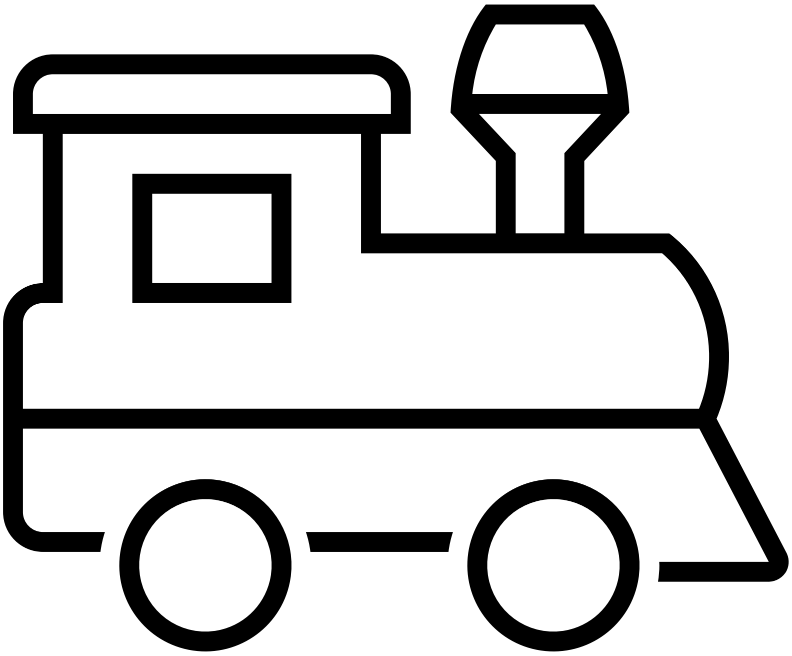
Integrating railway network development with hierarchically lower modalities of public transport

A case study on the Amsterdam – Lelystad corridor

By A.I. Mihalevschi



Integrating railway network development with hierarchically lower modalities

A case study on the Amsterdam – Lelystad corridor

By

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in Civil Engineering, Transport & Planning

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Preface

Dear reader,

With this thesis I complete my degree for the Master Transport & Planning of Civil Engineering at the TU Delft. Never could I have imagined the adventure it would be and the experience it would bring. I am, however, pleased at where the journey has brought me.

I would like to thank my graduation committee for their seemingly unending patience and continuous support throughout the process. I am proud to say that, as opposed to the many challenges that have crossed my path, my committee was an ally from beginning to end.

Many thanks go to the colleagues at SMA. For their support with my thesis, for their kindness towards a stranger, and for sharing the joy of the railway world.

And I am thankful and forever indebted to all my friends and family, (ex-)girlfriends and their family, the people that have been with me from the beginning, the people that helped me push through, the people that have started to cheer me on, on the way, and the people that are now less present in my life, but of whom I know support me with all their warmth still.

I hope you will find this an enjoyable read.

Anton Ioan Mihalevschi,

Delft, 31 July 2023

Summary

Urbanization, a desire for a reduction of CO2 and a need for a more efficient use of space are likely to greatly increase demand for rail travel in the coming decades. This is likely to put a capacity strain on existing heavy-rail infrastructure. To improve railway capacity, extra infrastructure can be built, or existing track can be optimized. A silo analogy provides an interesting idea for an integral approach to network development that combines the demand of heavy-rail and bus, tram, and metro: either obtain more demand for the heavy-rail system and thus validate expensive infrastructural investments or reduce demand. Both options require a broadening of the analysis so that it includes bus, tram, and metro networks. To explore the practical implications of this analogy, the research question is set up as follows:

“Does integrated public transport network development in the form of a simultaneous consideration for infrastructural investment in both heavy-rail and hierarchically lower public transport modes offer a better solution for fulfilling transportation needs, compared to a segregated approach?”

To answer the research question, literature review has been used to gain insights in public transport integration from a technical and a governance perspective. Literature has also been used to form integration strategies that could be applied in network development. The formed strategies consist of using network hierarchy as a guideline for either applying bus, tram, and metro to take over lower hierarchy services from the heavy-rail. Or, for trying to take over bus, tram, and metro services with the heavy-rail system by developing its network to allow for more lower hierarchy services. A case study on the corridor Amsterdam – Lelystad in The Netherlands was used to apply the integration strategies on and to analyze the effects of the development following the different strategies in a real-life situation. For this, three different variants of public transport network development for 2040 have been worked out into feasible timetables on meso-level. Cost, travel time and synthetic demand analyses have been carried out. With a multi-criteria analysis the resulting variants have been compared on the criteria of generalized travel time, operational costs, investment costs, synthetic demand, fairness of the offer and the fulfillment of public transport related political ambitions. A stakeholder reflection was performed to obtain a deeper perspective of what is considered a good network development, and for whom.

The results show that the variant following the strategy of assigning lower hierarchy services to heavy-rail appears best in terms of generalized travel time, synthetic demand, and investment costs. It scores well on fairness of the offer, but lowest on ambition fulfillment and operational costs. It turned out that each variant needed investment in more heavy-rail infrastructure to allow for completing of the heavy-rail ambitions. The *Ijmeer* connection between Amsterdam and Almere via a new connection passing the Pampus area of Almere is expected to be by far the largest item in terms of investment costs. The variant with more tasks assigned to bus, tram, and metro scored the worst, except for ambition fulfillment. This could be an indication that the criteria, as set-up in this research, did not account well enough for the intended positive effects of the ambitions. Furthermore, the multicriteria analysis, although useful for providing insights in the qualities of the different variants, does not give a definitive answer on what the best variant would be. Using external input to assign weights to the multicriteria analyses would have been a good improvement in getting to that answer.

By doing a case study, an example is shown of one of many ways to integrate the development of future heavy-rail networks with hierarchical lower systems, like bus, tram, and metro. The idea of this research was to show what is possible. In that sense, the research suggests that

it is worth considering ambitions and problems outside of just the bus, tram, and metro or just the heavy-rail system.

The process of brainstorming based on expertise, using qualitative multicriteria analyses for making decisions with supporting arguments in the design phase, planning a plausible timetable and analyzing and comparing several variants forms a good skeleton for investigating the possibilities of public transport network development in places where heavy-rail capacity becomes problematic.

At any given part in the process, but especially in the cost and the demand analysis, improvement of the input is possible, which is expected to lead to more accurate results.

Further research by going into more detail regarding the bus, tram, and metro system, considering all stops and stations and a better travel time assessment for them could offer a more truthful insight in the benefits of these systems.

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List of abbreviations

Almoa – *Almere Oostvaarders aansluiting*

BTM – Bus, tram, and metro

Gpda – *Gaasperdammerweg aansluiting*

GTT – Generalized travel time

IC – Intercity

IC-D – Intercity Direct

IR – Interregio

MCA – Multicriteria analysis

PT – Public transport

SPR – Sprinter

TD-diagrams – Time-distance diagrams

1. Introduction

Urbanization, a desire for a reduction of CO2 reduction and a need for more efficient use of space are likely to greatly increase demand for rail travel in the coming decades (Arup, 2019). In urban areas where space is already scarce, this is likely to put a capacity strain on existing heavy-rail infrastructure. To improve railway capacity, extra infrastructure can be built, or current track can be optimized by operational interventions (Lai & Barkan, 2011). However, the cost of building extra infrastructure could be high, especially in densely populated areas. And although other kind of investments like the introduction of the ETCS signaling systems have promising theoretical results with respect to capacity efficiency (Goverde et al., 2013) by allowing shorter headway times, it is possible that these systems alone will not be enough. There is thus additional need for a way of developing the heavy-rail system that provides a better ratio between development costs and provided benefits.

An example for the situation sketched in the previous section is that of the Netherlands: in the Dutch government's policy program from 2022, the ambition is set for an emission free mobility sector in 2050. To achieve this, an increase in PT usage is mentioned as one of the necessary steps (*Beleidsprogramma Infrastructuur en Waterstaat 2022*, 2022). The national railway network is mentioned to continue to play a crucial role in the PT system (*Ontwikkelagenda Toekomstbeeld OV*, 2021). However, the Dutch heavy-rail network is predicted to have capacity challenges by the year 2040, with other PT system components, like Bus, Tram and Metro (BTM) being predicted to face capacity challenges too (*IMA 2021 Hoofdrapport deel 4*, 2021). These capacity problems hinder the achievement of the government's political ambitions and are problematic for the involved PT stakeholders.

It appears that up until now, the organization of railway planning and operations is done independently form other PT systems: the Dutch long-term railway planning report Landelijke Netwerkuitvoering Spoor 2040, (ProRail, 2020) mentions that, while for transportation forecasts the Bus-Tram-Metro (BTM) networks are considered, the development of those networks is out of the report's scope. It may therefore be plausible that there are solutions that would tackle the capacity challenges for both the national railway network and local networks which are yet unexplored. An analogy can be made with grain silos, where the silos are the infrastructure capacity and the grain is the demand. If only one silo is considered, it may be a problem if the surplus grain is not enough to validate the construction of an entirely new silo. However, if two silos (heavy-rail and BTM) have a surplus, the total surplus may be enough. The construction of a new silo is considered a system shift, as it requires a large investment and brings the whole system in a new situation, with much more capacity. By changing the approach from developing a heavy-rail network as a stand-alone system to developing a PT network formed of multiple systems, including that of heavy-rail, the grain silo analogy could lead to new service concepts that would not be considered otherwise. These service concepts may lead to a better performing PT network than the ones based on the approach of developing modes separately. Thus, for instance, transferring excessive demand on the railway network towards an already desired local alternative, like a light-rail, metro, or BRT service, might give the necessary demand to make this alternative feasible. Insights in these possibilities may form part for the solution for the Dutch PT challenges. These insights may also be relevant for solving similar problems on networks outside of the Netherlands.

1.1 Problem statement and research gap

The silo analogy provides an idea for an integral approach to network development that combines the demand of heavy-rail and BTM: either obtain more demand for the heavy-rail system and thus validate expensive infrastructural investments or reduce demand. Both options require a broadening of the analysis so that it includes BTM networks.

However, it is not clear if the analogy is applicable in practice. To the best of the author's knowledge, a method for investigating the benefits of doing an integrated approach is not yet available. It would be useful to have insights in the possible approaches and the resulting benefits, as this could facilitate system shifts where necessary and thus ensure a smooth growth of the PT network that matches development in other domains like population and industry. This study aims to provide that knowledge by applying a series of existing methods used for network analysis and development design to a case study.

1.2 Research questions

The described problem is formalized in a main research question:

"Does integrated PT network development in the form of a simultaneous consideration for infrastructural investment in both heavy-rail and hierarchically lower PT modes offer a better solution for fulfilling transportation needs, compared to a segregated approach?"

To answer the main research question and to structure the research, the following sub questions are posed:

a. "How is heavy-rail network development in The Netherlands integrated with the local PT development and what is the governance background for this?"
b. "What network developments are needed based on an integrated, and what on a segregated approach?"
c. "Which network development is better and from what perspective?"
d. "What are governance related challenges to implement the better solution?"

The objective of this research is to define a form of integration between heavy-rail and hierarchically lower PT modes and to develop and test a framework that is used to investigate the benefits of that integration.

1.3 Thesis outline

This research report is structured as follows: The research processes, used methods and necessary tools and data are discussed in Chapter 2. This includes the introduction of the case study that is the core of this research. In Chapter 3 a literature review is performed on the topic of PT network design, integrated PT network design and PT governance. Chapter 4 is on strategies for integrated PT network development. Chapter 5 is on the selected case and the respective PT network. In Chapter 6 the result of creating integrated network development variants is presented. Chapter 7 is on the scheduling of the network development variants. Chapter 8 applies analysis methods to obtain data. Chapter 9 evaluates the findings. Chapter 10 reflects upon the results from the perspective of several stakeholders. Finally, Chapter 11 discusses the results, presents the drawn conclusions, and offers recommendations.

2. Methodology

In this chapter, the research process is laid out and the used methods are motivated. To answer the research questions, literature review has been used for answering sub-question a. Literature has also been used to form the integration strategies, which form an answer on sub-question b. A case study was used to apply the integration strategies on, and to analyze the effects of the development following the different strategies, thus answering sub-question c. Finally, a stakeholder reflection was used to answer sub-question d.

An overview of the processes, methods and tools is given in Figure 2-1. These are discussed in the next sections.

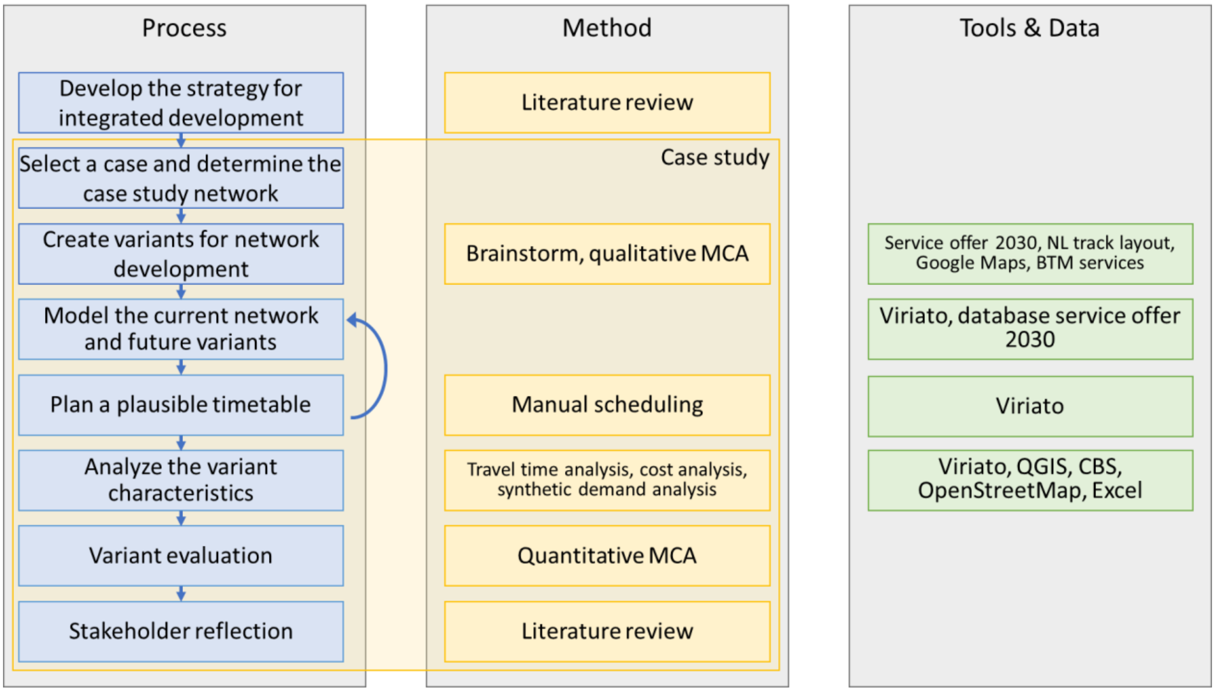


Figure 2-1: Overview of the processes, methods, tools, and data used

2.1 Research process

The different processes that have been performed to obtain an answer to the research sub-questions which could not be answered by literature review are only presented here.

2.1.1 Case study

A case study is defined by Gerring (2004), as a method that is “*an intensive study of a single unit with an aim to generalize across a larger set of units*”. However, it can be seen as a process as well since it is the main component of this research, and it contains multiple processes for which multiple methods are applied. For that reason, it is discussed first. The case study allows for the use of real data and may offer a more deepened insight into why a particular integration strategy would lead or not to a better solution.

The purpose of the case study in this research was to test two strategies for integrated network development inspired on the silo analogy in a real-world situation. The application of the strategies leads to a set of plausible network development variants that could be compared and thus offer an answer on the research questions from a more applied perspective than from theoretical situations alone. The scope of the case study is geographically around the Dutch heavy-rail network. This includes the neighboring PT networks of BTM modalities. In terms of time, the development is aimed at the year 2040, as this allows for serious infrastructural developments to be built.

2.1.2 Formation of integration strategies

The integration strategies are guidelines made to steer the process of creating network development variants. They offered a practical interpretation of integration which could be followed in the network development variant creation process. By following different strategies, the created network development variants could be differentiated in terms of integration. The strategies thus also further define the scope of the case study. The strategy formation process is worked out in Chapter 4. Part of the literature review was input for this process.

2.1.3 Case selection and network determination

In the case selection process characteristics are defined which an appropriate case should have. Then, a set of possible cases is determined after which a filtering process leads to an appropriate case that can be used for the study.

For this research, a case was needed that contained a network suitable for applying network development variants to. Therefore, the case selection process consisted of selecting an area that contains a suitable network, and determining what parts of the network would be considered.

Three desirable characteristics were defined for the case study area:

1. High expected demand for all heavy-rail products (local trains (in the Netherlands Sprinters (SPR) and InterCity's (IC)) should be predicted for this section, as well as high demand for BTM along the section. This is to ascertain enough demand among all hierarchical levels, which is necessary if modes are assigned to dedicated levels.
2. The corridor should be able to be considered stand-alone from the rest of the network. If this is not the case, effects from designs in the case study area cannot be seen independently from effects outside the case study area, leading to either a bad analysis or a too large or complex study area.
3. There should be sufficient ambitions for the heavy-rail and the BTM modalities. The ambitions are, next to growing demand, what drives the development of the PT network and are use in the network design process. The ambitions are political desires for network developments like a particular service or connection.

A set of corridors is defined by using the charts with expected high occupancy rates for IC and SPR trains (*IMA 2021 Hoofdrapport deel 4*, 2021, p. 78) to identify railway sections with high expected occupancy for both IC and SPR products. These corridors are cross-referenced with locations where high BTM occupancy rates are expected, based on the “BTM Challenges” chart (*IMA 2021 Hoofdrapport deel 4*, 2021, p. 79). Corridors not having also high BTM occupancy rates are removed from the selection. The relevant political ambitions for the remaining corridors are listed, based on the “building blocks” found in the *Ontwikkelagenda Toekomstbeeld OV* (2021) . Corridors with less than five ambitions are excluded, this number being estimated as a reasonable limit given number of ambitions for other corridors. The remaining corridors are individually evaluated by the researcher an

d excluded, based on the desired characteristics, until one corridor remains.

The heavy-rail stations along the corridor and the heavy-rail services using sections on the corridor were identified based on the 2021 ProRail service map (Klaas Hofstra, 2020). By use of regional PT maps, BTM lines interacting with the heavy-rail stations are identified. The BTM lines and stations were selected based on their importance for transport along the corridor, as transportation perpendicular to the corridor is out of scope.

Lines were also be simplified based on two rules of thumb: Lines are considered only up to 5 km perpendicular to the corridor, and stations without connections are removed when stopping distance is less than 2 km. The corridor is then presented in a line graph as the set of stations, lines an underlying infrastructure, including line frequencies.

2.1.4 Creation of development variants

Following the formed strategy, a set of variants for the development of the considered PT network for 2040 was made. The first step in this process was to translate the set of political ambitions, which was identified in the case selection step, into concrete services. A brainstorm session was then held to obtain a concept design of the network variants, each following one of the integration strategies, and aiming at fulfilling the ambitions. The participants of the brainstorm session were the researcher, and three railway planning experts of which two did not have previous knowledge of the case (see Appendix A). Relevant documents where provided to assist in the process. These were the relevant BTM and heavy-rail services (see Appendix B and Appendix C), infrastructure (see Appendix D), and general topography. There concept network design to the development variants still had some open design choices. These were made with the assistance of qualitative multicriteria analyses (MCA's). As no data for these variants was yet available, the scoring on the ordinal scale was done based on personal judgement of the researcher.

The case study network has been modelled in the railway planning program "Viriato". This consisted of entering stations, tracks, track topology and services with respective timetables in the database. The heavy-rail network was readily available as a database and only needed to be checked. The BTM part of the network had to be manually entered, for which public data provided by the operators has been used. This network represents the 2030 network, or the reference variant, as it does not contain the development variants resulting from the brainstorm. The network is not a completely correct representation of reality, as the 2030 heavy-rail network is combined with the 2022 BTM network. Moreover, it assumes a peak-hour frequency on all lines for a 24-hour period of time. This simplification was deemed acceptable as the heavy-rail network in the Netherlands has a base-hour pattern with limited variation for peak-hour traffic. And, because it is unlikely that, given the general ambition of more PT, it is likely that there will be more BTM in 2030 than in 2022. A netgraph, which is a graphical representation of a timetable and service network, is made to visualize the base network.

The 2040 variants were constructed by adding the necessary infrastructure and services to the base network variants. By adapting infrastructure and services, an attempt at forming a best compromise between infrastructural investments and service quality has been made. After introducing the desired services, the resulting infrastructural conflicts were detected by checking capacity based on minimum headway, minimum crossing and follow-up times and platform occupation. Additional infrastructure was then created, representing necessary infrastructural measures, to accommodate the extra services and remove all conflicts. Then, the need for infrastructural measures was reduced by adapting the service offer to a less desirable level. This process was iterated until a balance between infrastructural investments and service quality was reached. The result was a service concept for each network design variant on mesoscopic scale, with a plausible timetable. The service concepts and timetables were visualized by means of a netgraph.

2.1.5 Variant analysis

The resulting networks have been analyzed to retrieve data on generalized travel time (GTT), cost for infrastructural investments and operational costs, and synthetic demand between the considered OD-pairs (the stations and stops). To account for long-distance travel, a set of external nodes is defined as well. This set is chosen as each city in the country with a population over 100.000 and a direct heavy-rail connection to at least one of the nodes in the study area. The limit of 100.000 is chosen due to data availability, while the demand of a direct heavy-rail connection limits the set to the cities most relevant for the corridor.

Viriato travel time analysis tool and Excel have been to calculate the GTT. This resulted in an OD-matrix for each variant. The investment costs were calculated based on estimations of cost per kilometer track and per station (Baumgartner, 2001) and reference projects. When necessary, an indexation for inflation was applied. A fixed cost per extra vehicle kilometers was used for calculating the additional operational costs. A gravitation model was used to produce values for synthetic demand between the stations and stops. Input to this model is the GTT from the travel time analysis and number of inhabitants in the station catchment area. This lead to a synthetic demand value for each OD-pair. The methods for these analyses are further explained in sections 2.2.2, 2.2.3 and 2.2.5.

With the data from the analyses, it was possible to compare the variants objectively. To further aid that comparison, the matrices for GTT and synthetic demand were aggregated based on stop location and stop type. De differences between the GTT's of the variants were calculated in percentages, while the differences in synthetic demand were shown in absolute values. This difference because it was expected to be more relevant to show relative time travel reduction/increase, while demand is deemed more valuable in absolute units that can be compared between aggregates.

2.1.6 Variant evaluation

The core of the evaluation was an unweighted, normalized, quantitative MCA. This method is further discussed in section 2.2.3.

2.1.7 Stakeholder reflection

The stakeholder reflection added perspective to the unweighted MCA by suggesting possible criteria of interest based on the characteristics of the stakeholders and their role in the development of the PT network. The criteria that were deemed interesting for a particular stakeholder were weighted a score of 0,5 or 1, while criteria deemed not of interest were weighted 0.

2.2 Used methods

This section discusses in more detail some of the methods that were used in the described process.

2.2.1 Brainstorm

Because only a limited amount of development variants can be worked out, and due to the vast number of possibilities to further develop a PT network, it has been decided to perform a brainstorming session. The brainstorm session is meant to create ideas to a specific problem, and should adhere to a few rules (Alex F. Osborn, 1953, pp. 300–301): The ideas must be free of criticism, there is no limit on the extremity of the ideas, quantity goes over quality and enhancement of other ideas should be encouraged. The advantage of the session is that it allows for a creative take on the solutions, thus not limiting the solution space, while at the same time making them focused on solving the problem at hand given the restrictions imposed by the situation for which the solutions must be found.

2.2.2 Travel time analysis methods

The formula used for calculating the GTT is given by equation *(1)*. The GTT is used to offer the insight into the perceived travel time of a passenger using the network, which allows for a more realistic comparison between network variants.

$$GTT = T_A + T_{min} + N_T * P_T + T_w + T_E \tag{1}$$

Where:

GTT is the generalized travel time

T_A is the access time, estimated at 10 minutes for all stations based on the density of the stations in the research area

T_{min} is the minimum travel time from station to station which is determined based on the service timetables an assumption of a transfer time of 5 minutes, or 1 minute for cross-platform transfers

N_T is the minimum number of transfers

P_T is the penalty for transferring, set at 10 minutes per transfer

T_w is the average waiting time, calculated by dividing 60 minutes by the number of connections per hour and then divided by four. This assumes that passengers do not show up randomly at the station but consult the timetable beforehand. This assumption is deemed reasonable as the rail services are mostly half or quarterly hour services, as opposed to a 10-minute interval NS deems to be “timetable free travelling”.

T_E is the egress time, set at 10 minutes as for the access time

It must be mentioned that using the shortest travel time combined with the least number of transfers underestimates the GTT for connections where there is a choice between a fast connection with more transfers, or a slow connection with less transfers. However, this GTT guarantees that there is no faster connection possible, whereas a GTT considering the average number of transfers combined with the average travel time can become biased by considering too many possible slow connections. The GTT is calculated with excel and results in an OD-matrix for each variant.

2.2.3 MCA

The multicriteria analysis is a technique to compare different variants on multiple criteria. For this research, two types of MCA are used: The qualitative MCA and the quantitative MCA. The qualitative MCA scores criteria on an ordinal scale ranging from --, -, 0, + and ++, from very bad to very good. The quantitative MCA scores criteria with numbers obtained from data.

An empty scoring table of the qualitative MCA is shown in Table 2-1. The MCA criteria are generalized travel time for short distance and long-distance trips, construction and investment cost, and Variant relevance. Travel time reduction and costs are generally accepted characteristics of importance for network development, where lower costs are scored better. Variant relevance is on how well a particular choice fits with the integration strategy. The ambition fulfillment scores better for more fulfilled ambitions, as this was the aim of the network development. The fairness of the offer is introduced to allow for differentiation between variants where all connections improve equally and variants where some connections improve greatly at the cost of others. As no data is yet available for the qualitative MCA, the scoring is done on personal judgment, and can therefore differ depending on the interpretation of the researcher. The weights are all set to one for simplicity.

Table 2-1: Example scoring table for a qualitative MCA

Criterion	Weight	Option 1	Option 2	Option…
Gen. travel time Long	1	--, -, 0, +, or ++		
Gen. travel time Short	1			
Relevance for Variant 1	1			
Relevance for Variant 2	1			
Relevance for Variant …	1			
Investment costs	1			
Operational costs	1			
Fairness of the offer	1			
Ambition fulfillment	1			
Total V1				
Total V2				
Total V…				
Cumulative total				

The values Total V1, V2, V… give a subtotal of a particular option for the different variants. For choices that are only applicable to a specific variant, these totals are left out. The cumulative total score is where the scores for the variants are aggregated. This criterion is important for deciding upon a single option for all variants.

The quantitative MCA is adapted from the qualitative one, which makes sense because both MCA’s help to define which network is better based on what criteria. The variant specific criteria are removed, the GTT is unified for all levels, and the criteria “Demand” is added. The demand allows for differentiation between variants that have a good total GTT reduction, and variants that may have less GTT reduction, but in areas where more people benefit, which should be visible in the form of a higher demand.

The output of the analyses is input for the MCA scoring. The scores are then normalized. This means that for each criterion, the most favorable variant will score “1”, and the least favorable variant will score “0”. Variants that score intermediate have a score somewhere between 0 and 1, in proportion with the difference to the minimum and maximum score. The normalization formula for criteria where a higher value is favorable is given by equation *(2)*:

$$S_{Vn} = \frac{S_V - S_{\mathrm{min}}}{S_{max} - S_{min}} \tag{2}$$

For criteria where a lower value is favorable the normalization is given by equation *(3)*.

$$S_{Vn} = 1 + \frac{S_{min} - S_V}{S_{max} - S_{\mathrm{min}}} \tag{3}$$

Where:

S_{Vn} is the normalized scoring for variant V

S_V is the scoring for variant V

S_{min} is the minimum scoring for variant V

S_{max} is the maximum scoring for variant V

The normalization thus makes it easy to determine how much better one variant scores on a particular criterion compared to the others.

2.2.4 Cost analysis methods

Two types of costs are calculated. Investment costs are costs that, excluding renewal of worn infrastructure, must be made only once. Operational costs are made to operate the PT system. This categorization allows the different parties involved to get a better insight into the costs and benefits relevant to them: a party that must carry the operating costs is not necessarily the party responsible for carrying the investment costs. Additionally, situations can arise where a higher investment cost leads to lower operational costs and vice versa. E.g.: Investing in an extra track for fast turning can reduce the need for additional rolling stock which saves on operating costs (under the assumption that rolling stock depreciation is calculated as operational costs).

The investment costs are calculated using an estimated cost per kilometer extra track, cost per kilometer bridge, and cost per additional station for heavy-rail. These numbers are derived from tables from Baumgartner (2001). For BTM, reference projects are used to take over the cost directly, or to calculate the average cost per kilometer infrastructure first and multiply this with the extra kilometers of infrastructure necessary for the variant. The cost of reference projects is indexed for inflation by multiplying with a respective inflation index to the reference value of 2022, which is done with an online inflation calculator (*Value of 2001 Euro Today - Inflation Calculator*, 2023).

The operational costs are calculated by assuming a fixed rate per extra vehicle kilometers per year and apply this to the extra vehicle kilometers necessary to operate the services of the proposed variants. The fixed rate assumes the costs for vehicle acquisition, depreciation and maintenance, staff, cleaning, track charges, logistical and (empty) runs. Because the cost of the different systems is very different from a bus system, the operational costs are calculated for train, bus, and metro separately. First, the amount of extra vehicle kilometers per hour is calculated with equation *(4)*.

$$V = N_t * d * 2 \tag{4}$$

Where:

V is the number of extra vehicle kilometers per hour

N_t is the number of extra vehicles per direction per hour

d is the distance over which the extra vehicles run

And the multiplication by 2 accounts for the vehicles running in the opposite direction

Then, an estimated amount of extra vehicle kilometers per year is calculated with equation *(5)*.

$$C_o = V * C_V * H * D \tag{5}$$

Where:

C_o is the operational cost per year

V is the number of extra vehicle kilometers per hour

C_V is the cost per vehicle kilometer

H is the active hour equivalent per day, that accounts for the fact that services may not be operational every hour of the day

D is the number of active days per year, that take into account that the service does not run all days of the year

Combining equations *(4)* and *(5)* leads to equation *(6)*.

$$C_o = N_t * d * 2 * C_V * H * D \tag{6}$$

Using these equations offers a sense of the operational and investment costs, albeit very rough. The main goal for calculating the costs is to compare the different variants. As long as all variants are calculated in a similar fashion, the roughness of the cost calculation is deemed acceptable. The absolute value in euros, however, is not suitable for anything more than an indication of the scale of the proposed network developments.

2.2.5 Synthetic demand analysis

The demand is modelled with a gravity model. A differentiation can be made between a simple version, that needs little input and results in a synthetic demand, and a more complex version that additionally needs numbers of in- and outbound trips and has number of trips between OD-pairs as output. The latter version also needs calibration data (number of trips between OD-pairs or cross-section passenger counts on routes). If not calibrated, the resulting output can still be used for a relative analysis. The advantage over the relative analysis with output from the simple version is that the total numbers of passengers going in and out is used to scale the relative demand.

The simple version determines the attraction between two OD-pairs as a function of population in the catchment area divided by the squared generalized travel time, given by equation *(7)*.

$$F_{i,j} = G * \frac{M_i * M_j}{D^2{}_{i,j}} \tag{7}$$

Where:

$F_{i,j}$ is the attraction between nodes i and j
M_i is the number of inhabitants in station i

$D_{i,j}$ is the GTT between stations i and j
G is a constant of proportionality (Rodrigue, 2020)

With this model, a synthetic demand can be calculated. The absolute value of $F_{i,j}$ does therefore not need to have a meaning, resulting in the proportionality constant G to be equal to 1. The demand calculation is done in Excel, as this software is well-suited for this kind of matrix calculation.

The number of inhabitants is determined per station. A circular catchment area with an all-or-nothing assignment is assumed for simplicity. Zonal data on inhabitants' density is overlayed with the catchment areas, and an estimation of the number of inhabitants based on the surface of the zones and their respective population density is calculated. Where catchment areas overlap, an Voronoy polygon is used to define a catchment area border equidistant from the two stations. Excel and QGIS are used to graphically display the catchment areas and do the calculations. The zones are defined as is done by the Dutch Central Bureau for Statistics (CBS), which is also the source for the population data.

The synthetic demand of each future variant is compared to the reference variant and to each other. By determining the percentage of increase or decrease for each OD-pair, as well as for total relative increase/decrease in demand. This data is input for the MCA.

2.2.6 Calculation of unknown travel times

To obtain the travel times of existing services that have stations added or removed, or of services over new infrastructure, equation *(8)* is used:

$$T_{new} = \frac{T_{old}}{D_{old}} * D_{new} + T_{dec} + T_{stop} + T_{acc} \tag{8}$$

Where:

T_{new} is the new travel time

T_{old} is the known travel time, which can be of the service that is adapted, or a reference service

D_{old} is the old distance

D_{new} is the new distance

T_{dec} is deceleration time, the extra time lost due to deceleration from maximum speed to zero or a lower maximum speed.

T_{stop} is stopping time

T_{acc} is acceleration time, the extra time lost due to acceleration from zero or a lower maximum speed to a higher maximum speed

2.3 Tools

This section is on the used tools mentioned in the research process. Apart from Excel and Google Maps (*Google Maps*, n.d.), Viriato and QGIS were used to perform the research.

2.3.1 Viriato

Viriato is a timetabling tool, developed by SMA und Partner AG. This tool can model vehicles and infrastructure on mesoscale and assist in the planning process (SMA und Partner AG, 2022). For this research, Viriato is used to display the PT network, to assist in planning a plausible timetable, and to obtain travel time data between the stations following the application of the planned services.

The services performed by the vehicles over the infrastructure can be displayed graphically, via time-distance diagrams (TD-diagrams), platform occupation diagrams for stations, and net-graphs, which are simplified maps displaying stations services and departure times.

The interactive TD-diagrams are used to inspect services on a certain stretch of track, and thus provide information on the capacity use conflicts and opportunities for extra services or service changes. To check for plausibility, a built-in conflict analysis tool is used to check for minimum headway, minimum follow-up and crossing times, and platform occupation.

Viriato is also used to do a trip time analysis, which uses the stations and services as an input to calculate travel times between two stations, considering transfers and transfer time. The program allows for a shorter minimum transfer time for cross-platform transfers.

2.3.2 QGIS

QGIS is an open-source geographic information system (*Discover QGIS*, n.d.). It visualizes geographical data and has a range of tools to perform calculations and modifications to datasets.

QGIS is used in this research to graphically display the location of the stations that are considered on a geographical map. It is used to display the catchment areas of the stations, calculate Voronoy polygons and make sub-zones based on the overlap of catchment areas and areas from external sources that contain zonal data, in this case population density. QGIS then calculates the surface area of these newly made sub-zones, which then can be used to multiply with the population density to obtain an estimate for number of inhabitants in the catchment area.

