59.91 | 59.91 |

# 5. Evaluation

This Section evaluates each concept on frequency, infrastructure occupancy and generalized travel time. For this, first the best performing operational variants for each concept based on non-direct O-D pairs and frequency will be quantitatively selected using the computed running times, headways and extracted patterns from Section 4.

## 5.1 Quantitative selection

In this Section, the most promising patterns will be selected within each concept to ultimately evaluate the effectiveness of each concept. To this end, a base variant is also being considered for a better understanding of the performance of each concept.

### *Base variant*

The base variant is assumed to be a pattern in which two consecutive regional trains perform a full stopping pattern, alternated with a direct Intercity Train. For a better understanding, the corresponding time-distance diagram can be found in Figure 32.

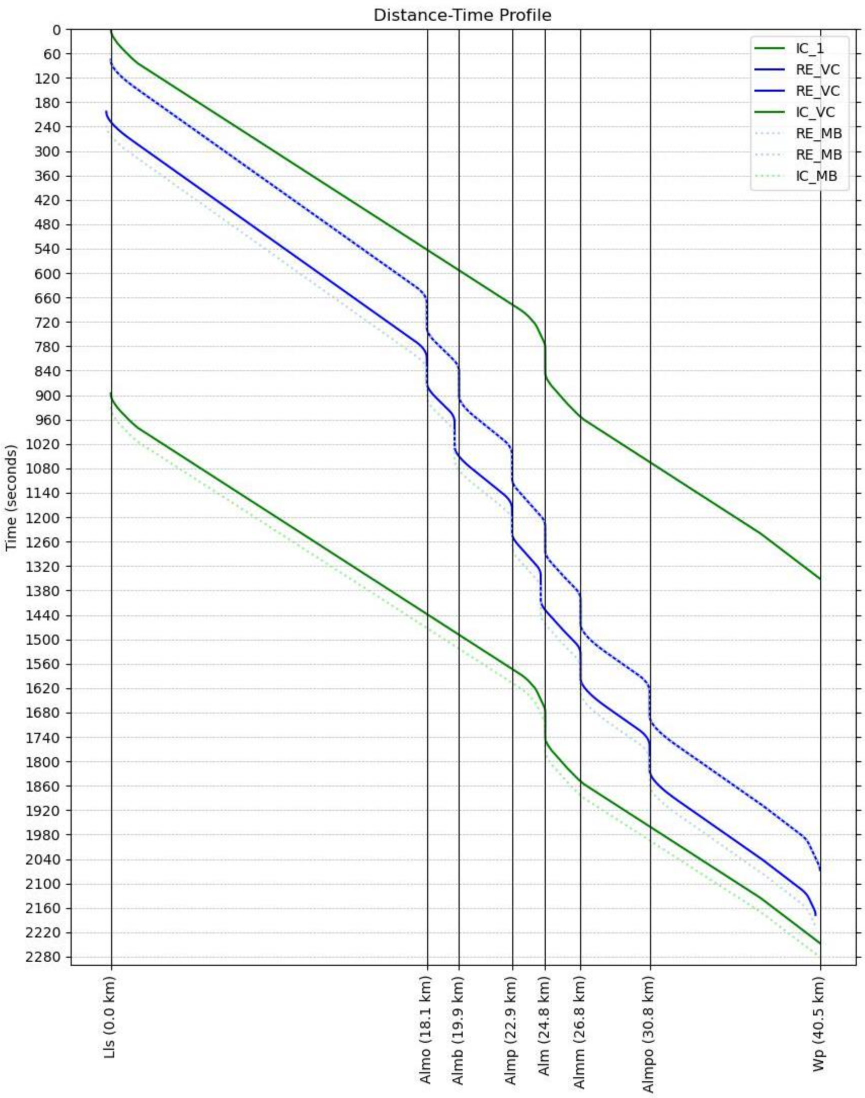



*Figure 32: Time-distance diagram for base-variant*

The maximum $f_{max,p,q}$ is calculated for a full stopping pattern $p$ and full stopping pattern $q$ by integrating the algorithm from Section 2.3 in Python. For this, a time period $T$ of one hour (i.e. 3600 seconds) was considered. The running time $r_{o,d,n}$ between each origin station $o$ and destination station $d$ for train $n$ are obtained from Section 4.4 and minimum headways $h_{l,n,n-1}$ at each location $l$ between train $n$ and the preceding train $n-1$ from Section 4.6. The algorithm from Section 2.3 was implemented in Python to simulate time-distance diagrams, providing detailed visualizations of each train path.

It is obtained that the maximum frequency is 3.87 cycles per hour for ETCS Level 2 MB and 4.02 cycles per hour for MB when the minimum time buffers are applied. The corresponding infrastructure occupancy is found to be 72.51% and 69.63% for MB and VC respectively when applying 3 cycles per hour. When applying 4 cycles per hour, the infrastructure occupancy is found to be 96.67% for MB and 92.84% for VC respectively.

## *Concept 1*

By applying the algorithm from Section 2.3.4 to each combination of patterns $p$ and $q$ compiled for concept 1, a total of 105 combinations have been evaluated on $f_{max,p,q}$, with detailed results in Appendix A. Again, a time period $T$ of one hour (i.e. 3600 seconds) was considered. In this Section, only the best performing outputs are evaluated for each of the following scenarios:

1. The skip-stop trains skips one station in both sections;
2. The skip-stop trains skips two stations in the first section and one in the second;
3. The skip-stop trains skips one station in the first section and none in the second;
4. The skip-stop trains skips two stations in the first section and none in the second;
5. The skip-stop trains skips no stations in the first section and one in the second.

Since skip-stop trains must skip at least one station, scenarios where all stations are either skipped or served are not relevant. For Scenarios 1 and 2, which include OD pairs requiring transfers, two sub-scenarios are considered:

- 'a': The best-performing pattern maximizing frequency, with passengers transferring for one OD pair.
- 'b': The best-performing pattern with no required transfers for any OD pairs.

The MB and VC occupation rates, frequencies, and infrastructure occupancy for all five scenarios are shown in Table 30. The infrastructure occupancy is calculated by multiplying the occupation rate by the associating applied frequency. For clarity and ease of comparison, the results are also visualized in a bar chart (see Figure 33). The corresponding time-distance diagrams are obtained through Python and provided in Appendix A for further reference.

*Table 30: Occupation rates, infrastructure occupancy and transfers for several F= frequencies concept 1*

| **Sce-nario** | **Pattern $p+q$** | **Max. F. with min. buffer (cycles/hour)** | | **Occupation rates** | | **Applied F** | **Infrastructure occupancy (%)** | | **Applied F** | **Infrastructure occupancy (%)** | | **# of OD-pairs with transfers** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **MB** | **VC** | **MB** | **VC** | | **MB** | **VC** | | **MB** | **VC** | |
| **1a.** | 1-2-2b + 2-1a | 4.91 | 5.15 | 0.19 | 0.18 | 4 | 74.72% | 70.92% | 5 | 93.40% | 88.65% | 1 |
| **1b.** | 1-2-2b + 2-1b | 4.29 | 4.59 | 0.22 | 0.20 | 4 | 86.68% | 80.44% | 5 | 108.35% | 100.55% | 0 |
| **2a.** | 1-2-1b + 1-2a | 4.93 | 5.37 | 0.19 | 0.17 | 4 | 74.52% | 67.80% | 5 | 93.15% | 84.75% | 1 |
| **2b.** | 1-2-1b + 1-2b | 4.29 | 4.63 | 0.22 | 0.20 | 4 | 86.68% | 79.72% | 5 | 108.35% | 99.65% | 0 |
| **3.** | 1-2-2b + 2-2a | 4.29 | 4.59 | 0.22 | 0.20 | 4 | 86.68% | 80.44% | 5 | 108.35% | 100.55% | 0 |
| **4.** | 1-2-1b + 2-2a | 4.29 | 4.63 | 0.22 | 0.20 | 4 | 86.68% | 79.72% | 5 | 108.35% | 99.65% | 0 |
| **5.** | 2-2-2a + 2-1a | 4.28 | 4.45 | 0.22 | 0.21 | 4 | 86.76% | 83.28% | 5 | 108.45% | 104.10% | 0 |

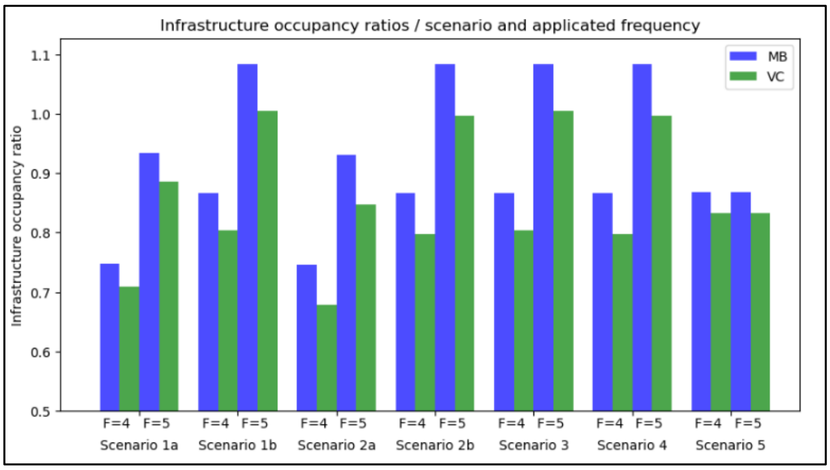



*Figure 33: Infrastructure occupancy ratio / scenario and applicated frequencies concept 1*

Based on Table 30 and Figure 33, Scenario 2a has the potential to offer the highest frequency, supporting 5 cycles per hour with VC and an associated infrastructure occupancy of 84.75%, compared to 93.15% under ETCS Level 2 MB.

The best-performing scenario without requiring passengers to transfer in any O-D pair is Scenario 2b, with an infrastructure occupancy of 79.72% at 4 cycles per hour. Although this scenario could technically support 5 cycles per hour, this would result in a high infrastructure occupancy of 99.65%, which is undesirable even with the implementation of VC and ATO. As a consequence, the maximum practical frequency remains at 4 cycles per hour for scenario 2b. Consequently, the practical maximum frequency for Scenario 2b is 4 cycles per hour. Scenarios 1b, 3, 4, and 5 also require no transfers but have higher infrastructure occupancy than Scenario 2b.

Considering all factors, Scenarios 2a and 2b are deemed the most promising for Concept One and are selected for final assessment.

## *Concept 2a*

By applying the algorithm from Section 2.3.4 to each combination of patterns $p$ and $q$ compiled for concept 2a, a total of 119 combinations have been evaluated on $f_{max,p,q}$, with detailed results in Appendix B. Again, a time period $T$ of one hour (i.e. 3600 seconds) was considered. In this Section, only the best performing outputs are evaluated for each of the following scenarios:

1. Maintain a traditional pattern at the first section in which the skip-stop train skips one station. At the second section, a skip-stop pattern is applied.
2. Maintain a traditional pattern at the first section in which the skip-stop train skips two stations. At the second section, a skip-stop pattern is applied.
3. Apply a skip-stop pattern at the first section for both regional trains. At the second section, a traditional pattern is maintained, in which the skip-stop train skips one station.
4. Apply a skip-stop pattern at the first and second section.

For scenario 4, two combinations of patterns have been analyzed: the first (4a.) features simultaneous arrivals and departures at all major stations, minimizing non-direct OD pairs by having the skip-stop train skip two stations. The second features (4b.) the best performing pattern best when solely focusing on maximizing frequency. Frequencies of each scenario, along with the corresponding MB and VC occupation rates, and amount of non-direct O-D pairs are shown in Table 31 and Figure 34.

*Table 31: Occupation rates, infrastructure occupancy and transfers for several F= frequencies concept 2a*

| **Scenario** | **Pattern $p+q$** | **Max. F. with min. buffer (cycles/hour)** | | **Occupation rates** | | **Applied F** | **Infrastructure occupancy (%)** | | **Applied F** | **Infrastructure occupancy (%)** | | **# of OD-pairs with transfers** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **MB** | **VC** | **MB** | **VC** | | **MB** | **VC** | | **MB** | **VC** | |
| **1.** | 1-2-2b + 1-1b | 4.93 | 5.34 | 0.19 | 0.17 | 4 | 74.52% | 68.28% | 5 | 93.15% | 85.35% | 2 |
| **2.** | 1-2-1b + 1-1b | 4.93 | 5.39 | 0.19 | 0.17 | 4 | 74.52% | 67.56% | 5 | 93.15% | 84.45% | 3 |
| **3.** | 1-1-1a + 2-1a | 4.96 | 5.43 | 0.18 | 0.17 | 4 | 73.92% | 66.96% | 5 | 92.40% | 83.70% | 4 |
| **4a.** | 1-2-1a1 + 1-1a | 5.64 | 6.03 | 0.16 | 0.15 | 5 | 80.40% | 74.60% | 6 | 96.48% | 89.52% | 4 |
| **4b.** | 1-1-1a + 1-1b | 5.83 | 6.16 | 0.15 | 0.15 | 5 | 77.45% | 72.85% | 6 | 92.94% | 87.42% | 6 |

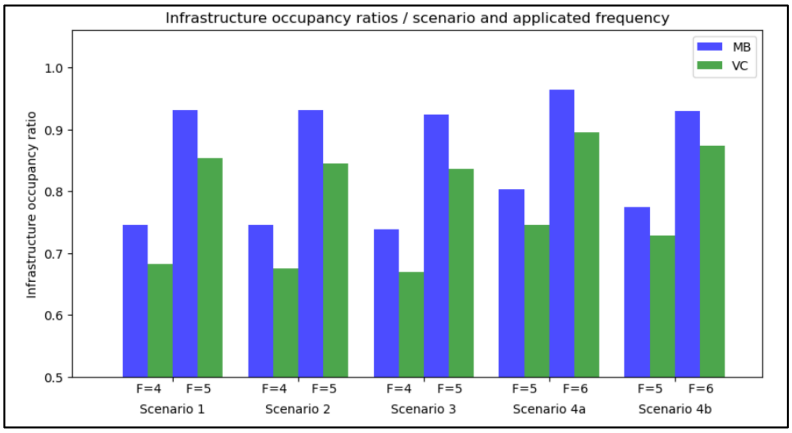


*Figure 34: Infrastructure occupancy / scenario and applicated frequencies concept 2a*

Based on Table 31 and Figure 34, it can be observed that scenarios 4a and 4b offer the highest frequency of 6 cycles per hour when VC is applied, with associated infrastructure occupancy values of 89.52% and 87.42%, respectively. In contrast, scenarios 1, 2, and 3 can each achieve a maximum frequency of 5 cycles per hour. Across all scenarios, the infrastructure occupancy for VC remains below 90% when applying the higher frequency, whereas in the case of MB, the capacity exceeds 90% in all scenarios.

Taking a closer look to the amount of non-direct O-D pairs each scenario involves, it can be observed that scenario 1 emerges as most favorable. Scenario 2 and 3, also with a maximal frequency of 5 cycles per hour, more O-D pairs require a transfer. Comparing Scenario 4a and 4b, both enabling 6 cycles per hour under VC, within scenario 4b travelers are required to transfer in 6 origin-destination (OD) pairs, while in scenario 4a, transfers are necessary for only 4 OD pairs, making scenario 4a more favorable.

Considering all factors, Scenarios 1 and 4a are deemed most promising for Concept 2a and therefore selected for final assessment.

## *Concept 2b*

By applying the algorithm from Section 2.3.4 to each combination of patterns $p$ and $q$ compiled for concept 2b, a total of 12 combinations have been evaluated on $f_{max,p,q}$, with detailed results in Appendix C. Again, a time period $T$ of one hour (i.e. 3600 seconds) was considered. In this Section, only the best performing outputs are evaluated for each of the following scenarios:

1. Temporarely skipping Almere Buiten during rush hour for all trains
2. Temporarely skipping Almere Parkwijk during rush hour for all trains

Fully skipping Almere Oostvaarders was not considered, as residents living between Lelystad and Almere Oostvaarders may already face long cycling distances to reach the nearest station. Additionally, closing more than one station is not deemed favorable, as it would result in an odd number of stations, which would again reduce the efficiency fully skipping a station. Frequencies of each scenario, along with the corresponding MB and VC occupation rates, and amount of non-direct O-D pairs are shown in Table 32 and Figure 35. Patterns $p$ are extracted from Table 19, while patterns $q$ are extracted from Table 18.

*Table 32: Occupation rates, infrastructure occupancy and transfers for several F= frequencies concept 2b*

| **Sce-nario** | **Pattern $p + q$** | **Max. F. with min. buffer (cycles/hour)** | | **Occupation rates** | | **Applied F** | **Infrastructure occupancy (%)** | | **Applied F** | **Infrastructure occupancy (%)** | | **# of OD-pairs with transfers** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **MB** | **VC** | **MB** | **VC** | | **MB** | **VC** | | **MB** | **VC** | |
| **1.** | 1-1a + 1-1a | 6.83 | 7.41 | 0.13 | 0.12 | 7 | 90.86% | 82.81% | 8 | 103.84% | 94.64% | 4 |
| **2.** | 1-1c + 1-1a | 7.07 | 7.44 | 0.12 | 0.12 | 7 | 87.29% | 82.39% | 8 | 99.76% | 94.16% | 4 |

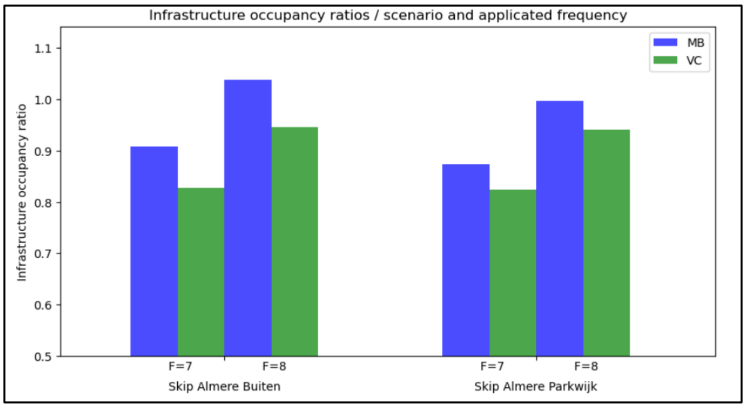



*Figure 35: Infrastructure occupancy ratio / scenario and applicated frequencies concept 2b*

Based on Table 32 and Figure 35, it can be observed that both scenarios able to operate a maximum of 7 cycles per hour, a frequency of 8 cycles per hour exceeds a infrastructure occupancy of 90%, this frequency is not deemed feasible. Although both scenarios show similar results regarding infrastructure occupancy, temporarily skipping Almere Parkwijk appears more favorable, as the infrastructure occupancy value for VC is slightly lower as compared to Scenario 1.