3. Literature

The literature section focuses first on transport networks and network design. The second part is then on the governance of PT in the Netherlands.

3.1 The transport system

Schoemaker et al. (1999) mention three system layers in a transport system, as shown in Figure 3-1. Based on this system, two networks are defined:

1. The traffic network, as a layer itself, consisting of the infrastructural elements.
2. The service network, formed by the services provided by transport companies.

The part of the service network that is accessible for everyone is the public transport network and is formed by two dimensions. The special dimension is the location of access points and the connection between those points. The time dimension is the timing of departure and arrival to and from the access points. To clarify this model, an example is given: The transport pattern, formed by an individual going from A to B, is facilitated transport service, for instance a railway operator, that needs in turn a railway network to run the trains on. However, the traffic network is of no use to the individual without a service.

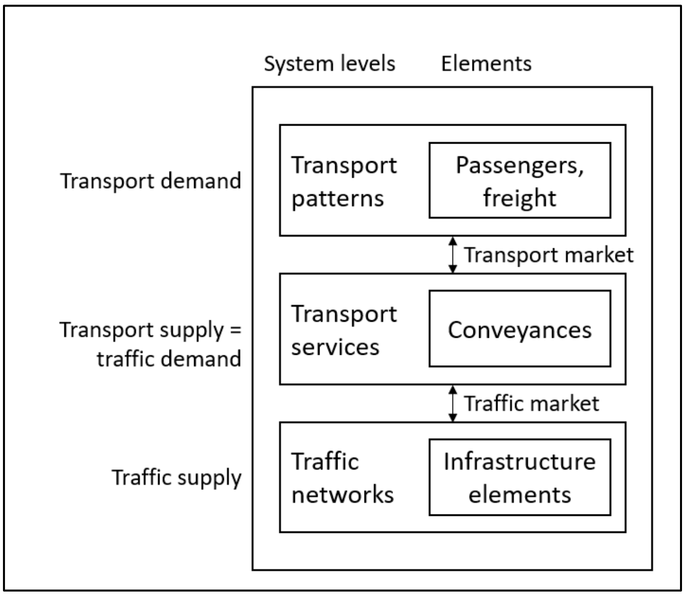


Figure 3-1: System layers and markets. Adapted from: Schoemaker et al. (1999, p. 177)

3.2 Interaction within the transport system components

Work by Immers et al. (2011) explains that, due to the constant changing of mobility patterns, a transportation network needs to adapt to comply with the mobility needs. As bottleneck-oriented responses to these changes may not be enough, a network redesign may be needed. This is a very complex problem where the interest of multiple stakeholders needs to be considered. An important aspect in network design is to first define the function of a network component, and only then decide upon the chosen system (mode) to fulfil that function. This fits with the layer model, where the demand from the passenger perspective asks for a service, which is supplied by modes, but not modes themselves.

3.3 Transport network hierarchy

This conclusion is also drawn by Van Nes (Nes, 2002), who uses the two distinct networks in his hierarchical approach to the design of a multi modal network. Multi modal mobility is defined as the use of multiple distinct transport services for a single trip (an individual's movement from origin to destination). It is mentioned that, as a multimodal trip implies transfers, there is a need for the characteristics of the main mode (the mode that covers the largest distance) to compensate for the transfer disutility. The concept of hierarchical transport networks is defined, where the higher level is classified as having a course network with few access points and high operating speed and the lower level has the opposite of these characteristics. It is argued that hierarchy is a natural way to optimize performance versus resources needed.

3.4 Example of transport system redesign

On the redesign of well-functioning PT networks, the best example found is given by (Orth et al., 2015) for the Zürich city and region area. Several alternatives for adapting the network are compared and discussed. The analyzed network is centralized with a single city center at its core, in which the hierarchically highest-level mode is the regional rail (S-Bahn) network. This paper mentions the gap between the lower-level PT network (tram and bus) and the upper level (S-Bahn), and how the need for an extra level can be fulfilled with either an extra level on a new infrastructure network, or a new service level on existing infrastructure. This paper also mentioned how the introduction of the S-Bahn system brought the need for a regional transportation agency, the ZVV.

3.5 PT governance

The mention of the introduction of the ZVV in the previous section forms the bridge between network design and governance. It suggests that governance has an influence on the PT network design. Understanding this role is therefore important for evaluating the performance of current and proposed network designs.

Veeneman (2021) provides a comprehensive view on the relationship between governance and public transport. He further suggests that a more integrated approach on PT governance could lead to a better transportation system by resolving conflicting governance. Finally, he provides a framework that could help take steps towards this more integrated governance design. He defines governance within this context as "the rule set under which actors are making decisions that drive the performance of public transport services". These rule sets are categorized as done by Powell,(Powell, 1990) in the forms of hierarchy, market and network organization. Hierarchies imply that the predefined structure determines the rule set. For instance, within a company it is the boss that takes decisions over employees. Markets are on case-to-case agreements, defined in contracts, like for instance a passenger agreeing to use a transportation service for a fixed ticket price. Networks imply interdependency between actors, where negotiation sets the rules.

The concept of multi-level governance linked to multi-level PT networks is discussed by Veeneman and Mulley (2018). They show through three case studies and literature analysis that governments must be seen as a multi-layered. The governmental level that has agency (decision power) through funding, has effect on the focus of PT development and the resulting

PT network structure: When agency is centralized, higher hierarchy modes with a focus on linking are developed, at the cost of lower-level modes. Furthermore, governmental levels do not necessarily operate in coordination, leading to conflicting governance.

3.6 Conclusion

In the case of the Dutch railways, the many expected bottlenecks may indicate that the current PT network designed does not fit the projected mobility needs. It may be possible that, due to the development of PT in The Netherlands, following the structure of governmental layers and their (lack of) PT agency, the heavy-rail component is charged with fulfilling some network functions for which it is not the right technique. It appears to be out of the scope of ProRail and NS to assess the network design on a level superseding the heavy-rail component.

4. Integration strategy

This chapter forms an interpretation of the necessary integration and creates a strategy of how to apply this interpretation on the development variants. The strategy is then steering in the design process.

First, it is necessary to interpret “integrated design” and to develop an approach for the application on the design process. Two types of integrated design are defined: technical integration and governance integration. The technical integration focusses on including more than one system in the creation of a particular service concept. Integrating governance is on the inclusion of more than one stakeholder in the creation of a particular service concept.

4.1 Design strategy based on technical integration

In the case of PT, the idea of integration inspired by the silo analogy is to try to invest in infrastructure so that both the heavy-rail and the BTM capacity constraints are helped to solve. The question arises what that investment would be. It is not straightforward to assume that demand for heavy-rail services can be taken over by BTM and the other way around, so it is important to get an idea of which tasks of the PT network might be eligible to be performed by both BTM and heavy-rail.

In section 3.3 the concept of hierarchy is introduced as being an aspect of a transport network. Specific characteristics that determine hierarchy are mentioned: operational speed, network coarseness and number of access points. It is clear that in general the heavy-rail system has a higher operational speed than BTM: A city bus or metro system goes slower and calls more often than an international IC service. However, there are buses that travel longer distances, and there are SPR services that stop quite often. That a certain modality can serve a certain hierarchical level, does not mean that it should, from the perspective of cost versus service offered. It could be, that the total cost versus the total service offered, is better when each system focuses on a separate range of hierarchical levels. It is therefore decided to use the hierarchy of the heavy-rail and BTM systems to identify services that could potentially be carried out by the other system. And to use the stopping distance, the distance between stations, as an indicator of hierarchy. This is done because it is easily measurable and only a dependent on the service offer. This assignment of systems to services based on hierarchic levels, determined by stopping distance, is determined in this study as being the technical integration of public transport network design.

To investigate what this type of integration brings, three variants of future network designs are worked out. The first one is not integrated, in the second one it is tried to carry out more low-hierarchy services with the heavy-rail system, and in the third less. See Table 4-1. For clarity purposes, hierarchy levels are defined for this thesis based on stopping distance and presented in Table 4-2.

Table 4-1: Strategies for integrated design

Variant	Strategy	Description and reasoning
V1	Not integrated	A mixed, disaggregated approach with respect to which system is used to what hierarchical level: each system serves the levels it already does today.
V2	Integrated: more heavy-rail	This variant aims to serve as many hierarhcy levels with the heavy-rail system. By serving more levels, more benefits could be obtained allowing for the development of the heavy-rail system.
V3	Integrated: focus heavy-rail	This variant aims to limit the levels served by heavy-rail. By serving less levels, the available capacity can be dedicated to the levels the heavy-rail system serves best.

The levels are defined based on the information from section 3.3. This results in the definition as provided in Table 4-2.

Table 4-2: Definition of levels

Stopping distance [km]	Denomination	Description
1 to 3	Level 4	Agglomeration
3 to 10	Level 3	Regional
10 to 30	Level 2	Interregional
30 to 100	Level 1	National

4.2 Design strategy base on integrating governance

Irrespective of whether a service concept is technically integrated or not, the definition of whether it is “good” is shallow if it is based on the interests of only one of the stakeholders. Therefore, it was tried to involve stakeholders in the creation and evaluation process by two steps:

a. Stakeholders are involved in setting up the criteria for the qualitative and quantitative MCA’s
b. Stakeholders are involved in the process of evaluating the developed variants.

However, due to lack of time and candidate stakeholders on time, no official interviews could be held within the timeframe of this research. Instead, It was chosen to do the stakeholder reflection in chapter 10.

5. Case study network

This section is about selecting a case study area and determining the part of an existing PT used in the case study. In paragraph 5.1 the requirements for an appropriate case study area are presented and motivated. In paragraph 5.2 the approach for searching an appropriate area, including applying the set requirements is elaborated upon. The process performed during the research is discussed and the defined case study area is presented. In 5.3 the part of the PT network within the case study area that is used in the rest of the research is defined.

5.1 Requirements for a suitable case study area

The requirements are set so the case study is properly applicable to answer the research questions. These requirements are explained below and summarized in Table 5-1.

The area must contain a heavy-rail corridor that encompasses multiple stations of all service types (IC stations and SPR stations). This way the assignment of heavy-rail on different network levels can be investigated. The heavy-rail corridor should have little network effects, meaning that the services along the corridor can be modified with minimal effect on the service network outside of the case study area. A BTM system should be present running parallel to the heavy-rail corridor in such a fashion that taking over a heavy-rail service by the BTM system would be theoretically possible. In line with the silo analogy, there should be a need for development following an expected capacity shortage (bottlenecks), on every service level, for both the heavy-rail and the BTM system. Because when all layers have a need for development, the possibility arises to solve the need of multiple levels within both the BTM system and heavy-rail system, with improvements in only one system. Political ambitions are used to interpret the desires regarding the future development of PT networks. The presence of enough ambitions is therefore required.

Table 5-1: Requirements for selecting a case study area

Requirement
Presence of heavy-rail
Little heavy-rail network effects
Projected heavy-rail capacity issues
Projected BTM capacity issues
BTM parallel to the heavy-rail corridor
Sufficient PT ambitions

5.2 Case study area selection

This paragraph is on the case study area selection process. It consists of elaborating on the approach, after which the performed steps are discussed, ending with the selected case study area. The case study area is then the area that contains the case study network, which in turn is further defined in paragraph 5.3.

By using an initial requirement, a set of suitable heavy-rail corridors is created. Then, the set is filtered by going stepwise through the other requirements, until a suitable refined set remains. From those remaining corridors, a best corridor is selected based on written argumentation.

5.2.1 Defining and filtering suitable heavy-rail corridors

The steps that are made for guiding the definition and filtering of the heavy-rail corridors, following the requirements from Table 5-1, are presented here. They are made for this specific case study, based on the data available, and form an interpretation of applying the requirements. For other cases, different steps could be made, depending on the available sources. The reasoning behind the steps as well as the execution is described below:

1. In the introduction the example of the Dutch railways is given for a heavy-rail network with projected future capacity constraints. For this reason, the Dutch heavy-rail network is considered.
2. Figure 5-1 presents sections of the Dutch railway network that are expected to have crowded IC trains, indicated by a high percentage of standing places occupancy. It is assumed that high occupancy is caused by a lack of infrastructure capacity, as the obvious solution to this problem would otherwise be running more trains. Therefore, the high occupancy rate is used as an indicator for sections with capacity issues, which thus fulfill part of the projected heavy-rail capacity issues requirement. The services using this section are identified using Figure C-2. The corridors are identified by attempting to combine one or more of the identified sections with the affected services. This process has a subjective aspect and different results could be obtained by different researchers. The resulting 14 corridors are presented in Table 5-2 and Figure 5-2.

Table 5-2: Identified corridors

#	**Identified corridor**
1	*Dordrecht - Vlissingen*
2	*Den Haag Centraal – Dordrecht*
3	*Eindhoven – Zwolle*
4	*Eindhoven – Utrecht*
5	*Den Haag Centraal – Utrecht*
6	*Nijmegen – Utrecht Centraal*
7	*Deventer – Utrecht Centraal*
8	*Den Haag Centraal – Schiphol Airport*
9	*Amsterdam Centraal – Leiden Centraal*
10	*Amsterdam Centraal – Utrecht Centraal*
11	*Alkmaar – Amsterdam Centraal*
12	*Amsterdam Centraal – Meppel*
13	*Amersfoort – Schiphol Airport*
14	*Groningen – Leeuwarden*

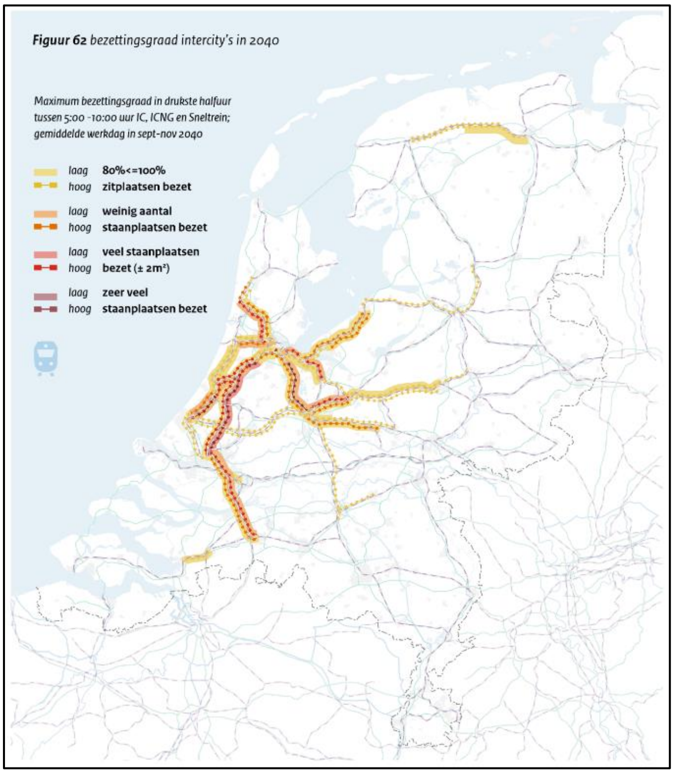


Figure 5-1: Occupancy rate ICs in 2040 – From: *IMA 2021 Hoofdrapport deel 4* (2021, fig. 62)

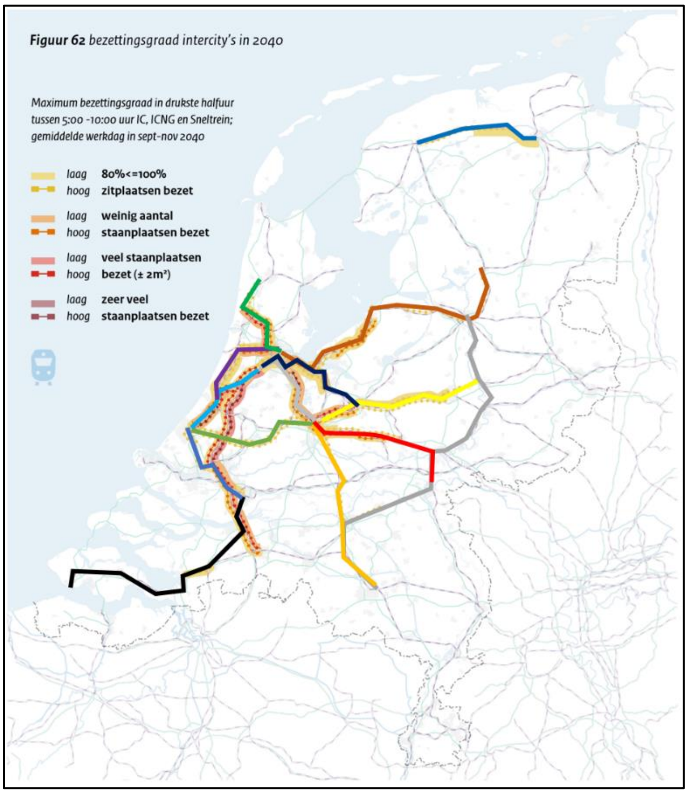


Figure 5-2: Intercity corridors based on the 2030 service concept and busy IC track sections. Adapted from: *IMA 2021 Hoofdrapport deel 4* (2021, fig. 62)

3. The requirement for having capacity issues on all heavy-rail network levels is completed by cross-referencing the set of corridors with the sections in Figure 5-3, which shows SPR services with high expected occupation. By having both the IC and

SPR services covered regarding capacity issues, it is assumed that all service levels within the heavy-rail system are taken into consideration and that the requirement is fully met. This step eliminates corridors 1 and 6.

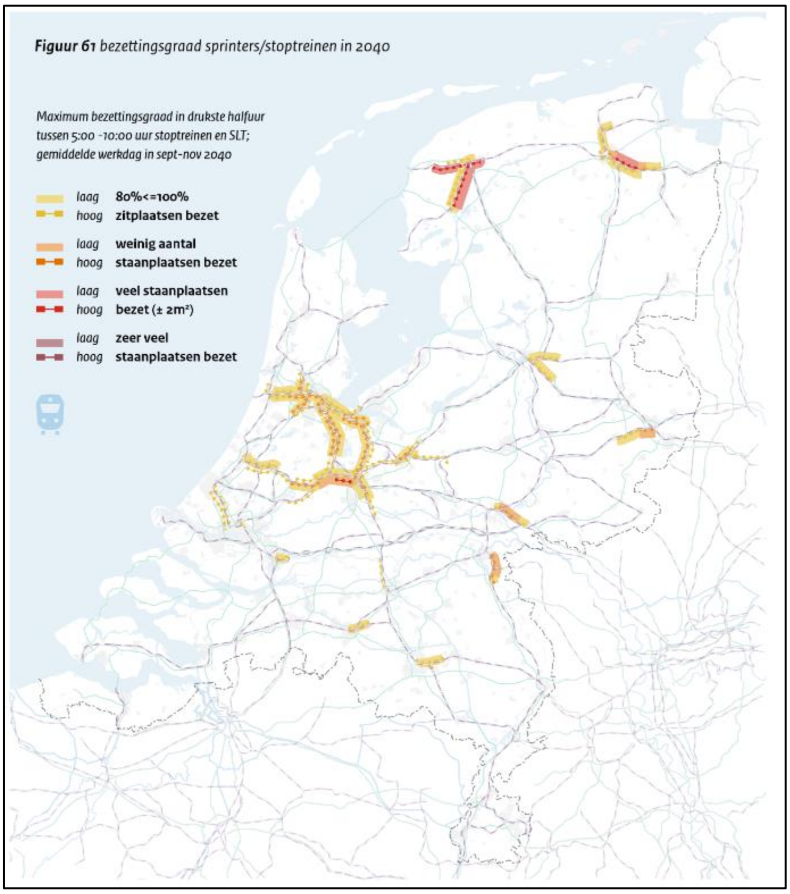


Figure 5-3: Occupancy rate Sprinters in 2040 – Adapted from: *IMA 2021 Hoofdrapport deel 4* (2021, fig. 61)

4. Locations in the BTM network with potential capacity challenges from Figure 5-4 are used to cross-reference for the requirement regarding the projected BTM capacity issues requirement. All the 12 remaining corridors turn out to fulfill the requirement.

Figure 5-4: BTM capacity challenges. Adapted from: *IMA 2021 Hoofdrapport deel 4* (2021, fig. 63)

5. The ambitions connected to the identified corridors are retrieved from the Development Agenda Future Vision PT report (Ontwikkelagenda Toekomstbeeld OV, 2021). In this document, so called “Bouwstenen” (building blocks) are mentioned as solutions to implement a more abstract governmental desire for the future PT. The building blocks from this document are therefore treated as ambitions. They are registered, and the corridors that overlap topographically with the ambition location are noted. See Table G-1, Appendix G. The number of ambitions per corridor is noted and displayed in a bar chart, see Figure 5-5. Upon inspection it turns out that the ambitions vary a lot between one another (frequency increase versus the construction of an entire new track section), which makes it difficult to establish which number is “enough” ambitions. Therefore, based on the range of number of ambitions per corridor from Figure 5-5, a threshold of at least five ambitions is chosen, to eliminate the corridors on the lower end of number of ambitions. This eliminates corridors 3, 8 and 14, leaving nine corridors.

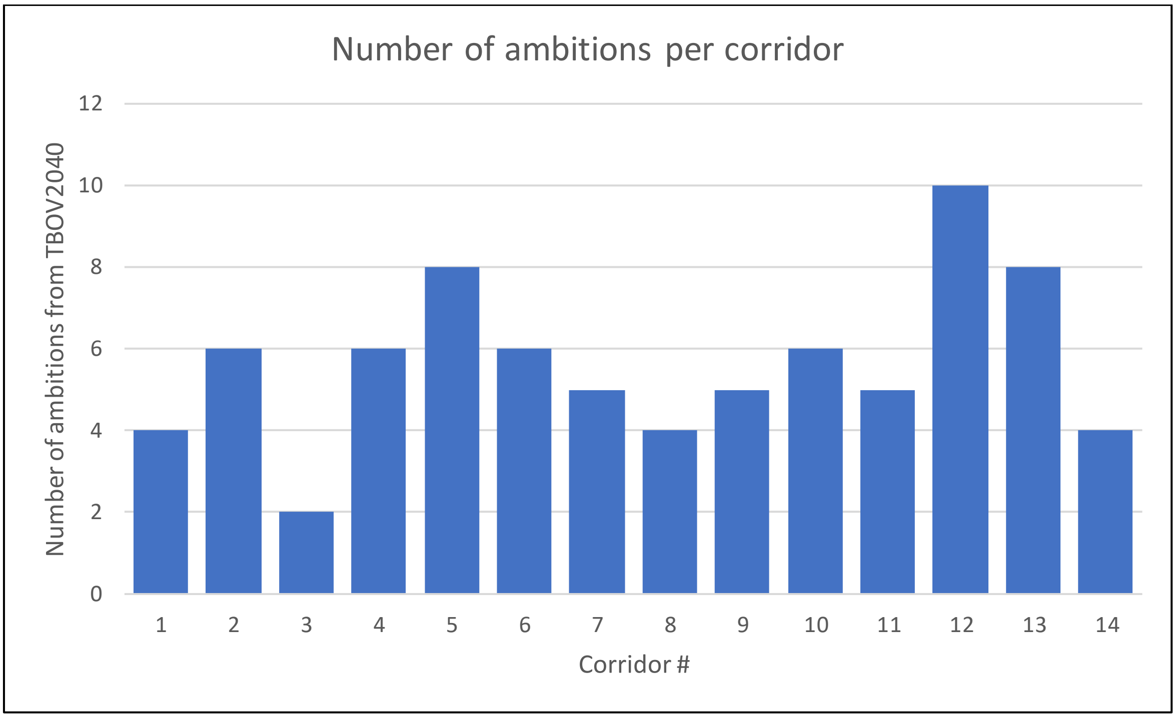


Figure 5-5: Number of ambitions per corridor

The definition of “Not too many network effects” is also not so straightforward. Therefore, it is defined as “a corridor that is connected to more than one other of the identified corridors on both ends. See Figure 5-6 for a clarification.

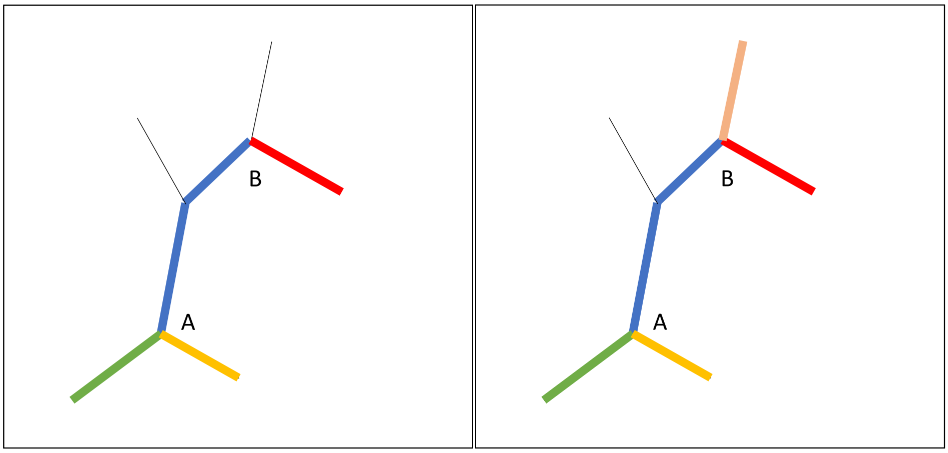


Figure 5-6: A blue corridor between A and B without (left) and with (right) too many network effects

The reason for picking other identified corridors as an indication is that it is assumed that these are also corridors with capacity issues, and therefore more sensitive to potential changes on the case study corridor. This excludes two more corridors, leading to a total of seven corridors.

Table 5-3: The steps of the case study area selection approach

#	Fulfilled requirement(s)	Step description	Source(s)
1	Presence of heavy-rail	Consider a heavy-rail network	
2	Projected heavy-rail capacity issues	Create a set of logical heavy-rail corridors that are expected to have capacity issues on the IC network	Figure 5-1, Appendix C
3	Projected heavy-rail capacity issues	Refine the set to contain only corridors with capacity issues on the SPR network	Figure 5-3
4	Projected BTM capacity issues	Refine the set to contain only corridors nearby BTM networks with capacity issues	Figure 5-4
5	Sufficient PT ambitions	Identify network development ambitions related to the corridor and refine based on a minimum number of ambitions	Ontwikkelagenda Toekomstbeeld OV, 2021
6	Not too many network effects	Remove corridors that are connected to too many other corridors	Figure 5-2

The seven remaining corridors are seen as a reasonable number to analyze in more detail. This is done in the next section. The “BTM parallel to the heavy-rail corridor” requirement is also treated in the next section, as it requires a more detailed look of the BTM ambitions and challenges to determine whether capacity issues are likely to be parallel to the corridor.

5.2.2 Final selection based on argumentation

For each of the remaining corridors a table is made to better evaluate and compare them. The tables contain information on which IC and SPR sections have capacity issues, the relevant BTM locations with expected capacity issues and the relevant ambitions. This can be found in Appendix H. Together with the requirements, the following considerations are made, leading to the selection of the most suitable corridor:

Corridor 2 (*Den Haag Centraal – Dordrecht*):
The ambitions that exist appear to be mostly aimed at optimizing the current network rather than further development (“S-Bahn type connection”,”Extra sprinters”, “Automatization of the Rotterdam metro”). The remaining three ambitions (“Intermodal crossing in Rotterdam”, “’Kings’ corridor” and “New connection Gorinchem – Dordrecht – Rotterdam”) are considered not parallel to the corridor enough to fulfill the “BTM parallel to the heavy-rail corridor” requirement. Therefore, this corridor is excluded from the set.

Corridor 4 (*Eindhoven – Utrecht Centraal*):
This corridor does not appear to have lower PT network hierarchy level issues, as it goes mainly through unpopulated areas. The BTM issues are around Utrecht, rather than along the corridor. Therefore, it does not meet the requirement of parallel BTM challenges and is excluded from the set.

Corridor 7 (*Deventer – Utrecht Centraal*):
This corridor has the same issue as corridor 4: The BTM issues are only around Utrecht Centraal, with little lower hierarchy level issues among the rest of the corridor. Therefore, this corridor is excluded from the set based on the parallel BTM requirement.

Corridor 9 (*Amsterdam Centraal – Leiden Centraal*):
After better inspection, this corridor has too many network effects when considering that it forms one of the two connecting pillars between Amsterdam and Leiden Centraal – Den Haag Centraal. The section between Amsterdam and Haarlem could be interesting but is rather small, and has high network effects as well, due to the connection with Uitgeest and Alkmaar.

Corridor 11 (*Alkmaar – Amsterdam Centraal*):
This corridor is also discarded based on the complexity of the network it is in, which can be seen as it passes three junctions (Amsterdam Sloterdijk, Zaandam, Uitgeest). Based on the "Little heavy-rail network effects" requirement, this corridor is excluded.

Corridor 12 (*Amsterdam Centraal – Meppel*):
This corridor has two BTM capacity challenge zones along the first part of the corridor. Furthermore, there is enough capacity challenge for both IC and sprinter. However, the implementation of three BTM areas, when Zwolle is included, seems out of scope.

Corridor 13: (*Amersfoort Centraal – Schiphol Airport*):
This corridor lacks BTM challenges except for concentrated in Amsterdam. This has the same problem as the corridors surrounding Utrecht. Therefore, it is excluded based on the "Parallel BTM challenges" requirement.

The remaining corridor, corridor 12, is selected to be the base for the case study area. Due to the presence of three BTM areas with challenges, it has been decided to shorten the corridor, and make it from *Amsterdam Centraal* to *Lelystad Centrum*. Moreover, based on the proposed service network for 2030 given in Appendix C, it is argued that it is not reasonable to consider only the network section towards *Amsterdam Centraal*: All IC trains from Lelystad towards Amsterdam are proposed to go to station *Amsterdam Zuid*, while only SPR services go on the route *Lelystad Centrum – Amsterdam Centraal*. Therefore, the case study area is the area around the corridor *Lelystad Centrum – Amsterdam Centraal* as well as *Lelystad Centrum – Amsterdam Zuid* (which overlap until station *Weesp*). See Figure 5-7 for a general overview of the chosen corridor and case study area. The exact network elements that are used for the case study are discussed in the next section.

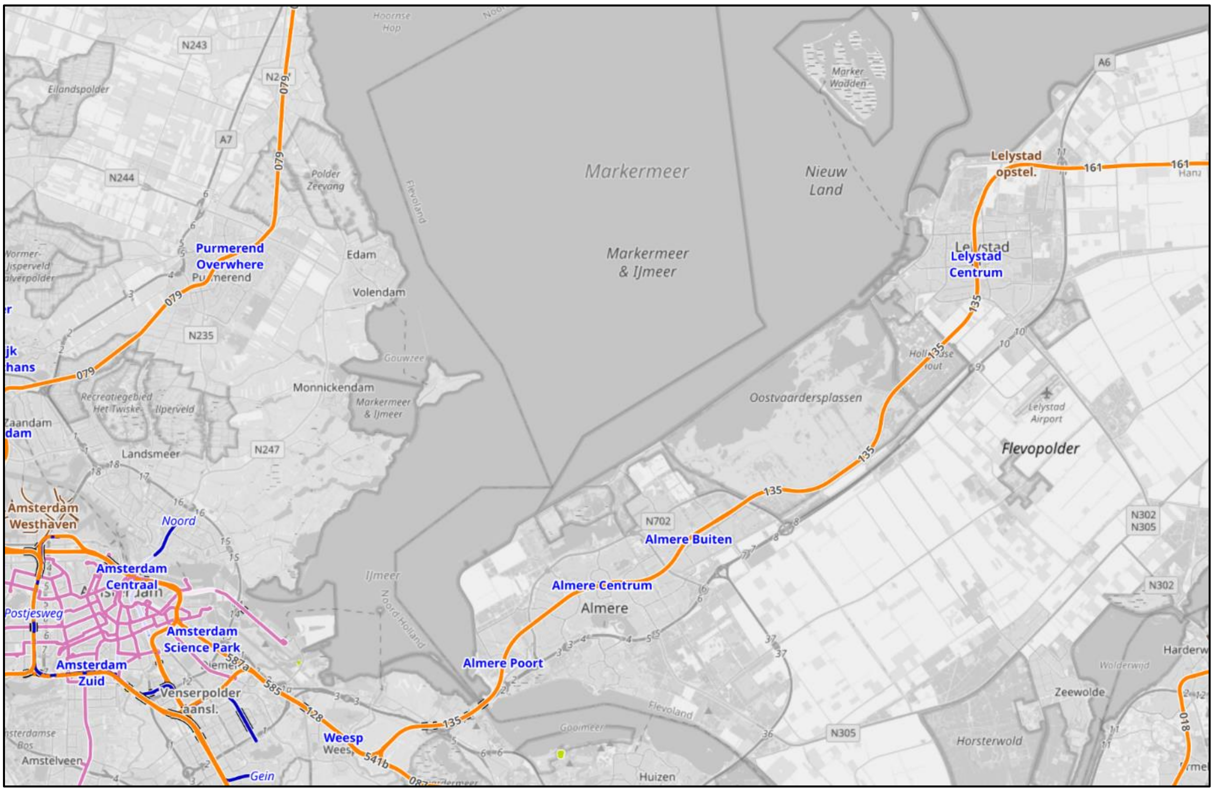


Figure 5-7: Topographical overview of the selected corridor with railway lines. From: OpenStreetMap (n.d.-a). Orange: heavy-rail main corridors, pink; tram lines, dark blue; metro lines.

5.3 Refinement and overview of the case study network

The selected case study area including the described heavy-rail corridor given in the previous section is here further elaborated into defined components of the PT network. First, the heavy-rail network components, consisting of the track sections, stations, and services, are defined. Then, the relevant underlying BTM network components are identified and when necessary simplified. Finally, all network components are graphically displayed.

5.3.1 Heavy-rail network components

The heavy-rail components consist of the heavy-rail infrastructure sections between the three end stations (*Amsterdam Zuid*, *Amsterdam Centraal* and *Lelystad Centrum*) and the stations on those sections. These are identified using, again, the 2030 service network map from Appendix C. The resulting stations are presented in Table 5-4 and Table 5-5. All services running on those sections are also considered part of the heavy-rail network.

Table 5-4: Corridor *Amsterdam Central – Lelystad Centrum* by order of stations

Station
Amsterdam Centraal
Amsterdam Muiderpoort
Amsterdam Science Park
Diemen
Weesp
Almere Poort
Almere Muziekwijk
Almere Centrum
Almere Parkwijk
Almere Buiten
Almere Oostvaarders
Lelystad Centrum

Table 5-5: Stations on the *Amsterdam Zuid – Weesp* section

Station
Amsterdam Zuid
Duivendrecht
Diemen Zuid
Weesp

5.3.2 BTM network components

The considered BTM components are selected by first identifying all BTM services in the case study area, and then simplifying the set. The simplification is necessary to get a manageable set of stops.

The BTM stops and services, with underlying infrastructure, are identified by investigating which companies are operating in the case study area and analyzing the company's respective network.