Examining the number of non-direct OD pairs, both variants require transfers for 4 OD pairs. Consequently, no distinction is observed between them.

Considering this, Scenario 1 is deemed the most promising for Concept 2b and selected for final assessment.

## 5.2 Final assessment

The selection process in Section 5.1 resulted in the selection of five pattern combinations (hereafter referred to as “variants”) that balanced frequency with a minimal number of non-direct OD pairs. Within Operational Concept 1, two variants were selected for final assessment:

1. **Variant 1**: This variant offers the highest possible frequency with no required transfers for any OD pairs, achieving a maximum frequency of 4 cycles per hour under both VC and ETCS Level 2 MB. Here, the leader train is a full-stopping regional train, and the follower is a skip-stop train.
2. **Variant 2**: This variant achieves a maximum frequency of 5 cycles per hour with VC and 4 cycles per hour with ETCS Level 2 MB, with one OD pair requiring a transfer. In this configuration, the skip-stop train skips two stations between Lelystad and Almere Centrum, then switches roles with the full-stopping train at Almere Centrum, skipping one station between Almere Centrum and Weesp.

Similarly, two variants were selected for final assessment within Operational Concept 2a:

3. **Variant 3**: This variant minimizes the required number of OD-pair transfers, supporting 5 cycles per hour with VC and 4 cycles per hour with ETCS Level 2 MB. It requires transfers for only 2 OD-pairs, achieving nearly the same cycle frequency as Variant 4, with 1 fewer cycle per hour.
4. **Variant 4**: This variant features simultaneous arrivals and departures at all major stations, minimizing non-direct OD pairs by having the skip-stop train skip two stations. Although the second train's running times are longer, it still supports a frequency of 6 cycles per hour with VC and 5 with ETCS Level 2 MB.

Lastly, for Concept 2b, one variant was selected:

5. **Variant 5:** This variant involves fully skipping Almere Parkwijk during the morning rush hour, creating an even number of stops and enabling higher frequencies with optimal performance. This setup allows up to 7 cycles per hour under both ETCS Level 2 MB and VC, with four OD pairs requiring a transfer.

The associated time-distance diagrams for each variant are visualized in Figures 36-40. These diagrams visually represent the relationship between travel time and distance for different train services, allowing for a comparison of how each variant affects passenger journey times and transfers. The blue lines represent the regional trains, while the green lines represent the IC-trains. Additionally, the light-colored dotted lines represent trains running at Moving Block, while the solid lines represent the scenario in which trains are able to virtually couple.

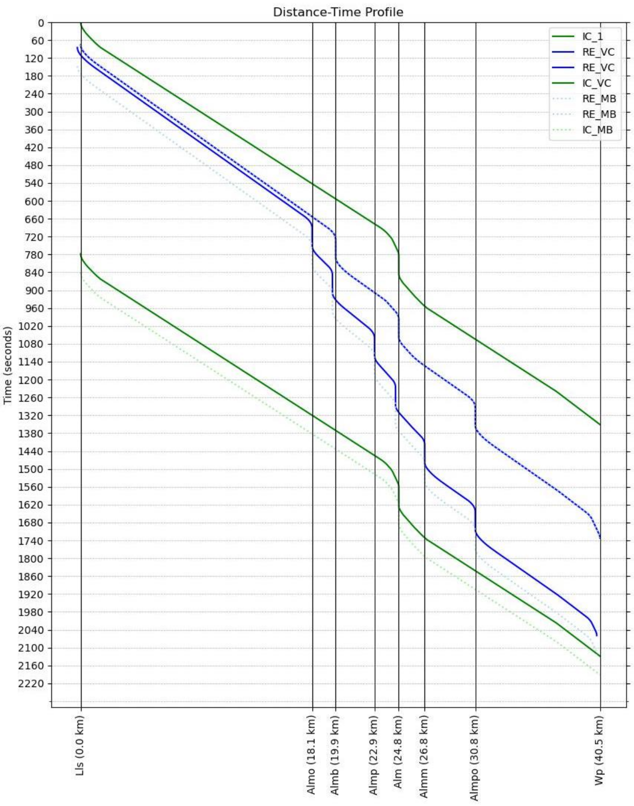



*Figure 36: Time-distance diagram variant 1*

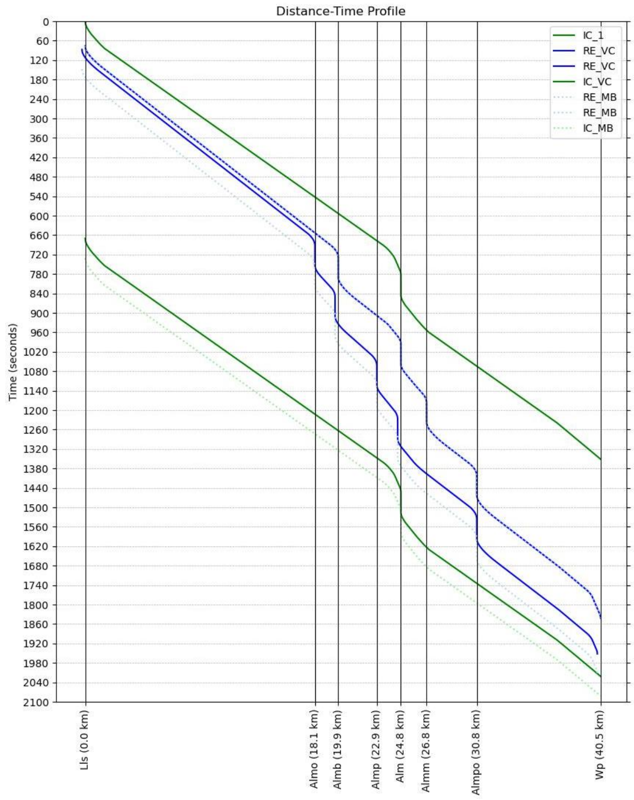



*Figure 37: Time-distance diagram variant 2*

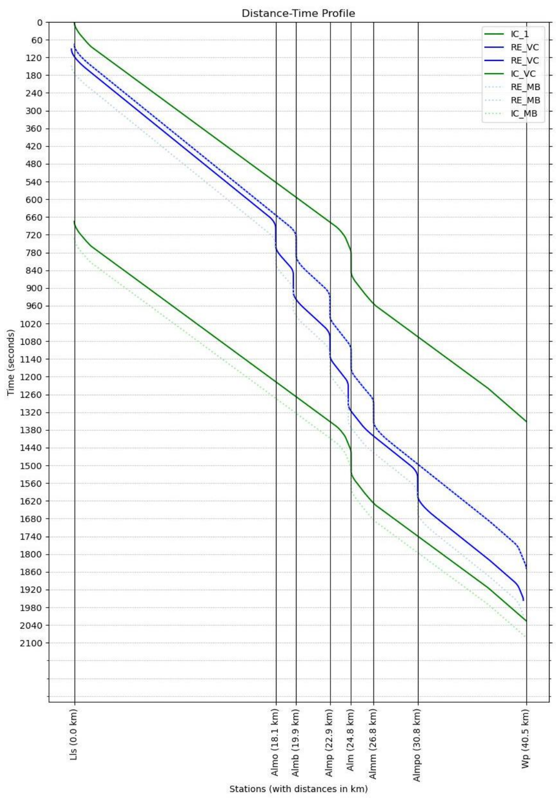



*Figure 38: Time-distance diagram variant 3*

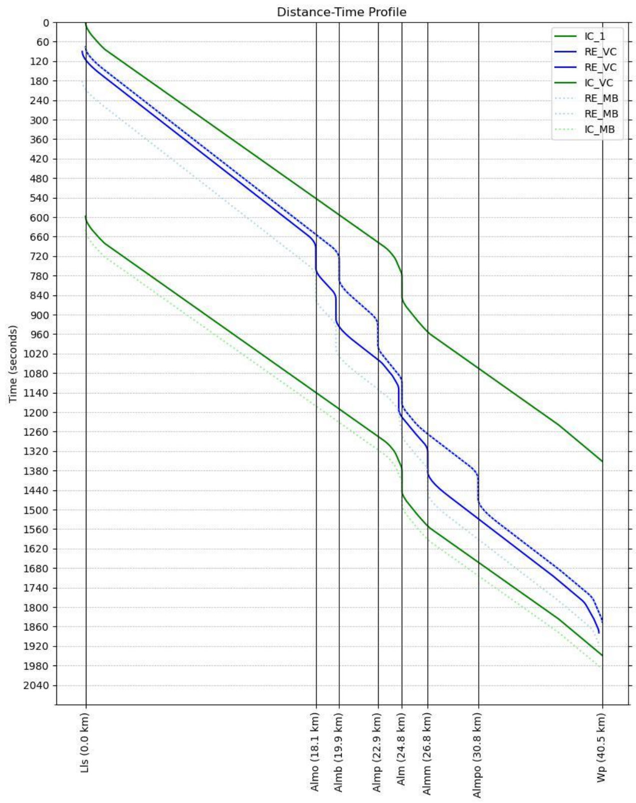



*Figure 39: Time-distance diagram variant 4*

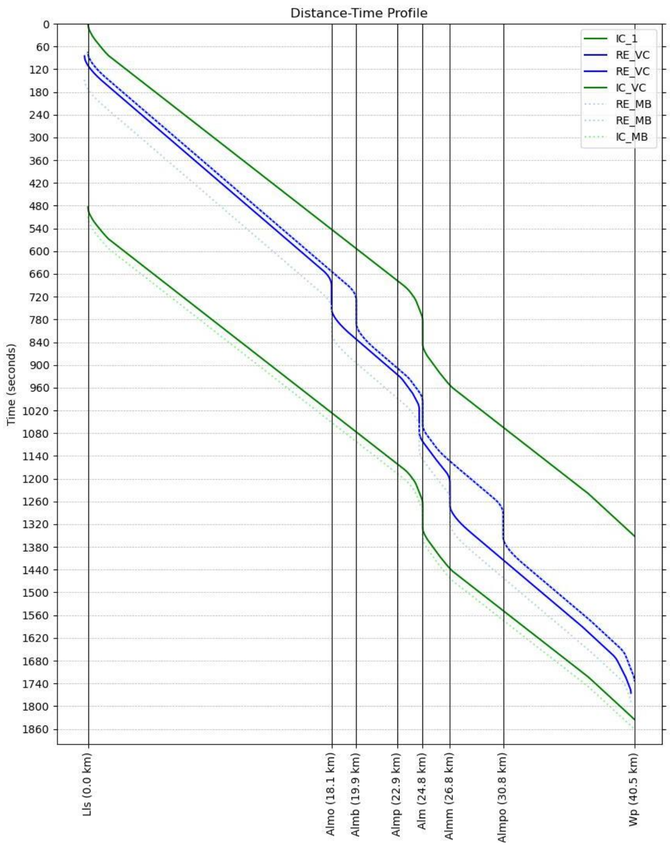



Figure 40: Time-distance diagram variant 5

The final assessment of these variants is based on three criteria: frequency, infrastructure occupancy, and generalized travel times.

## *Frequency and infrastructure occupancy*

The frequency and infrastructure occupancy for each variant have already been calculated in Section 5.1. To provide a clear comparison between all variants, the frequency and infrastructure occupancy for the final selected variants are summarized in Figure 41.

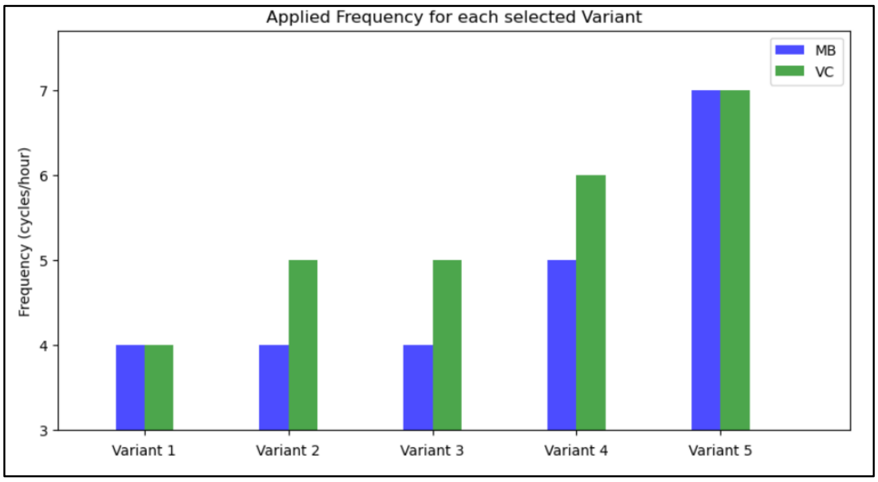



Figure 41: Applied maximum amount of cycles/ hour per variant for MB and VC

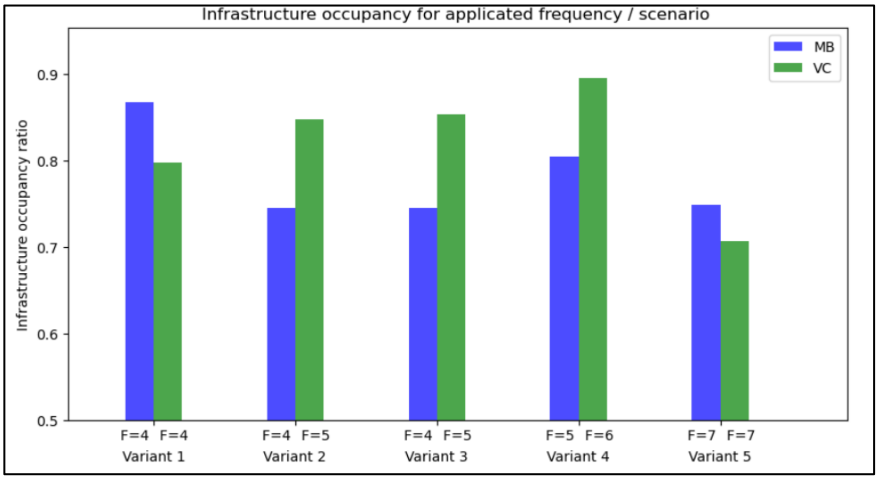



*Figure 42: Infrastructure occupancy at several frequencies for MB and VC*

When evaluating infrastructure occupancy and frequency from Figure 41 and Figure 42, Variant 5 was found to achieve the highest frequency for both ETCS Level 2 MB and VC operations, supporting 7 cycles per hour. However, implementing this odd number of cycles would result in uneven departure times and inconsistent train distribution, which can negatively affect the user experience by creating confusion due to irregular service intervals. As a result, a frequency of 6 cycles per hour, as already achieved by Variant 4, could potentially be the highest feasible operational frequency for this Variant. Although Variant 5 consumes a slightly higher infrastructure occupation when compared to all other Variants, these ratios are overall in the range between 85% to 90% with the selected frequency, and therefore comparable across all variants. Notably, the implementation of VC enables one additional cycle per hour in Variants 2, 3 and 4 compared to ETCS Level 2 MB. In contrast, Variant 1 exhibits the lowest number of cycles per hour when applied on the SAAL corridor. Similar to Variant 5, Variants 2 and 3 would also result in uneven departure times due to its odd number of cycles.

### *Generalized travel time*

Generalized travel times (GTT) were computed by accounting for five components, being bike time, waiting time, in-vehicle time, transfer time, and a transfer penalty. The waiting time, in-vehicle time, transfer time and transfer penalty are computed using the method description in Section 2.

The additional bike time, included in variant 5 to account for the impact of fully skipping a station, is calculated by identifying the point at which passengers would opt to cycle directly downstream to Almere Centrum instead of cycling upstream to Almere Buiten and then taking the train. At this point, the total disutility of cycling to a station upstream and taking a train is equal to the disutility to cycle a longer distance downstream. The consequent cycle time to the downstream station is found to be 888.6 seconds of cycling, equivalent to 3.7 km cycling distance. To determine the additional bike time, the cycle distance to Almere Parkwijk—0.74 kilometers in a straight line or 1.04 kilometers when accounting for the detour factor—was subtracted from the total obtained distance. This means that the maximum additional distance passengers would need to cycle is 2.66 kilometers, equivalent to 638.4 seconds at a speed of 15 km/h. The consequent mean additional bike time for the affected area is 319.2 seconds, or 5.32 minutes.

The linear components (being access bike time, access waiting time, in-vehicle time and transfer time) are normalized relative to in-vehicle time. The transfer penalty is normalized by assuming a mean transfer time and computing the equivalent in-vehicle time using the $\beta$-values from Table 4 and the formulas from Section 2.4:

$$10 * -0.097 - 0.113 = equavalent\ in\ vehicle\ time * -0.049$$

It is obtained that a 10 minute transfer time is equivalent to a 22 minute in-vehicle time. To express all components in terms of equivalent in-vehicle time, the linear components are normalized relative to in-vehicle time using the $\beta$-values from Table 4.