In The Netherlands, regional and urban PT is organized by public tender, for which the provinces and metropolitan regions dictate the concession conditions. Four cities are exempt from public tender for the urban PT, among which Amsterdam (Waterstaat, 2021). For the Amsterdam – Lelystad corridor, this comprises the concession areas of “Busvervoer Almere”, “Stadsvervoer Lelystad”, “IJsselmond”, “Gooi en Vechtstreek” and “Concessie Amsterdam”. The respective operators and responsible governmental institution are mentioned on the official provincial websites of Flevoland (Flevoland, 2019), Noord-Holland (Noord-Holland, 2016) and the “Vervoersregio Amsterdam” (Transportation Region Amsterdam) (*Concessie Amsterdam*, n.d.; *Openbaar vervoer*, n.d.). These are presented in Table 5-6.

Table 5-6: Relevant BTM concession areas with respective responsible institution and carrier

Concession area	Responsible governmental institution	Carrier
Busvervoer Almere	Municipality of Almere	Keolis
Ijsselmond	Province Flevoland	OV Regio Ijsselmond
Stadvervoer Lelystad	Province Flevoland	Arriva
Gooi en Vechtstreek	Province Noord-Holland	Transdev
Concessie Amsterdam	Vervoersregio Amsterdam	GVB

The network maps used for the identification of the lines relevant for the corridor can be found in Appendix B. After inspection of all the lines it is decided to exclude all BTM lines of the “Stadsvervoer Lelystad” concession area. This is due to the radial character of the Lelystad BTM network, combined with the absence of a parallel line along the Lelystad – Almere network sections. This does not fit the “BTM parallel to the heavy-rail corridor” requirement on this section, as it does not offer possibility for one system taking over another.

Within the “Consessie Amsterdam” area, only metro and the RNET buses are considered, as the transport facilitated by the trams and buses run by GVB are assumed to provide intra-urban transportation only, which is outside the scope of the research.

After the considered lines are selected (see Appendix B), the set of stations for each line is identified, using the operator’s publicly available line information (GVB, 2022b; Keolis, n.d.; Transdev, 2022b, 2022a). With Google Maps, the distance is measured between stops along the considered lines. BTM stops that are not hubs (where two or more lines meet) are removed from the set of considered stations in such a manner that the remaining stations are about 2 km apart. The 2km is selected as this is the median distance of the agglomeration level as defined in Table 4-2, which is the lowest network level that is considered in this research. Stops that connect to heavy-rail are also considered hubs and are kept. It is noted that all metro lines continuing westward from *Amsterdam Zuid* or Northward from *Amsterdam Centraal* are not considered, as these surpass the end of the defined heavy-rail corridor. Also, bus lines 159 and 160, leaving Almere in the southeast of the municipality, are only considered until stop “Vogelweg”, as this is where these lines connect and therefore the last “hub” between two of the considered lines.

Finally, it is decided to also include the heavy-rail network section from *Amsterdam Holendrecht* to *Amsterdam Centraal*, as this section can provide an alternative to the metro lines parallel to it, and therefore must be considered as well in the modelling part later. However, this section is considered as it is and is not going to be modified in the network development part of this research.

The set of considered stations and lines are visualized with the use of the program “Netvisio” into a graphic service network. The cutouts of the Amsterdam area and the Almere area are presented in Figure 5-8 and Figure 5-9. For the entire network, see Appendix J.

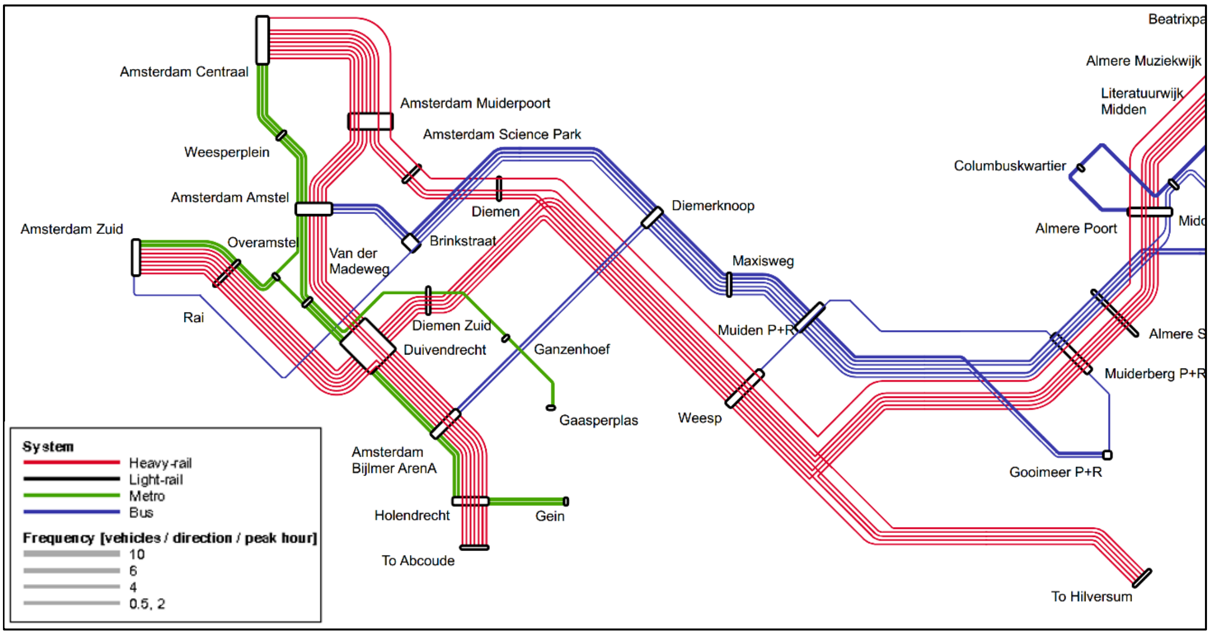


Figure 5-8: Cutout of the case study network including heavy-rail and BTM, Amsterdam Area

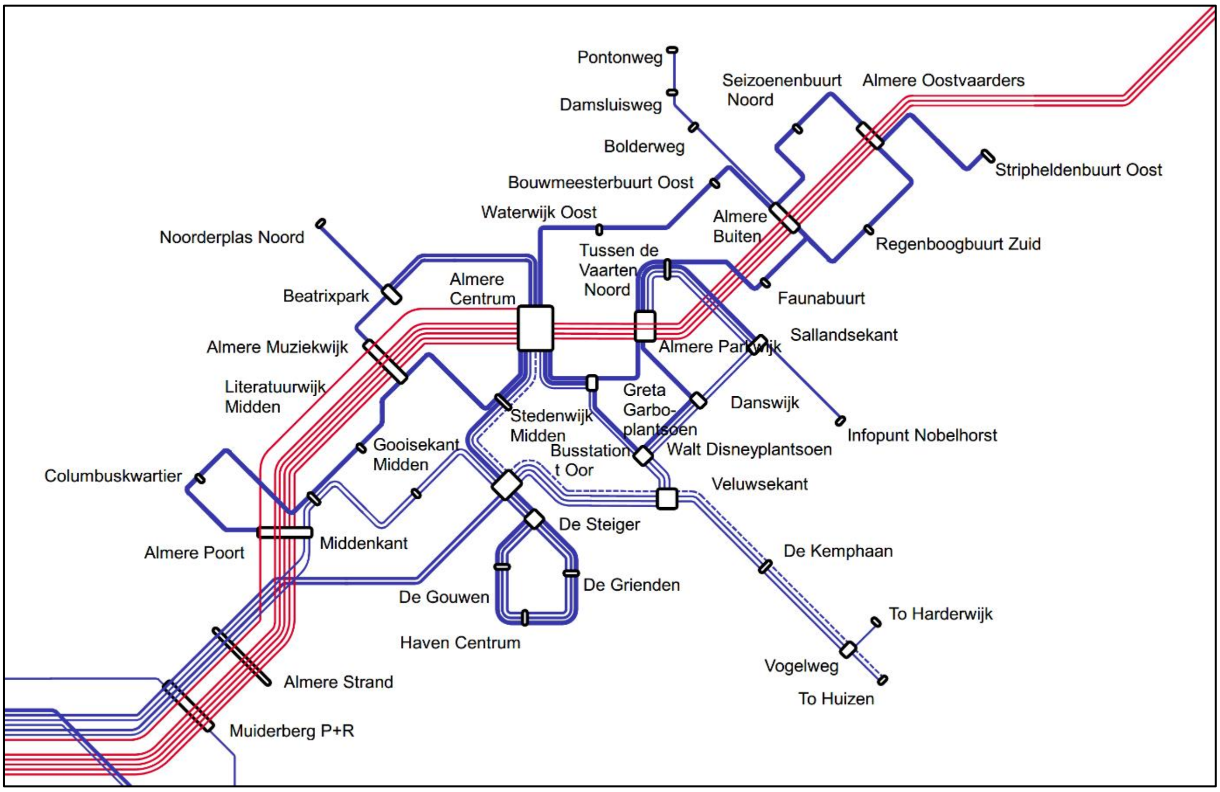


Figure 5-9: Cutout of the case study network including heavy-rail and BTM, Almere area

6. Development of the service networks

In this section the network development variants are worked out from concept to service network. At the service network stage an intended network is presented, consisting of services with their routes and frequencies, plus the PT system that is carrying out these services. To this process, there are three components, namely ambition interpretation, the brainstorm session and sub-variant selection with qualitative MCA's.

The case study network as defined in Chapter 5 is the base for all service networks, and underlying infrastructure networks. The political ambitions relevant for this corridor, discussed in section 5.2, are the elements used to develop the service network to one fit for 2040. Three network configuration concepts based on the strategies of PT systems form the basis of how the new service network should be shaped.

An interpretation of the ambitions, in which the written-out ambitions are translated into to a service, is done to enable fitting the ambitions into the service network. This is discussed in section 6.1. The brainstorm component is the first part of the development process and is discussed in section 6.2. In section 6.3 further design choices are made based on qualitative MCA's.

6.1 Ambition interpretation

The written ambitions are interpreted into a desired PT service. This is necessary because some of the ambitions in their current form can be interpreted in different ways, which in turn makes it difficult to say in the evaluation whether one variant fulfills an ambition better than the other. To give an example: "extra trains" could be two fast trains, or four slower trains.

The ambitions for the Amsterdam – Lelystad corridor have been presented in Table H-6, Appendix H. Each is written here again for clarity purposes, followed by the service interpretation and an argumentation. For some ambitions the interpretation leads to an exclusion from the set of ambitions, which is also elaborated:

a) "Extra (+2 "fast trains") between Utrecht – Almere
This ambition is interpreted as: "A 30-minute frequency service between Almere and Utrecht that calls at fewer stations than the existing sprinter services." The basis for this is the term "fast trains", that is not well defined in terms of station policy, as is the IC, which only calls at "intercity stations", but indicates an improvement in travel time compared to a slower service (SPR service).

b) "Intercity and sprinter services between Amsterdam and Almere/Amersfoort are to go to both *Amsterdam Zuid* and *Amsterdam Centraal*".
This ambition is interpreted as: "Almere should have a direct SPR and a direct IC connection to both *Amsterdam Zuid* and *Amsterdam Centraal*". Only Almere is mentioned as Amersfoort is outside of the corridor.

c) "Improving the travel time of the sprinter service between Utrecht – Almere"
This ambition is already clearly defined as a service ambition and is therefore not further interpreted. However, because this service runs mostly outside of the corridor and can be executed by interventions outside of the corridor alone (as opposed to the service in a), that needs extra capacity within the corridor), it is excluded from the set of ambitions.

d) "New connection between the "Randstad" and Groningen/Leeuwarden (*Lelylijn*)"
This ambition is interpreted as: "A 30-minute interval intercity service connecting Amsterdam with Leeuwarden and a 30-minute interval intercity service connecting Amsterdam with Groningen, of which both run via a new railway line connecting directly

the places Lelystad – Emmeloord – Heerenveen – Drachten – Groningen and by doing so significantly improve the travel time between Amsterdam and the two cities of Leeuwarden and Groningen". The *Lelylijn* project is the largest ambition of the set, and the interpretation of the routes is taken over directly from the project webpage (*Goed Gespoord van West naar Noord*, 2022). The frequency is set at a half-hour interval because it is the common minimum interval for a train service in the Netherlands, see Appendix C, and it can therefore be assumed that new infrastructure will not be built at all for a lower interval. The addition of the "significant improvement" is because it is in line with the mentioned website to have a faster connection between the "Randstad" area and the northern part of The Netherlands.

e) "Increase the frequency between the "Randstad" area and Groningen/Leeuwarden."
This ambition is interpreted as: "The total number of connections" between Amsterdam – Groningen and Amsterdam – Leeuwarden should be larger than in the current situation". The reason why "Amsterdam" is chosen as a replacement of "Randstad" is because with the *Lelylijn* ambition extra connections are automatically made if no other connections are broken, and it therefore makes plausible that "Randstad" is allowed to be interpreted as "Amsterdam".

f) "An intercity between Amsterdam and Enschede via Zwolle."
This ambition is not further interpreted because the ambition can be fulfilled without any changes inside the corridor. For instance, by rerouting the existing IC services from Zwolle on further.

g) "S-Bahn type connection between Haarlem – Weesp".
This ambition is interpreted as "There must be a direct sprinter service between Haarlem and Weesp, with a minimum frequency of 15 minutes". Because the "S-Bahn" type is not a tightly defined type of service, it is assumed plausible to say that the current sprinter services are an "S-Bahn" type of connection already. As they can or not be connected without influencing the services in the corridor, it is decided to exclude this ambition from the set.

h) "*Ijmeer* connection"
This ambition is interpreted as: "A new 10-minute interval metro service using new infrastructure between the south-west side of Almere and Amsterdam Ijburg". The "*Ijmeer* connection" is mentioned to be a metro line (Omroep Flevoland, 2020), connecting Almere, the new-to-be-built neighborhood "Almere Pampus" and the newly built neighborhood "IJburg" in Amsterdam, and joining the Amsterdam network east of *Diemen Zuid*. The 10-minute interval is the same frequency the other Amsterdam metro services have during peak hour (GVB, 2022b).

i) "New high-quality BTM for Almere"
This ambition is interpreted to be: "A minimum 10-minute interval PT-service in Almere for all local BTM lines, and no worsening of the absolute travel time for trips in the future compared to the today situation". Because this ambition is very generally defined, it is used in the context of this research to set a minimum standard to the PT system to be designed. The 10-minute interval is chosen, as this generally considered the interval at which pre-checking the timetable will not be necessary, which this researcher considers an important factor in making BTM high-quality. Not worsening the absolute trip travel time is a fairness factor, as this will encourage improving the network for every traveler instead of just a group of travelers. The fairness is also considered by the researcher to be an aspect of high-quality PT. Absolute travel time is chosen because it is easily measurable. Only local lines are considered, as the ambition mentions Almere specifically.

j) "Improve high-quality BTM in the north part of the Randstad, along the A9 corridor, Flevoland and "Noord-Holland""

This ambition is interpreted as: “All regional lines in the Almere region towards Amsterdam should have a minimum 15-minute interval”. For regional lines, a 15-minute interval is considered as the minimum, since it is an improvement of the 30-minute interval service that are found on the R-net lines.

An overview of the interpreted ambitions is given in Table 6-1.

Table 6-1 Service interpretation of the ambitions

#	Interpr.	Description	System	Route	Interval (minutes)
1	d)	“*Lelylijn*”	Heavy-rail	Lelystad – Heerenveen – Leeuwarden/Groningen	2x30
2	h)	“*IJmeer* connection”	Metro	Almere – Almere Pampus – Ijburg – *Diemen Zuid*	10
3	e)	“Increase frequency to the north”	Heavy-rail	Amsterdam – Leeuwarden/Groningen	< current
4	a)	“additional fast trains Almere – Utrecht”	Heavy-rail	Almere – Hilversum – Utrecht	30
5	b)	“alternating destinations ICs”	Heavy-rail	Leeuwarden/Groningen – Amsterdam-Zuid/Centraal	-
6	i)	“High-quality PT Almere”	BTM	Almere	≤ 10
7	j)	“High-quality PT region Almere”	BTM	Almere and surroundings	≤ 15

These interpreted ambitions are used in the next sections.

6.2 Brainstorm session

The goal of the brainstorm is to create a first version of the service network layout, for each variant, using the inputs mentioned in the introduction of this chapter. The brainstorm session is chosen because it allows for a broad solution field, in the sense that all ideas are allowed, while naturally limiting the solution space to solutions with a larger chance of success. The latter is aided by the participation experts, that bring up limitations on the solution space (for instance, the necessity of extra tracks given a certain number of trains), based on experience, without these limitations being defined before the brainstorm process.

The participants consist of the researcher and three experts (for details, see Appendix A) in the field of railway operations and planning. Even with the experts, there are many solutios that can be found, so it is likely that a different group would come up with different results. The documentation that needs to be prepared and provided to the participants for the session is:

- The interpretation of the ambitions as discussed in section 6.1 (verbally provided)
- The differentiation between the three variants, based on the assignment of the technical PT systems (heavy-rail and BTM) to the network levels (see chapter 4).
- Maps showing current and planned BTM infrastructure- and service networks, as well as information on the amount and location of planned housing development (see Appendix B)
- The 2021 and 2030 heavy-rail service network maps (see Appendix C)

- A schematical overview of the main heavy-rail infrastructure in the Netherlands, containing the current situation and planned changes (See Appendix D).

The brainstorm session took two hours and consisted roughly of half an hour introduction to the project, followed by half an hour to work on for each variant. The results of the brainstorm session are the sketches made during the process and the description of the characteristic components for each service network that are written down after the brainstorm session. These are discussed in the sections below. In some cases, multiple options were proposed to a particular design choice. These options are further discussed in section 6.3. To start, a sketch was made to indicate the interpretation of the strategies based on hierarchy, as discussed in section 4.1. This sketch is shown in Figure A-1, Appendix A.

6.2.1 Proposals for the V1 service network

The concept belonging to V1 is that assignment of the PT systems is left as it is. The participants attempted to implement the heavy-rail ambition services from the assumed perspective of ProRail. The resulting sketch is visualized in Figure A-2, Appendix A.

The relevant comments made regarding this network are:

- The ambitions are drawn, with the different colors indicating the network level this service is assumed to operate on.
    - Black, SPR trains
    - Green, the current IC trains
    - Red, an IC service performing on a higher network level than the current IC
- Based on the 2030 service intention from ProRail (2021 TBOV basis-6, Appendix C), only SPR services will run to *Amsterdam Centraal*, while IC services will run to *Amsterdam Zuid* only, which deviates from the services drawn in the sketch. While direct connections to *Amsterdam Centraal* and *Amsterdam Zuid* are seen as preferable for passengers due to the lack of transfers, an unbundling is assumed better for the infrastructure manager, as it allows for a simpler infrastructure. Moreover, more homogeneity in services on a particular stretch generally allows for more capacity.
- In terms of infrastructure investments, a track doubling (from two to four tracks) is probably necessary from the north of Almere towards Amsterdam

6.2.2 Proposals for the V2 service network

According to the concept of V2, the aim is to assign the heavy-rail system to take over transportation tasks from the BTM system. The resulting sketch is visualized in Figure A-3, Appendix A. The blue lines represent infrastructure. The colors of the station represent the network level of the stations. Again, it is attempted to give an interpretation of the ProRail perspective: No direct connection Almere – Bijlmer, lower network level services to *Amsterdam Centraal* and higher network level services to *Amsterdam Zuid*. The arguments for taking this perspective are the same as for variant 1.

The relevant comments made to this network are:

- The need for additional infrastructure remains, as in the V1 network, starting from the north of Almere towards Amsterdam. However, the additional tracks follow the A6, as this offers the possibility of additional catchment areas in Almere by enabling the construction of stations along the new line. It is also assumed that it will be cheaper to build and allow fast speeds due to the lack of tight curve.

- A second split of the extra tracks is done between Almere and *Gaasperdammerweg aansluiting* (Gpda), which is the junction where the sections from *Amsterdam Zuid* and *Amsterdam Centraal* meet. This is then following the A1, allowing for the construction of a station in Muiderberg and the bypass of Weesp for high level services.
- Each network level (Regional, Interregional, National) is assigned a service which would roughly correspond with the SPR, IC and IC-D (Intercity Direct) services from NS. The IC-Direct is a service that calls at fewer stations than a regular IC.
- Each service is assigned a route:
    - Because the many stations already present in center part of Almere, and the potential for the new line to have maximum higher speed than the old one, which could be beneficial for national services, it is decided to run the local service over the old track, and the national service on the new track around Almere.
    - The regional service is assigned to run over the new line around Almere, as this allows for more catchment along the new line.
    - Because the national service is not set for stopping in Weesp, it is decided to run the national service along the new track along the A1.
    - To allow the heavy-rail network to service Muiderberg as well (and by that taking over transportation from the regional bus service), it is necessary to introduce a station there. Because of the small size, it is reasonable to assume this needs to be a local service. This implies that the regional service is routed among Weesp, which is upgraded to a “regional services station” (regional services stop at Weesp as well).
- The regional BTM services will be cut where a heavy-rail alternative is introduced, while extra BTM is proposed for feeder services to the heavy-rail stations.

6.2.3 Proposal for the V3 service network

According to the V3 concept, the aim is to assign the heavy-rail system to do network level 1 and network level 2 services only, with the BTM system to perform network level 3 as well as level 4 transportation services. The result is shown in the sketch in Figure A-4, Appendix A. This sketch is less worked-out due to the time restriction of two hours for the brainstorm session. The most important feature is the bypass of Almere for heavy-rail and the adaptation of the current track through Almere from heavy-rail to BTM.

The relevant comments made regarding this network are:

- The many stations in Almere along the current line indicate a local service role for heavy-rail. To keep fulfilling this service here, it is proposed to change the old heavy-rail line into a metro line, which in turn can be connected to the *Ijmeer* connection.
- The national and regional rail services will run along a new section along the A6, that is built the same as that in the V2 service network. However, the new section is only around Almere, and does not continue towards Muiderberg.

6.3 Service network decision process

The proposal for the service network for each variant is made during the brainstorm session. In the following step, the proposals are further developed into a complete service network, by deciding upon a set of design options that follow from the brainstorm session. This decision process incorporates the use of qualitative MCA’s and is graphically shown in Figure 6-1: the identified design choices are walked through and decided upon one by one, leading to a set of choices that is a sub-variant of the original brainstorm proposal. This sub-variant is structuring for the scheduling process in Chapter 7. The choices are, however, indicative rather than definitive, as in the scheduling process new insights could lead to another option being considered a more appropriate choice.

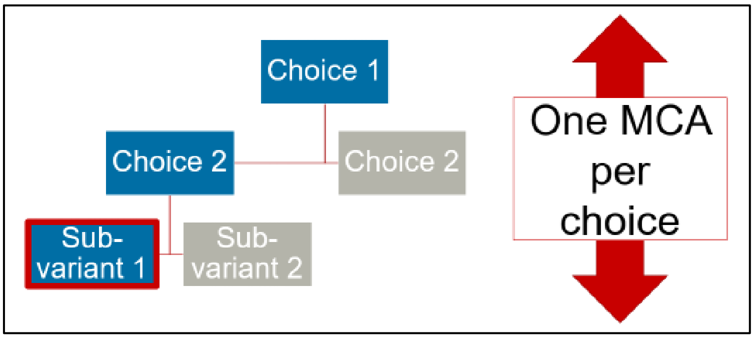


Figure 6-1: Structure of choices and MCA, leading to the sub-variant that is becoming the main variant

6.3.1 Identified design choices

There are several design choices with respective options identified during the brainstorm session. These are listed in the Table 6-2 and briefly elaborated below.

1. Routing of the new IC – The question is whether the IC's going northbound over the *Lelylijn* are routed via *Amsterdam Centraal*, *Amsterdam Zuid*, or both.
2. Stopping policy new IC service – The question is whether the new IC services will stop at Lelystad only, at Almere only or at both places.
3. Type of *Ijmeer* connection – The question is whether the *Ijmeer* connection should be made, as is the ambition. And if so, whether to realize the connection with a type of rail, bus rapid transit (BRT), or even ship.
4. Routing of the heavy-rail in V2 at Almere – In V2 the proposition is for a second heavy-rail section around Almere. The question then arises which service should be run on what section.
5. Routing of the heavy-rail in V2 at Muiden/Weesp – The question of which services should go over the new section via Muiden, and which via the existing section via Weesp.
6. Upgrade *Weesp* to IR station – The question is whether the IR services should be calling at Weesp in the new situation. Not doing so would lead to Weesp being excluded from the heavy-rail system in V3, as there are no more SPR services.
7. Routing of heavy-rail in V3 – IN V3 a new section of infrastructure is proposed, just as in V2. The question is whether the old infrastructure should be modified for BTM and the new one built for heavy-rail, or that the old infrastructure remains in use for heavy-rail and the new infrastructure is made for BTM.

Table 6-2: Design options and choices

	Choice	**Options**
1	Routing of the new IC services	Asdz, Asd, Both
2	Stopping policy new IC service	Lls, Alm, Both
3	Type of *Ijmeer* connection	BRT, Ferry, Metro connection, Light-rail connection, Heavy-rail connection, No connection
4	Routing of the heavy-rail in V2 at Almere	[set of 4 options]
5	Routing of the heavy-rail in V2 at Muiden/Weesp	[set of 6 options]
6	Upgrade *Weesp* to IR station in V3	Upgrade, Don't upgrade
7	Routing of the heavy-rail in V3	Heavy-rail over new track, Heavy-rail over old track

For each of these choices an MCA is set-up and filled in, as discussed in section 2.2.3, and is presented in Appendix E.

6.3.2 Resulting service networks

Taking the path of the best scoring options leads to a sub-variant that contains all those options. The choices made with the qualitative MCA, , are presented in Table 6-3.

Table 6-3: Choices and chosen options for the proposed service networks

	Choice	**Chosen V1**	**Chosen V2**	**Chosen V3**
1	Routing of the new IC services	Routed *Amsterdam Zuid*	Routed *Amsterdam Zuid*	Routed *Amsterdam Zuid*
2	Stopping policy new IC service	Stop in Lelystad	Stop in Lelystad	Stop in Lelystad
3	Type of *Ijmeer* connection	BTM (to be specified)	No connection	BTM (to be specified)
4	Routing of the heavy-rail in V2 at Almere	-	SPR via Almere, IC and IR via new section	-
5	Routing of the heavy-rail in V2 at Muiden/Weesp	-	IR over old track, SPR and IC over new track	-
6	Upgrade *Weesp* to IR station in V3	-	-	Upgrade
7	Routing of the heavy-rail in V3	-	-	Heavy-rail over new track

The service network is visualized for each variant in Figure 6-2, Figure 6-3, and Figure 6-4. The existing BTM system is not drawn for clarity purposes.

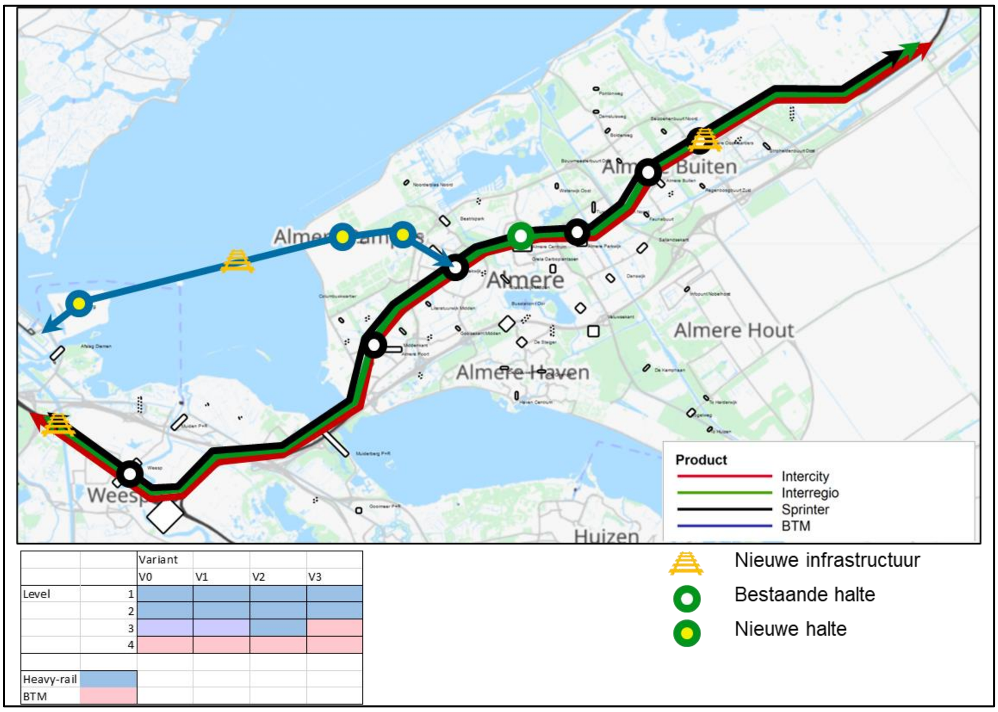


Figure 6-2: The resulting service network proposed for variant 1

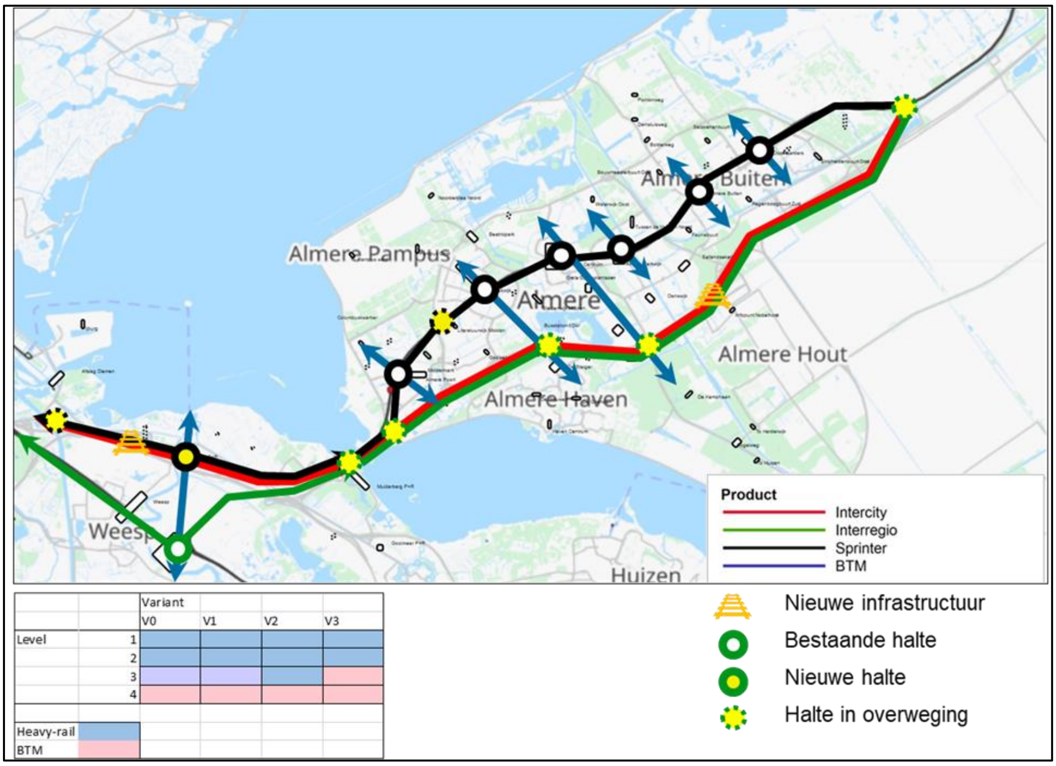


Figure 6-3: The resulting service network proposed for variant 2

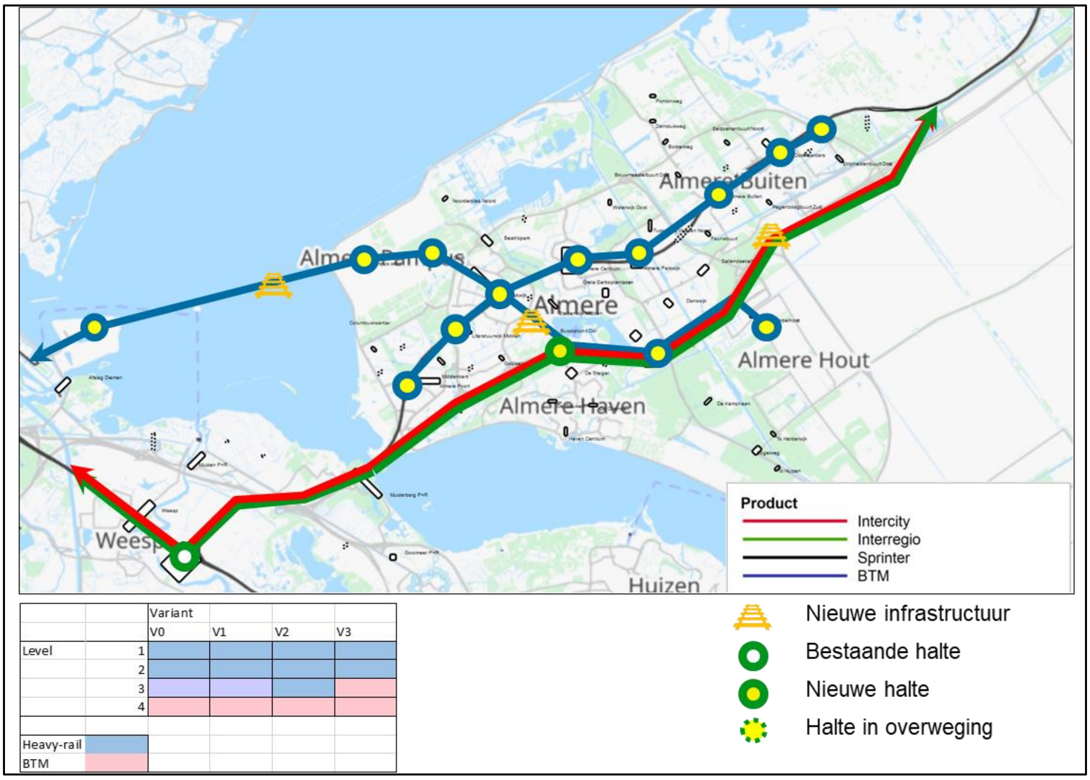


Figure 6-4: The resulting service network proposed for variant 3

7. Timetable planning

In this chapter the concept service networks from Chapter 6 are worked out into a feasible timetable and the necessary infrastructural measures. The first section is about the preparation steps that are done before the planning process. The following three sections are, for each of the development variants, the planning process described.

The timetable is created by modelling the existing infrastructure and services in Viriato and adding the services related to the ambitions that have been worked out in section 6.1. An important constraint for changing the existing services is that no changes are to be made outside of the case study area. This means that existing services arrive and depart in/from the case study area at their original times. This is to keep the feasibility of the created timetable as high as possible. Striking a balance between infrastructural needs and the desired services is a subjective and labor-intensive task, as many small decisions must be taken, leading to a huge number of possible solutions. Therefore, the planning process is reported per variant in a particular format. First, the concept regarding the development variant is summarized. Then, the intended approach for planning the services in line with the variant concept is laid out. Finally, key elements of the performed planning process are discussed. The timetable resulting from the planning process is given in the form of TD-diagrams and a netgraph.

7.1 Planning preparation

There are a few steps made before the scheduling of the variants. These are presented in the next sub-sections.

7.1.1 The Viriato database

The database contains infrastructure in the form of stations, junctions and sections that connect the stations and junctions. It also contains services that are made up from the route it takes between stations using the defined sections and junctions, and the travel time between the stations and junctions. A frequency can be added to a service, to make an hourly pattern.

To build a netgraph, the data stated above is sufficient, and it is wat is used to model the BTM network for this research. For the heavy-rail system, additional information is required:

- The length of the sections, to be able to create TD-diagrams.
- The number of tracks on a section, to know whether trains are allowed to run in parallel, or cross in opposite directions at the same time.
- The topological layout of stations and junctions, to be able to determine:
    - Which routes are physically possible
    - The possibility for simultaneous departure, arrival and/or halting of more than one train
    - Potential conflicts in junctions before/after stations

The abovementioned information is, for heavy-rail, already present in the used database, with the intended infrastructure and the possible service network for 2030, as shown by ProRail in the 2030 service network, see Appendix C. The services are crosschecked, and the topographical layout is crosschecked with the figure in Appendix D.

7.1.2 Modelling Variant 0

Variant 0 is the reference variant, which consists of the heavy-rail and BTM networks as presented in Chapter 5. On top of the given database for heavy-rail, the BTM network needs to be modelled. Capacity constraints are assumed not to be a problem for BTM, if the frequency is equal to or lower than one vehicle every five minutes for rail-bound services. For bus services, it is assumed that there are no capacity constraints. Although a high bus frequency on any given road or bus lane could lead to congestion, it is deemed out of scope to check for this as this requires more detailed modelling of roads and road vehicles, which is out of scope of this research. The stops and connecting sections are modelled following the network developed in Chapter 6. That leaves the BTM timetables, which are introduced from the operator's website. It must be noted that "Variant 0" thus has the heavy-rail infrastructure and service network from 2030, but a BTM network from 2022, when the timetables have been consulted.

It also must be remarked that, for simplicity, all services are modelled with a basic hour pattern based on the peak hour frequency. This can, especially for longer trips with transfers, give a shorter travel time than in reality, when part of the trip may be done outside peak hours where a lower frequency regime is active.

Variant 0 is visualized with a netgraph. See Figure 7-1 for a part of the netgraph. Each blue line represents one service per hour per direction. Departure times in minutes after the whole hour are further from the grey boxes representing stations, while the numbers close to the grey boxes represent arrival times.

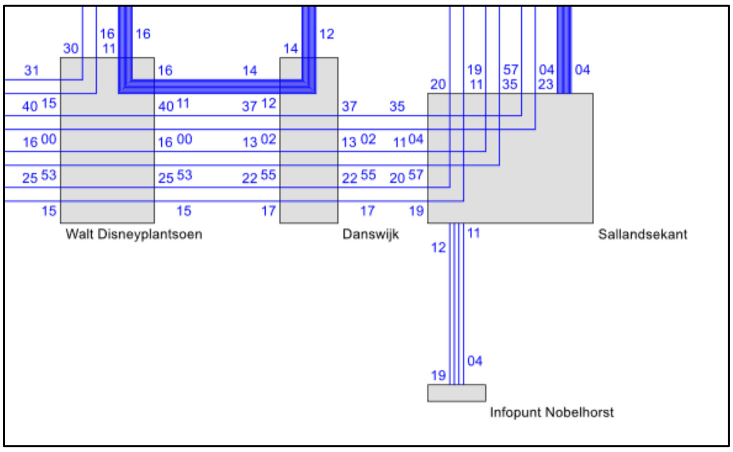


Figure 7-1: Part of a netgraph

See Appendix K for the entire netgraph.

7.1.3 Modelling the *Lelylijn* connection

The *Lelylijn* is an ambition consisting of a new section of infrastructure that connects Lelystad with Emmeloord, Heerenveen, Drachten and Groningen that should facilitate a faster connection between the north of the Netherlands and the *Randstad* area, according to the projects' website (*Goed Gespoord van West naar Noord*, n.d.). The interpretation of the ambition (see section 6.1) consists of four IC services per hour per direction. Of these, two trains per hour are routed along this new section, and two trains per hour are partially routed over the new section, the latter going Lelystad – Emelloord – Heerenveen – Leeuwarden. See Figure 7-2. The infrastructure is modelled based on this figure.

Figure 7-2: Overview of the *Lelylijn* route. From: (Lelylijn.nl, n.d.)

The scheduling of the services is done for each variant separately, best fitting the situation on the Amsterdam – Lelystad corridor for that variant. It is assumed that due to the importance of this train (long distance IC), there is no scheduling constraint on the section Heerenveen - Leeuwarden, or in Groningen. The *Lelylijn* itself is out of scope of this research, but its effect on demand for corridor inbound and corridor outbound traffic is relevant for the evaluation of the different ambitions. Especially because faster connections between the Randstad (Amsterdam) and the northern provinces is an explicit ambition. That is why a travel time for the *Lelylijn* services is needed. The process for calculating the travel times for the *Lelylijn* sections are presented in Appendix I, with the results in Table I-1.

7.1.4 Modelling the *Ijmeer* connection

For the *Ijmeer* connection, just as for the *Lelylijn*, assumptions must be made regarding the topographical layout of the new infrastructure and the travel time. Based on what is known on the *Ijmeer* connection, the layout is drawn as in Figure 7-3. Figure 7-4 and Figure 7-5 show the assumed routing in more detail.

Figure 7-3: *Ijmeer* connection complete overview. From *Google Maps* (n.d.)

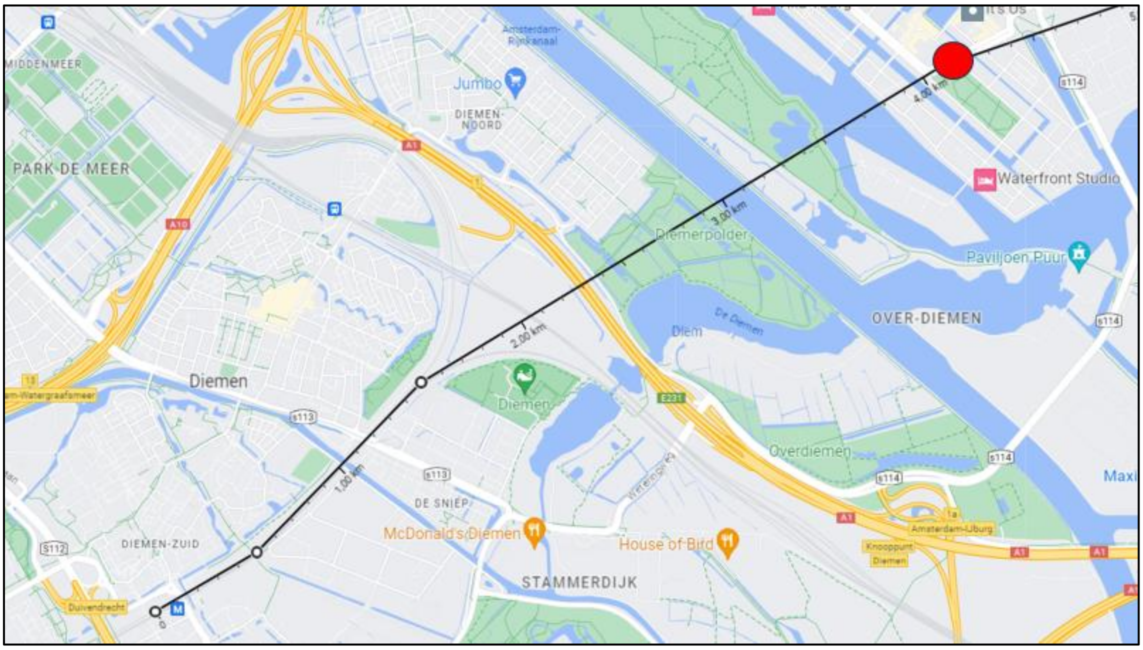


Figure 7-4: *Ijmeer* connection section Amsterdam. Adapted from: *Google Maps* (n.d.). The red dot indicates the *Ijburg* tram stop

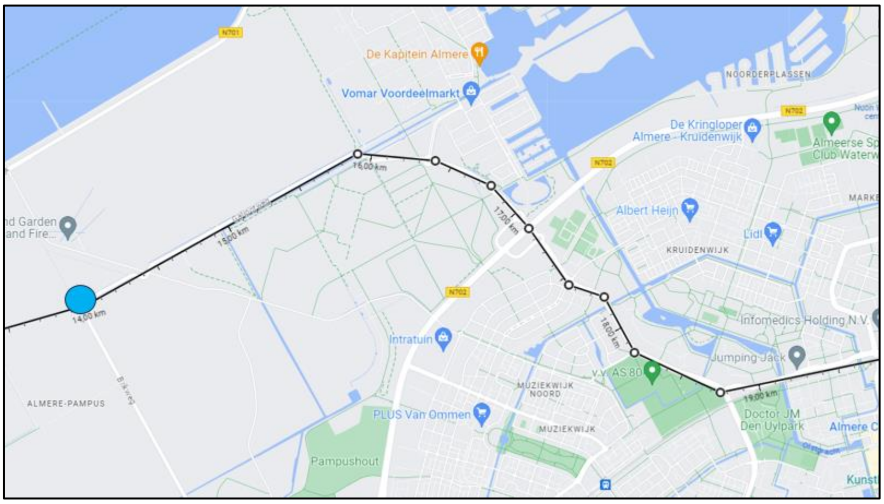


Figure 7-5: *Ijmeer* connection section Almere. Adapted from: *Google Maps* (n.d.). The blue dot indicates the location of the *Almere Pampus* stop as modelled in the 2040 development variants.

The calculation process of the *Ijmeer* connection shown in Appendix I. The results from Table I-3 give a travel time of 15 minutes between *Diemen Zuid* and *Almere Pampus*, and 26 minutes between station *Diemen Zuid* and station *Almere Centrum*. The frequency is chosen equal to that of the rest of the metro system, namely 6 times per hour per direction.

7.1.5 Rules for capacity conflicts

There are two types of conflicts that are checked in the scheduling process to defend the feasibility of the timetable. The first conflict to be detected is a headway conflict. That means, that trains are not allowed to be planned to run closer than a certain interval after one another on the same track. The headway limitation is set at 2 minutes. This is relatively tight compared to the common practice of 3 minutes, but possible under the assumption that by 2040 the signaling technology allows it. The second conflict to be checked upon is the separation time conflict, which is looked at in stations. Table 7-1 shows the separation times as entered in Viriato. These times are based on common practice in the field. Slight variations may be found depending on the heavy-rail network. The separation times ensure that in station areas one track or platform (track) is freed long enough before the next occupation. Viriato has the possibility to check for these conflicts, and this conflict detection is used during and at the end of the scheduling process.

Table 7-1: Basic separation times used for conflict detection

Type of interaction	Basic separation times [minutes]
Departure / Arrival (same platform)	3
Arrival / departure (same track)	1
Arrival / pass (same track)	2

7.2 Implementation Variant 1

The concept of Variant 1 is that there is no new task division between the heavy-rail and BTM systems, as is discussed in section 6.2.1. Therefore, the approach is aimed at introducing the desired services and expanding the current infrastructure only where necessary to accommodate the new services.

7.2.1 Planning approach V1

The approach is to start with the ambition that concerns the hierarchically highest-level services, which are the *Lelylijn* IC's. The existing sprinter services from *Amsterdam Zuid* towards Almere are set to call at additionally at *Almere Poort* and *Almere Muziekwijk*. The conflicts arising from the added and changed services are to be resolved with the infrastructural measures. Following the approach of expanding the current infrastructure only where necessary, it is chosen to do track doubling where headway conflicts exist, going from 2 to 4 tracks where necessary. A tradeoff between applying all the desired services and the size of the infrastructural intervention is made by looking for options that reduce the need for track doubling drastically compared to little changes in the desired services. Concerning BTM, the *Ijmeer* connection is implemented from *Diemen Zuid* via *Almere Pampus* to *Almere Centrum*, as shown in section 7.1.4.

7.2.2 Planning process V1

For the implementation of the four *Lelylijn* services, the opportunity is identified to extend the existing services ending in *Lelystad Centrum*. It is chosen to extend them to Leeuwarden, although from the perspective of this research it could have been Groningen as well. This leaves the services to Groningen via the *Lelylijn*. Ideally, these would depart 15 minutes after the Leeuwarden services, to form a 15-minute interval over the *Lelylijn* corridor. However, this would overlap with the existing IC services towards Zwolle. An option would be to either run a combined train from Amsterdam to Lelystad and split at Lelystad in a section for Zwolle and a section for the *Lelylijn*. However, it is probable that due to the expected high occupancy, there is no possibility to run a shortened train. Furthermore, this would increase the vulnerability of the timetable, as a delay on either one of the two services that are to be combined would delay the combined service. Finally, coupling and decoupling is a technical procedure that adds the risk of technical failure, which again adds to the vulnerability of the timetable. If a cross-platform transfer solution were chosen, the vulnerability due to codependence would remain, and instead of the risk of technical failure the discomfort of transfer would be added for passengers using the *Lelylijn*. Therefore, it is chosen to run an on-top service, from station *Schiphol Airport* to Groningen, that runs approximately 3 minutes after the existing IC service, for which the travel time is copied from the existing IC services. See also Figure 7-6 for the options for the on-top IC service. Finally, the sprinters from station *Amsterdam Zuid* are made to call in all the stations in Almere, for which the additional travel time is calculated with equation *(8)* using $T_{dec} = T_{stop} = T_{acc} = 0{,}5\ [min]$ per stop.

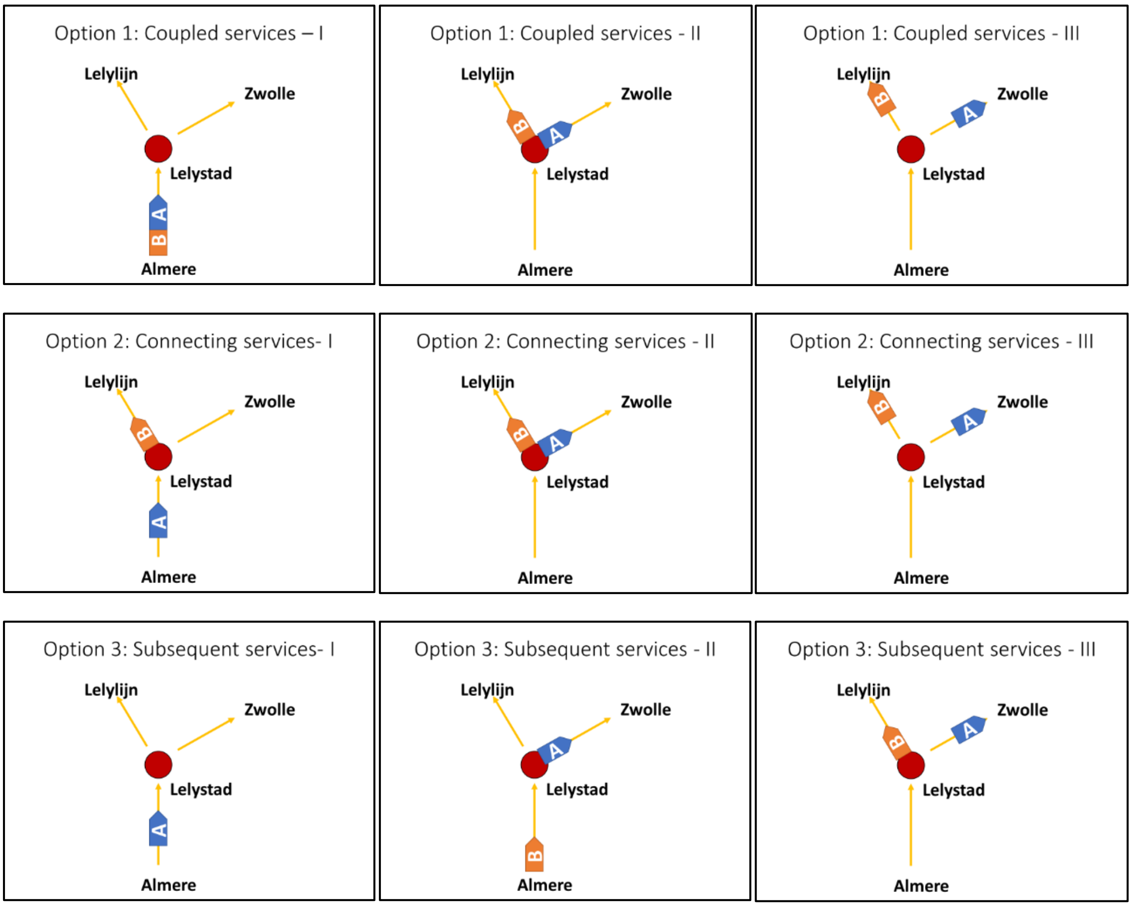


Figure 7-6: Options for the on-top *Lelylijn* service

The remaining conflicts, as described in section 7.1.5, are all on the stretch between *Almere Poort* and *Almere Oostvaarders*. It is decided that doubling the track on this stretch is in balance with the resulting service offer. Therefore, the infrastructural measures for heavy-rail for V1 consists of doubling the track between *Almere Poort* and *Almere Oostvaardres* from 2 to 4 tracks. A final round of conflict detection shows no more conflicts. Therefore, the timetable is deemed feasible. It can be inspected by means of TD-diagrams and the respective netgraph in Appendix K.

7.3 Implementation Variant 2

The concept of Variant 2 is to assign more tasks to the heavy-rail system and thus offer more demand to compensate for the higher investments costs. In chapter 6 the concept of a parallel track section, following a new route along the highways, is introduced. In exchange, the BTM system is to have a smaller task assignment, thus no *Ijmeer* connection is implemented in this variant.

7.3.1 Scheduling approach V2

The scheduling approach of V2 starts with the assumption of a new, high-speed (200km/h) line to be constructed that bypasses Weesp and forms a quick connection between Amsterdam and Almere. Then, it bypasses the existing stations in Almere and follows the highway towards Lelystad. Because more tasks are assigned to the heavy-rail system, a three-level service concept is applied. The SPR services remain. The IC services however are split up, so that there is a new IC-D service that calls at fewer stations, and an “Interregio” (IR) service that calls at more stations than the current IC, but less than the SPR service. In Chapter 6 it is mentioned that it is not yet decided whether it will be either the IR service or the SPR service that will take the route via Muiderberg. This is to be determined in the scheduling phase. Ideally the SPR service will be able to pass via Muiderberg as this would allow the construction of a stop there, and eliminate the need for the long-distance bus-, and thus BTM connections, in line with the Variant 2 concept. Finally, in line with the three levels heavy-rail system, the choice of whether the new IC-D will call at Almere depends on the available capacity on the track. For BTM, the creation of new stations along the new infrastructure demands a possible reconfiguration of the bus system in Almere.

7.3.2 Scheduling process V2

As with the *Lelylijn* and the *Ijmeer* connection, Google Maps is used to determine the distance of a plausible new section and assumptions are then made on the travel time. Following the A1 and A6 freeways from the Gpda junction up until the point where the existing heavy-rail infrastructure meets the A6 north of Almere (which is named in this report “*Almere Oostvaarders aansluiting”* (Almoa)), a length of 30,0 kilometers can be drawn. See Figure 7-7. Just like for the *Lelylijn*, a maximum velocity of 200 km/h is assumed for this section. The maximum velocity at Gpda and at Almoa is currently 140 km/h (OpenStreetMap, n.d.-a). For the travel time estimation, a velocity of 200 km/h over 30 km amounts to a 9-minutes travel time. A half minute delay for acceleration and deceleration from/to 140km/h leads to a travel time of 10 minutes. The infrastructure is put in Viriato, and the travel time is used as a basis for all trains using the new infrastructure.

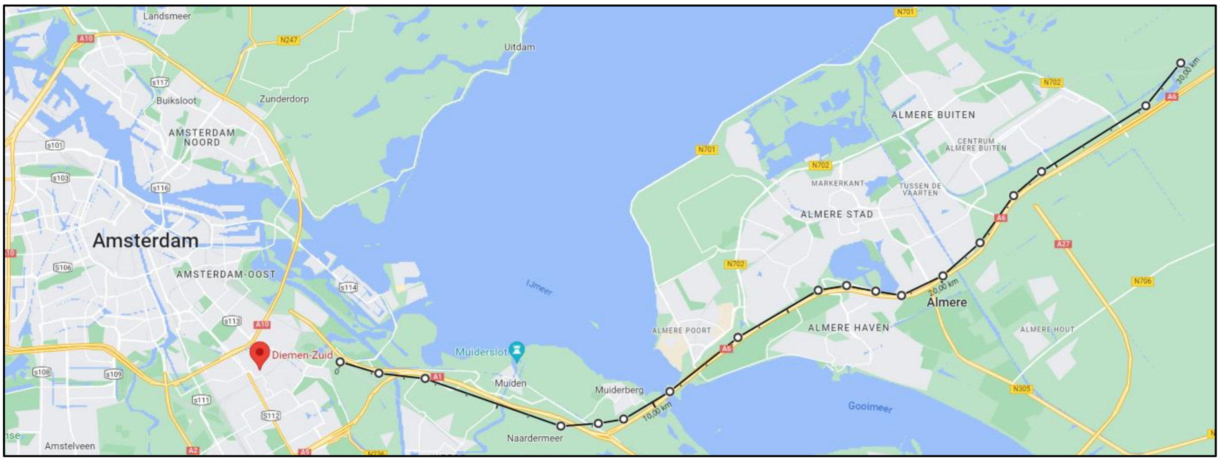


Figure 7-7: Overview new railway infrastructure V2. From *Google Maps* (n.d.)

Because the *Lelylijn* IC’s are supposed to form a faster connection towards Groningen/Leeuwarden, the are made into IC-D’s while the current services to those cities via Zwolle are made into IR services. And because of the variant 2 concept of more heavy-rail, it is decided to have all the *Lelylijn* services as on-top services within the corridor. These are set to depart 2,5 minutes before the original IC's from *Amsterdam Zuid*, and run without stop until *Lelystad Centrum*. Because of capacity limitations on the section *Amsterdam Zuid* – Gdpa, the train is set to call at *Duivendrecht* as well, as to not come in conflict (overtake) the original IC towards Hilversum.

Next, the existing IC's, now IR, are modelled. These services must call in Almere. Because the original track section in Almere is now for SPR services only, it is decided to create a new station, "*Almere Strand*" at the south of Almere where the existing track and the new track split course again. Furthermore, because these old IC is now an IR, a second stop in Almere is desirable. This stop is made at another new station, *'t Oor*, which is combined with the current *Busstation 't Oor*. This station is placed here because it has a good existing connection to the BTM system in Almere. It is also placed here because it is relatively close to the *Almere Strand* station. This means that the IR travelling between these two stations is assumed not to reach top speed, and therefore will have less "loss" of high speed travel between these two stations. Thus, it is possible to fit the IR to the original timetable west of *Amsterdam Zuid* and east of *Lelystad Centrum*. However, this is not possible if the IR passes via Weesp. Therefore, it is routed completely via the new track. For the travel time of the IR, the IC-D time is taken and, just like for the *Lelylijn*, two minutes are added for acceleration and deceleration from/to 200 km/h. However, as *Almere Strand* and 't Oor are relatively close to each other and full speed is assumed not to be reached between these sections. Therefore, only half a minute penalty is taken for acceleration and half a minute for deceleration between these stations.

Running the IR and IC-D over the new line means there is a homogeneous service pattern on the old section. This allows all the SPR trains to be extended until *Almere Oostvaarders*, thus improving the connectivity along that axis and allowing a good connection with the *Almere Strand* station. The SPR services are planned to arrive shortly before the IC-D in Almere, allowing a good transfer possibility towards Groningen/Leeuwarden. Finally, the SPR services between *Amsterdam Centraal* and Almere are increased in frequency, to maximize the use of the available capacity for heavy-rail services.

The long-distance buses are not removed, as they connect Muiderberg to Amsterdam and Almere. However, between '*t Oor* and *Almere Strand* they are routed on a route through the city, calling at *Gooisekant Midden* and *Middenkant*, to improve the service to the heavy-rail stations. Passengers from the south of Almere towards Muiden thus have a longer travel time, but travelers using this connection to reach Amsterdam can switch to the heavy-rail system sooner. Finally, to connect *Almere Pampus* without *Ijmeer* connection, a bus connection with a 10-minute service interval is created. This service runs as the *Ijmeer* connection would from *Almere Centrum* to *Almere Pampus* via *Beatrixpark*, but then goes on to *Columbuskwartier*, *Almere Poort* and finally *Almere Strand*, and so offers *Almere Pampus* a one transfer connection to the IR and SPR network. The travel speed is taken by measuring the distance and applying the average speed calculated by taking the travel time of the M4 Almere bus line.

Upon inspection of the new station *Almere Strand*, it appeared that the original plan of having one central platform with two tracks for the new section, and one platform with two tracks for the old section, would not meet the minimal follow-up times requirements. Therefore, the station layout is changed to allow for two additional passing tracks where the IC-D can pass. The designed timetable also shows a conflict with a freight path from *Duivendrecht* until Gpda. This conflict is ignored, as it is uncertain whether this freight path will used in the future (APPM, 2022). A possibility to double the track between *Duivendrecht* and Gpda would be a possible solution to keep the freight path and offer more possibilities for the trains between Asdz towards Hilversum. However, this is out of scope for this research.

The TD-diagrams, netgraph and track occupation graphs are displayed in Appendix K.

7.4 Implementation Variant 3

The concept of Variant 3 is to assign more tasks to BTM and focus the tasks of heavy-rail on the higher network level tasks. This means that the *Ijmeer* connection is to be constructed. The existing heavy-rail line through Almere is modified to a metro system, while, as in V2, a new track following the A6 highway is constructed for heavy-rail.

7.4.1 Scheduling approach V3

The approach for V3 consists of removing the sprinter service from the corridor. Instead, the existing services are either cut short or “upgraded” to a higher-level service, IR. The IC services will still only stop in Lelystad if possible, to allow for a truly high level, fast service between the Randstad and the north. The same new stations are constructed along the new heavy-rail line as in V2. SPR services intended for Almere will end at one of the new stations.

A decision must be made on how to connect the *Ijmeer* connection metro to the modified metro between *Almere Oostvaarders* and *Almere Poort*: Either by applying the same routing as in V1, meaning a metro stop parallel to the track at *Almere Centrum*, or a perpendicular crossing station at *Almere Centrum*, allowing for a possible continuation of the metro towards the southeast of Almere, and eventually station *‘t Oor*. The latter option is chosen. Moreover, after station *‘t Oor,* the metro has the option to continue to the northeast and connect *Almere Nobelhorst* as well. This is done too, ending in *Almere Sallandsekant*, which again forms a connection to the bus system. The idea is that extending the metro gives a good connection to the first heavy-rail station.

7.4.2 Scheduling process V3

The original IC’s to Lelystad and to Groningen / Leeuwarden via Zwolle are rerouted and extended to go over the *Lelylijn*. As there is no need for a SPR service in the corridor anymore, two of the four original sprinter services from *Amsterdam Zuid* are upgraded to IR within the corridor limits and from Lelystad onward takes over the service of the original ICs to Groningen/Leeuwarden via Zwolle. The other two are also upgraded to IR services, but after Lelystad take over the original SPR service to Zwolle. All services originally ending in Almere are extended to Lelystad, to maximize the available capacity. The stations between *Amsterdam Centraal* and *Weesp* are exempted from the upgrade to IR, because this would mean that these stations would not be serviced any longer. As no suitable metro alternative exists there, it has been decided to keep the service as is.

To offer a good connection with the remaining two heavy-rail stations, the interval on the modified metro line is set at 6 minutes, similar to the highest-interval bus connections in Almere. The *Ijmeer* connection keeps the same interval a in V1, of a metro every 10 minutes. Some of the bus services that coincide with the extended *Ijmeer* connection between *Almere Centrum* and *Almere Sallandsekant* are removed on grounds of redundancy. The resulting TD-diagrams and the V3 netgraph are shown in Appendix K.

The TD-diagrams show no conflict for the 2-minute headway along the tracks, nor for the follow-up times. *Almere Strand* does not need a 5th and 6th passing track ais is the case in V2. The other defined stations are conflict free. Therefore, the variant is declared to have a feasible timetable.

7.5 Conclusion on scheduling

Several differences in approach can be noted between the planning of the different variants. In V1 the approach to try to apply the task assignment between BTM and heavy-rail as close as it is today. For the heavy-rail this means following the ProRail approach as much as possible, irrespective of BTM development. This leads to an *Ijmeer* connection and two on-top services, limiting the infrastructural investment to expanding the number of tracks along the current section. For V2, the approach to assign more tasks to the heavy-rail system leads to the decision to plan all the *Lelylijn* services on-top. In V3, the focus of heavy-rail to the higher-level network services leads to "upgrading" the existing sprinter services into IR services, that are comparable to the original IC services. The IC services in V2 and V3 are made to skip Almere, in line with the thought of creating a faster connection between Amsterdam and the north. However, in V2, the number of services between Amsterdam (both Zuid and Centraal) and *Almere Centrum* stays the same. In V3, the number of services between *Almere Strand* and Amsterdam (both Zuid and Centraal) is two less than in V0. However, the *Ijmeer* connection carries deeper into Almere, which can be seen as extra services to Amsterdam as well.

Some similarities in approach can be found as well. For all variants the work order was from the IC's on the *Lelylijn* down to the sprinters. And, for all variants the choice is made to keep the sprinter services between *Weesp* and *Amsterdam Centraal* as they are, without implementing an IC service to *Amsterdam Centraal* directly.

In terms of opportunities, several have been found. The main opportunity for V1 were the prolongation of the original IC services and the prolongation of all sprinter services to *Almere Oostvaarders*. In V2, the possibility to run additional services between *Diemen* and *Amsterdam Centraal* as a result of expanding the capacity elsewhere on the corridor.

Compromises had to be made in the form of no IC services to *Amsterdam Centraal*. It has also been deemed impossible to connect Muiderberg to the heavy-rail network by making a SPR station along the new track, while running the IR services via *Weesp*. This would be in line with assigning more tasks to the heavy-rail system and may have made the long-distance bus connections redundant. Also, due to the bottleneck between *Duivendrecht* and *Gaasperdammerweg aansluiting* junction, it turned out not to be possible to skip the station *Duivendrecht* for the IC connection in V2, which would be more in line with the highest-level service.

8. Variant Analysis

In this section the numeric data necessary to compare the variants is acquired by analyzing the three service network variants. Section 8.1 provides insight in the investment costs and section 8.2 in operational costs.

8.1 Investment costs

The extra infrastructure necessary for implementing each variant is determined using the results of chapter 7 and is presented in Table 8-1.

Table 8-1: Overview of infrastructural investments

Infrastructural investment	Length [km]	Variant	Location
Additional double track through Almere	12,5	V1	Between stations *Almere Poort* and *Almere Oostvaarders*
Ijmeer connection	20	V1, V3	Between stations *Diemen Zuid* and *Almere Centrum*
New double track around Almere	18,9	V2, V3	Between stations *Almere Strand* and *Almere Oostvaarders aansluiting*
New double track near Muiderberg	11,1 (+0,5 bridge)	V2	Between railway junction *Gaasperdammerweg aansluiting* and station *Almere Strand*
Station *Almere Strand*	-	V2, V3	Between *Weesp* and *Almere Oostvaarders*, right north-east of the "*Hollandsche Brug"* railway bridge
3 x Flyover	-	V2	At station *Almere Strand*
Station *Almere 't Oor*	-	V2, V3	At the current stop *Busstation 't Oor* in Almere
Light-rail through Almere	8,3	V3	Between *Almere Centrum* and *Almere Sallandsekant* via *Almere 't Oor*
Modification of heavy-rail to metro track in Almere	16	V3	Between stations *Almere Strand* and *Almere Oostvaarders*

The heavy-rail investment costs are interpreted from literature (Baumgartner, 2001). These are presented in Table 8-2. The inflation index for 2001 is determined to be 1,6 and is included in the presented costs in millions of euros.

Table 8-2: Cost per kilometer for infrastructural investments based on Baumgartner (2001)

Infrastructural investment	Assumptions	Indexed Cost [million EUR]
Additional double track through Almere	- No land needs to be bought - Average construction difficulty - High speed	16, per kilometer
New double track around Almere	- Land needs to be bought in densely populated area - Average construction difficulty - High speed	32, per kilometer
New double track near Muiderberg	- Land needs to be bought in densely populated area - Low construction difficulty - High speed	25,6 per kilometer
New double track near Muiderberg (bridge)	- Difficult foundation	48, per kilometer
Station *Almere Strand*	- Large passenger station, lower side of the size range	80
Station *Almere 't Oor*	- Passing station	48
Flyover	-	24

The investment costs based on reference projects are displayed in Table 8-3. Only the *Ijmeer* connection reference is indexed, as the other reference projects are very recent, and the indexation would thus be insignificant.

Table 8-3: Costs of infrastructural investments based on reference projects

Infrastructural investment	Reference project	Method	Inflation index	Indexed cost [million EUR]
Ijmeer connection	Werkmaatschappij Amsterdam Almere (2011)	Direct takeover of cost	1,3	3.800
Light-rail through Almere	*Vernieuwing Amstelveenlijn* (2021)	Direct takeover of cost	1	300
Modification of heavy-rail to metro track in Almere	*Hoekse Lijn* (2023)	Derived cost per kilometer	1	350

Using the information from the previous tables, the investment costs for each variant can be calculated. The investment costs for variants 1, 2 and 3 are given in Table 8-4, Table 8-5, and Table 8-6.

Table 8-4: Investment costs for V1

Infrastructural investments V1	Cost per unit or kilometer	Units or kilometers	Total investment cost [million EUR]
Additional double track through Almere	16	12,5	200
Ijmeer connection	3.800	1	3.800
Total V1			**4.000**

Table 8-5: Investment costs for V2

Infrastructural investments V2	Cost per unit or kilometer	Units or kilometers	Total investment cost [million EUR]
New double track around Almere	32	18,9	604
New double track near Muiderberg	25,6	11,1	284
New double track near Muiderberg (bridge)	48	0,5	24
Station *Almere Strand*	80	1	80
Flyover	24	3	72
Station *Almere 't Oor*	48	1	48
Total V2			**1.112**

Table 8-6: Investment costs for V3

Infrastructural investments V3	Cost per unit or kilometer	Units or kilometers	Total investment cost [million EUR]
Ijmeer connection	3.800	1	3.800
New double track around Almere	32	18,9	604
Station *Almere Strand*	80	1	80
Station *Almere 't Oor*	48	1	48
Light-rail through Almere	300	1	300
Modification of heavy-rail to metro track in Almere	350	1	350
Total V3			**5.182**

The results are graphically shown in Figure 8-1.