*Table 33: Normalized GTT-values towards IVT*

| Parameter | Normalized value |
|---|---|
| **access_bike (BT)** | 1.94 |
| **wait_access (WT)** | 1.49 |
| **in-vehicle_train (IVT)** | 1.00 |
| **Transfer (T)** | 1.98 |

The transfer penalty $P$ is normalized by using the normalized linear values from Table 33 and the method from Section 2.4 with the assumed mean transfer time and equivalent in-vehicle time of 22 minutes:

$$10 * 1.98 + P = 22 * 1.00$$

It is obtained that the normalized transfer penalty $P$ is 5.81 minutes. Now, the GTT can be computed by using Formula (2):

$$GTT = 1.94 * Bike\ Time + 1.49 * Access\ Wait\ Time + In\ Vehicle\ Time + 1.98 * Transfer\ Time + P$$

Note that the transfer penalty $P$ is only applied to each OD pair requiring a transfer within a given variant. The bar chart in Figure 43 illustrates the resulting GTTs for each variant, calculated by summing the generalized time for all OD pairs within that variant. Notably, each OD pair is weighted equally in this analysis, as no demand data were incorporated. This means that both low-demand and high-demand travel streams contribute equally to the overall GTT. The generalized travel time for each O-D pair and associated element values can be found in Appendix D.

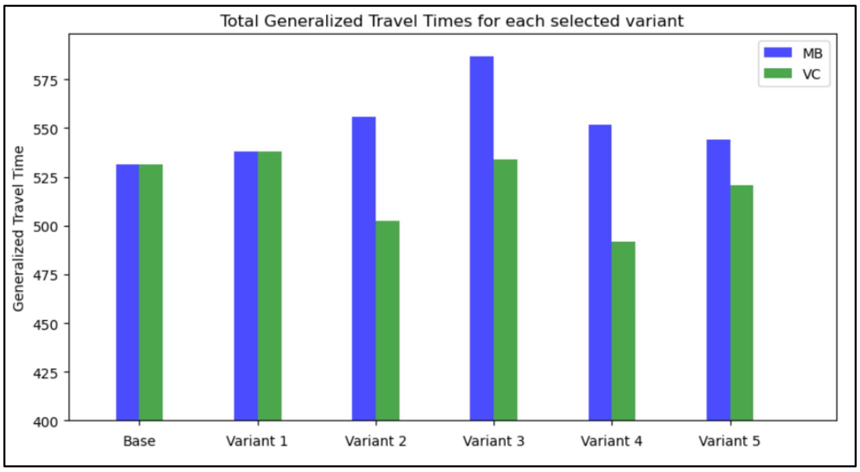



*Figure 43: Final comparison of generalized travel times per variant*

When evaluating the GTTs from Figure 43, Variant 4 was found to achieve the lowest GTT for implementing VC, followed by Variants 2, 5, 3, and 1. Notably, Variant 1 exhibited a slightly higher GTT compared to the base variant and showed no improvement with the introduction of VC. The increased GTT for Variant 1 is mainly due to longer waiting times at some stations, and the lack of improvement is because introducing VC does not affect its frequency, in-vehicle time, or required transfers.

In contrast, the introduction of VC significantly reduces GTTs for Variants 2, 3, and 4 when compared to ETCS Level 2 MB. For these variants, the GTT under VC is nearly half of that observed with ETCS Level 2 MB. Although lower GTTs were achieved with VC, it was observed that under ETCS Level 2 MB, these variants have higher GTTs compared to the base variant. This suggests that implementing skip-stop variants provides benefits under VC by improving flexibility but does not yield advantages for travelers under ETCS

Level 2 MB. Lastly, while Variant 5 enables the highest frequency, it does not achieve the lowest GTT, primarily due to the additional biking time factored into the calculations.

### *Sensitivity of the results*

A sensitivity analysis was conducted to examine the impact of varying input parameters on the capacity performance of Virtual Coupling. The results indicate a high sensitivity, suggesting that small changes in input parameters can significantly affect the outcomes. For instance, increasing the dwell time from 60 seconds to 90 seconds at each station where transfers within platoons are possible already demonstrated an impact on the maximum achievable frequency. Under these conditions, Variant 4 was found to support a maximum of only 5 cycles per hour. Additionally, the assumptions underlying these results, such as buffer time and maximum acceptable infrastructure occupancy, could also influence the performance results. For example, assuming a 90-second dwell time at each station where transfers within platoons are possible results in a GTT of 532.8 for Variant 4 (increment of 8.3%), making it less favorable than Variant 2 and Variant 5. However, both of these are also skip-stop patterns and still outperform a full-stopping variant as introduced in Variant 1 with direct connections only. Additionally, since dwell times, buffer times and maximum acceptable infrastructure occupancy are applied consistently across all variants, and therefore their impact on relative performance is expected to remain minimal.

Furthermore, as noted in Section 2, no demand data was incorporated into this analysis, as a consequence the GTT for a certain pattern treats all O-D pairs equally. These GTTs should hence be treated as comparative indicators rather than absolute values which would require the inclusion of demand-weighted factors. Moreover, the inclusion of additional bike time offers some insight into the disutility of temporarily fully skipping a Almere Parkwijk (e.g. Variant 5), but does not account for all potential negative impacts or the number of real affected travelers by introducing this variant. As such, it should be treated only as a comparative penalty factor of the variant’s impact rather than an absolute value.

Although this might give some bias, the obtained GTTs, infrastructure occupancy and frequency provide valuable insights into the relative impact of each variant, allowing to compare the relative performance of different stopping and operational plans. Incorporating real passenger demand for the SAAL corridor could potentially further support the implementation of skip-stop concepts during peak-demand hours, as the primary travel flows are likely concentrated from regional stations to major destinations rather than between regional stations.

# 6. Conclusions

This final chapter presents the conclusions of the research. It begins by addressing the sub-questions, providing detailed answers based on the findings. Finally, it concludes by answering the main research question, synthesizing the key insights from the study.

**Sub-question 1: What are the characteristics of current platooning and demand-driven transport concepts that could be used with VC?**

The first phase identified seven critical aspects through literature review and expert consultations for designing concepts tailored for VC main line implementation:

1. Different Stopping Plans: Different stopping plans are identified, such as point-to-point, full-stopping patterns, skip-stop patterns, and conventional IC-RE pattern.
2. (De)coupling Locations: (De)coupling of train units is found to occur at various locations, including at stations, dedicated points along the route, or "on-the-fly".
3. (De)coupling Sequences: When accounting for heterogeneous vehicles, a intercity train could decouple before slower regional service or vice versa. When having homogeneous trains, (de)couple sequence is not relevant.
4. Shunting: Deport locations could be positioned near or within stations or instead at shunting areas in case of limited space.
5. Timetable Models: Different timetable modes were identified, such as fixed, hybrid, and on-demand timetables.
6. Route: Units may share the same destination, serve destinations within the same group, or operate with entirely different destinations.
7. Platooning: This can involve random coupling of units, coordinated exchanges within existing platoons, or consistently maintaining the same platoon configuration throughout the journey.

**Sub-question 2: Which operational transport concepts can be defined specifically applicable for main-line railways operations?**

For each of the composed design aspects, the corresponding building blocks were randomly in the second phase, and combined into a total of four distinct operational concepts through a morphological chart:

- *Conventional Pattern with Full-Stopping Regional Services*: Alternating IC trains and full-stopping regional trains, with a skip-stop service added for increased capacity and direct connections to major stations.
- *Conventional Pattern with Skip-Stop Regional Services*: Alternating IC trains and skip-stop regional trains, connecting fewer regional stations directly.
- *Skip-Stop Pattern without IC-Trains*: Homogeneous regional trains operating in a flexible skip-stop pattern, facilitating random or coordinated platoon formation.
- *Point-to-Point Pattern with Direct Connections*: Operations based solely on specific origin-destination pairs, using an on-demand timetable and random platooning, requiring station-based shunting.

**Sub-question 3: What are the most promising transport concepts for implementation on a real-world case study under realistic conditions ?**

In the third phase, each concept was applied to the SAAL-corridor to qualitatively test the performance towards a set of objectives through SWOT-analysis. From this, the first and the second concept were identified as ‘most suitable’ for implementation on the SAAL-corridor. A variant of concept 2, involving the temporary skipping of a station, was also considered suitable, as this could be an effective strategy for specific peak hour demands and enhances the benefits of skip-stop patterns by eliminating an odd amount of stops between Lelystad and Almere Centrum. Each concept was quantitatively evaluated for its impact on frequency and non-direct OD pairs, resulting in the selection of five variants that best represent the potential of each concept:

- *Variant 1*: A combined skip-stop and full-stopping service with only one necessary transfer between Almere Oostvaarders and Almere Muziekwijk.
- *Variant 2*: A combined service ensuring direct connections between all regional stations.
- *Variant 3*: A skip-stop pattern that minimizes the required number of OD-pair transfers but does not feature synchronized stops.
- *Variant 4*: A skip-stop pattern implemented between all Major stations, facilitating synchronized stops at Almere Centrum and Weesp for quick transfers within platoons.
- *Variant 5*: Temporarily skipping Almere Parkwijk, enhancing frequency but requiring additional transfers.

**Sub-question 4: How does each concept perform in terms of frequency, infrastructure occupation and generalized travel times for the selected corridor?**

A final evaluation on infrastructure occupancy, frequency, and generalized travel times showed that skip-stop patterns (specifically Variants 4 and 5) achieved the highest frequencies and lower occupancy rates compared to the combined full-stop and skip-stop services (Variants 1 and 2). While Variant 5 offered the highest frequency (seven cycles per hour), it introduced an uneven distribution of departure times, potentially impacting user experience. Variant 4 provided the lowest generalized travel time, striking the best balance of service frequency and minimal transfer impact by accounting for synchronized stops facilitating efficient transfers within platoons. Infrastructure occupancy across all variants ranged between 85% and 90%.

**Main research question: "Which operational concept(s) are most effective in terms of generalized travel times, infrastructure occupation and frequency for implementing Virtual Coupling on Dutch main-line passenger railway corridors?"**

To address the main research question, this study showed that an operational concept that alternates a skip-stop service with synchronized stops while preserving intercity services (as in Variant 4) was identified as the most effective approach for implementing VC on mainline railway corridors. This concept aligns best with current infrastructure capabilities and service goals, ensuring regional trains have more coupling options and enabling synchronized stops for regional services, while maintaining fast and direct connections between major stations. Although it sacrifices some direct connections between nearby stations, the synchronized stops and the increased frequency of platoon formation under VC facilitate efficient transfers within platoons. This makes it well-suited to address future peak-time passenger demands in terms of generalized travel times.

A key consideration for implementing this concept is to ensure an even number of stops for both regional trains, as this enables synchronized stops. The study revealed that when having an odd number of stations, fully skipping a station is not the most efficient option in terms of GTT. Instead, making two stops at one station so that both regional trains maintain the same number of stops proved more beneficial. While adding an extra station is another possibility, this approach was not favored in the analyzed case study due to the high station density. Additionally, allowing intercity trains to form platoons with regional trains could enhance system efficiency by creating shorter transfers and travel times, maximizing the flexibility and benefits VC could potentiality offer.

The frequency benefits of VC over ETCS Level 2 MB in this study were found to be limited, primarily due to the preservation of existing infrastructure, station layouts, and the maintained distinction between intercity and regional trains. This approach minimizes the need for significant modifications to current operations, supporting a gradual transition to a VC-capable system, but limited the coupling options. Additionally, the high station density in the case study restricted the number of feasible coupling points.

Despite these constraints, this thesis demonstrated the advantages of integrating VC into conventional operations, highlighting its potential to enhance operational flexibility and passenger service. These findings underscore the importance of further research into transitioning beyond ETCS Level 2 MB toward a more advanced VC system.

**Societal / practical recommendations**

The methodology developed in this research for calculating headways, infrastructure occupancy, and generalized travel times serves as a flexible tool for future studies and railway planning, supporting decisions around VC adoption. This work bridges theory and practice, providing PD ERTMS and the rail industry with a framework for understanding and deploying VC to enhance the efficiency and user-friendliness of Dutch mainline services. Given the scope, this study focused on VC concepts while preserving current operations and infrastructure layouts, excluded real passenger streams to emphasize relative effectiveness, and assessed only a corridor segment. The following recommendations address areas for refinement and should be included in the developed methodology to provide a more comprehensive understanding of VC feasibility on mainline corridors:

1. *Incorporate Passenger Volumes for Each OD Pair:* Within this study, all OD pairs were treated equally, which may distort the results by giving low-demand OD pairs the same weight as high-demand ones. Consequently, the findings, particularly those related to GTT, should only be used to compare the performance of specific stopping and operational plans and not interpreted as absolute values. The additional bike time included in Variant 5 offers some insight into the disutility of fully skipping a station, but it does not encompass all potential negative impacts and should only be viewed as an added penalty for comparative purposes. Including real passenger flows would allow for more accurate assessments of generalized travel time (GTT) impacts and better optimization of VC operations to prioritize high-demand OD pairs. This would likely further support skip-stop patterns during peak hours toward Amsterdam, as demand is concentrated between regional and major stations rather than between regional stations.
2. *Consider Modifications to Mainline Layouts and Operations:* This research primarily focused on devising concepts within the constraints of preserving conventional operations, without modifying infrastructure or station layouts. However, minor adjustments to infrastructure—for example extending platform lengths—could increase coupling/decoupling locations and improve station efficiency. Additionally, by operating smaller homogeneous trains to a metro-like system, more coupling options could be created, potentially allowing for coordinated coupling between regional and intercity trains. This approach could allow the formation of platoons with more than two units and facilitate the integration of intercity and regional trains into these platoons, potentially further enhancing short and efficient transfers. Introducing dynamic schedules that adjust to real-time conditions could further enhance system flexibility and responsiveness.
3. *Expand Analysis to the Entire SAAL Corridor:* This study focused on a segment of the SAAL corridor. Given its central role in the Dutch rail network, future research should assess VC impacts along the entire SAAL corridor or even the national network. This broader analysis would provide a comprehensive understanding of VC's benefits and challenges for the Dutch rail system as a whole.
4. *Analyze Impact of Assumptions:* Assumptions regarding buffer time, dwell time, and accepted infrastructure occupancy significantly influence the feasible frequency, potentially affecting the outcomes. An initial analysis with higher dwell times, especially when transfers within platoons are possible, demonstrates a substantial impact on infrastructure occupancy. For instance, when considering a dwell time of 90 seconds during transfers within platoons, Variant 4 was found to support a maximum of only 5 cycles per hour. This reduces the relative advantage of skip-stop over a full-stopping variant. However, even at 5 cycles per hour, the initial analysis indicates that skip-stop implementations remain the preferred choice.

**Scientific recommendations**

In addition to the specific recommendations regarding the impact of implementing Virtual Coupling (VC) on mainline railway corridors, several broader research areas are proposed to support the effective adoption of VC and related technologies in the railway sector:

1. *Perform additional research on Dynamic Coupling Processes in VC:* One of the key challenges in implementing Virtual Coupling (VC) is managing the dynamic coupling process between trains. As highlighted in the literature, the leader train typically accelerates to its maximum speed, making it difficult for the following train to catch up and virtually couple. Speed restrictions near switches can further complicate this process. Additional research is needed to refine strategies for determining when and how trains can effectively couple, particularly when dynamic safety margins are considered. The efficiency of this coupling process is crucial to the operational success of VC, making it a critical focus for future studies. This challenge was also emphasized in the MOVINGRAIL Deliverable 4.3, which points out the

need for a specialized approach to managing train speed and braking distances during the coupling process.

2. *Analyze impact of Skip-Stop Patterns on Railway Operations:* While skip-stop patterns are common in urban transit, their effects in mainline railway operations are less understood. Research should examine their impact on operational efficiency, passenger behavior, service perception, and infrastructure use in the railway context, as these patterns may influence modal shifts and network capacity.
3. *Analyze Operational Impact of ATO and Regulatory Constraints on VC:* The precise operational impact of Automatic Train Operation (ATO) and the regulatory framework for implementing VC remain uncertain. While this research assumes that capacity utilization could reach 85-90% with the introduction of VC, this assumption is speculative. Further research is needed to evaluate actual capacity gains under current regulatory and technological constraints, examining if these capacity levels are realistic given limitations such as signaling systems and safety requirements.

# Appendix A

The table below shows the maximum number of cycles per hour achievable with minimal time buffers, assuming the regional trains can virtually couple. This table specifically illustrates the implementation of a full stopping train combined with a skip-stop train applied to the whole corridor section between Lelystad and Weesp.

*Table A1: Frequency (cycles per hour) per combination of patterns concept 1*

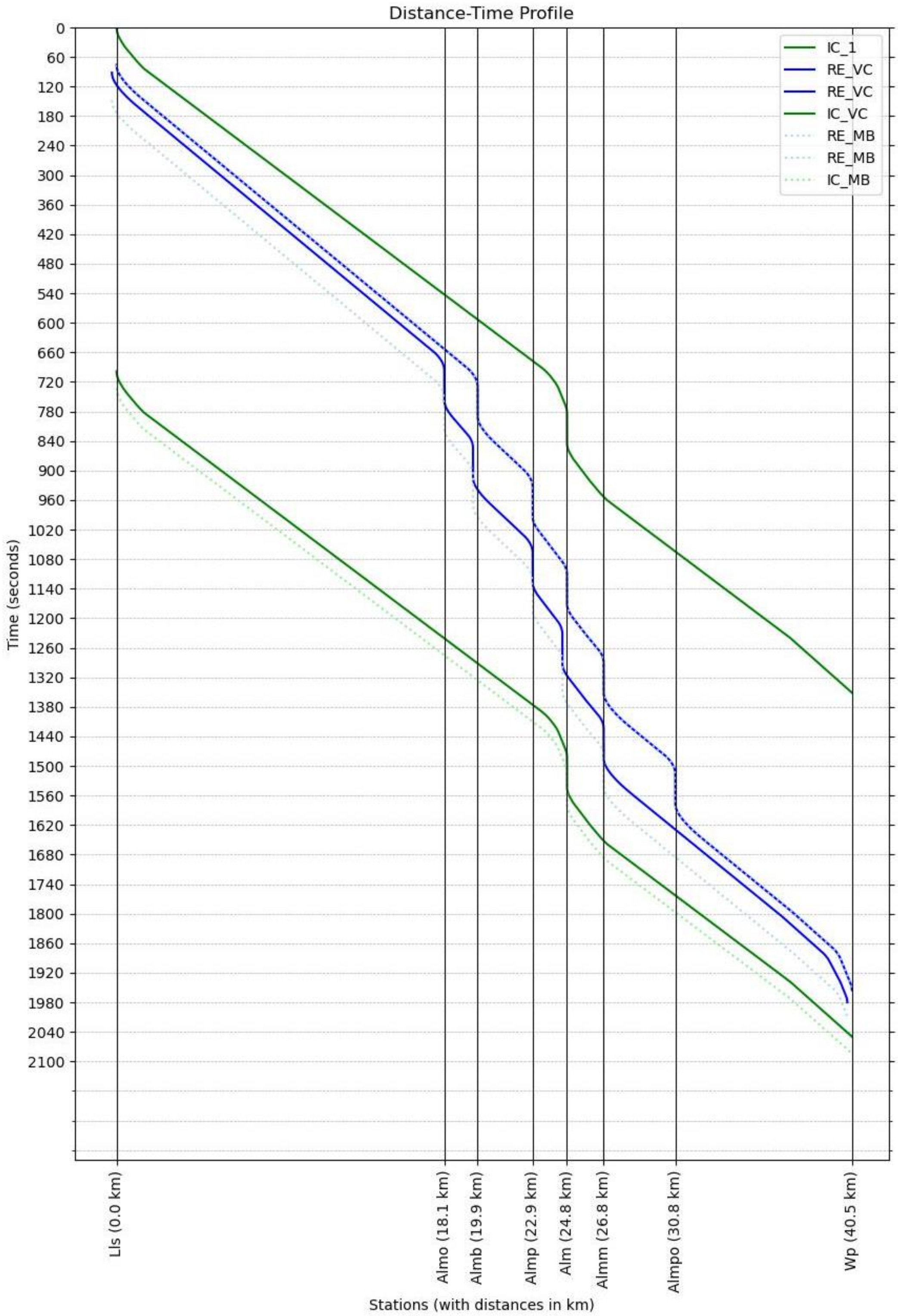
| **Pattern p / q** | **1-2a** | **1-2b** | **2-1a** | **2-1b** | **2-2** |
|---|---|---|---|---|---|
| **1-1-2a** | 4.02 | 4.02 | 4.45 | 4.02 | 4.02 |
| **1-1-2b** | 5.35 | 4.62 | 5.19 | 4.62 | 4.62 |
| **1-1-2c** | 4.83 | 4.40 | 4.92 | 4.40 | 4.40 |
| **1-2-1a** | 4.02 | 4.53 | 4.45 | 4.02 | 4.02 |
| **1-2-1b** | 5.37 | 4.63 | 5.20 | 4.63 | 4.63 |
| **1-2-1c** | 4.84 | 4.42 | 4.95 | 4.42 | 4.42 |
| **1-2-1d** | 4.61 | 4.55 | 5.10 | 4.55 | 4.55 |
| **1-2-2a** | 3.90 | 3.89 | 4.29 | 3.89 | 3.89 |
| **1-2-2b** | 4.59 | 4.59 | 5.15 | 4.59 | 4.59 |
| **1-2-2c** | 4.20 | 4.20 | 4.67 | 4.20 | 4.20 |
| **1-2-2d** | 3.90 | 3.89 | 4.29 | 3.89 | 3.89 |
| **2-1-2a** | 4.02 | 4.02 | 4.45 | 4.02 | 4.02 |
| **2-1-2b_1** | 4.58 | 4.02 | 4.44 | 4.02 | 4.02 |
| **2-1-2b_2** | 4.62 | 4.14 | 4.59 | 4.14 | 4.14 |
| **2-1-1a** | 4.02 | 4.53 | 4.45 | 4.02 | 4.02 |
| **2-1-1b_1** | 4.58 | 4.02 | 4.44 | 4.02 | 4.02 |
| **2-1-1b_2** | 4.74 | 4.14 | 4.59 | 4.14 | 4.14 |
| **2-2-1a** | 4.02 | 4.53 | 4.45 | 4.02 | 4.02 |
| **2-2-1b_1** | 4.59 | 4.03 | 4.45 | 4.03 | 4.03 |
| **2-2-1b_2** | 4.61 | 4.16 | 4.62 | 4.16 | 4.16 |
| **2-2-2** | 4.02 | 4.03 | 4.45 | 4.02 | 4.02 |

These patterns have been combined and analyzed in chapter 5. Below, the time-distance diagrams can be found for the best performing combinations (in terms of frequency) for the following scenarios:

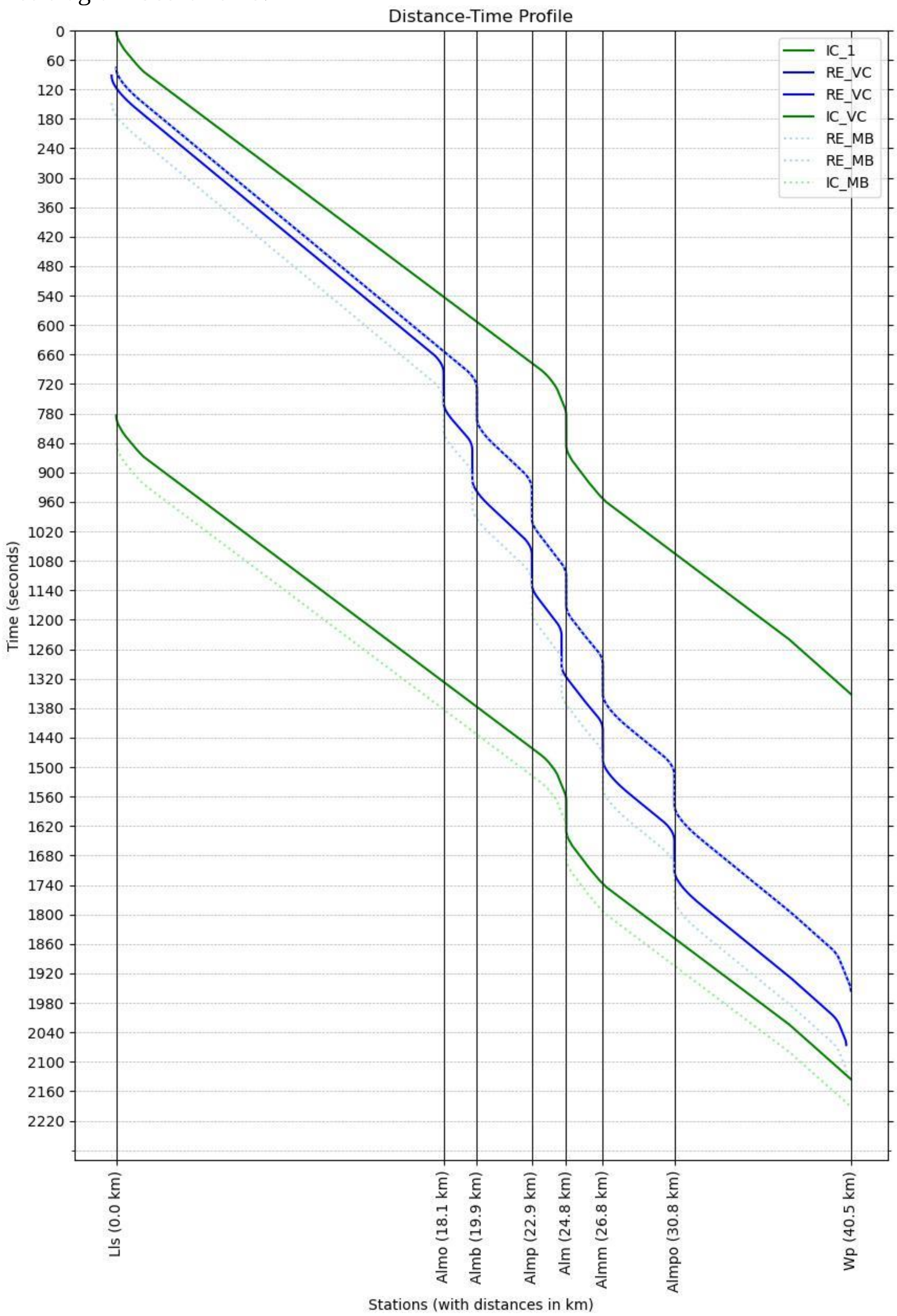
1. The skip-stop train skips one station in both sections;
2. The skip-stop train skips two stations in the first section and one in the second;
3. The skip-stop train skips one station in the first section and none in the second;
4. The skip-stop train skips two stations in the first section and none in the second;
5. The skip-stop train skips no stations in the first section and one in the second.

Since scenario 1 and 2 contain OD-pairs in which travelers need to transfer in order to reach their desired destination, two sub-scenarios for these scenarios are considered, including the best performing pattern with no transfers and with (at least) one transfer. The first ( referred to by adding an ‘a’) is the best-performing pattern in terms of maximizing frequency in which passengers need to transfer for 1 OD-pair, and the second (referred to by adding an ‘b’) is the best-performing pattern where no OD-pairs need a transfer.

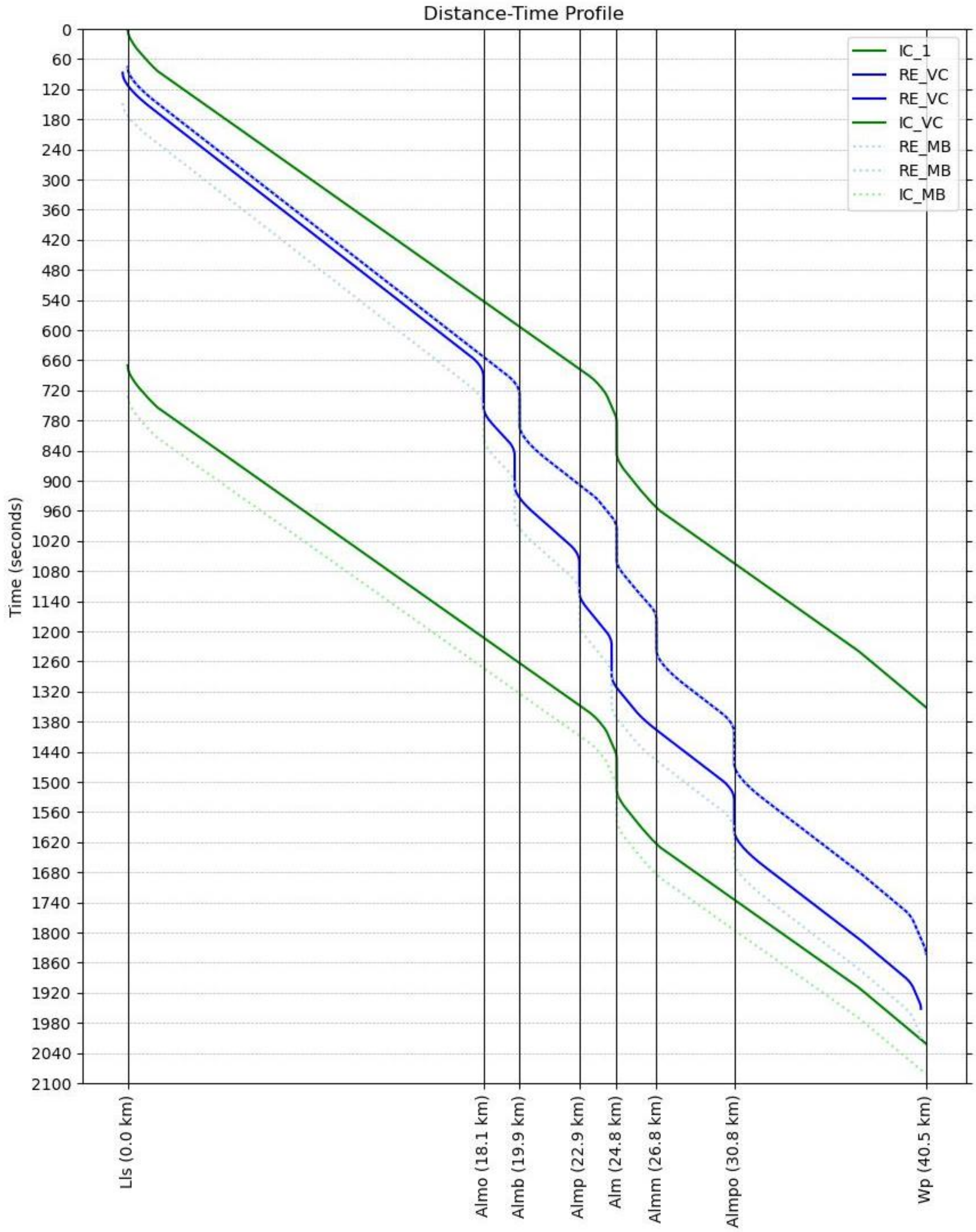
Time-distance diagram Scenario 1a:



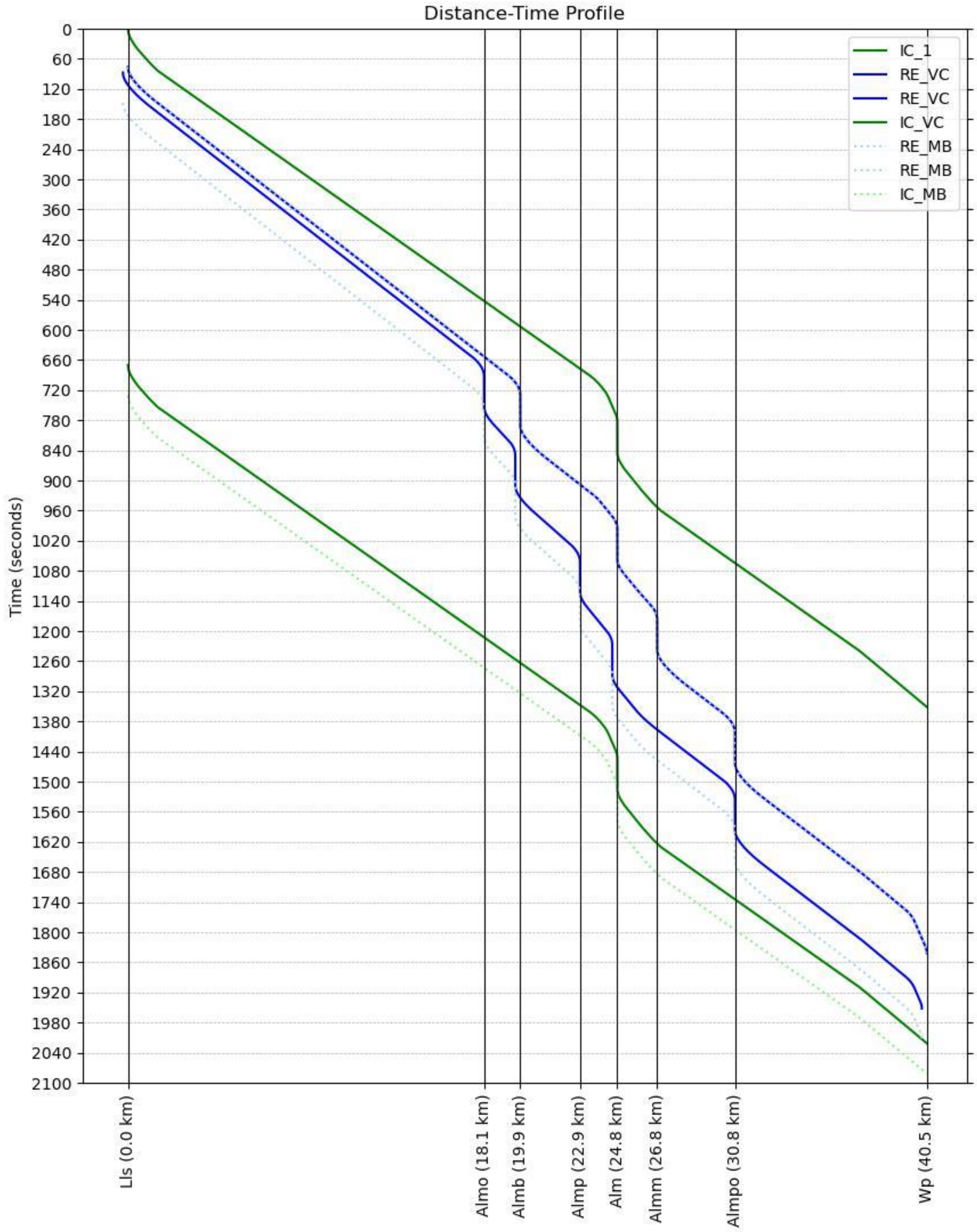
Time-distance diagram Scenario 1b:



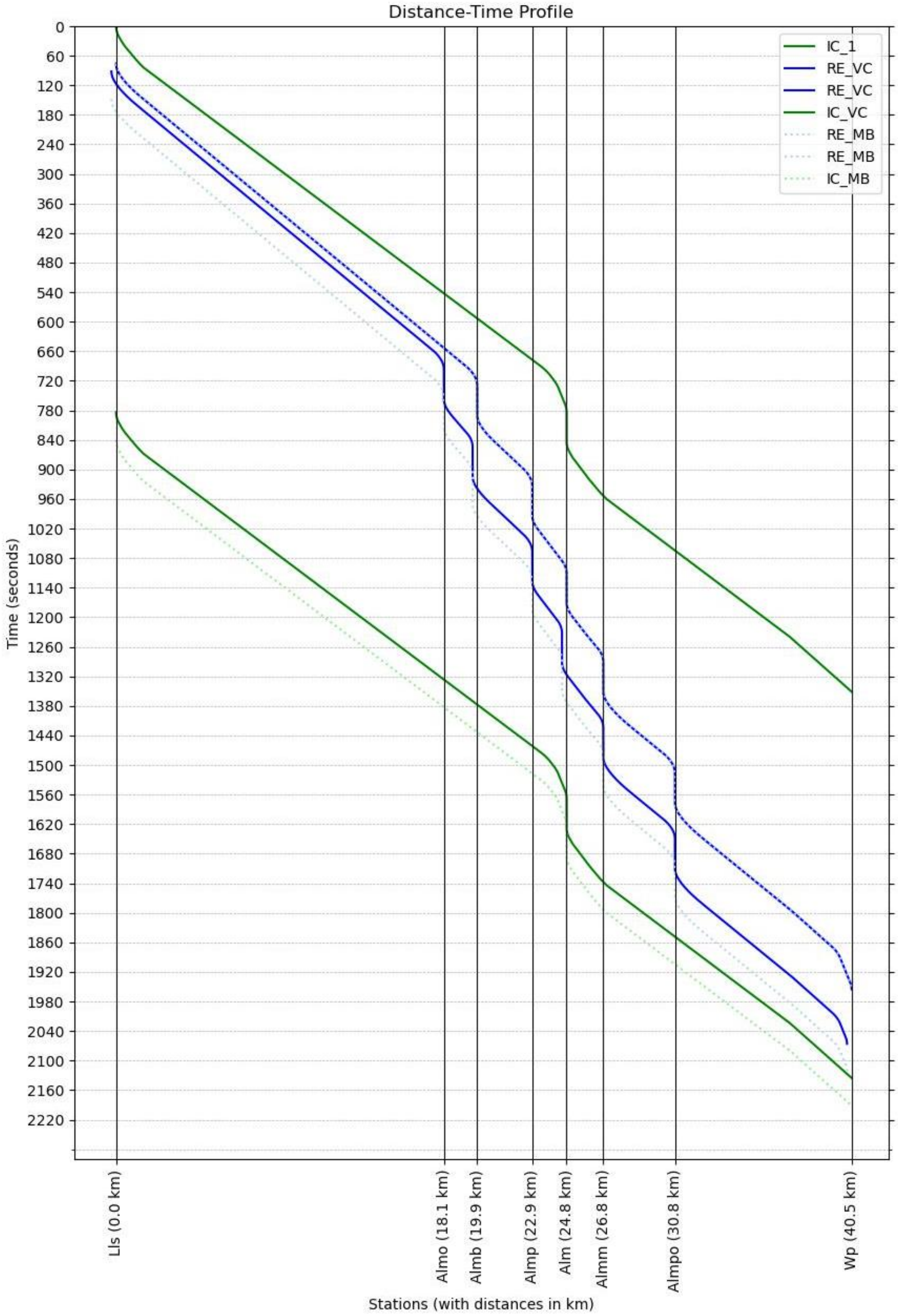
Time-distance diagram Scenario 2a:



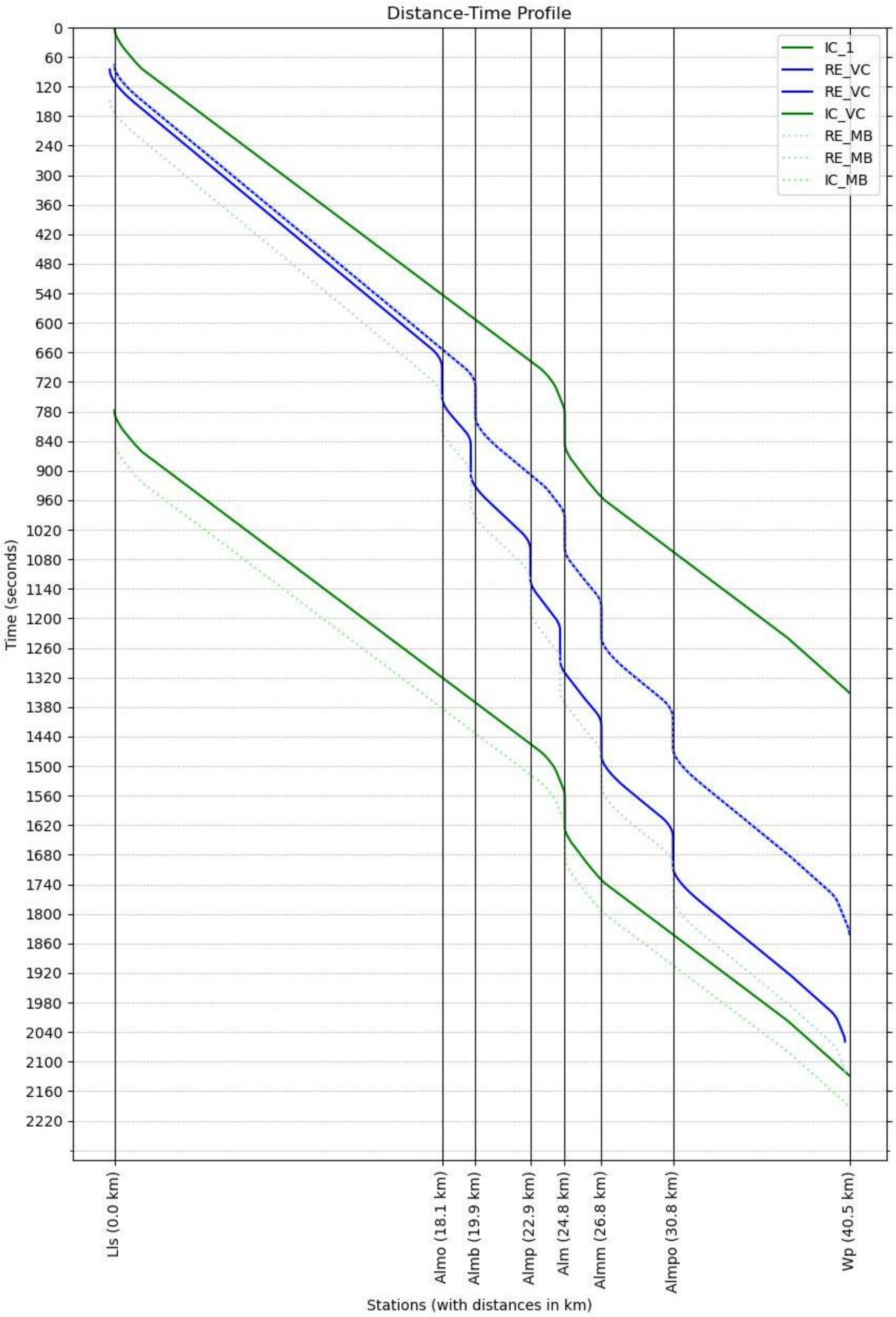
Time-distance diagram Scenario 2b:



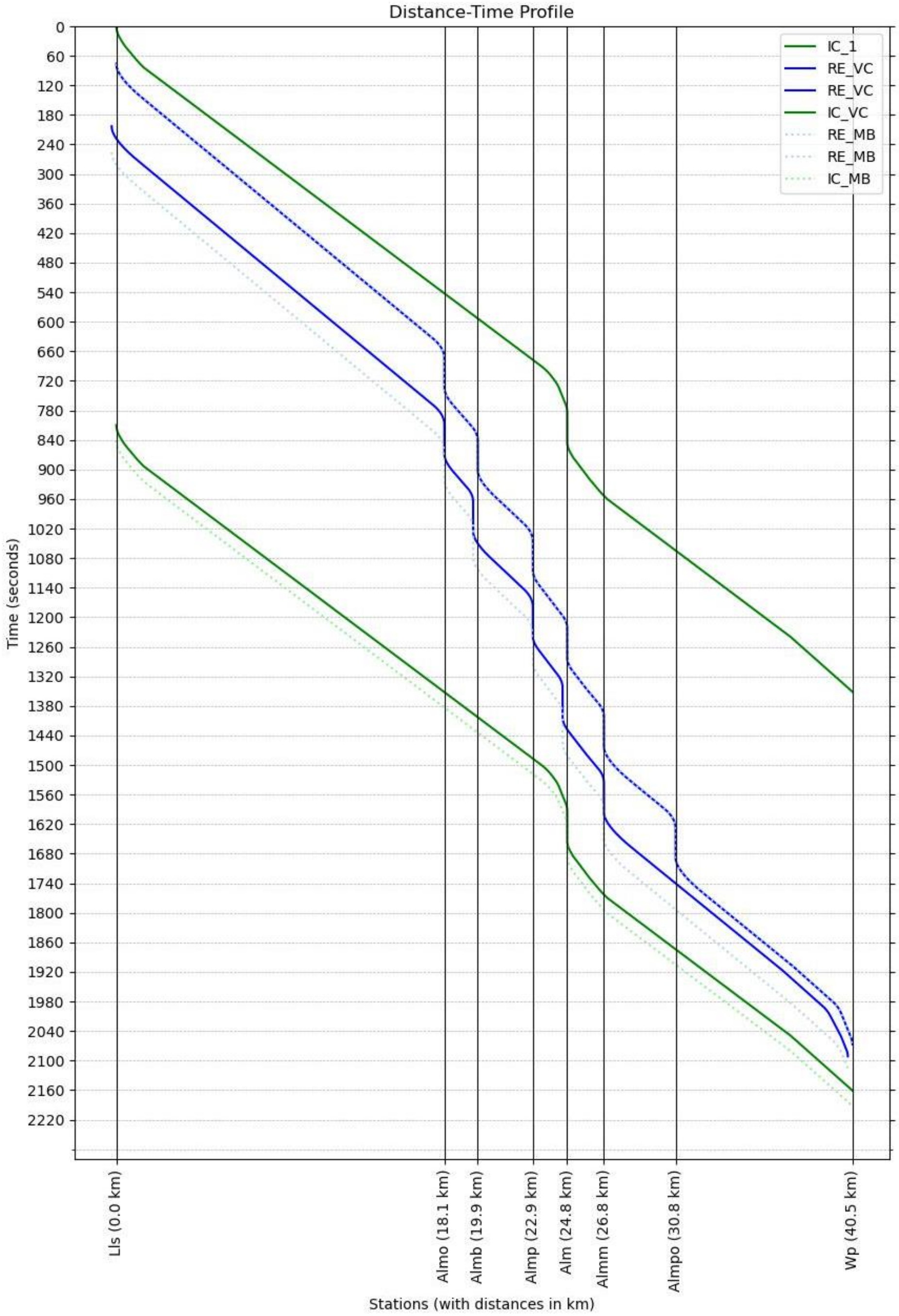
Time-distance diagram Scenario 3



Time-distance diagram Scenario 4



Time-distance diagram Scenario 5



# Appendix B

The table below shows the maximum number of cycles per hour achievable with minimal time buffers, assuming the regional trains can virtually couple. This table specifically illustrates the implementation of a Skip-stop pattern applied on both regional trains between Lelystad and Almere Centrum, while still maintaining a combined skip-stop / full stopping train between Almere Centrum and Weesp.

*Table B1: Frequency (cycles per hour) per combination of patterns concept 2a*

| **Pattern p / q** | **1-2a** | **1-2b** | **2-1a** | **2-1b** | **2-2** |
|---|---|---|---|---|---|
| **1-1-1a** | 5.37 | 5.43 | 6.16 | 5.37 | 5.37 |
| **1-1-1b** | 4.59 | 5.27 | 5.16 | 4.59 | 4.59 |
| **1-1-1c1** | 4.62 | 5.31 | 5.20 | 4.62 | 4.62 |
| **1-1-1c2** | 4.84 | 4.89 | 5.48 | 4.84 | 4.84 |
| **1-1-1d1** | 5.37 | 4.62 | 5.19 | 4.62 | 4.62 |
| **1-1-1d2** | 4.20 | 4.80 | 4.67 | 4.20 | 4.20 |
| **1-1-1e1** | 4.61 | 4.58 | 5.14 | 4.58 | 4.58 |
| **1-1-1e2** | 4.83 | 5.12 | 5.46 | 4.83 | 4.83 |
| **1-1-1f** | 5.35 | 5.41 | 6.14 | 5.35 | 5.35 |
| **1-2-1a** | 4.59 | 5.27 | 5.16 | 4.59 | 4.59 |
| **1-2-1b** | 4.61 | 4.55 | 5.10 | 4.55 | 4.55 |

Similarly, the table below illustrates the maximum number of cycles per hour achievable with minimal time buffers for the implementation of a skip-stop pattern for both regional trains between Almere Centrum and Weesp, while still maintaining a combined skip-stop / full stopping train between Lelystad and Almere Centrum

*Table B2: Frequency (cycles per hour) concept 2a while maintaining partly full-stop*

| **Pattern p / q** | **1-1a** | **1-1b** |
|---|---|---|
| **1-1-2a** | 4.45 | 4.58 |
| **1-1-2b** | 5.19 | 5.37 |
| **1-1-2c** | 4.92 | 5.08 |
| **1-2-1a** | 5.08 | 4.62 |
| **1-2-1b** | 5.20 | 5.39 |
| **1-2-1c** | 4.95 | 5.11 |
| **1-2-1d** | 5.10 | 5.28 |
| **1-2-2a** | 4.29 | 4.42 |
| **1-2-2b** | 5.15 | 5.34 |
| **1-2-2c** | 4.67 | 4.81 |
| **1-2-2d** | 4.29 | 4.42 |
| **2-1-2a** | 4.45 | 4.58 |
| **2-1-2b_1** | 4.44 | 4.58 |
| **2-1-2b_2** | 4.59 | 4.74 |
| **2-1-1a** | 5.08 | 4.62 |
| **2-1-1b_1** | 4.44 | 4.58 |
| **2-1-1b_2** | 4.59 | 4.74 |
| **2-2-1a** | 5.08 | 4.62 |
| **2-2-1b_1** | 4.45 | 4.59 |
| **2-2-1b_2** | 4.62 | 4.76 |
| **2-2-2** | 4.45 | 4.59 |

Lastly, the table below illustrates the maximum number of cycles per hour achievable with minimal time buffers when implementing a Skip-stop pattern for both regional trains at the whole corridor section between Lelystad and Weesp

*Table B3: Frequency (cycles per hour) concept 2a for a skip-stop applied to both sections*

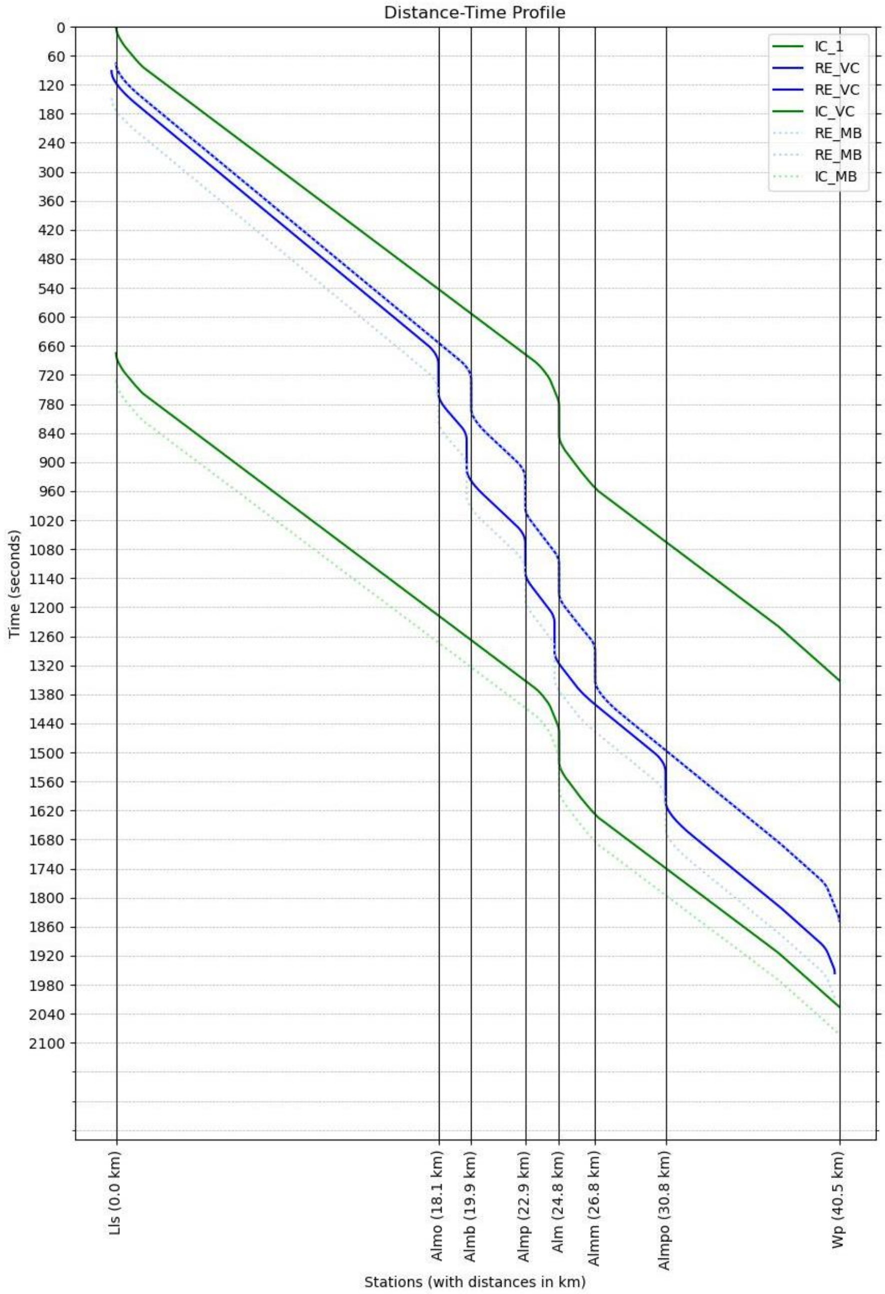
| **Pattern p / q** | **1-1a** | **1-1b** |
|---|---|---|
| **1-1-1a** | 6.24 | 6.50 |
| **1-1-1b** | 6.03 | 5.39 |
| **1-1-1c1** | 6.08 | 5.44 |
| **1-1-1c2** | 5.54 | 5.74 |
| **1-1-1d1** | 5.19 | 5.37 |
| **1-1-1d2** | 5.42 | 4.86 |
| **1-1-1e1** | 5.14 | 5.32 |
| **1-1-1e2** | 5.83 | 5.72 |
| **1-1-1f** | 6.21 | 6.47 |
| **1-2-1a** | 6.03 | 5.39 |
| **1-2-1b** | 5.10 | 5.28 |