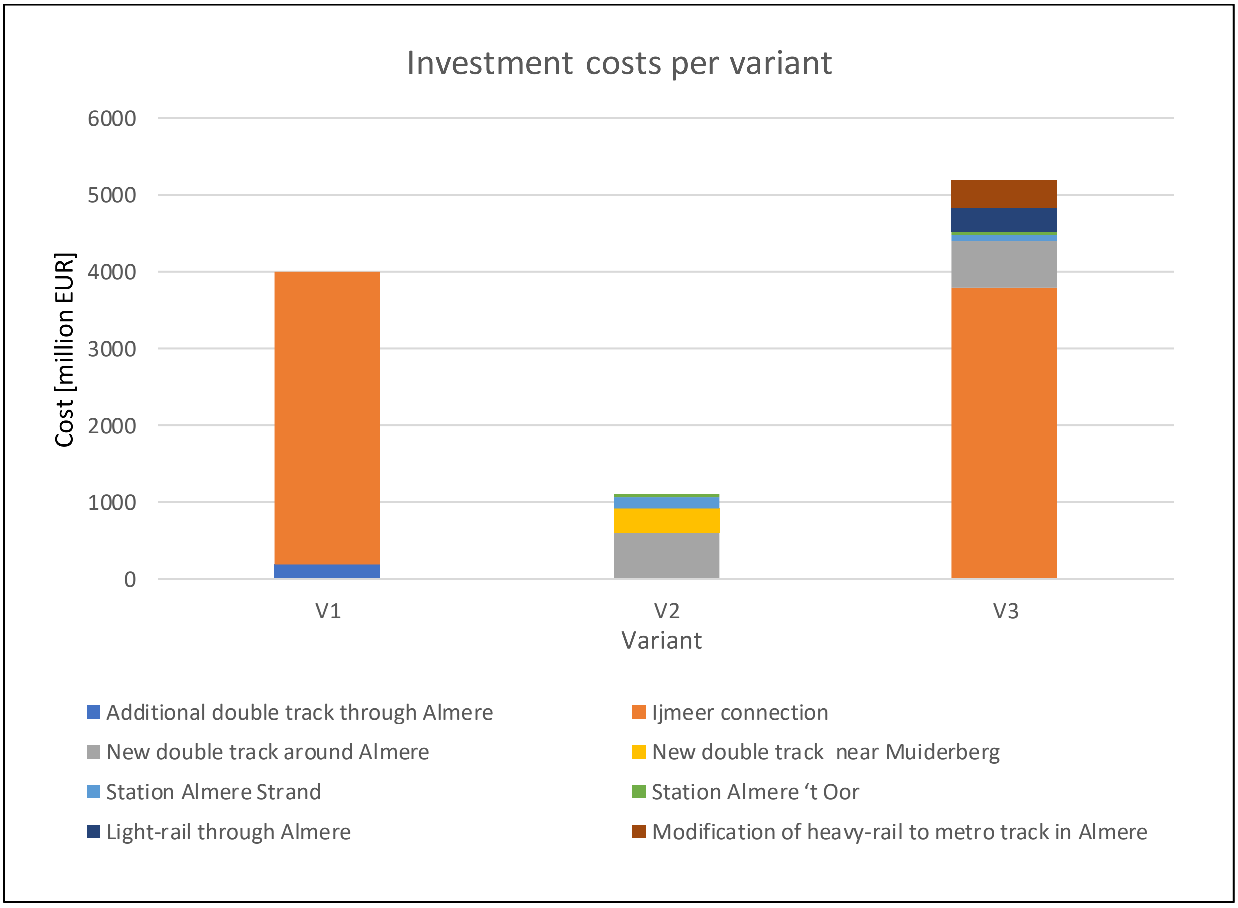


Figure 8-1: Investment costs per variant

8.2 Operational costs

The operating costs are calculated according to the methods presented in section 2.2.4. The estimated values necessary for applying equation *(6)* are given in Table 8-7.

The cost per vehicle kilometer is based on estimation tables for train, metro (SMA und Partner, personal communication, 2022), and bus (Muñoz et al., 2022). For the train it is estimated that there are 20 active hours equivalent H, and D being 360 active days per year. For metro and bus, it is estimated that H is 16 during weekdays and 8 during weekend days, with a respective D being 261 for weekdays and 104 for weekend days. For these estimations a general knowledge of bus and train timetables is applied. This is deemed acceptable as the resulting numbers are used for comparison between the variants in the first place.

Table 8-7: Costs per extra vehicle kilometer by mode

Mode	Cost [EUR / km]	Active Hour Equivalent (week / weekend)	Active days per year (week / weekend)
Train	12	20 / -	360 / -
Metro	10	16 / 8	261 / 104
Bus	2	16 / 8	261 / 104

The results from Chapter 7 are used to determine how many extra vehicles per direction N_t there are, and over what distance d. See Table 8-8.

Table 8-8: Extra vehicles per variant

Variant	Section	Mode	N_t [vehicles / h]	d [km]
V1	*Schiphol Airport – Lelystad Centrum*	Train	2	62
V1	*Diemen Zuid – Almere Centrum*	Metro	6	20
V2	*Schiphol Airport – Lelystad Centrum*	Train	4	62
V2	*Almere Centrum – Almere Oostvaarders*	Train	4	7
V2	*Amsterdam Centraal – Lelystad Centrum*	Train	4	53
V2	*'t Oor – Almere Strand* (reroute)	Bus	8	+3
V2	*Almere Strand – Pampus – Almere Centrum*	Bus	6	14
V2	*Almere Poort – Almere Strand*	Bus	10	2
V3	*Almere Strand – Lelystad Centrum (partial reroute)*	Train	4	25
V3	*Almere Strand – Lelystad Centrum (partial reroute)*	Train	4	16
V3	*Diemen Zuid – Almere Centrum – Sallandsekant*	Metro	6	28
V3	*Almere Strand – Almere Oostvaarders*	Metro	10	14
V3	*'t Oor – Almere Strand* (reroute)	Bus	8	+3
V3	*Almere Poort – Almere Strand*	Bus	10	2
V3	*Beatrixpark – Almere Centrum – 't Oor*	Bus	-12	5

The data from the two tables is used as input for equation *(6)* to calculate the operational costs per mode per variant. The results are presented in Table 8-9.

Table 8-9: Operational costs per mode per variant in million EUR per year

	V1	V2	V3
Train	21	84	30
Bus	0	2	-0,3
Metro	12	0	31
Total	**33**	**86,0**	**60,7**

The results are also shown graphically in Figure 8-2.

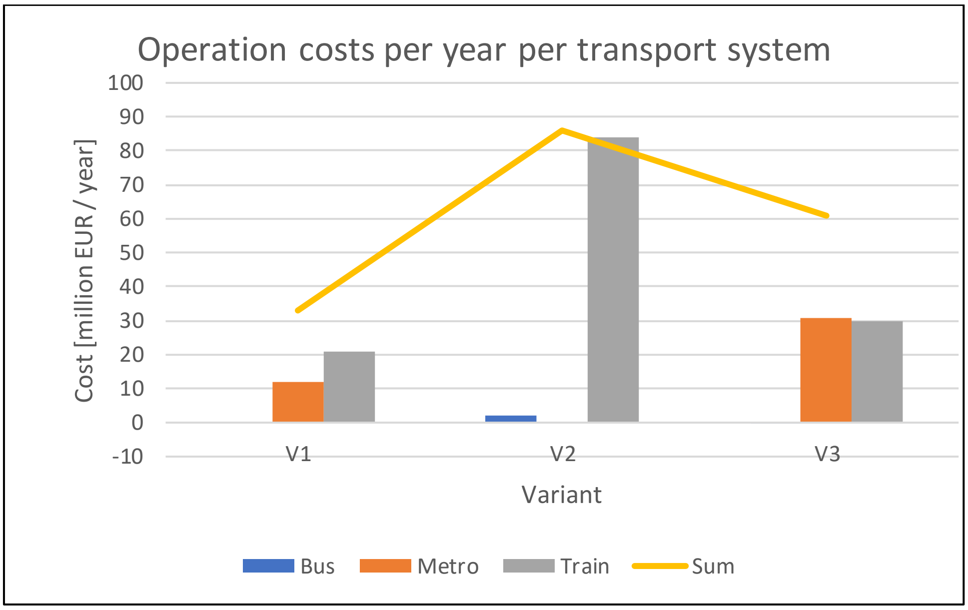


Figure 8-2: Operation cost per system per year for each variant

8.3 Travel time analysis

In this section the results of calculating the generalized travel time as described in sections 2.1.5 and 2.2.2 are presented. The set of OD-pairs contains the stops and stations determined in chapter 5, plus the heavy-rail stations that are considered outside the case study corridor and are presented in Appendix F.

Then, the travel time is generalized using the formula for GTT and the GTT is calculated for each OD-pair. These steps are discussed in the next sections.

8.2.1 Absolute travel time

The Viriato plugin uses the created timetable as a basis for the travel time calculation. These are the timetables created in chapter 7, with for each variant a different timetable. A minimum transfer time must be defined, which is chosen to be 5 minutes, in line with common practice in the field. A minimum transfer time of 1 minute is defined for a same or cross-platform transfer. 1 minute is short and may need to be increased if in practice it turns out insufficient. This is done for the stations *Lelystad Centrum*, *Almere Strand*, *Almere Centrum*, *Weesp* and *Amsterdam Zuid*, where same platform connections are an important factor in the timetable.

Viriato gives a set of possible connections, and thus the desired data must be specified. To calculate the generalized travel time, CSV files are exported containing, for each OD-pair, the shortest absolute travel time, the minimum number of transfers, and the total number of connections within the specified timeframe.

8.2.2 Generalized Travel Time

With Excel the GTT is calculated for all variants using the mentioned inputs. The aggregated average travel time for each variant, as well as a percentual comparison between the variants can be seen in Table 8-10.

Table 8-10: Average travel time for each variant

Variant	Average of travel times [min]	Compared to V0	Compared to V1	Compared to V2
V0	89,4			
V1	88,2	-1,4%		
V2	87,2	-2,4%	-1,1%	
V3	92,2	3,1%	4,6%	5,7%

To allow for better insight, the OD-pairs are aggregated based on stop type and based on stop location. The first one is on whether it considers a current rail or BTM station or stop. The second aggregation is on the location of the stops and stations: Almere, Lelystad, Amsterdam, Other and External. An overview of the exact aggregations is given in Appendix F. This aggregation leads to the results shown in Table 8-11, Table 8-12, Table 8-13, Table 8-14, Table 8-15, Table 8-16, and Table 8-17.

Table 8-11: Results of aggregation based on station/stop type: BTM

Variant	Average BTM [min]	Compared to V0	Compared to V1	Compared to V2
V0	81,5			
V1	80,8	-0,8%		
V2	79,7	-2,0%	-1,2%	
V3	84,5	3,7%	4,5%	5,8%

Table 8-12: Results of aggregation based on station/stop type: heavy-rail

Variant	Average heavy-rail [min]	Compared to V0	Compared to V1	Compared to V2
V0	97,3			
V1	95,5	-1,9%		
V2	94,6	-2,8%	-1,0%	
V3	99,9	2,7%	4,6%	5,7%

Table 8-13: Results of aggregation based on station/stop location: Almere

Variant	Average Almere [min]	Compared to V0	Compared to V1	Compared to V2
V0	79,8			
V1	78,6	-0,8%		
V2	77,8	-2,2%	-1,4%	
V3	83,6	5,0%	6,4%	7,8%

Table 8-14: Results of aggregation based on station/stop location: Amsterdam

Variant	Average Amsterdam [min]	Compared to V0	Compared to V1	Compared to V2
V0	74,0			
V1	73,5	-0.7%		
V2	72,1	-2,2%	-1,4%	
V3	76,3	3,3%	4,1%	5,6%

Table 8-15: Results of aggregation based on station/stop location: Lelystad

Variant	Average Lelystad [min]	Compared to V0	Compared to V1	Compared to V2
V0	77,5			
V1	75,4	-3,2%		
V2	70,9	-9,3%	-6,3%	
V3	77,4	-0,7%	2,8%	9,7%

Table 8-16: Results of aggregation based on station/stop location: Other

Variant	Average Other [min]	Compared to V0	Compared to V1	Compared to V2
V0	75,8			
V1	75,3	-0,7%		
V2	75,1	-1,1%	-0,4%	
V3	77,0	1.4%	2,2%	2,6%

Table 8-17: Results of aggregation based on station/stop location: External

Variant	Average External [min]	Compared to V0	Compared to V1	Compared to V2
V0	119			
V1	117	-2,2%		
V2	116	-2,8%	-0,6%	
V3	121	1,3%	3,6%	4,2%

8.3 Demand analysis

To calculate the demand, the formula as discussed in section 2.2.5 is used. This requires the previously calculated GTT, and the number of inhabitants within the capture area of the stops and stations. In the next section the results of using QGIS to display the stop and station capture areas and to use the available data to create a population estimation. In the section thereafter, the step for calculating the actual synthetic demand is provided.

8.3.1 Catchment areas and population estimation

The catchment area is defined as the area with a 1 km radius around the stop, because this allows for a natural division of the catchment area between the modelled stops and stations, meaning not too much overlap or uncovered ground in the area of interest. The catchment areas and stops and stations are projected on a map of the Netherlands, retrieved from OpenStreetMap (OpenStreetMap, n.d.-b), see Figure 8-3. In this figure, a less opaque area means more inhabitants. Blue dots are BTM stops, red dots are heavy-rail stations (that may or may not incorporate a BTM stop with the similar name).

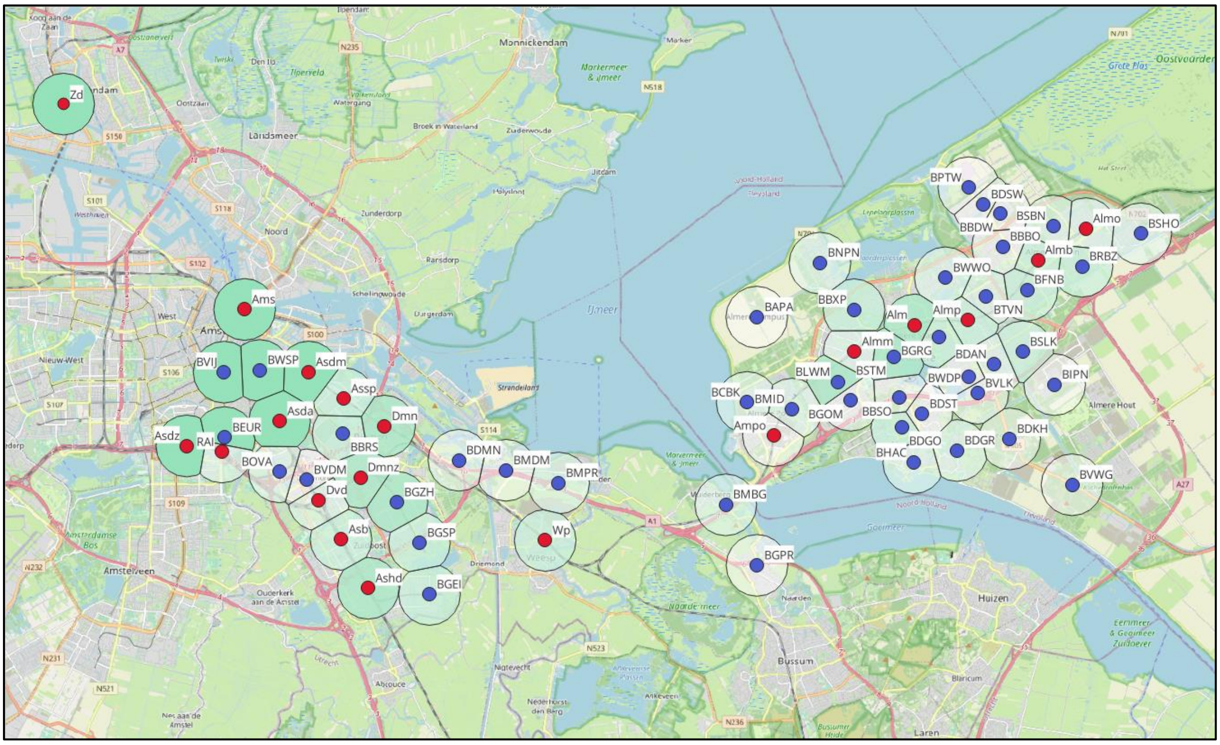


Figure 8-3: Capture areas of the considered stops and stations.

The zonal data is provided per neighborhood, a zonal demarcation for which a value for density is provided. See Figure 8-4.

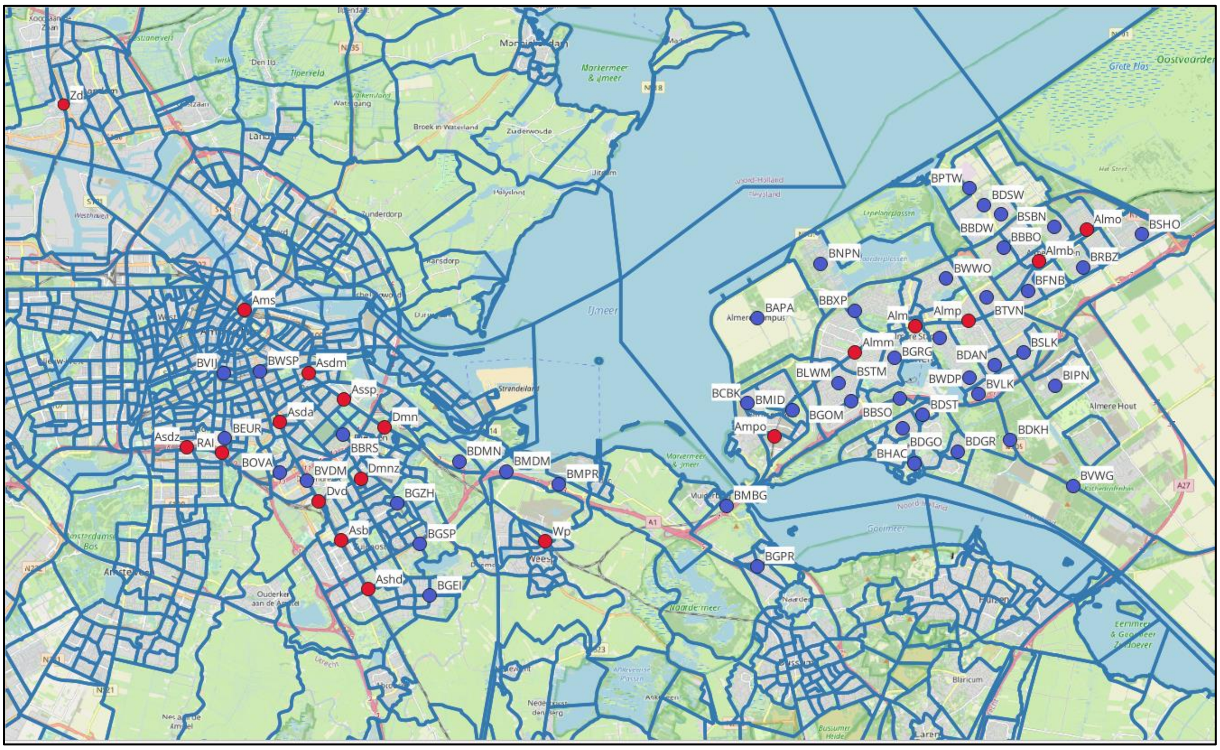


Figure 8-4: Topographical delimitation of the CBS "buurten"

By overlapping the neighborhood areas with the caption areas, a network of smaller areas, each with the respective population density, is created. See Figure 8-5.

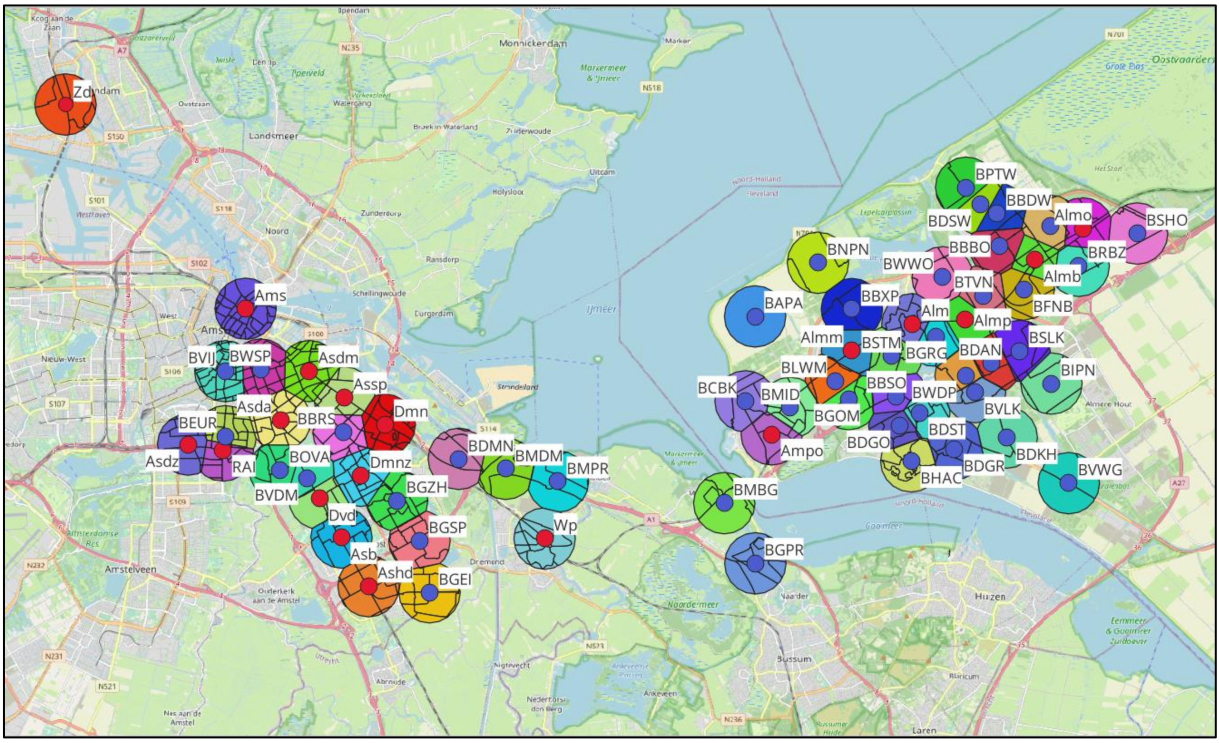


Figure 8-5: Capture area with corresponding sub-groups

QGIS is used to calculate the surface area of the smaller areas, thus estimating the population for each sub-area. Exporting the datafile into excel and summing up the population of each area results in an estimation of the population within the caption area.

8.3.2 Synthetic demand calculation

As with the GTT, the aggregated synthetic demand for all stops and stations is calculated from the data. The results are shown in Table 8-18.

Table 8-18: Synthetic demand per variant with comparison

Variant	Average synthetic demand [unitless]	Compared to V0	Compared to V1	Compared to V2
V0	38.407			
V1	38.747	340 (0,9%)		
V2	39.025	619 (1,6%)	279 (0,7%)	
V3	36.899	-1.508 (-3,9%)	-1.847 (-4,8%)	-2.126 (-5,4%)

The same sub-aggregation categories are applied to the synthetic demand as to the GTT. This gives the results as presented in Table 8-19

Table 8-19: Results of aggregation based on station/stop type and location

	V0	V1	V2	V3	V1 vs V0	V2 vs V0	V3 vs V0	V2 vs V1	V3 vs V1	V2 vs V3
BTM	24.060	24.181	24.426	23.194	0,5%	1,5%	-3,6%	1,0%	-4,1%	-5,0%
Heavy-rail	52.770	53.329	53.642	50.621	1,1%	1,7%	-4,1%	0,6%	-5,1%	-5,6%
Almere	17.340	17.718	17.833	15.379	2,2%	2,8%	-11,3%	0,7%	-13,2%	-13,8%
Amsterdam	94.411	94.641	95.306	92.289	0,2%	0,9%	-2,2%	0,7%	-2,5%	-3,2%
Lelystad	31.356	34.227	39.889	31.818	9,2%	27,2%	1,5%	16,5%	-7,0%	-20,2%
Other (Weesp)	26.220	26.408	26.260	24.174	0,7%	0,2%	-7,8%	-0,6%	-8,5%	-7,9%
External	32.631	32.942	33.099	32.313	1,0%	1,4%	-1,0%	0,5%	-1,9%	-2,4%

9. Evaluation

This chapter elaborates on the analysis results from Chapter 8 regarding travel time, cost, and demand. Furthermore, an evaluation of the ambition fulfillment is done. A short analysis determines the fairness of the offer. Finally, a qualitative MCA is performed to structure the analysis and given an answer to what, from a cost versus demand perspective, would be the better choice.

9.1 Cost evaluation

The results of the cost calculation are summarized in Table 9-1.

Table 9-1: Costs per variant

	V1	V2	V3
Total investment costs [million EUR]	4000	1100	5200
Total operating costs [million EUR / year]	33	86	61

It can be observed that the cost of the *Ijmeer* connection is a larger component of the total cost than the sum of all other components, for any given variant. Regarding the operational costs, both V2 and V3 have significantly larger operational costs compared to V1, of which V2 has the largest. The share of the bus system in the operational costs is minimal, due to the limited number of extra vehicle kilometers. In V3 the share of operational costs between the heavy-rail and metro system is almost equal. The assumptions made for the cost per vehicle hour and for the active hour equivalent could influence the share in such a way that it cannot be clearly said that V2 will really have the highest operational costs.

9.2 Travel time evaluation

The GTT analysis and the synthetic demand analysis both show a consistent picture, whether in fully aggregated or partially aggregated form. V1 and V2 perform better than V0, with V2 performing better than V1. Only for the “other” subcategory does V2 perform slightly worse compared to V1 in the synthetic demand analysis. This is not the case for the GTT. The all-or-nothing assignment of the 1 km Voronoi catchment areas may influence the results of the synthetic demand, as it does not consider the choice to have a slightly longer access distance in exchange for a shorter GTT, for instance because a different stop would offer a direct connection instead. This is mostly of influence on short-distance trips. Furthermore, the use of number of inhabitants only understates the importance of industrial or commercial-only areas, where there are many jobs but limited number of inhabitants.

9.3 Ambition fulfillment

Each variant has fulfilled one or more of the ambitions presented in Table 6-1. The fulfillment of the criteria is scored between 0 and 1, based on argumentation, which is given below. The results are presented in the Table 9-2.

To begin, all variants have four trains per hour per direction running on the *Lelylijn*. Therefore, maximum score is awarded to every variant. Variant 2 is the only variant without an *Ijmeer* connection, therefore this variant scores 0 on this topic. The frequency northbound is also increased equally in every variant, therefore they all receive the maximum score. The connection to Utrecht Centraal consisted of a service stopping in *Almere Poort* and *Almere Centrum*. This is unchanged in V1. In V3, the train calls again at two stations in Almere. In V2, the service calls at every station. Therefore, it receives a zero score for V2, and half a score for V1 and V3. Neither of the variants have alternating stations, therefore they all score the minimum score. The frequency of the original BTM lines has not been changed. In V1 and V3, BTM is added to Almere, of which in V3 a lot more. Therefore, the score is 0,5 for V1, 0 for V2 and 1 for V3. The *Ijmeer* connection also helps to add High-quality PT to the "Ijburg" neighborhood in Amsterdam (east of *Diemen Zuid*). Although the individual stops are not modelled, it makes sense to assume the metro connection is going to have stops there as well. Therefore, V1 and V3 score 1 in "High-quality PT region Almere".

Table 9-2: Rating of ambition fulfillment per variant

	V1	V2	V3
"*Lelylijn*"	1	1	1
"*IJmeer* connection"	1	0	1
"Increase frequency to the north"	1	1	1
"additional fast trains Almere – Utrecht"	0,5	0	0,5
"alternating destinations ICs"	0	0	0
"High-quality PT Almere"	0,5	0	1
"High-quality PT region Almere"	0,5	0	0,5
Total	4,5	2,0	5,0

9.4 Fairness of the offer

The fairness of the offer is an indicator of how much some passengers benefit compared to others. This is done for each variant based on the aggregated scores for the GTT from Table 8-13, Table 8-14, Table 8-15, Table 8-16 and Table 8-17. Fair is defined here that no group of stops and stations is allowed to get a higher aggregated GTT while other aggregates get a lower GTT. Looking at the tables, it can be determined that the aggregate of stops and stations in Lelystad are the only ones with a lower GTT after implementation of variant 3, compared to the original situation. Therefore, variant 1 and variant 2 get a maximum score for fairness (1), while variant 3 gets the minimum score (0).

9.5 Quantitative MCA

In Table 9-3 the minimum, maximum and favorability of each criterion is showed.

Table 9-3: Normalization table for the MCA criteria

Criterion	Minimum score	Maximum score	Favorable/unfavorable
Gen. Travel time	87,2	92,2	U
Investment costs	1110 mil. Euro	5180 mil. Euro	U
Operational costs	33 mil. Euro/year	86 mil. Euro/year	U
Fairness of the offer	0	1	F
Ambition fulfillment	2	5	F
Demand	36899	39025	F

A normalization is applied following the method explained in section 2.2.3 and using equations *(2)* and *(3)*.

Table 9-4: Normalized MCA for the variant choices

Criterion	Weight	V1	V2	V3
GTT	1	0,80	1	0
Investment costs	1	0,29	1	0
Operational costs	1	1	0	0,47
Fairness of the offer	1	1	1	0
Ambition fulfillment	1	0,83	0	1
Demand	1	0,87	1	0
Total		4,79	4	1,47

The results in Table 9-4 form an answer to the third research question: which variant is better from what perspective. Without any weights, variant 1 is deemed the best variant.

10. Stakeholder reflection

The normalized, unweighted MCA from Table 9-4 can and should be weighted by the stakeholders. However, insufficient stakeholders could be found in time to incorporate their views on the relative importance of each criterion. Therefore, a stakeholder reflection is done. This consists of listing all stakeholders deemed relevant for the PT development as shown in the variants. For each stakeholder, it is argued what their interests with respect to the network development are, and how this connects to the MCA criteria. Based on this insight, something can be said on their opinion regarding each of the variants. This is shown with MCA's as possibly weighted by a particular stakeholder. A short discussion on the results wraps up the chapter.

Many parties are involved in the planning, financing, construction, and operation of the future PT network. However, to be in line with the level of detail the variants are modelled, the five deemed most important are mentioned below.

10.1 Stakeholder: The railway undertaking

The railway undertaking is operating the heavy-rail services. On the case study network, the only passenger heavy-rail operator is the state-owned "Nederlandse Spoorwegen" (NS, Dutch Railways). It is therefore assumed that NS is going to be the operator in all future variants.

NS is responsible for the operational costs, which is therefore directly an important criterion within the MCA. It pays the infrastructure manager a fee per train for using the heavy-rail infrastructure (treinreiziger.nl, 2022). Furthermore, NS must provide the rolling stock and personnel, which are elements of operating costs. However, the railway operator does usually not have to pay for the investment costs (*Kosten spoorgebruik*, n.d.). Therefore, it is assumed that NS will not have to pay directly for investment costs. This criterion therefore is of little importance to NS. As NS is allowed to sell tickets for its services, a higher demand is desirable for heavy-rail connections. The model does not show the demand per route, and therefore an increase in total demand is not a one-on-one increase in the demand for NS. However, it can be assumed that a higher demand is desirable for NS, and therefore an important criterion. The fairness of the offer is not a direct concern for NS, as it must run the services as described in the concession, and therefore gets a low score in importance. The ambition fulfillment is also not a direct concern for NS. And although a lower GTT is assumed to lead to a higher demand, it is not a direct benefit for NS, and therefore gets half a point. This results in the MCA, as it could be weighted by the railway undertaking, shown in Table 10-1.

Table 10-1: MCA with a possible weight distribution for the railway undertaking

Criterion	Weight	V1	V2	V3
GTT	0,5	0,80	1	0
Investment costs	0	0,29	1	0
Operational costs	1	1	0	0,47
Fairness of the offer	0	1	1	0
Ambition fulfillment	0	0,83	0	1
Demand	1	0,87	1	0
Total		2,27	1,5	0,47

10.2 Stakeholder: The infrastructure manager

The infrastructure manager is responsible for the availability, quality, and safety of the heavy-rail infrastructure. The infrastructure manager is also responsible for the allocation of the available capacity to the railway undertakings. In the case study the infrastructure manager is ProRail.

ProRail does track maintenance, and charges for the track usage. ProRail is in charge of rail traffic control. ProRail is owned by the Dutch state. ProRail manages the construction of railway infrastructure like track, stations and viaducts. Apart from the track charges, ProRail receives financing from the Dutch state for the network operation, maintenance and development. The assignment of ProRail is specified through a ten-year concession, that is also set-up by the state. (*Veelgestelde vraag*, n.d.).

Based on this information it can be concluded that none of the criteria are impacting ProRail directly. A lower GTT, operational costs, fairness of the offer, a higher demand, and ambition fulfillment should not be of direct concern to ProRail. And although investment costs are something that ProRail is directly concerned with, a higher investment cost is not necessarily something positive or negative for ProRail, as the state is responsible for large infrastructure projects that it feels need to be carried out. Therefore, half a point is allotted to the investment costs and zero weight to all other criteria. See Table 10-2.

Table 10-2: MCA with a possible weight distribution for the infrastructure manager

Criterion	Weight	V1	V2	V3
GTT	0	0,80	1	0
Investment costs	0,5	0,29	1	0
Operational costs	0	1	0	0,47
Fairness of the offer	0	1	1	0
Ambition fulfillment	0	0,83	0	1
Demand	0	0,87	1	0
Total		0,15	0,5	0

10.3 Stakeholder: The BTM operators

The BTM operators have similar responsibilities to that of the railway undertaking. The BTM operators in the case study are the GVB, OV Regio Ijsselmond, Keolis and Transdev. GVB is the only operator that is publicly owned (by the Municipality of Amsterdam) and the only operator that is responsible for rail infrastructure, namely the tram and metro network. All operators run services under concession, are allowed to sell tickets and get financing in various forms from governmental institutions.

A lower travel time is not directly beneficial for operators. However, this can lead to a higher demand and lower operational costs, both of interest for the operators. Just like with NS, ambition fulfillment, fairness of the offer and investment costs, although items that can have influence on the operator, are not a direct concern. See Table 10-3.

Table 10-3: MCA with a possible weight distribution for the BTM operators

Criterion	Weight	V1	V2	V3
GTT	0,5	0,80	1	0
Investment costs	0	0,29	1	0
Operational costs	1	1	0	0,47
Fairness of the offer	0	1	1	0
Ambition fulfillment	0	0,83	0	1
Demand	1	0,87	1	0
Total		2,27	1,5	0,47

10.4 Stakeholder: National government

Governments from national to local level have a range of values they expect public transport to secure (Veeneman & van de Velde, 2006). This range of values has not been explicitly mentioned in this research. However, it can be assumed that the ambitions mentioned throughout this document are set-up in such a manner that fulfilling them leads to the securing of one or more of the values. Therefore, ambition fulfillment is considered important for the national government. Lowering the GTT makes public transport more attractive, and therefore this criterion is considered of some interest.