These patterns have been combined and analyzed in chapter 5. Below, the time-distance diagrams can be found for the best performing combinations (in terms of frequency) for the following scenarios:

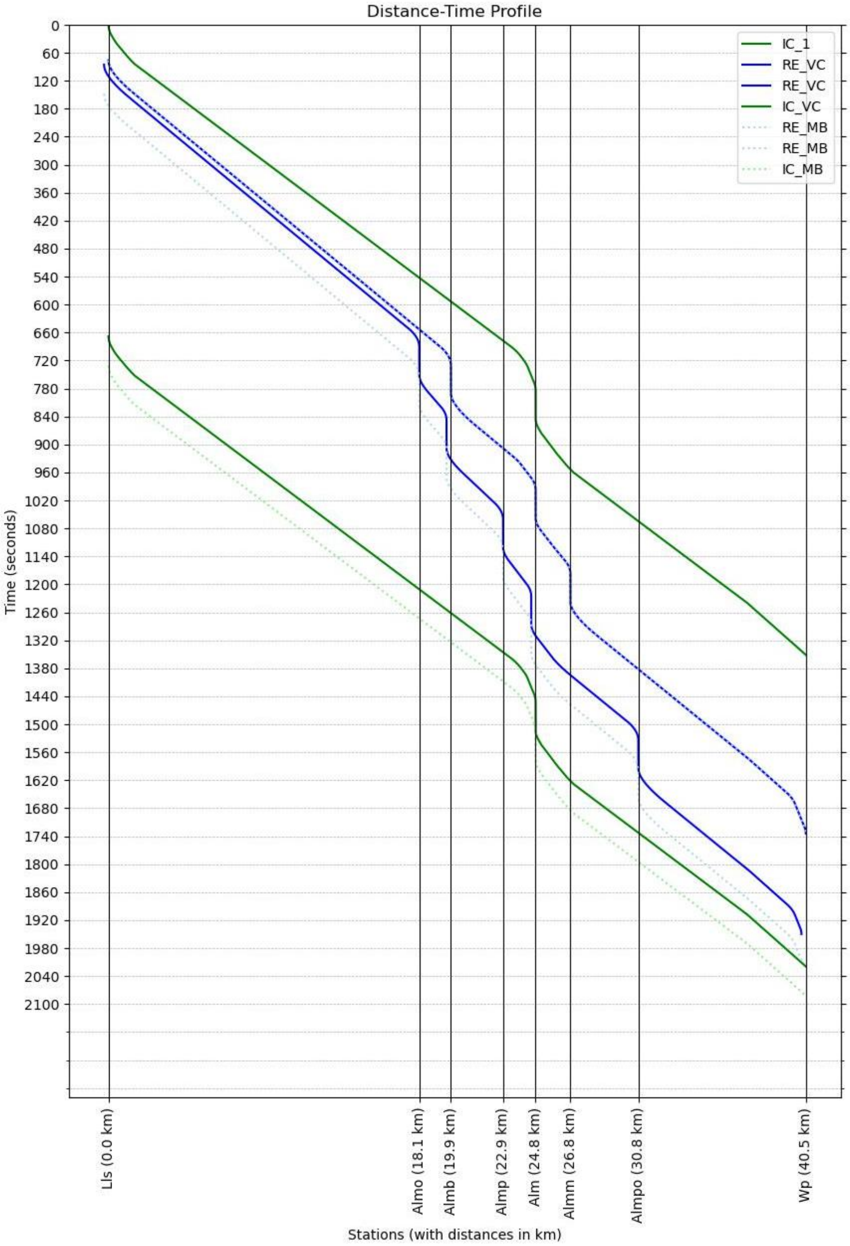
1. Maintain a traditional pattern at the first section in which the skip-stop train skips one station. At the second section, both trains perform a skip-stop pattern;
2. Maintain a traditional pattern at the first section in which the skip-stop train skips two stations. At the second section, both trains perform a skip-stop pattern;
3. Apply a skip-stop pattern at the first section for both regional trains. At the second section, a traditional pattern is maintained, in which the skip-stop train skips one station.
4. Apply a skip-stop pattern at the first and second section.

For scenario 4, two combinations of patterns have been analyzed: the first (4a.) is the best-performing pattern in terms of maximizing frequency, and the second (4b.) is the best-performing pattern where passengers can make direct transfers between both regional trains at Almere Centrum, as both trains stop there simultaneously.

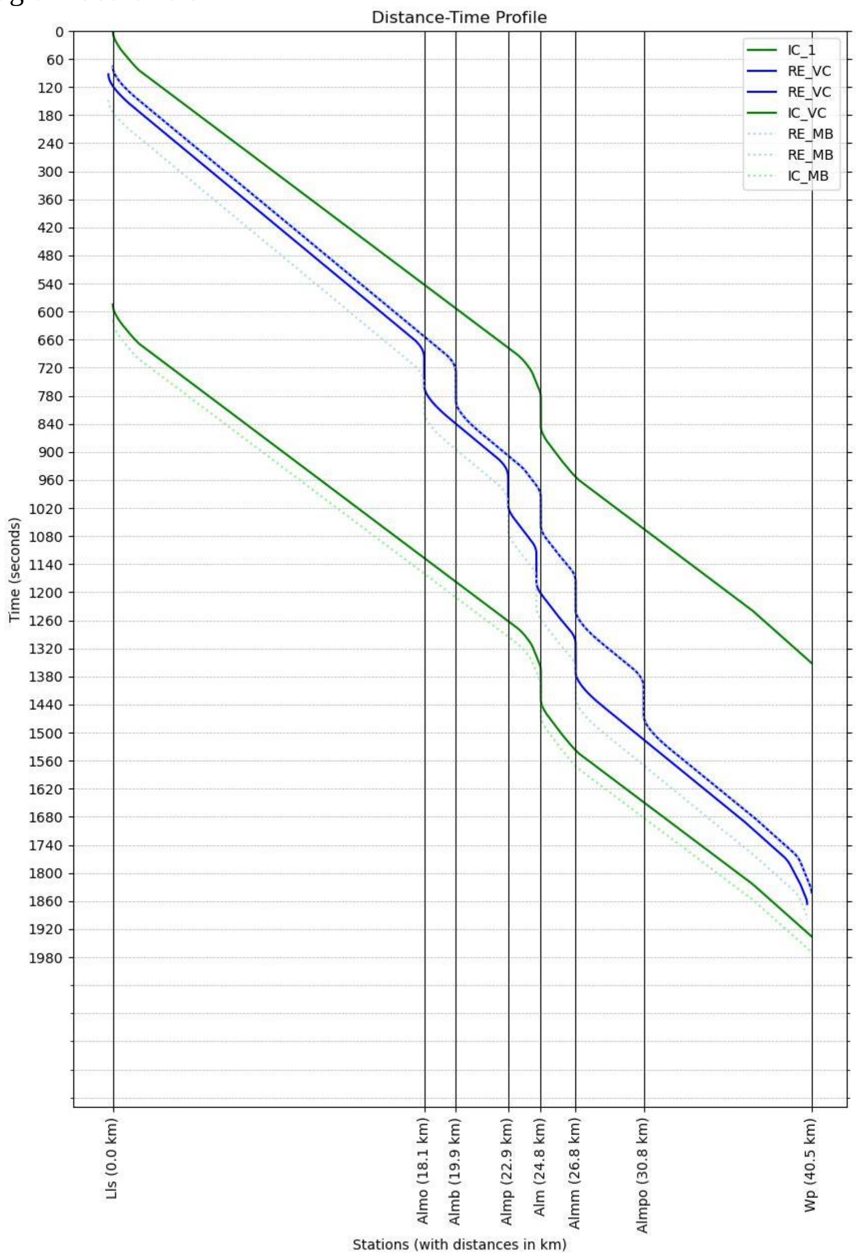
Time-distance diagram Scenario 1



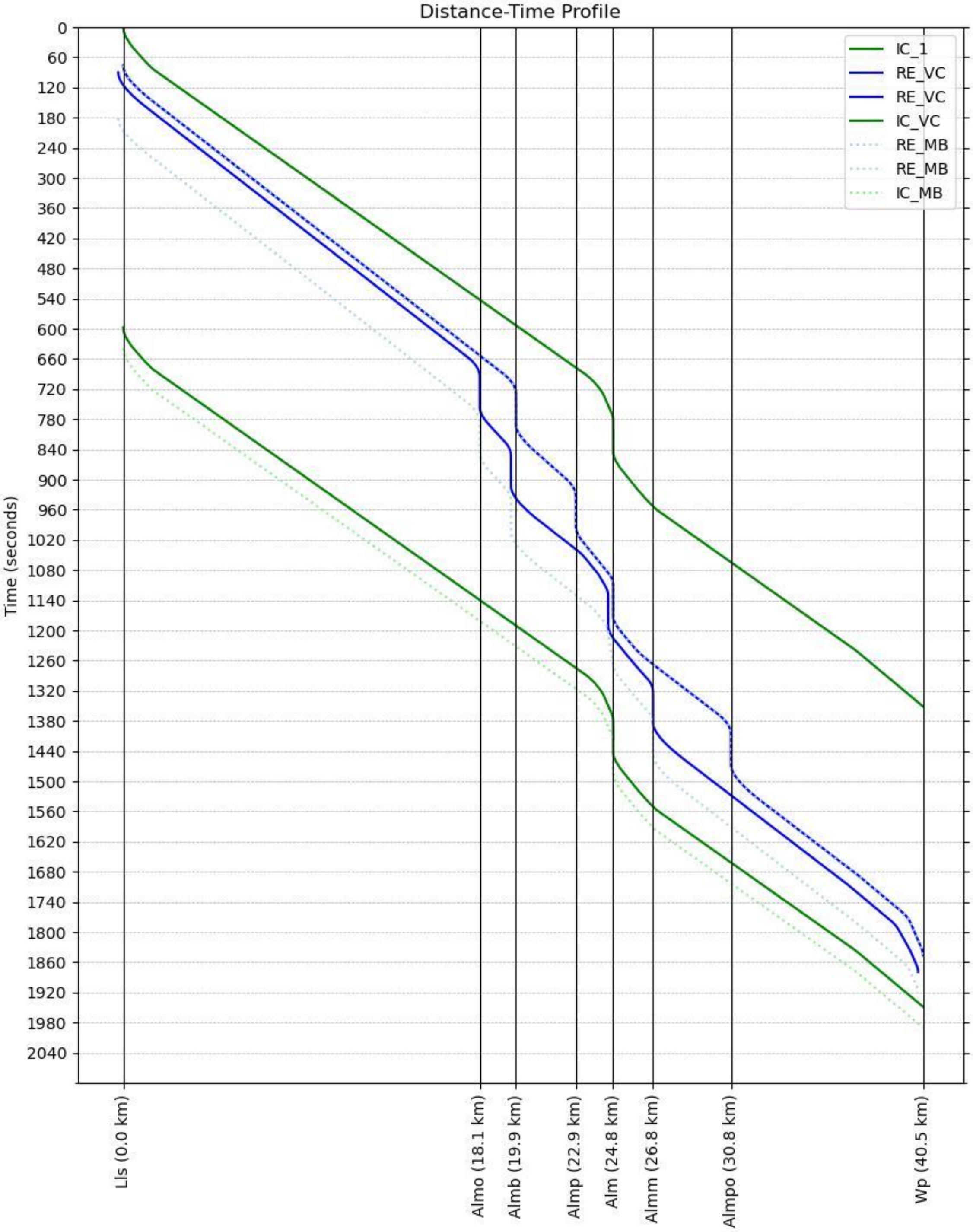
Time-distance diagram Scenario 2



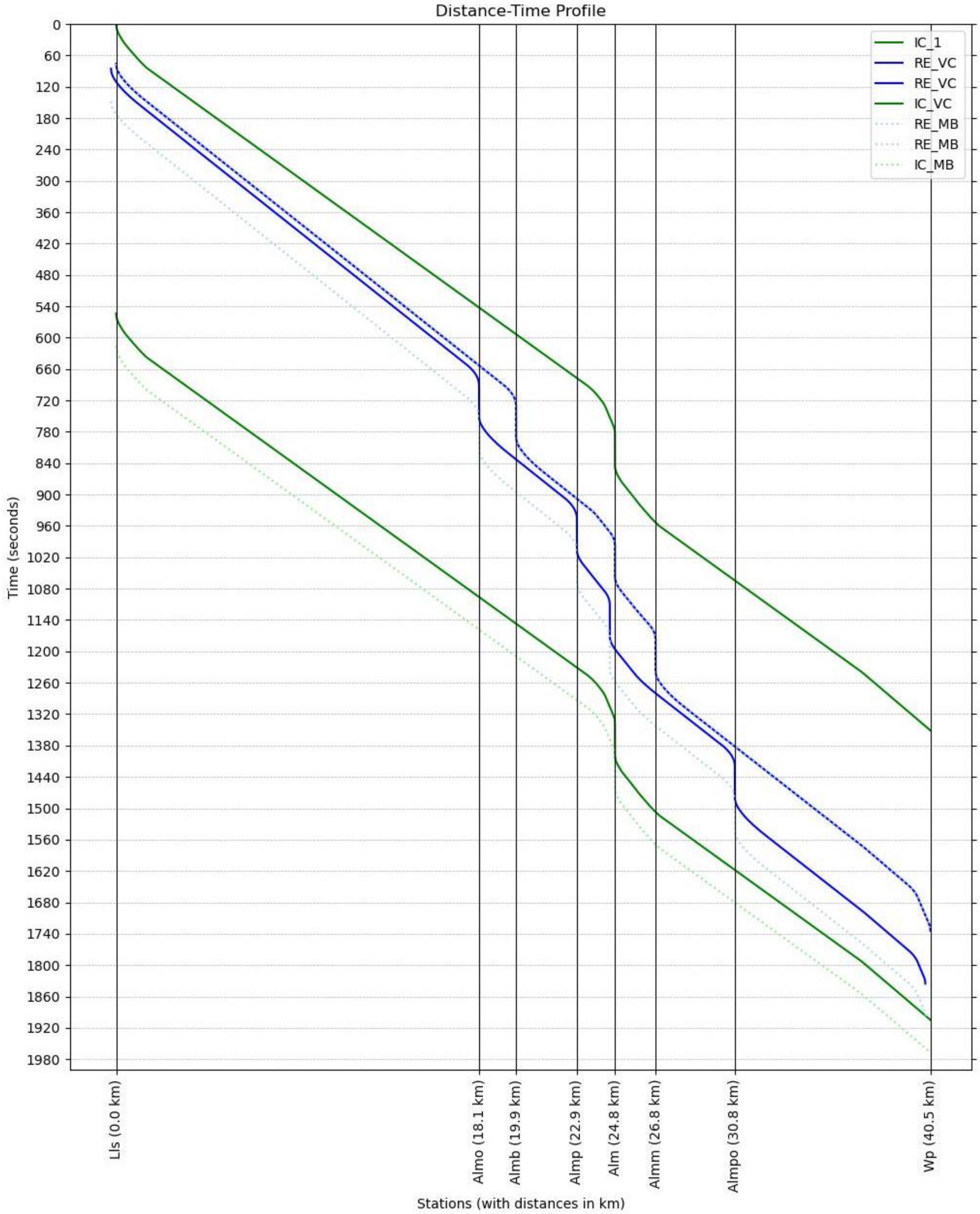
Time-distance diagram Scenario 3



Time-distance diagram Scenario 4a



Time-distance diagram Scenario 4b



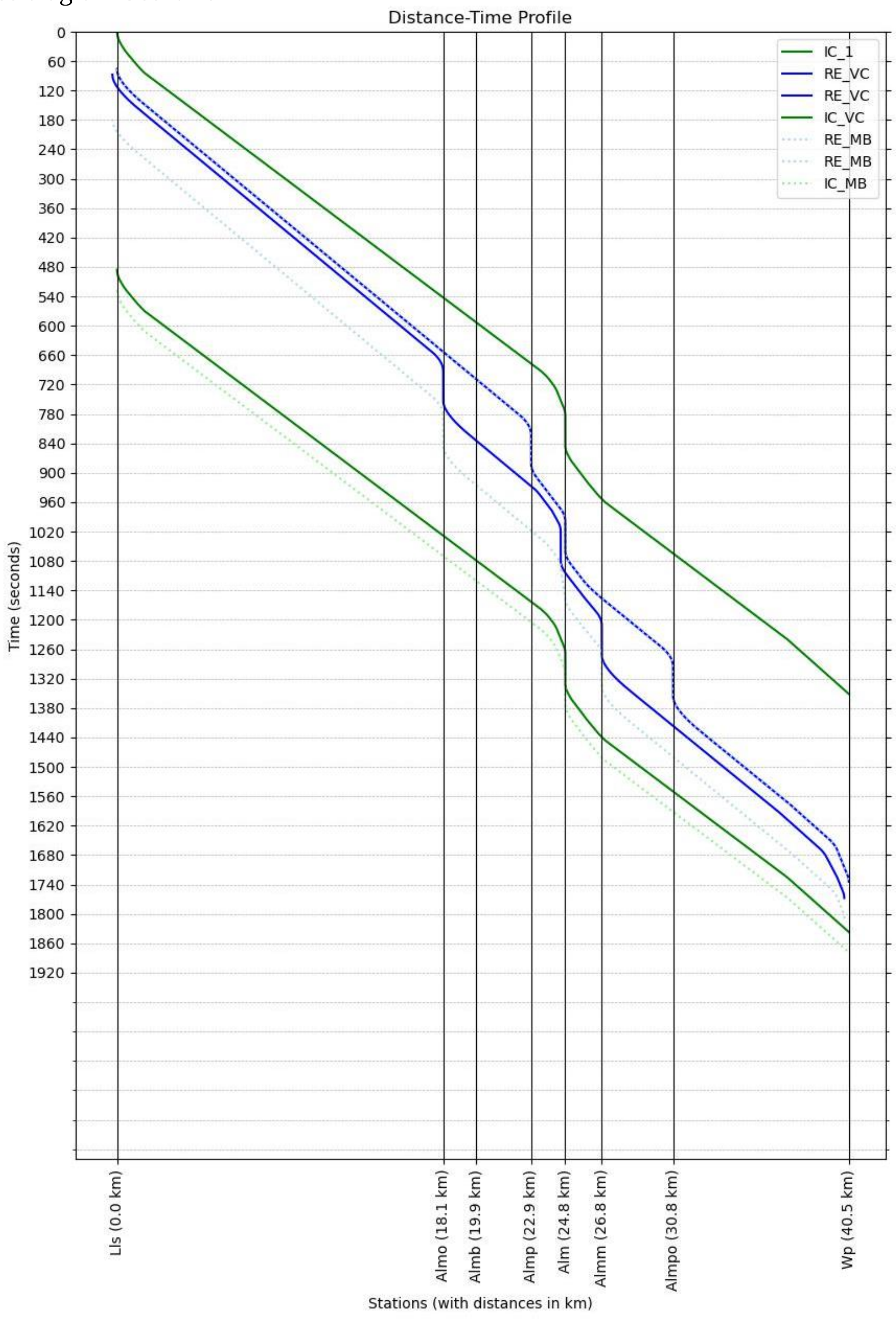
# Appendix C

The table below shows the maximum number of cycles per hour achievable with minimal time buffers, assuming the regional trains can virtually couple. This table specifically illustrates the implementation of a Skip-stop pattern applied on both regional trains at the whole corridor section between Lelystad and Weesp while (temporarily) either Almere Buiten or Almere Parkwijk is fully skipped.

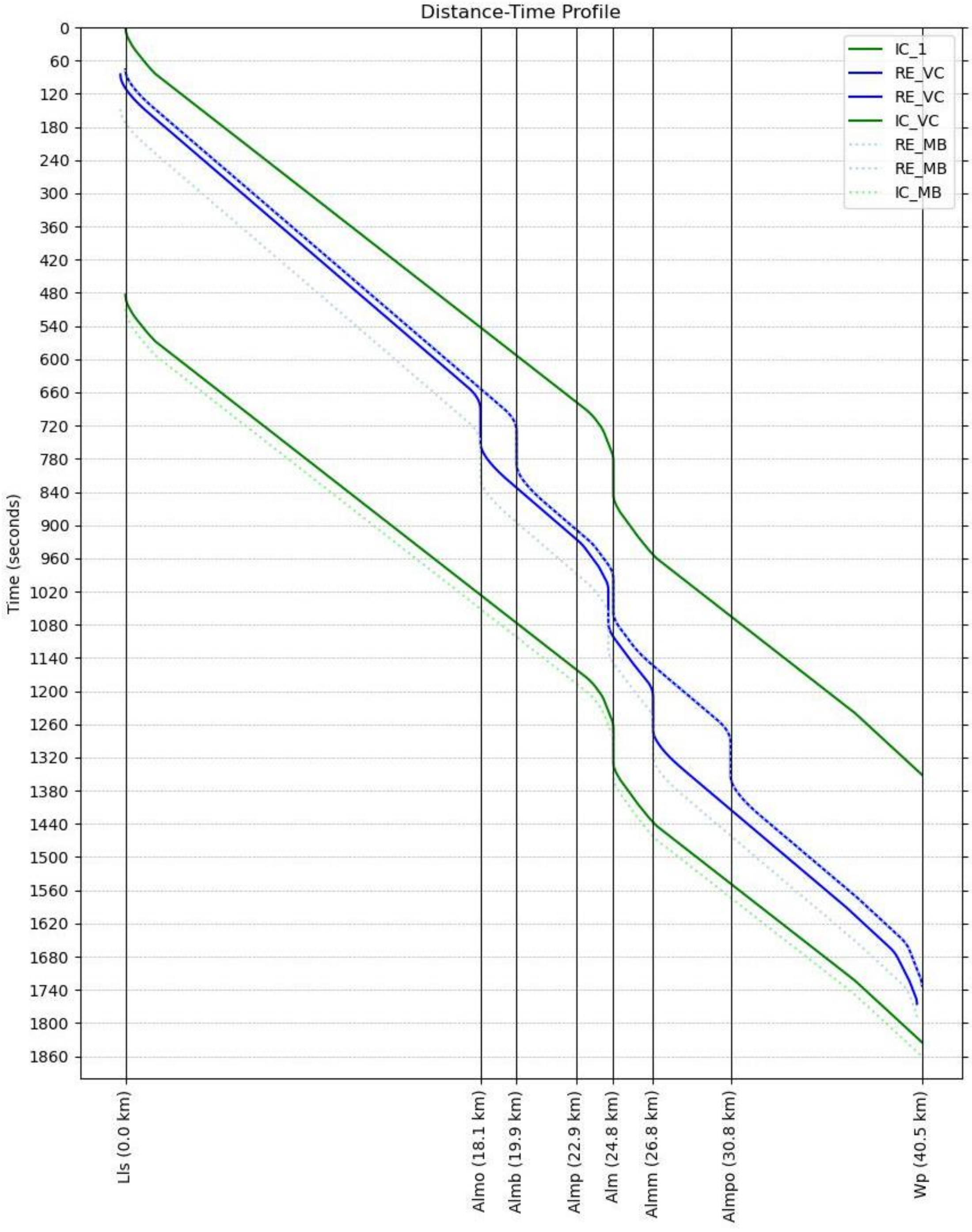
*Table C1: Frequency (cycles per hour) per combination of patterns concept 2b*

| | **Pattern p / q** | **1-1a** | **1-1b** |
|---|---|---|---|
| Close Almere Buiten | 1-1a | 7.41 | 6.48 |
| | 1-1b1 | 6.18 | 6.45 |
| | 1-1b2 | 6.48 | 5.76 |
| Close Almere Parkwijk | 1-1c | 7.44 | 6.50 |
| | 1-1d1 | 6.10 | 6.36 |
| | 1-1d2 | 6.51 | 5.78 |

Time-distance diagram Scenario 1



Time-distance diagram Scenario 2



# Appendix D

Below, the generalized travel times for each OD-pair are showed for implementing VC between Lelystad and Weesp. The right side of the table show the delta increment / decrement generalized travel time ratio relative to the base scenario, in which two consecutive regional trains are able to virtually couple and perform a full stopping pattern, alternated with a direct Intercity Train.

*Table D1: GTT per O-D pair for VC*

| From | To | Gen tt. variant base | Gen tt. variant 1 | Gen tt. variant 2 | Gen tt. variant 3 | Gen tt. variant 4 | Gen tt. variant 5 | Delta variant base | Delta variant 1 | Delta variant 2 | Delta variant 3 | Delta variant 4 | Delta variant 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Lelystad** | **Almere Oostvaarders** | 17.4 | 21.1 | 18.9 | 18.9 | 17.4 | 16.3 | 1.0 | 0.8 | 0.9 | 0.9 | 1.0 | 1.1 |
| | **Almere Buiten** | 20.2 | 16.5 | 15.4 | 15.4 | 14.6 | 17.3 | 1.0 | 1.2 | 1.2 | 1.2 | 1.3 | 1.1 |
| | **Almere Parkwijk** | 23.6 | 27.3 | 25.1 | 18.8 | 21.7 | 27.6 | 1.0 | 0.8 | 0.9 | 1.2 | 1.1 | 0.8 |
| | **Almere Centrum** | 26.5 | 20.9 | 19.8 | 21.7 | 21.0 | 18.5 | 1.0 | 1.2 | 1.3 | 1.2 | 1.2 | 1.3 |
| | **Almere Muziekwijk** | 29.5 | 33.3 | 27.3 | 29.2 | 27.7 | 24.7 | 1.0 | 0.9 | 1.1 | 1.0 | 1.1 | 1.2 |
| | **Almere Poort** | 33.4 | 25.9 | 26.6 | 33.0 | 29.6 | 26.7 | 1.0 | 1.2 | 1.2 | 1.0 | 1.1 | 1.2 |
| | **Weesp** | 40.7 | 33.2 | 34.0 | 34.0 | 33.2 | 30.8 | 1.0 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| **Almere Oostvaarders** | **Almere Buiten** | 9.2 | 13.0 | 10.7 | 10.7 | 9.2 | 28.5 | 1.0 | 0.6 | 0.8 | 0.8 | 1.0 | -1.1 |
| | **Almere Parkwijk** | 12.6 | 16.4 | 14.1 | 13.1 | 35.2 | 21.1 | 1.0 | 0.7 | 0.9 | 1.0 | -0.8 | 0.3 |
| | **Almere Centrum** | 15.6 | 19.3 | 15.2 | 16.1 | 13.7 | 10.8 | 1.0 | 0.8 | 1.0 | 1.0 | 1.1 | 1.3 |
| | **Almere Muziekwijk** | 18.6 | 22.3 | 18.2 | 42.9 | 16.7 | 13.8 | 1.0 | 0.8 | 1.0 | -0.3 | 1.1 | 1.3 |
| | **Almere Poort** | 22.4 | 26.1 | 22.0 | 21.0 | 17.6 | 22.8 | 1.0 | 0.8 | 1.0 | 1.1 | 1.2 | 1.0 |
| | **Weesp** | 29.7 | 33.5 | 29.3 | 28.4 | 26.0 | 21.6 | 1.0 | 0.9 | 1.0 | 1.0 | 1.1 | 1.3 |
| **Almere Buiten** | **Almere Parkwijk** | 9.8 | 8.0 | 6.9 | 6.9 | 6.1 | 10.3 | 1.0 | 1.2 | 1.3 | 1.3 | 1.4 | 1.0 |
| | **Almere Centrum** | 12.8 | 9.0 | 7.9 | 9.8 | 7.2 | 9.8 | 1.0 | 1.3 | 1.4 | 1.2 | 1.4 | 1.2 |
| | **Almere Muziekwijk** | 15.8 | 13.9 | 10.9 | 12.8 | 10.2 | 21.3 | 1.0 | 1.1 | 1.3 | 1.2 | 1.4 | 0.7 |
| | **Almere Poort** | 19.6 | 14.0 | 14.7 | 14.8 | 14.0 | 14.8 | 1.0 | 1.3 | 1.2 | 1.2 | 1.3 | 1.2 |
| | **Weesp** | 26.9 | 21.3 | 22.1 | 20.2 | 19.5 | 22.1 | 1.0 | 1.2 | 1.2 | 1.2 | 1.3 | 1.2 |
| **Almere Parkwijk** | **Almere Centrum** | 9.4 | 13.1 | 10.9 | 13.1 | 9.4 | 10.3 | 1.0 | 0.6 | 0.8 | 0.6 | 1.0 | 0.9 |
| | **Almere Muziekwijk** | 12.4 | 16.1 | 36.8 | 13.9 | 11.4 | 18.7 | 1.0 | 0.7 | -1.0 | 0.9 | 1.1 | 0.5 |
| | **Almere Poort** | 16.2 | 19.9 | 15.8 | 15.8 | 14.3 | 20.6 | 1.0 | 0.8 | 1.0 | 1.0 | 1.1 | 0.7 |
| | **Weesp** | 23.5 | 27.3 | 23.1 | 18.7 | 21.7 | 24.8 | 1.0 | 0.8 | 1.0 | 1.2 | 1.1 | 0.9 |
| **Almere Centrum** | **Almere Muziekwijk** | 9.4 | 13.2 | 10.9 | 10.9 | 9.4 | 8.4 | 1.0 | 0.6 | 0.8 | 0.8 | 1.0 | 1.1 |
| | **Almere Poort** | 13.3 | 9.5 | 8.4 | 12.9 | 11.4 | 10.3 | 1.0 | 1.3 | 1.4 | 1.0 | 1.1 | 1.2 |
| | **Weesp** | 20.6 | 16.8 | 15.7 | 15.7 | 15.0 | 14.5 | 1.0 | 1.2 | 1.2 | 1.2 | 1.3 | 1.3 |
| **Almere Muziekwijk** | **Almere Poort** | 10.3 | 14.0 | 11.8 | 32.6 | 29.1 | 26.6 | 1.0 | 0.6 | 0.9 | -1.2 | -0.8 | -0.6 |
| | **Weesp** | 17.6 | 21.3 | 19.1 | 17.2 | 15.7 | 14.7 | 1.0 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 |
| **Almere Poort** | **Weesp** | 13.8 | 11.9 | 10.8 | 15.3 | 13.8 | 12.7 | 1.0 | 1.1 | 1.2 | 0.9 | 1.0 | 1.1 |
| **Gen. tt** | | **578.0** | **493.1** | **459.2** | **453.9** | **500.8** | **459.6** | | | | | | |

Below, the generalized travel times for each OD-pair are showed for implementing MB between Lelystad and Weesp. The right side of the table show the delta increment / decrement generalized travel time ratio relative to the base scenario, in which two consecutive regional trains run at ETCS Level 2 MB and perform a full stopping pattern, alternated with a direct Intercity Train.

*Table D2: GTT per O-D pair for MB*

| From | To | Gen tt. variant base | Gen tt. variant 1 | Gen tt. variant 2 | Gen tt. variant 3 | Gen tt. variant 4 | Gen tt. variant 5 | Delta variant base | Delta variant 1 | Delta variant 2 | Delta variant 3 | Delta variant 4 | Delta variant 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Lelystad** | **Almere Oostvaarders** | 17.4 | 21.1 | 21.1 | 21.1 | 18.9 | 16.3 | 1.0 | 0.8 | 0.9 | 0.9 | 1.0 | 1.1 |
| | **Almere Buiten** | 20.2 | 16.5 | 16.5 | 16.5 | 15.4 | 17.3 | 1.0 | 1.2 | 1.2 | 1.2 | 1.3 | 1.1 |
| | **Almere Parkwijk** | 23.6 | 27.3 | 27.3 | 19.9 | 23.2 | 27.6 | 1.0 | 0.8 | 0.9 | 1.2 | 1.1 | 0.8 |
| | **Almere Centrum** | 26.5 | 20.9 | 20.9 | 22.8 | 21.7 | 18.5 | 1.0 | 1.2 | 1.3 | 1.2 | 1.2 | 1.3 |
| | **Almere Muziekwijk** | 29.5 | 33.3 | 29.5 | 31.4 | 29.2 | 24.7 | 1.0 | 0.9 | 1.1 | 1.0 | 1.1 | 1.2 |
| | **Almere Poort** | 33.4 | 25.9 | 27.8 | 35.2 | 31.1 | 26.7 | 1.0 | 1.2 | 1.2 | 1.0 | 1.1 | 1.2 |
| | **Weesp** | 40.7 | 33.2 | 35.1 | 35.1 | 34.0 | 30.8 | 1.0 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| **Almere Oostvaarders** | **Almere Buiten** | 9.2 | 13.0 | 13.0 | 13.0 | 10.7 | 28.5 | 1.0 | 0.6 | 0.8 | 0.8 | 1.0 | -1.1 |
| | **Almere Parkwijk** | 12.6 | 16.4 | 16.4 | 15.4 | 33.7 | 21.1 | 1.0 | 0.7 | 0.9 | 1.0 | -0.8 | 0.3 |
| | **Almere Centrum** | 15.6 | 19.3 | 17.4 | 18.3 | 15.2 | 10.8 | 1.0 | 0.8 | 1.0 | 1.0 | 1.1 | 1.3 |
| | **Almere Muziekwijk** | 18.6 | 22.3 | 20.4 | 47.0 | 18.2 | 13.8 | 1.0 | 0.8 | 1.0 | -0.3 | 1.1 | 1.3 |
| | **Almere Poort** | 22.4 | 26.1 | 24.2 | 23.3 | 37.7 | 38.7 | 1.0 | 0.8 | 1.0 | 1.1 | 1.2 | 1.0 |
| | **Weesp** | 29.7 | 33.5 | 31.6 | 30.6 | 27.5 | 21.6 | 1.0 | 0.9 | 1.0 | 1.0 | 1.1 | 1.3 |
| **Almere Buiten** | **Almere Parkwijk** | 9.8 | 8.0 | 8.0 | 8.0 | 6.9 | 16.7 | 1.0 | 1.2 | 1.3 | 1.3 | 1.4 | 1.0 |
| | **Almere Centrum** | 12.8 | 9.0 | 9.0 | 10.9 | 7.9 | 9.8 | 1.0 | 1.3 | 1.4 | 1.2 | 1.4 | 1.2 |
| | **Almere Muziekwijk** | 15.8 | 13.9 | 12.0 | 13.9 | 10.9 | 22.8 | 1.0 | 1.1 | 1.3 | 1.2 | 1.4 | 0.7 |
| | **Almere Poort** | 19.6 | 14.0 | 15.9 | 15.9 | 14.8 | 14.8 | 1.0 | 1.3 | 1.2 | 1.2 | 1.3 | 1.2 |
| | **Weesp** | 26.9 | 21.3 | 23.2 | 21.3 | 20.2 | 22.1 | 1.0 | 1.2 | 1.2 | 1.2 | 1.3 | 1.2 |
| **Almere Parkwijk** | **Almere Centrum** | 9.4 | 13.1 | 13.1 | 13.1 | 10.9 | 10.3 | 1.0 | 0.6 | 0.8 | 0.6 | 1.0 | 0.9 |
| | **Almere Muziekwijk** | 12.4 | 16.1 | 43.0 | 16.1 | 20.0 | 18.7 | 1.0 | 0.7 | -1.0 | 0.9 | 1.1 | 0.5 |
| | **Almere Poort** | 16.2 | 19.9 | 18.1 | 18.1 | 15.8 | 20.6 | 1.0 | 0.8 | 1.0 | 1.0 | 1.1 | 0.7 |
| | **Weesp** | 23.5 | 27.3 | 25.4 | 19.8 | 23.1 | 24.8 | 1.0 | 0.8 | 1.0 | 1.2 | 1.1 | 0.9 |
| **Almere Centrum** | **Almere Muziekwijk** | 9.4 | 13.2 | 13.2 | 13.2 | 10.9 | 8.4 | 1.0 | 0.6 | 0.8 | 0.8 | 1.0 | 1.1 |
| | **Almere Poort** | 13.3 | 9.5 | 9.5 | 15.1 | 12.9 | 10.3 | 1.0 | 1.3 | 1.4 | 1.0 | 1.1 | 1.2 |
| | **Weesp** | 20.6 | 16.8 | 16.8 | 16.8 | 15.7 | 14.5 | 1.0 | 1.2 | 1.2 | 1.2 | 1.3 | 1.3 |
| **Almere Muziekwijk** | **Almere Poort** | 10.3 | 14.0 | 14.0 | 37.8 | 32.6 | 26.6 | 1.0 | 0.6 | 0.9 | -1.2 | -0.8 | -0.6 |
| | **Weesp** | 17.6 | 21.3 | 21.3 | 19.5 | 17.2 | 14.7 | 1.0 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 |
| **Almere Poort** | **Weesp** | 13.8 | 11.9 | 11.9 | 17.5 | 15.3 | 12.7 | 1.0 | 1.1 | 1.2 | 0.9 | 1.0 | 1.1 |
| **Gen. tt** | | **531.1** | **538.2** | **555.6** | **586.6** | **551.6** | **544.3** | | | | | | |