The ministry of Infrastructure and Water management finances the construction and the largest share of the maintenance of the heavy-rail network (Goverment of The Netherlands, n.d.). Therefore, investment costs are an important criterion. Operational costs are also important, although not in such a direct fashion: lower operational costs means that less subsidy is required for operating companies to operate the desired services. Equality under citizens is a probable value the government wants to secure. Therefore, fairness of the offer can be considered of some importance. A higher demand means that more people will use the PT network. Under the assumption that a higher usage of the PT system is generally beneficial, for instance by lowering the usage of less desired modalities, a higher demand can be claimed to be of some interest to the national government. This leads to the MCA as presented in Table 10-4.

Table 10-4: MCA with a possible weight distribution for the central government

Criterion	Weight	V1	V2	V3
GTT	0,5	0,80	1	0
Investment costs	1	0,29	1	0
Operational costs	0,5	1	0	0,47
Fairness of the offer	0,5	1	1	0
Ambition fulfillment	1	0,83	0	1
Demand	0,5	0,87	1	0
Total		2,96	2,5	1,2

10.5 Stakeholder: regional and local governments

Regional and local governments are the provinces, municipalities, and administrative partnerships that is represented by multiple municipalities and provinces, like the Metropolitan Area Amsterdam (*Over de Metropoolregio Amsterdam*, 2023). These oversee setting up the

PT concession of their respective concession areas, which often includes some form of subsidy. The national government has a yearly budget for transportation, which is divided between the relevant institutions with a key. It is up to the local and regional authorities to decide which part of that financing goes into the concession, what part in infrastructural investments, and what part goes towards other transportation related costs (CROW, 2013). With respect to the MCA weights, it seems reasonable to assume that it resembles that of the national government. However, operational costs need to be considered directly, which is why it is weighted heavier. On the other hand, large infrastructural projects of national interest can be assumed to be at least partially carried by the national government, which is why these costs are valued less. This leads to the numbers in Table 10-5.

Table 10-5: MCA with a possible weight distribution for the central government

Criterion	Weight	V1	V2	V3
GTT	0,5	0,80	1	0
Investment costs	0,5	0,29	1	0
Operational costs	1	1	0	0,47
Fairness of the offer	0,5	1	1	0
Ambition fulfillment	1	0,83	0	1
Demand	0,5	0,87	1	0
Total		3,31	2	1,47

10.6 Discussion of the estimated stakeholder MCA’s

For four out of five stakeholders V1 scores the highest and V3 the lowest weighted total. Only for the infrastructure manager V2 scores best with V3 still lowest. This means that even with a varying focus on the criteria, V1 is usually the best score according to the MCA. There is however a large shortcoming of these MCA’s to be considered before it can be concluded that indeed V1 would be best and V3 worst. This is that the weights given to this normalized MCA indicate the importance of a criterion for a particular stakeholder, and not the relative importance of the absolute values of the criteria. It therefore does not give, for instance, insight in how an extra passenger kilometer relates to a euro of investment or an EUR in operational costs per year. This, combined with the absolute difference for each criterion for each variant, would need to be combined to have an MCA that would give a definite answer on which variant would be better given the chosen criteria.

11. Conclusion & Discussion

At the beginning of this chapter the conclusions are presented and the answers on the research questions are provided. The discussion section then elaborates on the limitations, implications, and recommendations.

11.1 Conclusion

To gain insight in the possible integration of network development between heavy-rail and hierarchically lower transportation systems, a case study of a heavy-rail corridor in the Netherlands is performed.

The answer on the first research sub-question "How is heavy-rail network development in The Netherlands integrated with the local PT development and what is the governance background for this?" is given by first looking at the plans for developing the PT network for the year 2040. Although for both the BTM and the heavy-rail system many ambitions exist, ranging from new infrastructure to increasing frequency, specific cooperation for development between the two systems are not given. The heavy-rail system provides transportation on the national, interregional, and regional level, while BTM focusses mostly on local level transportation. Overlap in the form of regional buses or short spaced heavy-rail stations with SPR services exists. But, especially on the network level that could possibly be performed by both systems, there is no clear task division between the two systems. Moreover, the BTM system is run by different organizations with local and regional governments being responsible for the services through concessions, while the heavy-rail system is run by a national operator with accountability towards the national government. The service network proposal for the heavy-rail in 2030 shows a network optimized for running the maximum number of services on the existing heavy-rail infrastructure. The presence and potential benefit of BTM on optimizing this network is not considered. To conclude, while there is an overlap between the two systems, and awareness of the beneficial possibilities of having an integrated development strategy, these have not yet been explored extensively in a real-world setting.

The second research sub-question is "What network developments are needed based on an integrated, and what on a segregated approach?". This question is answered by developing three network variants. These variants show possible interpretations to one segregated and two different integrated approaches. There are many more options imaginable, but some conclusions can be drawn based on the experience of these three networks. It turned out that each variant needed investment in more heavy-rail infrastructure to allow for the ambitions. In variant 3, this necessity was not as compulsory as in the other variants, as there was the option of investing in BTM infrastructure only. In variant 2 and 3, new stations had to be built as well. It has been considered unnecessary to build an *Ijmeer* connection in variant 2, where more tasks are assigned to the heavy-rail service. To conclude the second sub-question, using a pre-established task assignment regarding the application of either one of the PT systems to a particular hierarchical level of the service network leads to an integrated approach where a large investment in one system reduces the need for a large investment in the other.

The third research sub-question is then answered by performing analyses and evaluating network variants. "Which network development is better and from what perspective?". It turned out that overall, variant 2 was the best option in terms of travel time and demand. On the other hand, it fulfilled less ambitions than the other variants. Most obviously that of the *Ijmeer* connection. As it turned out, the *Ijmeer* connection is expected to be by far the largest item in terms of investment costs. On the other hand, the many heavy-rail services also made variant 2 the most costly variant in terms of operational costs. Variant 3 performed poorly in travel time and demand. Only the connections to and from Lelystad had, on average, a slight improvement, but not as high as with the other variants. The MCA, although useful for providing insights in the qualities of the different variants, does not give a definitive answer on what the best variant would be without being properly weighted. To conclude the third sub-question, the variant where more tasks are assigned to heavy-rail is better from the perspective of GTT, demand and investment costs, while when the perspective of operational costs and ambition fulfillment are taken, the segregated approach of variant 1 performs better.

The question of what is better leads to the last research sub-question: “What are governance related challenges to implement the better solution?” The first challenge is to determine what is better, because that depends on the point of view of the involved stakeholder. Looking at travel time and demand only, it appears that variant 2 would be preferred. This variant allows for improving travel time for all network levels. Whether or not a variant is going to be easy to implement will also depend on which stakeholder has both the interest and agency to do so. Implementation becomes more difficult when parties that do not benefit need to act. For instance, if running the SPR services in variant 2 proves not to be profitable for the railway undertaking, action must be taken by the national government, for instance by making the services a compulsory part of the concession. However, the SPR services are more likely to serve regional and agglomerational passengers as opposed to national passengers, which in turn could make it less likely of the national government to act.

Now to zoom out and answer the main research question: “Does integrated PT network development in the form of a simultaneous consideration for infrastructural investment in both heavy-rail and hierarchically lower PT modes offer a better solution for fulfilling transportation needs, compared to a segregated approach?”. To answer this question, integration is interpreted as a mutually agreed upon task division, in terms of which system serves what layer of the transportation network. Given some cases, like variant 2, where it is attempted to assign a larger part of the PT network to the heavy-rail system, it is possible to have shorter travel times, a higher demand and relatively low investment costs compared to the option in which integration is performed by carrying out more of the services by the BTM system, or no integration is performed and the two systems are developed irrespective of one another.

11.2 Discussion

By doing a case study, an example is shown of one of many ways to integrate the development of future heavy-rail networks with hierarchical lower systems, like BTM. The idea of this research was to show what is possible. In that sense, the research suggests that it is worth considering ambitions and problems outside of just the BTM or just the heavy-rail system. The *Ijmeer* connection and the *Lelylijn* are examples of two huge projects that could influence one another. The need for more heavy-rail capacity to run trains over the new *Lelylijn*, which is aimed at serving the national interest, can either demand the presence of an *Ijmeer* connection that is to replace some heavy-rail services, as in variant 3, or render the *Ijmeer* connection unnecessary by demanding a heavy-rail investment around Almere, as in variant 2.

It is also notable that in a busy heavy-rail network, where capacity becomes an issue, homogeneity is applied on the different services, in this case the SPR and original IC services: it is very likely that capacity limitations are the reason behind the SPR services from *Amsterdam Zuid* towards Almere to be skipping some stations, and thereby becoming closer to an IC service. The other way around, IC services are forced to call at an extra station, and thereby becoming closer to a SPR service. It could be speculated that these kinds of scheduling measures are an indication of a saturated corridor. The sudden jump in capacity that is created by making new infrastructure in this case study was aimed at allowing the heavy-rail system to perform more of the lower network layer services. But, as variant 2 shows, it also made for the possibility to introduce the higher network layer. The “IC-Direct” layer, where the station in Almere is skipped in favor of a faster long-distance connection. The aggregated GTT's show that this does not have to influence the travel time of Almere itself negatively.

Variant 3 performed worst compared to the other two variants in every GTT aggregate and had the most expensive investment costs. However, there are some factors to be considered before assuming that the strategy of assigning more of the networks' services to the BTM system is not beneficial. To start, the assumptions for the *Ijmeer* connection, including the routing and travel time, are very rough, but greatly influence the performance of the system. Then, the inhabitants of the yet to be built neighborhood "Almere Pampus", and the neighborhood "Ijburg" on the Amsterdam side of the water, have not been considered. These are the areas that would most benefit from the *IJmeer* connection. Furthermore, the BTM network is kept as much as possible in the original situation, which is very heavy-rail oriented. A full BTM redesign of Almere could improve the efficiency of the system, and lead to better results.

The relatively large focus on heavy-rail in the design process is a limitation of the research. In general, many assumptions have been made throughout the process, leading to a large range of values, especially regarding the MCA criteria. The method for modelling the demand is simple, which makes it a good tool for first impression. However, without the proper calibration it is not possible to tell how many extra passengers, and thus passenger kilometers there are to give a better indication of the benefits of some specific services. And as no difference is made in the modality specific factor for the perceived travel time, the quality of the comparison between heavy-rail and BTM is reduced.

The research results show the use of doing a mesoscopic timetable planning, where the possibilities provided by large infrastructural investments can be analyzed relatively easily, even at an early stage. The focus on other modalities is an important extra dimension, as it can determine the desired services that are to run on the heavy-rail network. Even with rough assumptions, much information can be obtained on the possibilities and benefits for the public transport network on all hierarchical layers, but also the interaction between investments in BTM and heavy-rail. The process of brainstorming based on expertise, using qualitative MCA's for making decisions with supporting arguments in the design phase, planning a plausible timetable and analyzing and comparing several variants forms a good skeleton for investigating the possibilities of public transport network development in places where heavy-rail capacity becomes problematic. At any given part in the process, but especially in the cost and the demand analysis, improvement of the input is possible, leading to better results.

It is recommended to expand the quality of this approach by improving one or more of its many aspects. Possibilities for improving the demand analysis lie for instance in introduction of jobs as attractions for the gravity model, improvement of the caption area from a one-kilometer area into a set of areas covering the research area surface and improving the assignment from all-or-nothing to a gradual assignment depending on distance. The cost analysis can be improved by breaking up the different components into more and less general items, like personnel wages, vehicle depreciation and track charges. Further research by going into more detail regarding the BTM system, considering all stops and stations and a better travel time assessment for the metro system, could offer a more truthful insight into the benefits of BTM. Finally, it is also recommended to apply this research method to other cases, and to use this to gain insights. It thus may help decision making regarding PT network development for similar situations around the world.

Bibliography

Alex F. Osborn. (1953). *Applied imagination; principles and procedures of creative thinking*.

APPM. (2022). *OAO-notitie GNOE (Eindconcept)*. APPM.

Arup. (2019). *Future of Rail 2050*. Arup.

Baumgartner, J. P. (2001). *Prices and costs in the railway sector*. EPFL.

Beleidsprogramma Infrastructuur en Waterstaat 2022. (2022). Ministerie van Infrastructuur en Waterstaat. https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/rapporten/2022/05/17/bijlage-1-ienw-beleidsprogramma-2022/bijlage-1-ienw-beleidsprogramma-2022.pdf

Cartostudio. (2019). *Lijnennetkaart Lelystad Arriva*.

Cartostudio. (2021). *Lijnennetkaart Gooi-en-Vechtstreek Transdev*. https://www.transdev.nl/nl/onze-routes/dienstregeling-en-halte-informatie/lijnennetkaarten-en-lijnfolders

Concessie Amsterdam. (n.d.). Retrieved August 31, 2022, from https://www.vervoerregio.nl/pagina/20160121-concessie-amsterdam

CROW. (2013). *Achtergronden Organisatie en Spelregels: Financiering openbaar vervoer*. https://www.crow.nl/kennis/bibliotheek-verkeer-en-vervoer/kennisdocumenten/achtergronden-organisatie-ampamp-spelregels-financ

Discover QGIS. (n.d.). Retrieved June 30, 2023, from https://qgis.org/en/site/about/index.html

Flevoland. (2019, February 27). *Openbaar vervoer* [ContentPage]. Provincie Flevoland; Flevoland. https://www.flevoland.nl/wat-doen-we/wegen-vaarwegen-en-openbaar-vervoer/openbaar-vervoer

Gemeente Almere. (2020). *Thuis in Almere—Woonvisie 2020-2030*. https://www.almere.nl/fileadmin/files/almere/bestuur/beleidsstukken/Beleidsnota_s/200710_19c_BL_Woonvisie_Thuis_in_Almere_2020-2030_WOONVISIE.pdf

Gerring, J. (2004). What Is a Case Study and What Is It Good for? *American Political Science Review*, *98*(2), 341–354. https://doi.org/10.1017/S0003055404001182

Goed Gespoord van West naar Noord. (n.d.). Lelylijn. Retrieved August 16, 2022, from https://www.lelylijn.nl/

Goed Gespoord van West naar Noord. (2022, August 16). Lelylijn. https://www.lelylijn.nl/

Google Maps. (n.d.). Google Maps. Retrieved July 7, 2023, from https://www.google.nl/maps/@52.367045,5.0328053,12.17z?entry=ttu

Goverde, R. M. P., Corman, F., & D'Ariano, A. (2013). Railway line capacity consumption of different railway signalling systems under scheduled and disturbed conditions. *Journal of Rail Transport Planning & Management*, *3*(3), 78–94. https://doi.org/10.1016/j.jrtpm.2013.12.001

Goverment of The Netherlands. (n.d.). *Organisation of public transport—Mobility, public transport and road safety—Government.nl*. Government.Nl; Ministerie van Algemene Zaken. Retrieved June 20, 2023, from https://www.government.nl/topics/mobility-public-transport-and-road-safety/public-transport/organisation-of-public-transport

GVB. (2022a). *Daglijnenkaart 2022*. https://www.gvb.nl/sites/default/files/daglijnenkaart2022.pdf

GVB. (2014, December 12). *Materieel en Cijfers*. https://archive.ph/HNZWP

GVB. (2022b). *Lines | GVB*. https://reisinfo.gvb.nl/en/lijnen

Hoekse Lijn. (2023, March 20). Hoekse Lijn. https://www.hoekselijn.nl/

IMA 2021 Hoofdrapport deel 4. (2021). Ministerie van Infrastructuur en Waterstaat. https://www.tweedekamer.nl/downloads/document?id=53e3ce83-471f-4d4f-9776-b8064ae0e570&title=Hoofdrapport%20deel%204.pdf

Immers, L., Egeter, B., & van Nes, R. (2011). Transport network planning: Methodology and theoretical notions. In *Handbook of transportation engineering. Vol. 1: Systems and operations* (2. ed, p. 2.1-2.33). McGraw-Hill. https://www.researchgate.net/publication/268258208_TRANSPORT_NETWORK_PLANNING_METHODOLOGY_AND_THEORETICAL_NOTIONS

Integrale Mobiliteitsanalyse 2021—Deelrapportage Spoor en BTM. (2021). ProRail. https://open.overheid.nl/repository/ronl-3d564087-2989-4d0c-9dd7-5b23d293acea/1/pdf/bijlage-3-achtergrondrapport-2-spoor-en-btm.pdf

Keolis. (n.d.). *All bus lines Allgobus*. Retrieved October 1, 2022, from https://reizen.keolis.nl/en/allgo/lijnen

Keolis. (2020). *AllGo met verkooppunten 2020-2021 V3*. https://www.allgobus.nl/getmedia/108aab1e-2f62-4ecb-ac94-e47075077489/KEO_allGo-met-verkooppunten-2020-2021_V3.pdf

Keolis. (2022). *Keolis RNET Almere Amsteredam*. https://www.allgobus.nl/getmedia/6e2502ef-6902-4e0a-bc8d-3051a4ef72ea/KEO_R-net_2020-2021_V1_1.pdf

Klaas Hofstra. (2020). *Spoorkaart-2021-v2*. https://www.treinreiziger.nl/wp-content/uploads/2021/01/Spoorkaart-2021-v2.pdf

Klaas Hofstra. (2021). *Infra NL 2022*.

Kosten spoorgebruik. (n.d.). Retrieved June 13, 2023, from https://www.prorail.nl/samenwerken/vervoerders/kosten-spoorgebruik

Lai, Y.-C., & Barkan, C. P. L. (2011). Comprehensive Decision Support Framework for Strategic Railway Capacity Planning. *Journal of Transportation Engineering*, *137*(10), 738–749. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000248

Lelylijn.nl. (n.d.). *Overview of the Lelylijn route*. Retrieved May 7, 2023, from https://www.lelylijn.nl/

Ministerium für Verkehr Baden-Württemberg. (2022, May 9). *So sehen die 130 neuen Doppelstockzüge fürs Land aus*. Baden-Württemberg.de. https://vm.badenwuerttemberg.de/de/service/presse/pressemitteilung/pid/so-sehen-die-130-neuen-doppelstockzuege-fuers-land-aus

Muñoz, P., Franceschini, E. A., Levitan, D., Rodriguez, C. R., Humana, T., & Correa Perelmuter, G. (2022). Comparative analysis of cost, emissions and fuel consumption of diesel, natural gas, electric and hydrogen urban buses. *Energy Conversion and Management*, *257*, 115412. https://doi.org/10.1016/j.enconman.2022.115412

Nes, R. van. (2002). *Design of multimodal transport networks: A hierarchial approach*. TU Delft.

Noord-Holland. (2016, May 30). *Openbaar vervoer—Provincie Noord-Holland*. Noord-Holland. https://www.noord-holland.nl/Onderwerpen/Verkeer_vervoer/Openbaar_vervoer

NOS nieuws. (2017, April 6). *Test Noord/Zuidlijn: "Op volle snelheid deed hij wat-ie moest doen."* https://nos.nl/artikel/2166848-test-noord-zuidlijn-op-volle-snelheid-deed-hij-wat-ie-moest-doen

Oeververbinding. (n.d.). Oeververbindingen MIRT-verkenning. Retrieved August 5, 2022, from https://oeververbindingen.nl/maatregelen/oeververbinding/

Omroep Flevoland. (2020, November 9). *Minister ziet kansen voor IJmeerverbinding*. Omroep Flevoland. https://www.omroepflevoland.nl/nieuws/202309/minister-ziet-kansen-voor-ijmeerverbinding

Ontwikkelagenda Toekomstbeeld OV. (2021). Ministerie van Infrastructuur en Waterstaat. https://open.overheid.nl/repository/ronl-2311ee8d-89c9-4278-9f75-8dd8f3e4db51/1/pdf/Ontwikkelagenda%20Toekomstbeeld%20OV%20-%20Nu%20instappen%20naar%202040.pdf

Openbaar vervoer. (n.d.). Retrieved August 31, 2022, from https://www.vervoerregio.nl/pagina/20151219-openbaar-vervoer

OpenStreetMap. (n.d.-a). *OpenRailwayMap*. Retrieved July 7, 2023, from https://openrailwaymap.org/

OpenStreetMap. (n.d.-b). *OpenStreetMap tiles* [Data set]. Retrieved June 1, 2023, from https://www.openstreetmap.org/

Orth, H., Nash, A., & Weidmann, U. (2015). Level-Based Approach to Public Transport Network Planning. *Transportation Research Record: Journal of the Transportation Research Board*, *2537*(1), 1–12. https://doi.org/10.3141/2537-01

OV regio IJsslemond. (n.d.). *Lijnennetkaart OV regio Ijsselmond.pdf*.

OV regio IJsslemond. (2022). *Lijnennetkaart OV regio Ijsselmond*. https://www.ovregioijsselmond.nl/nl/onze-routes/dienstregeling-en-halte-informatie/lijnennetkaarten-en-lijnfolders

Over de Metropoolregio Amsterdam. (2023). metropoolregioamsterdam. https://www.metropoolregioamsterdam.nl/over-mra/

OVER R-NET. (n.d.). R-Net. Retrieved September 1, 2022, from https://rnet.nl/dit-is-rnet/

Powell, W. W. (1990). Neither Market Nor Hierarchy: Network Forms of Organization. *Research in Organizational Behavior*, *12*, 25–336.

ProRail. (2020). *Eindrapportage Landelijke Netwerkuitwerking Spoor 2040*. https://open.overheid.nl/repository/ronl-d30ae1e8-5051-400a-9024-d6da6eb3d2e7/1/PDF/Eindrapport%20Landelijke%20Netwerkuitwerking%20Spoor%20-%20achtergrondinformatie.PDF

ProRail—Feiten en cijfers. (2012, October 16). https://web.archive.org/web/20121016222854/http://www.prorail.nl/Publiek/Infraprojecten/Overijssel/Hanzelijn/Meerinformatie/Pages/Feitenencijfers.aspx

Rodrigue, J.-P. (2020). *The Geography of Transport Systems* (5th ed.).

Schoemaker, T. J. . H., Koolstra, K., & Bovy, P. H. L. (1999). Traffic in the 2rt Century: A Scenario Analysis of the Traffic Market in 2030. In Delft Interfaculty Research Centre Design and Management of Infrastructures (Ed.), *The infrastructure playing field in 2030: Proceedings of the first annual symposium ; Noordwijk, November 19, 1998* (pp. 175–194). Delft University Press.

SMA und Partner AG. (2022). *Viriato 8.39 Standard User Manual*.

Transdev. (2022a). *Lijnfolder buslijnen OV Regio IJsselmond*.

Transdev. (2022b). *Lijnfolder-Gooi-Vechtstreek*.

treinreiziger.nl. (2022, September 28). *Spoorgebruik wordt 12% duurder (en daardoor ook het treinkaartje).* Treinreiziger.nl. https://www.treinreiziger.nl/spoorgebruik-wordt-12-duurder-en-daardoor-ook-het-treinkaartje/

Value of 2001 Euro today—Inflation Calculator. (2023). INFLATIONTOOL. https://www.inflationtool.com/euro/2001-to-present-value?amount=100&year2=2023&frequency=yearly

Veelgestelde vraag: Hoe legt ProRail financiele verantwoording af? (n.d.). Retrieved June 16, 2023, from https://www.prorail.nl/nieuws/veelgestelde-vraag-hoe-legt-prorail-financiele-verantwoording-af

Veeneman, W. (2021). The governance of public transport towards integrated design. In *Handbook of Public Transport Research* (pp. 137–155). Edward Elgar Publishing Limited.

Veeneman, W., & Mulley, C. (2018). Multi-level governance in public transport: Governmental layering and its influence on public transport service solutions. *Research in Transportation Economics*, *69*, 430–437. https://doi.org/10.1016/j.retrec.2018.07.005

Veeneman, W., & van de Velde, D. (2006). *THE VALUE OF BUS AND TRAIN: PUBLIC VALUES IN PUBLIC TRANSPORT*.

Vernieuwing Amstelveenlijn: Waarom nodig en wat is er gebeurd? (2021, June 1). https://amstelveenlijn.nl/over-het-project/over-het-project/

Waterstaat, M. van I. en. (2021, April 6). *Afspraken over regionaal en stedelijk openbaar vervoer—Openbaar vervoer (ov)—Rijksoverheid.nl* [Onderwerp]. Ministerie van Algemene Zaken.

https://www.rijksoverheid.nl/onderwerpen/openbaar-vervoer/afspraken-over-het-openbaar-vervoer/afspraken-over-regionaal-openbaar-vervoer

Werkmaatschappij Amsterdam Almere. (2011). *M55-IJmeerlijn Vervoerconcept, ontwerp en business case*.

Appendix A Brainstorm participants and sketches

This appendix contains background information on the participants attending the brainstorm session and the sketches made during that session. The sketches can be seen as a first version of each variant.

a. Participants' background

All participants, except for the researcher, are fully employed at SMA und Partner AG and considered experts railway planning experts. Participants 1 and 2 were not previously involved in the project. The description in italics below is taken over from the company's internal database. Participant 3 is the company supervisor for this MSc thesis project.

1. Michael Frei – *"Michael Frei studied civil engineering at the ETH Zürich and did his dissertation on "Studies on the procurement of railway vehicles". He then worked as a project leader Traffic Engineer/Traffic Planner at Gruner AG. In 2002, he joined SMA as a project engineer, where he now works as a project leader in the consulting department with a geographical focus on Switzerland, South Germany and the USA. Furthermore he is – based on his experience – a Subject Matter Expert with main focus of Service concept planning."*
2. Lukas Regli – *"Lukas Regli obtained a diploma in civil engineering at the ETH Zürich specialising in traffic with project planning and construction management. He worked at the Institute for Traffic Planning and Transport Systems at the ETH Zürich until his graduation, before joining SMA as a project engineer in 2007. In 2011, he took a six month sabbatical from SMA and worked in the business development department of Dutch State Railways for international transport services (NS Hispeed). Today he is a project leader for projects in the German-speaking countries and Team Leader."*
3. Warner Oldenziel – *"Warner Oldenziel obtained a diploma in civil engineering specialising in transport and mobility at the ETH Lausanne. He then worked as a project leader for Citec Ingénieurs Conseils SA in Geneva. In 2010 he joined SMA as a project leader and today he is a Team Leader and also Region Manager responsible for Belgium and the Netherlands."*
4. Anton Mihalevschi – Student researcher

b. Network levels and PT systems per variant

To clarify the intended assignment of PT systems to the network levels for each variant, a sketch was made. Note that the service product names (IC-Direct, IC/IR, SPR) are assigned to levels to get a feeling for the network level. However, they do not correspond one on one, as a service product name is defined by the operator to particular services, while the network level is defined by the distance between two stops or stations.

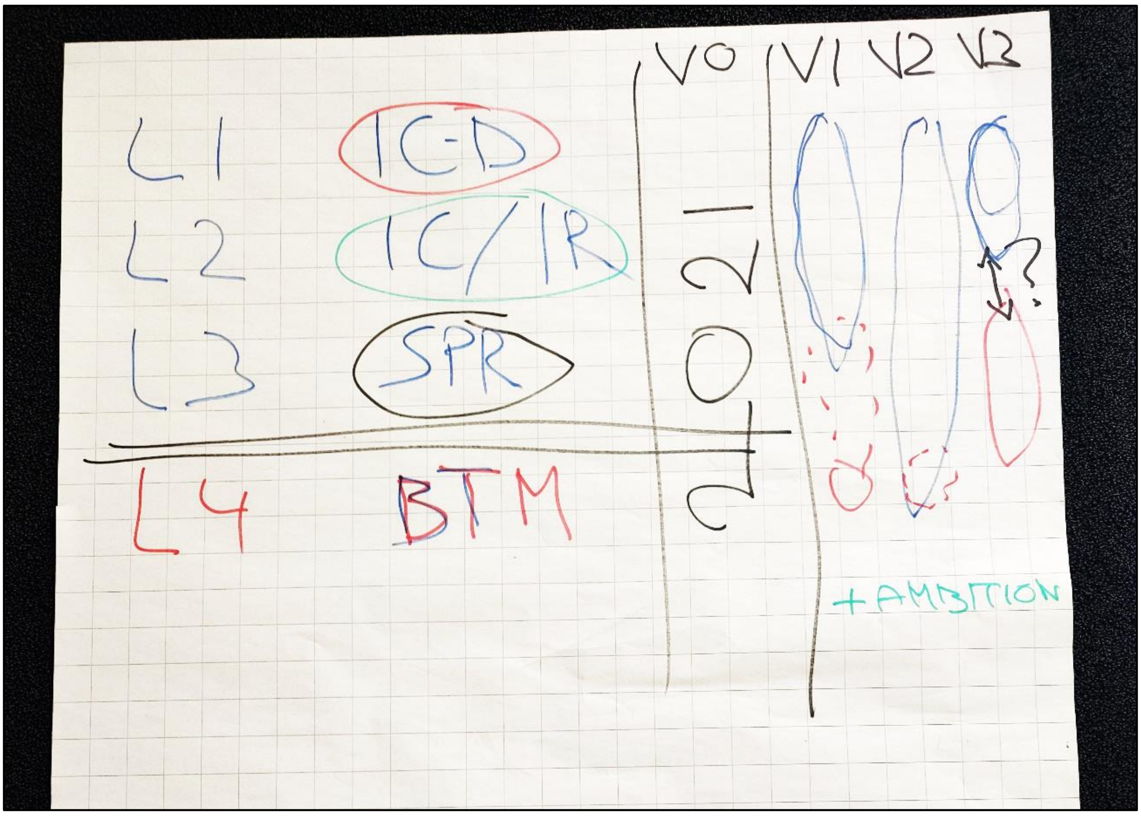


Figure A-1: The intended assignment of PT systems to the network levels for each variant.

c. Sketch to development variant 1

Each line represents a 30-minute interval service. The network level of stations and services is shown by the color: Red for national, green for regional and black for agglomeration level. The letters represent the cities:

- G/L = *Groningen/Leeuwarden*
- L = *Lelystad Centrum*
- Z = *Zwolle*
- A = *Almere Centrum*
- U = *Utrecht Centraal*
- A-C = *Amsterdam Centraal*
- S = *Schiphol Airport*

The text indicates that although the connections are alternating with destination *Schiphol Airport* / *Amsterdam Centraal* in the image, ProRail plans to connect Almere and *Amsterdam Centraal* exclusively with lower network level trains, while all higher network level trains run on the connection Almere – Schiphol. The reason for showing the alternating connections is because the members of the brainstorm group consider it better from the passenger perspective, as there is a broader offer of direct connections. They also consider the non-alternating option as ProRail does it a logical step from the perspective of the network manager, as alternating connections demand more from the infrastructure network.

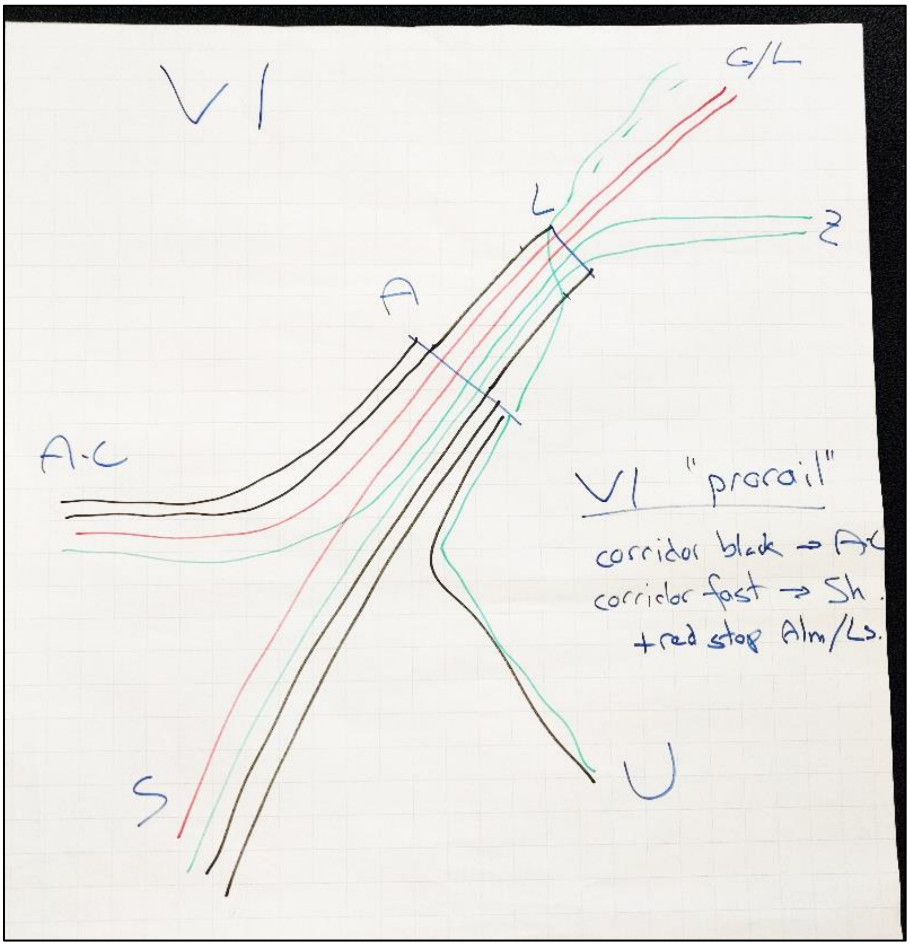


Figure A-2: The brainstorm sketch of variant 1. Black: SPR, Green: IC, Red: IC-Direct

d. Sketch to development variant 2

Figure A-3 shows the sketch made during the brainstorm session to help with the idea of development variant 2. The network level of stations and services is shown by the color: Red for national, green for regional and black for agglomeration level. The letters represent the following:

- C = *Amsterdam Centraal*
- A = *Almere Centrum*
- B = *Amsterdam Bijlmer ArenA*
- S = *Schiphol Airport*

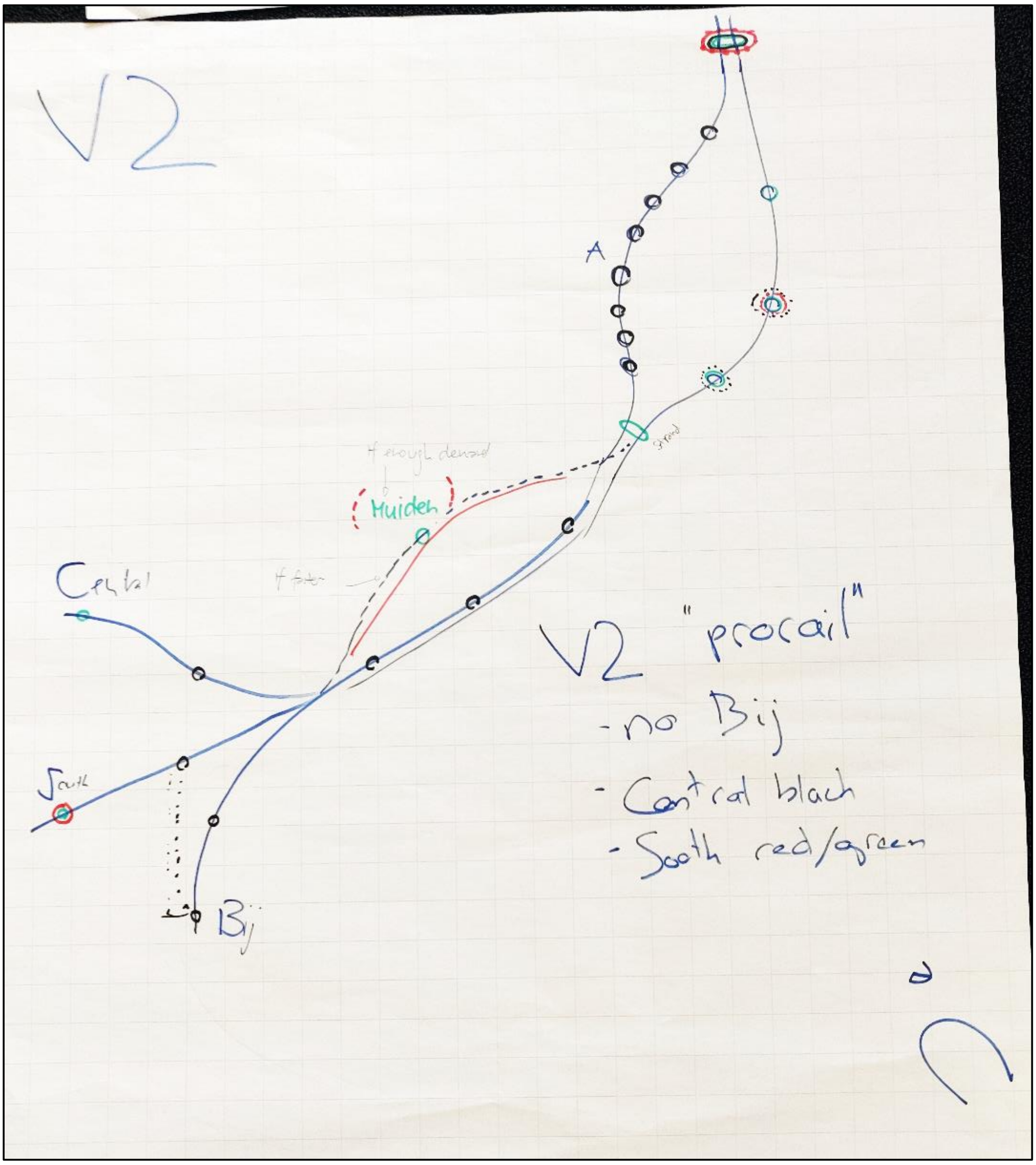


Figure A-3: The brainstorm sketch of variant 2. Black: SPR, Green: IC, Red: IC-D

e. Sketch to development variant 3

Figure A-4 shows the sketch to development variant 3. The letters represent the following:

- CS = *Amsterdam Centraal*
- A = *Almere Centrum*
- B = *Amsterdam Bijlmer ArenA*
- S = *Schiphol Airport*
- L = *Lelystad Centrum*

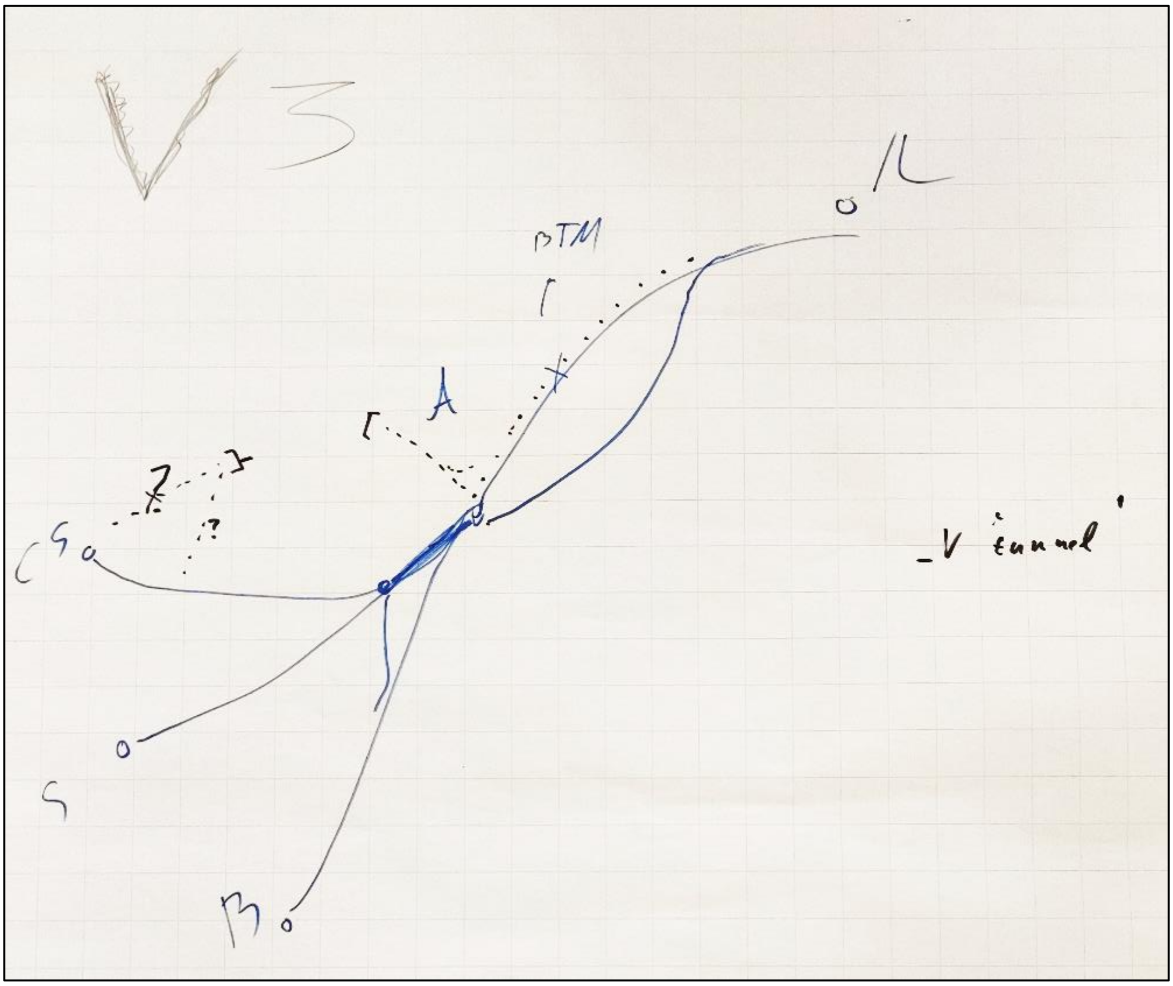


Figure A-4: The brainstorm sketch of variant 3. Black: SPR, Green: IC, Red: IC-Direct

Appendix B Corridor documentation

This appendix contains the maps of the various service- and infrastructure networks that are relevant for the case study area. They are provided for the participants on paper during the brainstorm session. It also contains the considered lines for the BTM part of the case study network.

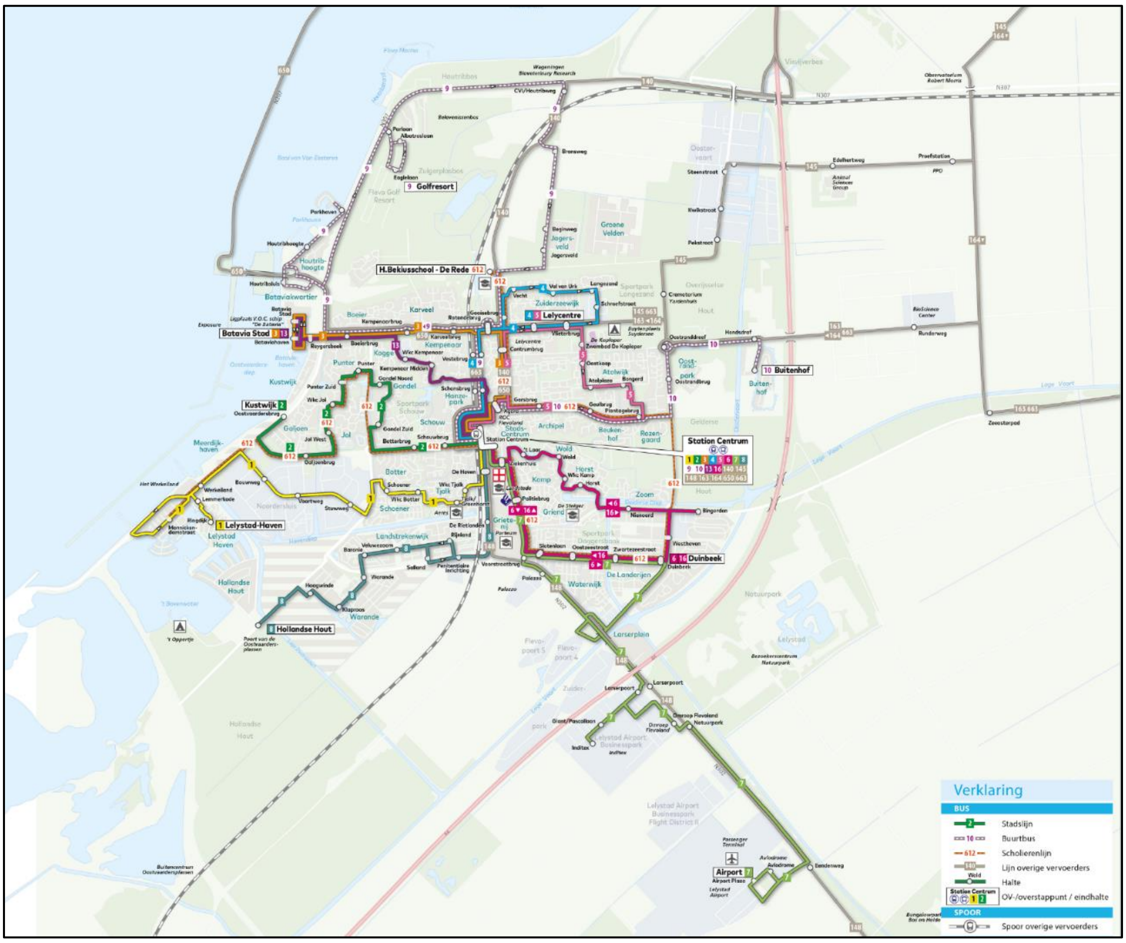


Figure B-1: Map of the “Stadsvervoer Lelystad” local bus service network. Adapted from: (Cartostudio, 2019)

The BTM services in Lelystad are centralized towards the only currently active heavy-rail station, in the center of the city, see Figure B-1. Based on the lack of any kind of PT stops between the cities of Almere and Lelystad and the presence of the “Oostvaarders plassen” nature area (see also Figure B-3), it is assumed that on the stretch of corridor between Almere and Lelystad there are no particular points of interest from the PT perspective. It is therefore assumed to be reasonable to exclude local BTM in Lelystad, as it has little to now corridor effects.

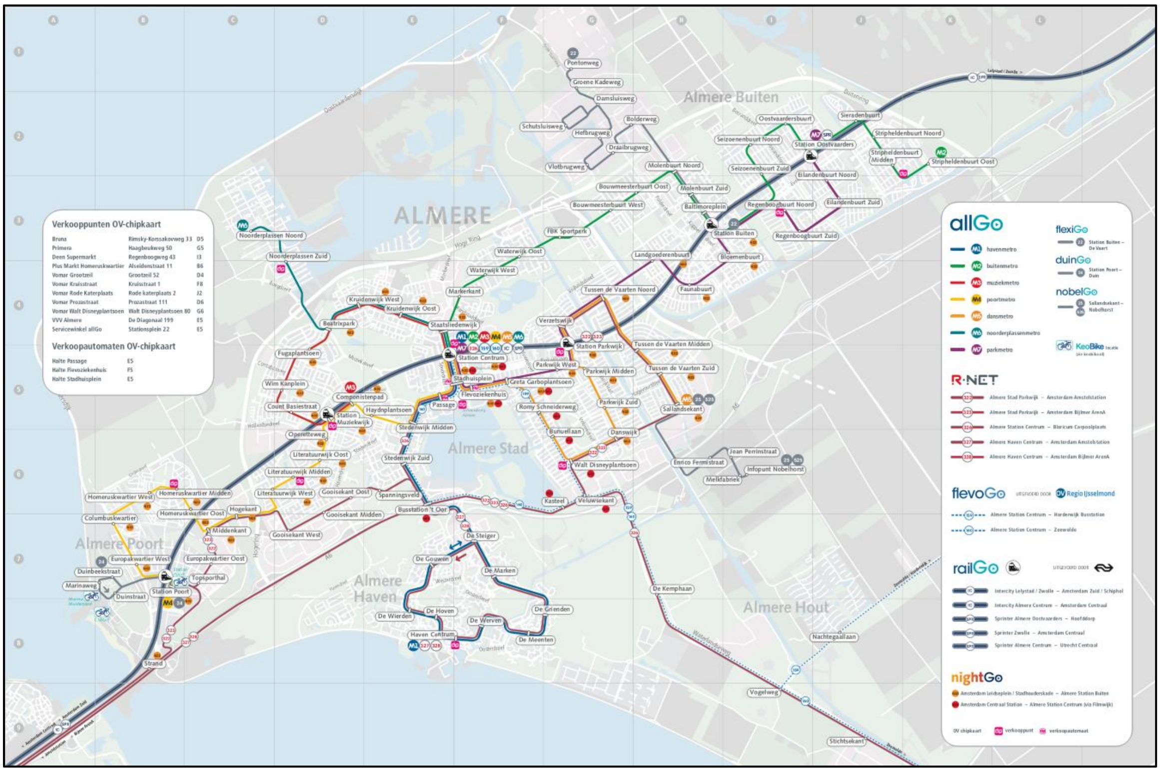


Figure B-2: Map of the “Busvervoer Almere” local bus service network. From: (Keolis, 2020)

Figure B-2 portrays the service network of the city of Almere. The lines are presented in Table B-1.

Table B-1: Lokal Almere buslines

Line	Origin	Destination	Considered in the case study?
M1	*Almere Haven, Centrum*	*Almere Stad Station Centrum*	Yes
M2	*Almere Buiten, Stripheldenbuurt*	*Almere Stad Station Centrum*	Yes
M3	*Almere Stad, Componistenpad*	*Almere Stad Station Centrum*	Yes
M4	*Almere Station Poort*	*Almere Stad Station Centrum*	Yes
M5	*Almere Stad, Sallandsekant*	*Almere Stad Station Centrum*	Yes
M6	*Almere Stad, Noorderplassen Noord*	*Almere Stad Station Centrum*	Yes
M7	*Almere Station Oostvaarders*	*Almere Stad Station Centrum*	Yes
22	*Almere Buiten, Pontonweg*	*Almere Station Buiten*	Yes
24	*Almere Poort, Duinbeekstraat*	*Almere Station Poort*	No, distance <2 km
25 /525	*Almere Hout, Infopunt Nobelhorst*	*Almere Stad, Sallandsekant*	Yes

Figure B-3: Map of the “IJsselmond” regional bus service network. Adapted from: (OV regio IJsslemond, 2022)

The network in Figure B-3 is part of the relatively large “Ijsselmond” concession area. Because not all lines are visible, information on additional lines are taken from the lines’ timetables (OV regio IJsslemond, n.d.). Only the Monday-Friday on non-holiday weeks lines are considered. The lines are presented in Table B-2.

Table B-2: Regional lines in the “Ijsselmond” concession area

Line	Origin	Destination	
11	*Kampen Station*	*Kampen Station*	No, outside corridor
21	*Dronten Station*	*Dronten Station*	No, outside corridor
22	*Dronten Station*	*Dronten Station*	No, outside corridor
70	*Zwolle Busstation*	*Steenwijk Station*	No, outside corridor
71	*Zwolle Busstation*	*Emmeloord Busstation*	No, outside corridor
74	*Zwolle Busstation*	*Kampen Station Zuid*	No, outside corridor
75	*Marknesse Busstation*	*Steenwijk Station*	No, outside corridor
76	*Emmeloord Busstation*	*Steenwijk Station*	No, outside corridor
77	*Lemmer Busstation*	*Emmeloord Busstation*	No, outside corridor
140	*Emmeloord Busstation*	*Lelystad Station Centrum*	No, outside corridor
141	*Kampen Station*	*Urk Vlaak*	No, outside corridor
142	*Nijkerk Station*	*Harderwijk Busstation*	No, outside corridor
143	*Kampen Station*	*Dronten Station*	No, outside corridor
144	*Zeewolde Langezand*	*Harderwijk Busstation*	No, outside corridor
145	*Lelystad Station Centrum*	*Swifterbant Het Blazoen*	No, outside corridor
146	*Emmeloord Busstation*	*Dronten Station*	No, outside corridor
147	*Harderwijk Busstation*	*Dronten Station*	No, outside corridor
148	*Lelystad Station Centrum*	*Harderwijk Busstation*	No, outside corridor
149	*Urk Gemeentehuis*	*Nagele Domineesweg*	No, outside corridor
159	*Almere Stad Station Centrum*	*Harderwijk Busstation*	Yes, until stop *Vogelweg*
160	*Almere Stad Station Centrum*	*Zeewolde Mast*	No, outside corridor
171	*Zwolle Busstation*	*Vollenhove Clarenberglaan*	No, outside corridor
510	*Kampen Station Zuid*	*Kampen Station Zuid*	No, outside corridor
625	*Zeewolde Kastanjelaan*	*Amersfoort GSG Arnhemseweg*	No, outside corridor
641	*Zwolle Campus*	*Urk Vlaak*	No, outside corridor
663	*Lelystad Station Centrum*	*Kampen GSG Pieter Zandt*	No, outside corridor
674	*Staphorst Redder*	*Kampen GSG Pieter Zandt*	No, outside corridor
679	*Vollenhoven Clarenberglaan*	*Meppel Station*	No, outside corridor
681	*URK Rotholm*	*Kampen CSG Pieter Zandt*	No, outside corridor

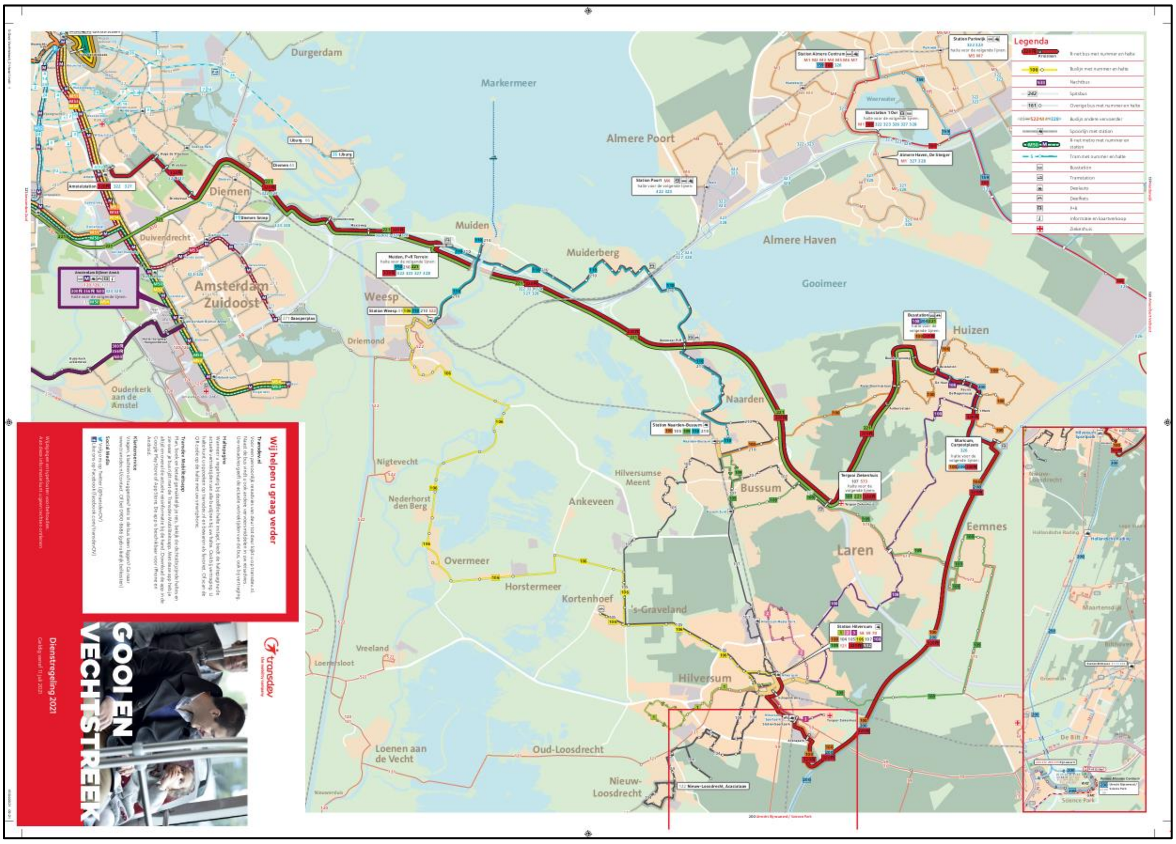


Figure B-4: Map of the “Gooi- en Vechtstreek” regional bus service network. From: (Cartostudio, 2021)

Figure B-4 shows the Gooi- en Vechtstreek concession area. Because of the size of this area, the line brochure is used to identify the lines in the area. Because the lines corresponding to “Stadsdienst Hilversum” (city service Hilversum) are by definition out of the research area, these will not be noted among the lines in Table B-3.

Table B-3: Overview lines concession area "Gooi- en Vechtstreek"

Line	Origin	Destination	Included?
100	*Bussum Station*	*Hilversum Station* via *Huizen Busstation*	No, outside corridor
104	*Hilversum Station*	*Nieuw-Loosdrecht*	No, outside corridor
105	*Bussum Station*	*Hilversum Station* via *Kortenhoef*	No, outside corridor
106	*Weesp Station*	*Hilversum Station*	No, outside corridor
107	*Blaricum Ziekenhuis Tergooi*	*Hilversum Station* via *Bussum*	No, outside corridor
108	*Huizen Busstation*	*Hilversum Station* via *Laren*	No, outside corridor
109	*Bussum Station*	*Hilversum Station* via *Eemnes*	No, outside corridor
110 /210	*Bussum Station*	*Weesp Station* via *Muiden P+R*	Yes, from *Goimeer P+R*
200	*Huizen Busstation*	*Utrecht Science Park* v.v.	No, outside corridor
221	*Huizen Busstation*	*Amsterdam VUmc* v.v.	Yes, from *Goimeer P+R*
320	*Amsterdam Amstelstation*	*Hilversum Station*	Yes, from *Goimeer P+R*

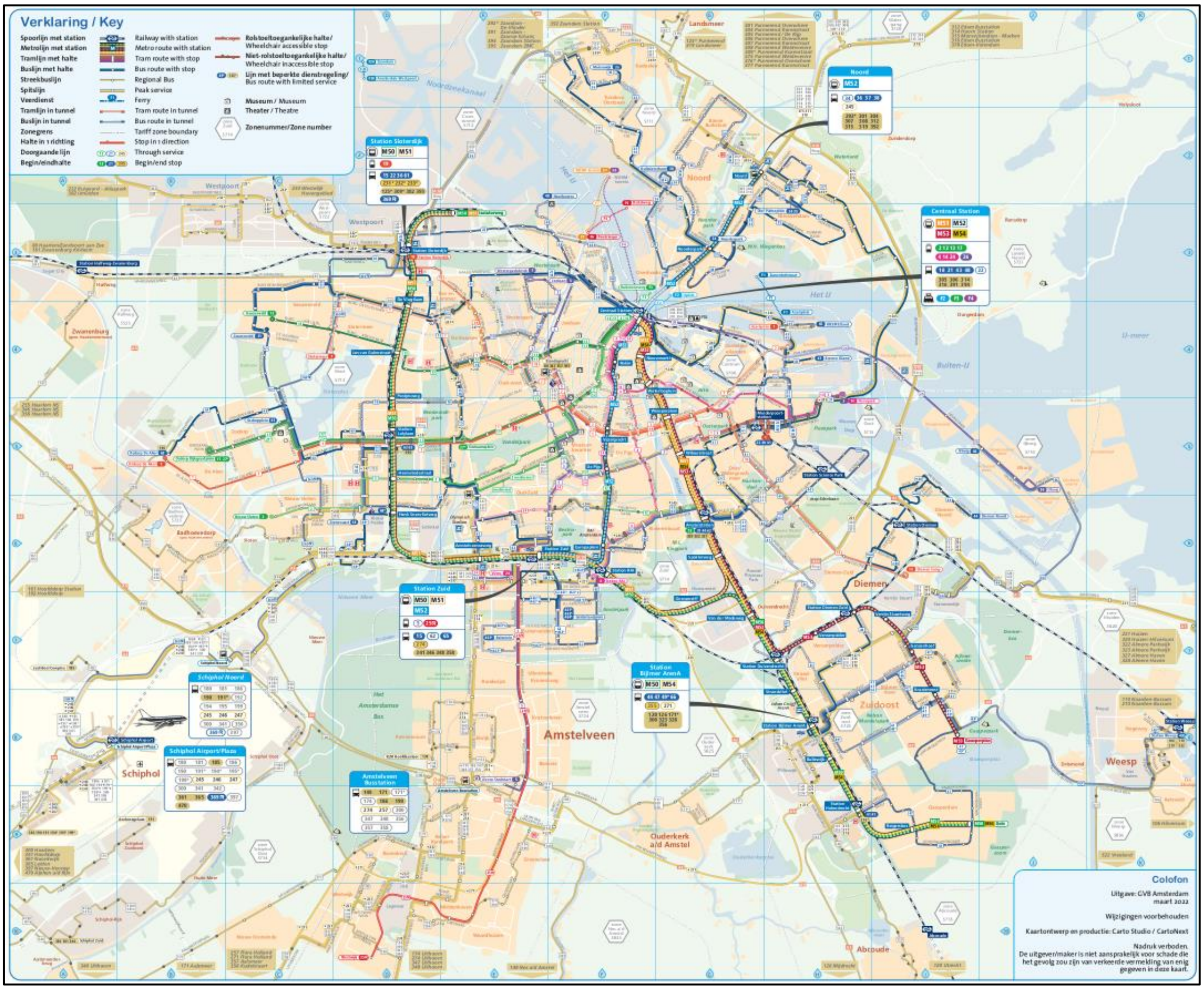
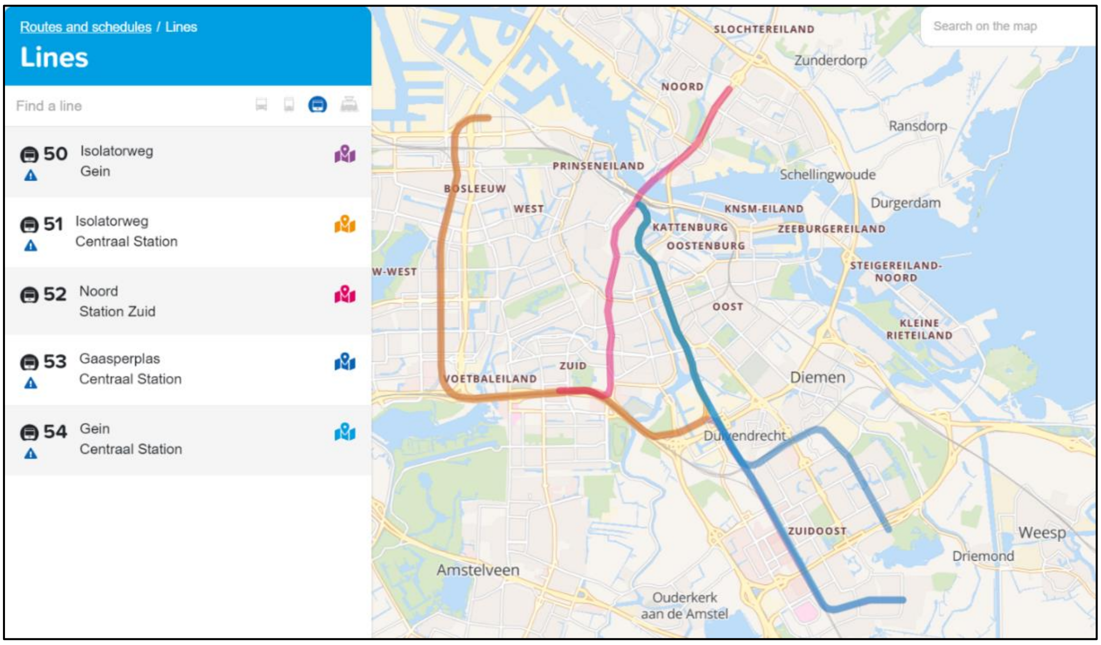


Figure B-5: Map of the “Concessie Amsterdam” public transport service network. From: (GVB, 2022a)

Due to the scope of the study, it is not of interest to analyze intra-urban traffic (From Amsterdam to Amsterdam). Therefore, from the GVB only the metro lines will be considered. See Figure B-6.



Routes and schedules / Lines

Lines

Find a line

50 Isolatorweg
Gein

51 Isolatorweg
Centraal Station

52 Noord
Station Zuid

53 Gaasperplas
Centraal Station

54 Gein
Centraal Station

Figure B-6: GVB metrolines in Amsterdam. From: (GVB, 2022b)

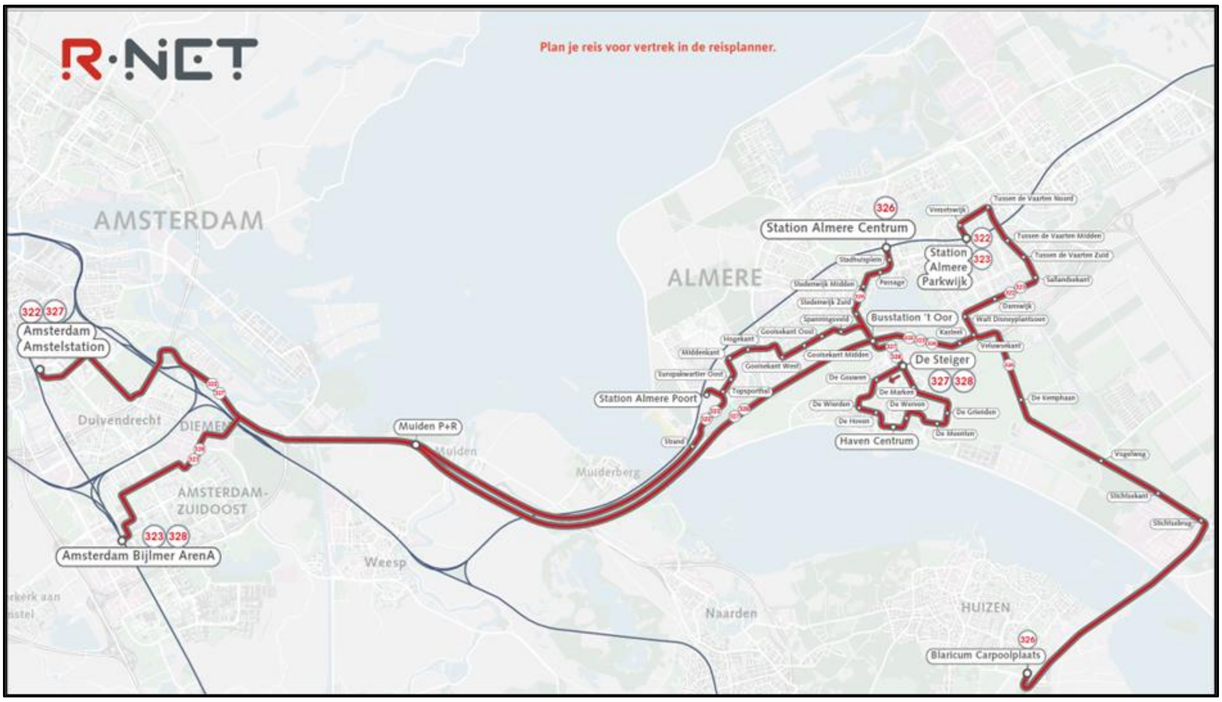


Figure B-7: Map of the “R-NET” product regional bus service network operated by Keolis. Adapted from: (Keolis, 2022)

In Figure B-7 the part of the so-called R-NET network that is operated by Keolis is shown. RNET is a label for PT adhering to a certain set of standards, carried by different carriers throughout the Netherlands (*OVER R-NET*, n.d.). The following lines can be identified:

Line	Origin	Destination	Considered in the case study?
322	*Almere Stad parkwijk*	*Amsterdam Amstelstation*	Yes
323	*Almere Stad Parkwijk*	*Amsterdam Bijlmer ArenA*	Yes
326	*Almere Station Centrum*	*Blaricum Carpoolplaats*	Yes
327	*Almere Haven Centrum*	*Amsterdam Amstelstation*	Yes
328	*Almere Haven Centrum*	*Amsterdam Bijlmer ArenA*	Yes

Figure B-8: Overview of the planned housing development in Almere. From: (Gemeente Almere, 2020, p. 27)

Appendix C Dutch heavy-rail service network –2021 & 2030

The Dutch heavy-rail services are displayed for 2021 in Figure C-1 and the service proposal for 2030 in Figure C-2.