# Bibliography

Aoun, J., Quaglietta, E., Goverde, R., Jack, A., Blumenfeld, M., Redfern, B., . . . Söser, S. (2020). *Cost-Effectiveness Analysis for Virtual Coupling.* Récupéré sur European Commision: https://projects.shift2rail.org/download.aspx?id=16d44cbe-5743-4a4f-bc2a-b26c709a2e39

Aoun, J., Quaglietta, E., Goverde, R., Nicholson, G., Pachl, J., Scheidt, M., & Chaddock, J. (2020). *Market Potential and Operational Scenarios for Virtual Coupling.* Récupéré sur European Commision: https://movingrail.eu/images/Deliverables/D4.1-MOVINGRAIL_Market-Potential-and-Operational-Scenarios-for-VC-20200707.pdf

Arentze, T. A., & Molin, E. J. (2013). Travelers' preferences in multimodal networks: Design and results of a comprehensive series of choice experiments. *Transportation Research Part A, 58,* 15-28.

Börekçi, N. A. (2018, November). Design Divergence Using the Morphological Chart. *Design and Technology Education: An International Journal , 23*(3), pp. 62-87.

Borges, R., & Quaglietta, E. (2021). Assessing Hyperloop Transport Capacity Under Moving-Block and Virtual Coupling Operations. *IEEE Transactions on Intelligent Transportation Systems, 23(8),* pp. 12612-12621.

Boysen, N., Briskorn, D., & Schwerdfeger, S. (2018, March). The identical-path truck platooning problem Voliume 109. *Transportation Research Part B,* pp. 26-39.

Cao, Z., & Ceder, A. (. (2019, May 2019). Autonomous shuttle bus service timetabling and vehicle scheduling using skip-stop tactic. *Transportation Research Part C: Emerging Technologies, 102,* pp. 370-395.

Chai, S., Yin, J., D'ariano, A., Samà, M., & Tang, T. (2023, February). Scheduling of Coupled Train Platoons for Metro Networks: A Passenger Demand-Oriented Approach. *Transportation Research Record Volume 2677, Issue 2*, pp. 1671-1689.

Chai, S., Yin, J., D'Ariano, A., Liu, R., Yang, L., & Tang, T. (2024, March). A branch-and-cut algorithm for scheduling train platoons in urban rail networks. *Transportation Research Part B: Methodological Volume 181*, p. 102891.

Chai, S., Yin, J., Tang, T., D'Ariano, A., & Samà, M. (2023, February). Scheduling of Coupled Train Platoons for Metro Networks: A Passenger Demand-Oriented Approach. *Transportation Research Record: Journal of the Transportation Research Board, 2667*(2), pp. 1671 - 1689. doi:https://doi.org/10.1177/03611981221109175

Delft Hperloop. (2024). *The Hyperloop Concept*. Consulté le April 16, 2024, sur Delft Hyperloop: https://www.delfthyperloop.nl/the-hyperloop-concept

Doppelbauer, J. (2023). *Hyperloop- an Innovation for Global Transportation?* doi:10.13140/RG.2.2.14261.04323.

Eichelberger, M., Geiter, D. T., Schmid, R., & Wattenhofer, R. (2020, September 20). High-Throughput and Low-Latency Hyperloop. *IEEE 23rd International Conference on Intelligent Transportation Systems.* Rhodes: ITSC. doi:10.1109/ITSC45102.2020.9294573

ERTMS Progam Directorate. (2020, June 30). *Programmadirectie ERTMS,* 1.2. Consulté le May 16, 2024, sur ERTMS.nl: https://www.ertms.nl/programmaorganisatie/over-programmadirectie/default.aspx

Es, A. v. (2024, March 18). (J. Plasmeijer, Intervieweur)

Ginn, M., Amuna, F., Colmenares, J., Stewart, A., Diong, B., Wang, Y., & Yang, J. (2017). Conceptual Design and Prototyping of a Slim Semi-autonomous Bus Rapid Transit Vehicle. Dans K. S. University (Éd.), *SoutheastCon 2017* (pp. 1-6). Marietta: IEEE Xplore. doi:10.1109/SECON.2017.7925292

Hardt Hyperloop. (2023, August). *Hyperloop Progress Paper.* Récupéré sur Hardt Hyperloop: https://docs.hardt.global/hyperloop-progress-paper#1dd403f289914775a7bc0382d3665a3c

Jongenotter, E. (2023, January). Operatonail characteristics of the CityCoaster. (J. Plasmeijer, Intervieweur)

Jonkeren, O., Harms, L., Jorritsma, P., Huibregtse, O., & Bakker, P. (2018). *Waar zouden we zijn zonder de fiets en de trein?* Kennisinstituut voor Mobiliteitsbeleid (KiM). Ministerie van Infrastructuur en Waterstaat.

Jonkeren, O., Kager, R., Harms, L., & Bommelstroet, M. t. (2019, October 26). The bicycle-train travellers in the Netherlands: personal profiles and travel choices. *Transportation, 48*, 455-476. Récupéré sur https://link.springer.com/article/10.1007/s11116-019-10061-3#Sec2

Knutsen, D., Olsson, N. O., & Fu, J. (2024). Capacity evaluation of ERTMS/ETCS hybrid level 3 using simulation methods. *Journal of Rail Transport Planning & Management, 30*, 1-13.

Larsen, R., Rich, J., & Rasmussen, T. K. (2019, May). Hub-based truck platooning: Potentials and profitability. *Transportation Research Part E 127*, pp. 249-264.

Liang, K.-Y., Martensson, J., & Johansson, K. H. (2013). When is it Fuel Efficient for a Heavy Duty Vehicle to Catch Up With a Platoon? *7th IFAC Symposium on Advances in Automotive Control* (pp. 738-743). Japan: The International Federation of Automatic Control.

Liang, K.-Y., Mårtensson, J., & Johansson, K. H. (2016, April). Heavy-Duty Vehicle Platoon Formation for Fuel Efficiency. *IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS VOL. 17 NO.4*, pp. 1051-1061.

Liatsos, V., Golias, M., Hourdos, J., & Mishra, S. (2024, March). The capacitated hybrid truck platooning network design problem. *Transportation Research Part A: Policy and Practice, 181*(103999). Récupéré sur https://doi.org/10.1016/j.tra.2024.103999.

Liu, L., & Ping Wang, Y. W. (2019). Dynamic train formation and dispatching for rail transit based on virtually coupled train set. *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*, (pp. 2823-2828). Auckland, New Zealand.

Liu, Y., Ou, D., Yang, Y., & Dong, D. (2022). A Method for Maintaining Virtually Coupled States of Train Convoys. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit., 237*(2), pp. 243-252. doi:10.1177/09544097221103333

Loop, J. v. (1997). Intermodality: successes by integrating public transport modes and cycling. *Transportation research board, 9*, 21-28. Récupéré sur http://trid.trb.org/view/486447

Lott, J. S., Young, S. E., Duvall, A., & Henao, A. (2022). Passenger Boarding Station and Curbfront Configuration Concepts for On-Demand Services with Small Automated Vehicles. *International Conference on Transportation and Development* (pp. 1-11). Seattle, Washington: National Renewable Energy Laboratory (NREL). Récupéré sur www.nrel.gov/publications

Maschek, U. (2015). Sicherung des Schienenverkehrs. *Springer Fachmedien Wiesbaden*.

Meex, L. (2017, August 31). *Feasibility study of the City Coaster.* Récupéré sur repository.tudelft.nl: https://repository.tudelft.nl/islandora/object/uuid%3A6eb99c62-65fe-48d5-b3b0-3a628a8be730

Mil, J. F., Leferink, T. S., Annema, J. A., & van Oort, N. (2021). Insights into factors afecting the combined bicycle-transit mode. *Public Transport, 13*, 649–673. doi:https://doi.org/10.1007/s12469-020-00240-2

Ministerie van Infrastructuur en Waterstaat. (2022). *Voortgangsrapportage 2021 tweede half jaar.* Den Haag: Ministerie van Infrastructuur en Waterstaat.

Nederlandse Spoorwegen. (2023). *Reizigersgedrag 2023*. Consulté le 07 10, 2024, sur NS Jaarverslag: https://dashboards.nsjaarverslag.nl/reizigersgedrag/

Nguyen, T., Xie, M., Liu, X., Arunachalam, N., Rau, A., Lechner, B., . . . Wong, Y. D. (2019, September 21). Platooning of Autonomous Public Transport Vehicles: The Influence of Ride Comfort on Travel Delay. *Sustainability Volume 11*, pp. 1-14.

Ning, Z., Ou, D., Xie, C., Zhang, L., Gao, B., & He, J. (2023, September). Optimal convoy composition for virtual coupling trains at junctions: A coalition formation game approach. *Transportation Research Part C: Emerging Technologies Volume 154*, pp. 1-19.

Nold, M., & Corman, F. (2021, June). Dynamic train unit coupling and decoupling at cruising speed: Systematic classification, operational potentials, and research agenda. *Journal of Rail Transport Planning & Management, 2021*, pp. 1-26. doi:https://doi.org/10.1016/j.jrtpm.2021.100241.

Noruzoliaee, M., Zou, B., & Zhou, Y. (. (2021, January). Truck platooning in the U.S. national road network: A system-level modeling approach. *Transportation Research Part E 145*, p. 102200.

Pan, H., Yang, L., & Liang, Z. (2023). Demand-oriented integration optimization of train timetabling androlling stock circulation planning with flexible train compositions: A column-generation-based approach. *European Journal of Operational Research 305*, pp. 184-206.

Pan, J., Peng, Q., Zhan, S., & Bai, J. (2021, December 21). Multiscenario-Based Train Headway Analysis under Virtual Coupling system. *Journal of Avanced Transportation 2021 Volume 10*, pp. 1-20.

Pawlik, M., Kycko, M., & Zakrzewski, K. (2021, June 24). Hyperloop vehicles spacing control challenges and possible solutions. *Archives of Civil Engineering, vol. 67*(No 2), pp. 261-274.

Programma Directie ERTMS. (2024). *20e voortgangsrapportage ERTMS.* Den Haag: Rijksoverheid.
Quaglietta, E., & Goverde, R. (2019). Exploring Virtual Coupling: operational principles and analysis. *Proceedings of the 10th ASPECT Conference of the Institution of Railway Signalling Engineers*, (pp. 1-12).
Quaglietta, E., Spartalis, P., Wang, M., Goverde, R. M., & Koningsbruggen, P. v. (2022). Modelling and analysis of Virtual Coupling with dynamic safety margin considering risk factors in railway operations. *Journal of Rail Transport Planning & Management*.
Quaglietta, E., Wang, M., & Goverde, R. M. (2020, September). A multi-state train-following model for the analysis of virtual coupling railway operations. *Journal of Rail Transport Planning & Management, 2020*, pp. 1-17. doi:https://doi.org/10.1016/j.jrtpm.2020.100195
Quaglietta, E., Wang, M., & Goverde, R. M. (2020). A multi-state train-following model for the analysis of virtual coupling railway operations. *Travel Behaviour and Society*, 120-132.
Raua, A., Tian, L., Jain, M., Xie, M., Liu, T., & Zhou, Y. (2019). Dynamic Autonomous Road Transit (DART) For Use-case Capacity More Than Bus. *Transportation Research Procedia 41*, pp. 812-823.
Robenek, T., Azadeh, S. S., Maknoon, Y., & Bierlaire, M. (2017, February). Hybrid cyclicity: Combining the benefits of cyclic and non-cyclic timetables. *Transportation Research Part C: Emerging Technologies, 75*, pp. 228-253.
Schumann, T. (2017, January). Increase of capacity on the shinkansen high-speed line using virtual coupling. *nternational Journal of Transport Development and Integration, 1*, pp. 666–676. doi:10.2495/TDI-V1-N4-666-676
Sebron, W., Gol-Hashem, E., Krebs, P., & Tschürtz, H. (2021, August). The Impact of Train Station Topologies on Operation of Autonomous People Movers. *Communications in Computer and Information Science, 1442*, pp. 223–237. doi:https://doi.org/10.1007/978-3-030-85521-5_15
Sigger, B. (2024, April 9). (J. Plasmeijer, Intervieweur)
Stacy, M. (2014, May 8th). *Communications Based Train Control*. Consulté le October 5, 2024, sur Rail Engineer: https://www.railengineer.co.uk/communications-based-control/
Tang, C., Ceder, A. (., Zhao, S., & Ge, Y.-E. (2016). Determining Optimal Strategies for Single-Line Bus Operation by Means of Smartphone Demand Data. *Transportation Research Record: Journal of the Transportation Research Board, No. 2539*, pp. 130–139.
Tian, Q., Lin, Y. H., Wang, D. Z., & Liu, Y. (2022, May). Planning for modular-vehicle transit service system: Model formulation and solution methods. *Transportation Research Part C: Emerging Technologies, 138*(103627), pp. 1-19.
University of Cambridge. (s.d.). *Design and NPD management tools: morphological charts*. Consulté le May 7, 2024, sur University of Cambridge: https://www.ifm.eng.cam.ac.uk/research/dmg/tools-and-techniques/morphological-charts/
VLAIO. (n.d.). *The status and potential of the transportation concept 'Hyperloop' for Flanders.* Récupéré sur Hardt Hyperloop: https://docs.hardt.global/studies/the-status-and-potential-of-the-transportation-concept-'hyperloop'-for-flanders#f0a6599d4b1d4cb1a122aa5cf4f7447e
Wang, Y., D'Ariano, A., Yin, J., Meng, L., Tang, T., & Ning, B. (2018, December). Passenger demand oriented train scheduling and rolling stock circulation planning for an urban rail transit line. *Transportation Research Part B, 118*, pp. 193-227.
Wu, Z., Chunhai, G., & Tao, T. (2021, April 08). A Virtually Coupled Metro Train Platoon Control Approach Based on Model Predictive Control. *IEEE Access Volume 9*, pp. 56354 - 56363.
Xue, Z., Lin, H., & You, J. (2021). Local container drayage problem with truck platooning mode. *Transportation Research Part E 147*, p. 102211.
Zhang, J., Ge, Y.-E., Tang, C., & Zhong, M. (2024, April). Optimising modular-autonomous-vehicle transit service employing coupling–decoupling operations plus skip-stop strategy. *Transportation Research Part E: Logistics and Transportation Review Volume 184*, pp. 1-21.
Zhang, W., Jenelius, E., & Ma, X. (2017). Freight transport platoon coordination and departure time scheduling under travel time uncertaint. *Transportation Research Part E 98*, pp. 1-23.
Zhong, Q., Xu, C., Yang, R., & Zhong, Q. (2023, March). Equivalences between analytical railway capacity methods. *Journal of Rail Transport Planning & Management Volume 25*, pp. 1-16.
Zhou, H., Qi, J., Yang, L., Shi, J., Pan, H., & Gao, Y. (2022). Joint optimization of train timetabling and rolling stock circulation planning: A novel flexible train composition mode. *Transportation Research Part B 162*, pp. 352-385.