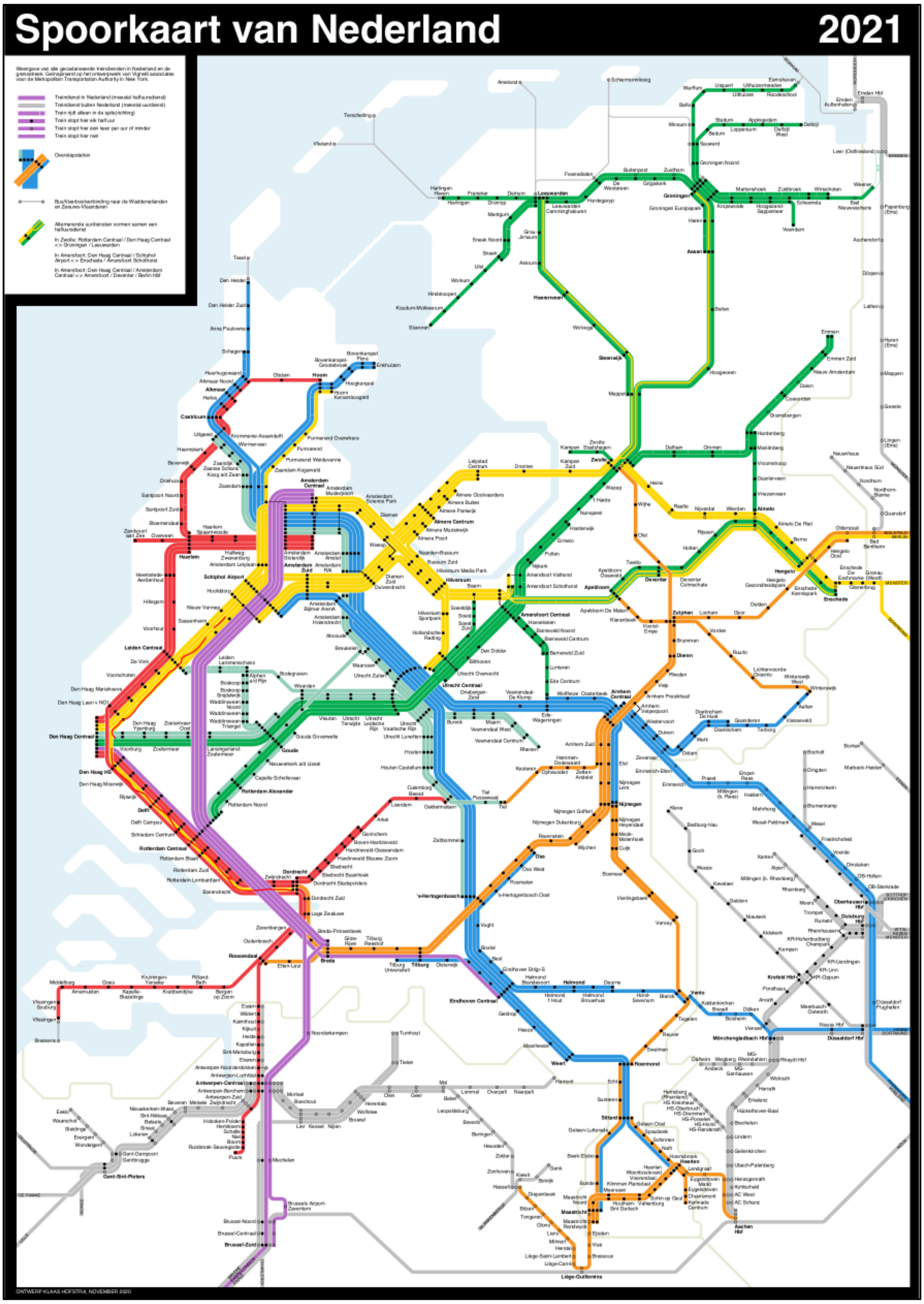


Figure C-1: The 2021 heavy-rail service offer. From: Klaas Hofstra (2020)

The intended service offer from ProRail for the year 2030

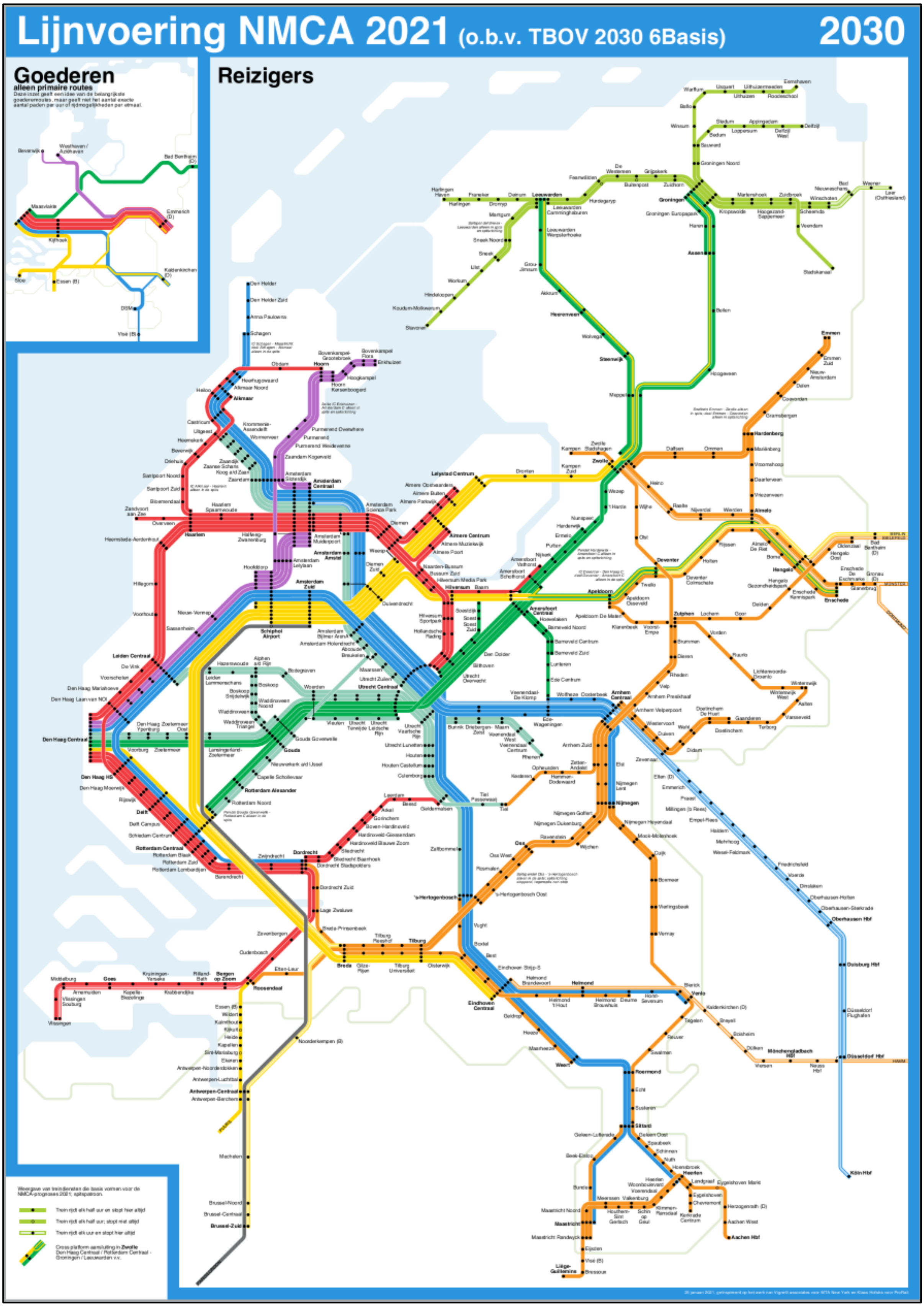


Figure C-2 The intended service offer from ProRail for the year 2030. From: (*Integrale Mobiliteitsanalyse 2021 - Deelrapportage Spoor en BTM*, 2021, p. 112).

Appendix D Schematical overview of the Dutch heavy-rail infrastructure

This appendix contains the schematical overview of the main heavy-rail infrastructure in the Netherlands, containing the current situation and planned changes. This is obtained directly from ProRail for this research. Due to the size of the original file, only a cutout of the section relevant for the case study is shown. This contains, among other places: Amsterdam, Almere, Lelystad, Leeuwarden, Groningen and Hilversum.

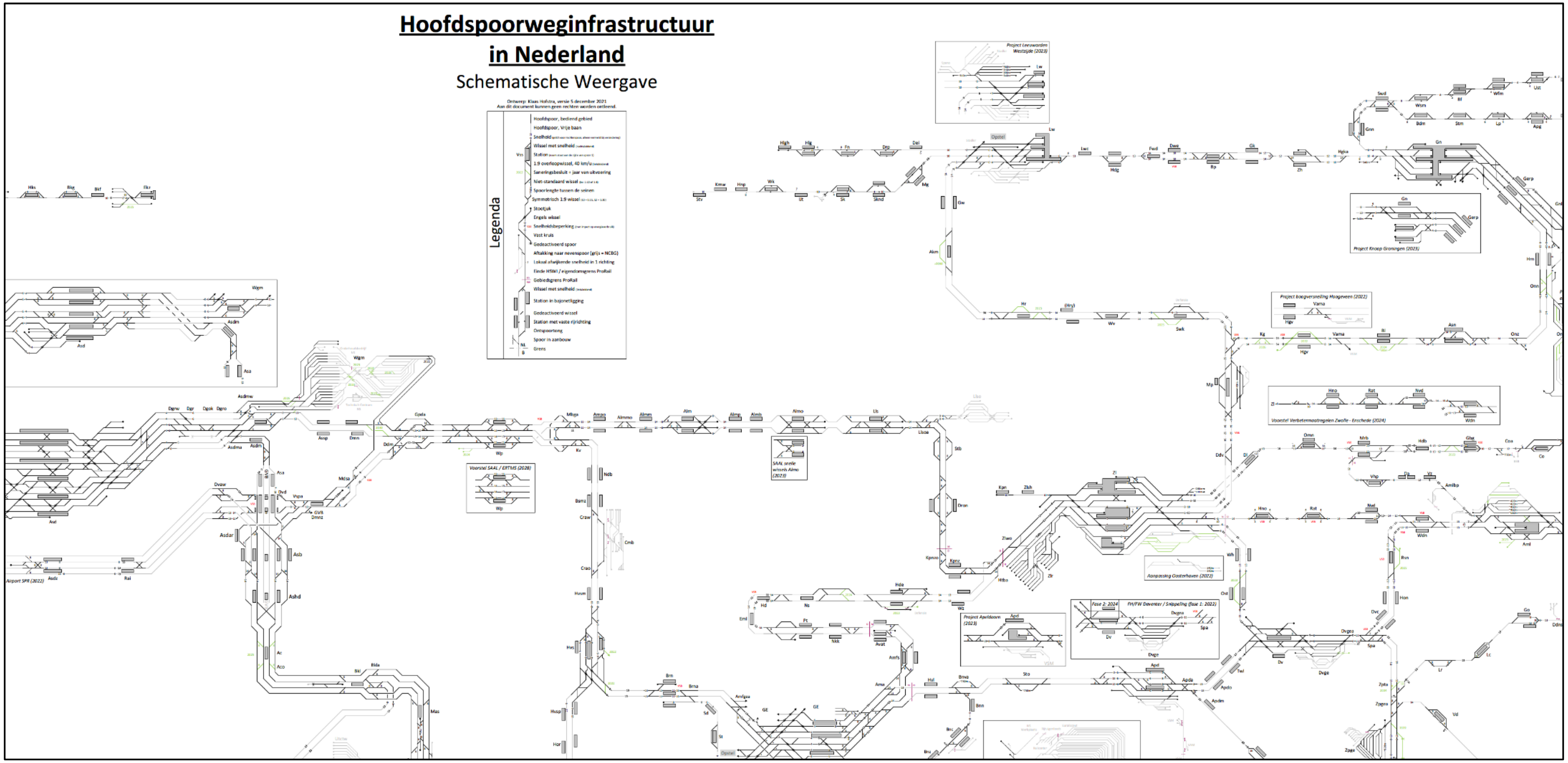


Figure D-1 Cut-out of the schematical overview of the Dutch heavy-rail infrastructure. Adapted from: (Klaas Hofstra, 2021)

Appendix E Evaluation of variant choices with qualitative MCA’s

Each of the choices is shown in the MCA’s below, including the results.

a. Routing of the IC from Groningen/Leeuwarden to Amsterdam

Situation:

The new IC running on the *Lelylijn* has two possible destinations in Amsterdam: *Amsterdam Centraal* and *Amsterdam Zuid*. This gives the following routing options:

- Alternate: Two times per hour to *Amsterdam Centraal*, two times to *Amsterdam Zuid*
- All IC’s to *Amsterdam Zuid*
- All IC’s to *Amsterdam Zuid*

Expert comments:

- From the point of view of connectivity, it is preferable to alternate.
- From an infrastructural perspective, settling on one direction requires less infrastructure, and so is cheaper.
- From an operational perspective, settling on one destination is cheaper and simpler to run.
- Between *Amsterdam Zuid* and *Amsterdam Centraal*, the former is better suited for long-distance travel, as it offers better options further south
- All IC’s to *Amsterdam Zuid* is most in line with the current practice and therefore most applicable to Variant 1.
- Alternating is most applicable to variant 2 and variant 3, as variant 2 attempts to offer more heavy-rail services to all OD’s, and Variant 3 only has Level 1 and Level 2 network services to facilitate, leaving either destination with too little services if one has only Level 2.

Table E-1: Routing of the *Lelylijn* ICs

Criterion	Weight	Alternate	IC to *Amsterdam Centraal*	IC to *Amsterdam Zuid*
Gen. travel time L1+L2	1	0	-	+
Gen. travel time L3+L4	1	0	0	0
Relevance for Variant 1	1	-	--	0
Relevance for Variant 2	1	+	-	-
Relevance for Variant 3	1	+	-	-
Investment costs	1	--	-	+
Operational costs	1	-	0	0
Fairness of the offer	1	+	0	0
Ambition fulfillment	1	0	0	0
Total V1		-3	-4	1
Total V2		-1	-3	1
Total V3		-1	-3	1
Total Total		-1	-6	0

Decision: In every variant the IC is routed to Asdz

b. Stopping policy IC

Stopping in Amsterdam, Almere and Lelystad is too often compared to the theoretical Level 1 IC stopping distance. This gives the following options:

- Stop in Almere only
- Stop in Lelystad only
- Stop in both Almere and Lelystad

Expert comments:

- Stop in Almere would service both the demand *Lelylijn* – Amsterdam and the demand Almere – Amsterdam. As the latter is substantial, this could lead to an unbalanced occupation, with high occupation on the Amsterdam – Almere section.
- Stop in Lelystad would allow the interaction with the Lelystad-Zwolle line.
- Stop in both Lelystad and Almere downgrades the Level 1 IC to a IR, and slows the “fast” connection of the north with Amsterdam

Table 4: Stopping policy of the *Lelylijn* IC

Criterion	Weight	Almere	Lelystad	Almere and Lelystad
Gen. travel time L1+L2	1	0	+	0
Gen. travel time L3+L4	1	0	0	+
Relevance for Variant 1	1	0	0	0
Relevance for Variant 2	1	0	0	-
Relevance for Variant 3	1	0	0	-
Investment costs	1	0	0	0
Operational costs	1	0	0	-
Fairness of the offer	1	-	0	0
Ambition fulfillment	1	0	0	-
Total V1		-1	1	-1
Total V2		-1	1	-2
Total V3		-1	1	-2
Total Total		-1	1	-3

Decision: The IC will only stop in Lelystad in every variant.

c. Type of *Ijmeer* connection

One of the ambitions is a second PT connection between Almere and Amsterdam. This connection is generally assumed to be between the “Almere Pampus” and Amsterdam’s “Ijburg” neighborhoods. There are several options to make this connection:

i. Bus connection
ii. Ferry connection
iii. Metro connection
iv. Light-rail connection
v. Heavy-rail connection
vi. No connection

Expert comments:

- A railway connection is very difficult to implement on the desired route
- A ferry could technically complete the ambition, but is very slow

Table 5: MCA for the types of *Ijmeer* connection

Criterion	Weight	BRT	Light-rail	Metro	Heavy-rail	No connection
Gen. travel time L1+L2	1	0	0	0	+	0
Gen. travel time L3+L4	1	0	+	+	+	-
Relevance for Variant 1	1	0	0	0	0	-
Relevance for Variant 2	1	-	-	-	+	+
Relevance for Variant 3	1	+	+	+	-	-
Investment costs	1	+	0	0	-	++
Operational costs	1	+	0	0	-	++
Fairness of the offer	1	0	+	+	0	-
Ambition fulfillment	1	+	+	+	+	-
Total V1		3	3	3	1	0
Total V2		2	2	2	2	2
Total V3		4	4	4	0	0
Total Total		3	3	3	1	0

Decision: V1 and V3 will have some kind of BTM connection, V2 will have no connection. Because a metro has been mentioned so far in the ambitions, it will become a metro connection.

d. Routing of the heavy-rail in V2 at Almere

There are multiple options regarding which service is routed where. It is assumed that due to the many stations and therefore the difference in travel speed, a combination of SPR and IC is not possible. This leaves the following options, see Table E-2:

Table E-2: Routing of services around Almere

	Almere "old section"	Almere "new section"
Option 1	IC, IR	SPR
Option 2	IC	IR, SPR
Option 3	SPR	IC, IR
Option 4	IR, SPR	IC

Expert comments:

- Since there are already many SPR Level 3 stations along the old track in Almere, it would be useful to keep using them by routing the SPR there.
- As there is no IC stop in Almere, the only way to serve the south-eastern part is to route the IR through there

Criterion	Weight	Option 1	Option 2	Option 3	Option 4
Gen. travel time L1+L2	1	0	0	+	+
Gen. travel time L3+L4	1	+	0	+	0
Relevance for Variant 1	1	0	--	0	-
Relevance for Variant 2	1	-	-	0	0
Relevance for Variant 3	1	0	0	0	0
Investment costs	1	0	-	+	-
Operational costs	1	0	0	0	0
Fairness of the offer		0	-4	3	-1

Decision: The SPR will keep running on the old track, while the IC and IR will go over the new section.

e. Routing of the heavy-rail in V2 at Muiden/Weesp:

There are six possible routes for Muiden/Weesp. Four more than for the Almere section, as this one is shorter and is expected to have fewer stations. Therefore, the possibility of IC combined with SPR is seen as plausible. The options thus are:

Table E-3: Routing of the heavy-rail in V2 at Muiden/Weesp

	Muiden	Weesp
Option 1	IC, IR	Sp
Option 2	IC	IR, Sp
Option 3	Sp	IC, IR
Option 4	IR, Sp	IC
Option 5	IC, Sp	IR
Option 6	IR	IC, Sp

Expert comments:

- Muiden and Muiderberg are unlikely to have more demand than for a SPR (Level 3) network. Therefore, they are not serviced in any option without the SPR route via Muiden
- *Weesp* could be “upgraded” to an IR (Level 2) station, in the case that there are no SPR from Almere anymore.
- In terms of rail capacity, it is better to use the new tracks for at least two network levels

Table 7: MCA for routing the heavy-rail at Muiden/Weesp

Criterion	Weight	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Gen. travel time L1+L2	1	0	+	-	-	+	0
Gen. travel time L3+L4	1	-	-	+	-	+	-
Relevance for Variant 2	1	-	-	+	-	+	-
Investment costs	1	+	+	0	0	0	+
Operational costs	1	0	0	0	0	0	0
Fairness of the offer	1	0	0	+	-	+	0
Ambition fulfillment	1	0	0	+	-	+	0
Total		-1	0	3	-5	5	-1

Decision: Only the IR will be routed through Weesp, which will be upgraded to an IR station. The IC and SPR will be routed over the new line, with stations for the SPR along the way.

f. Upgrade *Weesp* to IR in V3

The question is whether *Weesp* should be upgraded to an IR station, as using heavy-rail for Level 1 IC and Level 2 IR only, would mean *Weesp* wouldn't be connected to the heavy-rail. The options are:

- Upgrade to IR station
- Do not upgrade

Expert comments:

- *Weesp* could be upgraded if there is enough demand to allow for an IR connection
- Otherwise, service is lower, assuming that all sprinters from the direction Almere are cancelled
- The IC Level 1 network would still not stop in Weesp, and could compensate the slowing down of the IR Level 2 network

Table 4: MCA for whether to upgrade station *Weesp*

Criterion	Criterion Weight	Upgrade	Don't upgrade
Gen. travel time L1+L2	1	0	0
Gen. travel time L3+L4	1	0	-
Relevance for Variant 3	1	0	0
Investment costs	1	0	0
Operational costs	1	-	0
Fairness of the offer	1	+	-
Ambition fulfillment	1	0	0
Total Total		0	-2

Decision: Station *Weesp* will be upgraded to the IR Level 2 network

g. Routing of the heavy-rail in V3

The SPR will be removed from Almere as well. Moving the SPR Level 3 network from the heavy-rail modality to BTM means that the existing SPR stations must either close or be serviced by another modality. This gives the following options:

- Build new infrastructure for the heavy-rail system, change the old system to BTM
- Build new infrastructure for BTM if necessary, close the SPR stations and run heavy-rail on existing infrastructure

Expert comments:

- The closing of stations is very unpopular; therefore it makes more sense to reroute heavy-rail
- If the current infrastructure is changed from heavy-rail to BTM, it should get good connections to the new heavy-rail network, for the IR Level 2 connection

Table 7: MCA for Routing of the heavy-rail and BTM services around Almere

Criterion	Weight	BTM on existing heavy-rail infrastructure	Heavy-rail on existing infrastructure
Gen. travel time L1+L2	1	0	0
Gen. travel time L3+L4	1	+	0
Relevanz für Variante	1	0	0
Investment costs	1	-	0
Operational costs	1	0	0
Fairness of the offer	1	+	0
Ambition fulfillment	1	0	0

Decision: It is decided to route the heavy rail over a new section along the highway.

Appendix F List of stops and stations forming the OD-pairs with population

From left to right in Table F-1: Name in Viriato, Name in QGIS, Population estimation, the location category used for the aggregation (H for heavy-rail, B for BTM) and the considered stop or station type used for the aggregation (Almere, Amsterdam, Lelystad, OTHER, EXTERNAL).

Table F-1: List of stops and stations forming the OD-pairs with population and aggregation category

61BAPA	BAPA	0	Almere	B
61BBBO	BBBO	6704	Almere	B
61BBDW	BBDW	238	Almere	B
61BBRS	BBRS	9189	Amsterdam	B
61BBSO	BBSO	1537	Almere	B
61BBXP	BBXP	9759	Almere	B
61BCBK	BCBK	6032	Almere	B
61BDAN	BDAN	8075	Almere	B
61BDGO	BDGO	5641	Almere	B
61BDGR	BDGR	5596	Almere	B
61BDKH	BDKH	141	Almere	B
61BDMN	BDMN	100	OTHER	B
61BDSW	BDSW	2	Almere	B
61BEUR	BEUR	23445	Amsterdam	B
61BFNB	BFNB	9392	Almere	B

61BGEI	BGEI	15690	Amsterdam	B
61BGOM	BGOM	3978	Almere	B
61BGPR	BGPR	3128	OTHER	B
61BGRG	BGRG	7425	Almere	B
61BGSP	BGSP	11355	Amsterdam	B
61BGZH	BGZH	20991	Amsterdam	B
61BHAC	BHAC	7218	Almere	B
61BIPN	BIPN	1831	Almere	B
61BLWM	BLWM	7486	Almere	B
61BMBG	BMBG	2003	OTHER	B
61BMDM	BMDM	190	OTHER	B
61BMID	BMID	5603	Almere	B
61BMPR	BMPR	1382	OTHER	B
61BNPN	BNPN	4553	Almere	B
61BOVA	BOVA	3396	Amsterdam	B
61BPTW	BPTW	7	Almere	B
61BRBZ	BRBZ	8190	Almere	B
61BSBN	BSBN	7667	Almere	B
61BSHO	BSHO	6217	Almere	B

61BSLK	BSLK	5326	Almere	B
61BSTM	BSTM	10146	Almere	B
61BTVN	BTVN	6784	Almere	B
61BVDM	BVDM	3433	Amsterdam	B
61BVGW	BVWG	282	Almere	B
61BVIJ	BVIJ	36313	Amsterdam	B
61BVLK	BVLK	67	Almere	B
61BWDP	BWDP	5305	Almere	B
61BWSP	BWSP	33735	Amsterdam	B
61BWWO	BWWO	10894	Almere	B
Arnhem Centraal	Ah	14989	EXTERNAL	H
AMERSFOORT	Amf	15465	EXTERNAL	H
Alkmaar	Amr	16356	EXTERNAL	H
APELDOORN	Apd	15864	EXTERNAL	H
Amsterdam Muiderpoort	Asdm	48146	Amsterdam	H
Amsterdam Science Park	Assp	11778	Amsterdam	H
BREDA	Bd	16763	EXTERNAL	H
Dordrecht	Ddr	23849	EXTERNAL	H
Diemen	Dmn	14165	OTHER	H

Delft	Dt	31218	EXTERNAL	H
DEVENTER	Dv	20040	EXTERNAL	H
Ede-Wageningen	Ed	8069	EXTERNAL	H
Eindhoven Centraal	Ehv	16521	EXTERNAL	H
Enschede	Es	5850	EXTERNAL	H
Groningen	Gn	10889	EXTERNAL	H
DEN HAAG HS	Gv	15352	EXTERNAL	H
DEN HAAG C	Gvc	10108	EXTERNAL	H
Haarlem	Hlm	28618	EXTERNAL	H
's-Hertogenbosch	Ht	18447	EXTERNAL	H
Leiden	Ledn	20536	EXTERNAL	H
Lelystad Centrum	Lls	13218	Lelystad	H
Leeuwarden	Lw	17439	EXTERNAL	H
MAASTRICHT	Mt	7690	EXTERNAL	H
Nijmegen	Nm	27789	EXTERNAL	H
84QDvd	Dvd	6969	Amsterdam	H
Rotterdam C	Rtd	34788	EXTERNAL	H
UTRECHT C	Ut	27194	EXTERNAL	H
Venlo	Venlo	17165	EXTERNAL	H

Zaandam	Zd	13003	EXTERNAL	H
Zwolle	Zl	13559	EXTERNAL	H
85ALM	Alm	8743	Almere	H
85ALMB	Almb	8440	Almere	H
85ALMM	Almm	10301	Almere	H
85ALMO	Almo	10285	Almere	H
85ALMP	Almp	7023	Almere	H
85AMPO	Ampo	3927	Almere	H
85ASA	Asda	33695	Amsterdam	H
85ASB	Asb	13005	Amsterdam	H
85ASD	Ams	33681	Amsterdam	H
85ASDZ	Asdz	15967	Amsterdam	H
85ASHD	Ashd	13692	Amsterdam	H
85BDST	BDST	2247	Almere	B
85DMNZ	Dmnz	13683	OTHER	H
85RAI	RAI	5742	Amsterdam	H
85WP	Wp	11801	OTHER	H

Appendix G Ambitions per corridor

Table G-1 shows the building blocks taken over from the “Agenda Future Vision PT” (*Ontwikkelagenda Toekomstbeeld OV*, 2021).

Table G-1: Building blocks for PT in 2040, interpreted from *Ontwikkelagenda Toekomstbeeld OV* (2021)

“Building block”	Relevant System	Relevant corridors
Expansion of the North-South Amsterdam metro line to Hoofddorp	BTM	13
Extra ICs between Amsterdam and Utrecht	Heavy-rail	10
Extra ICs between Schiphol – Leiden – Den Haag	Heavy-rail	8
Extra ICs between Amersfoort – Harderwijk/Zwolle	Heavy-rail	-
Extra ICs between Amsterdam – Rotterdam – Breda	Heavy-rail	-
Faster ICs between Zwolle – Deventer	Heavy-rail	-
Extra ICs between Amsterdam – Haarlem – Leiden	Heavy-rail	9
Extra ICs between Nijmegen – Den Bosch	Heavy-rail	3
Extra ICs between Dordrecht – Breda	Heavy-rail	1
Fast train service between Utrecht – Almere (+2 sneltrains)	Heavy-rail	13, 12
Extra ICs between Utrecht and Tilburg/Breda	Heavy-rail	4
Extra ICs between Utrecht and Eindhoven	Heavy-rail	4
Extra IC stop in Lunetten	Heavy-rail	4
IC+ between Den Haag – Schiphol – Amsterdam	Heavy-rail	8, 13
Extra ICs between Breda – Tilburg	Heavy-rail	-
Extra IC stop in Berkel Enschot	Heavy-rail	-
IC+ between Den Haag – Utrecht	Heavy-rail	5
IC+ between Utrecht – Arnhem	Heavy-rail	6
ICs and Sprinters from Almere and Amersfoort to both *Amsterdam Zuid* and *Amsterdam Centraal*	Heavy-rail	12, 13
IC+ between Rotterdam – Utrecht	Heavy-rail	5
Faster sprinters between Utrecht – Almere	Heavy-rail	12, 13
New connection between the “Randstad” and Groningen/Leeuwarden (*Lelylijn*)	Heavy-rail	12(*Goed Gespoord van West naar Noord*, n.d.)
IC connection between the “Randstad” area and the province Zeeland	Heavy-rail	1
Extra sprinters between the “Randstad” area and the province Zeeland	Heavy-rail	1
Fast train service between Venlo and Nijmegen	Heavy-rail	-
Extra trains between the “Randstad” area and Groningen/Leeuwarden	Heavy-rail	7, 12
IC between Enschede – Zwolle – Amsterdam	Heavy-rail	12
New connection between Arnhem – Enschede	Heavz-rail / BTM	

IC+ between Amsterdam – Eindhoven – Maastricht/Heerlen	Heavy-rail	4, 10
IC+/IC between Alkmaar – Amsterdam/Schiphol	Heavy-rail	11
S-Bahn type connection between Den Haag and Dordrecht	Heavy-rail / BTM	2
S-Bahn type connection between Haarlem – Weesp	Heavy-rail / BTM	9, 11 ,12
New connection between Almere and Amsterdam	BTM	12
Closing the Amsterdam metro ring	BTM	9, 11
S-Bahn type connection between Amsterdam West and Hoofddorp	Heavy-rail / BTM	9,11,13
S-Bahn type connection between Groningen – Zernike	Heavy-rail / BTM	14
S-Bahn type connection between Assen – Groningen – Zernike	Heavy-rail / BTM	14
Extra sprinters between Breukelen – Utrecht – Driebergen-Zeist	Heavy-rail	6, 10
Extra sprinters between Den Haag – Rotterdam – Dordrecht	Heavy-rail	2
Automatization Rotterdam metro network	BTM	2
A new (multimodal (*Oeververbinding*, n.d.)) river crossing in Rotterdam	BTM	2
“Kings’ corridor” Den Haag – Zoetermeer	Heavy-rail / BTM	2, 5
Extra sprinters between Purmerend – Schiphol	Heavy-rail	-
Extra sprinters between Goes – Breda	Heavy-rail	1
Extra sprinters between Woerden – Utrecht	Heavy-rail	5
Extra sprinters between Den Helder – Alkmaar	Heavy-rail	-
Extra ICs between Leiden and Utrecht	Heavy-rail	5
Extra station Woerden-Molenvliet	Heavy-rail	5
Extra fast train service between Groningen – Leeuwarden	Heavy-rail	14
Introducing the “Nedersaksenlijn”	Heavy-rail	-
Extra sprinters between Woerden – Amsterdam	Heavy-rail	10
Extra sprinters between Sittard – Maastricht	Heavy-rail	-
Extra sprinters between Ede-Wageningen – Amersfoort	Heavy-rail	7
Introduction local service between Apeldoorn – Zutphen – Winterswijk	Heavy-rail	-
Travel time reduction between Zwolle – Emmen	Heavy-rail	-
Extra fast train service between Winterswijk – Arnhem	Heavy-rail	-
Extra fast service between Zwolle – Almelo	Heavy-rail	-
New connection between Gorinchem – Dordrecht – Rotterdam	Heavy-rail	2
Extra sprinters between Eindhoven – Deurne	Heavy-rail	-
Extra sprinters between Amersfoort and Apeldoorn with additional stations	Heavy-rail	7

Connecting sprinter services between Arnhem – Nijmegen	Heavy-rail	6
Extra fast service between Amersfoort – Ede – Arnhem	Heavy-rail	6
New station Berkel-Enschot	Heavy-rail	-
New station Staphorst	Heavy-rail	12
Connecting Nijmegen Heijendaal to the IC service	Heavy-rail	6
New station Veenendaal-Zuid	Heavy-rail	6
Connecting Maastricht Randwyck to the IC service	Heavy-rail	-
Connecting Harderwijk to the IC service	Heavy-rail	-
New station Barneveld-Noord	Heavy-rail	7
Moving station from Hollandsche Rading to Maartensdijk	Heavy-rail	-
“High Quality PT” investments for, Zoetermeer-Leiden	BTM	5, 8
“High Quality PT” investments for, among other places, Utrecht, Amersfoort and “Food-Valley”	BTM	4, 5, 6, 7, 10, 13
“High Quality PT” investments for, among other places, the A9-corridor and the provinces of Flevoland and Noord-Holland	BTM	8, 9, 10, 11, 12, 13
Investments for, among other places, Groningen Zernike and “Netwerk Fryslân”	BTM	14
“High Quality PT” investments for, among other places, Arnhem – Wageningen, Arnhem – Nijmegen, Arnhem – Apeldoorn – Zwolle and Achterhoek – Twente	BTM	3, 6
“High Quality PT” investments for, among other places, Bus Rapid Transit (BRT) Breda – Gorinchem – Utrecht, Breda, Oosterhout, Tilburg, Waalwijk, Den Bosch, Veghel and Uden	BTM	4

Appendix H High occupancy heavy-rail sections, BTM challenges and ambitions of the seven remaining corridors

Table H-1: Corridor 2, name, capacity challenges and ambitions

# 2	**Ambitions** - S-Bahn type connection between Den Haag and Dordrecht - Extra sprinters between Den Haag – Rotterdam – Dordrecht - Automatization Rotterdam metro network - A new, multimodal river crossing in Rotterdam - “Kings’ corridor” Den Haag – Zoetermeer - New connection between Gorinchem – Dordrecht – Rotterdam
Name *Den Haag Centraal – Dordrecht*	
"busy" IC *Den Haag Centraal – Rotterdam Centraal – Dordrecht*	
"busy" sprinter *Den Haag Centraal – Rotterdam Centraal – Rotterdam Lombardije*	
BTM Den Haag, Rotterdam	

Table H-2: Corridor 4, name, capacity challenges and ambitions

# 4	**Ambitions** - Extra ICs between Utrecht and Tilburg/Breda - Extra ICs between Utrecht and Eindhoven - Extra IC stop in Lunetten - IC+ between Amsterdam – Eindhoven – Maastricht/Heerlen - “High Quality PT” investments for, among other places, Utrecht, Amersfoort and “Food-Valley” - “High Quality PT” investments for, among other places, Bus Rapid Transit (BRT) Breda – Gorinchem – Utrecht, Breda, Oosterhout, Tilburg, Waalwijk, Den Bosch, Veghel and Uden
Name *Eindhoven – Utrecht Centraal*	
"busy" IC ’*s-Hertogenbosch – Utrecht Centraal*	
"busy" sprinter *s-Hertogenbosch – Geldermalsen*	
BTM Eindhoven	

Table H-3: Corridor 7, name, capacity challenges and ambitions

#	**Ambitions**
7	- Extra trains between the “Randstad” area and Groningen/Leeuwarden - Extra sprinters between Ede-Wageningen – Amersfoort - Extra sprinters between Amersfoort and Apeldoorn with additional stations - New station Barneveld-Noord - “High Quality PT” investments for, among other places, Utrecht, Amersfoort and “Food-Valley”
Name *Deventer – Utrecht Centraal*	
"busy" IC *Deventer – Amersfoort Centraal – Utrecht Centraal*	
"busy" sprinter *Barneveld – Amersfoort Centraal – Utrecht Centraal*	
BTM Utrecht	

Table H-4: Corridor 9, name, capacity challenges and ambitions

#	**Ambitions**
9	- Extra ICs between Amsterdam – Haarlem – Leiden - S-Bahn type connection between Haarlem – Weesp - Closing the Amsterdam metro ring - S-Bahn type connection between Amsterdam West and Hoofddorp - “High Quality PT” investments for, among other places, the A9-corridor and the provinces of Flevoland and Noord-Holland
Name *Amsterdam Centraal – Leiden Centraal*	
"busy" IC *Amsterdam Centraal – Haarlem – Leiden Centraal*	
"busy" sprinter *Amsterdam Centraal – Haarlem*	
BTM Amsterdam	

Table H-5: Corridor 11, name, capacity challenges and ambitions

# 11	**Ambitions** - IC+/IC between Alkmaar – Amsterdam/Schiphol - S-Bahn type connection between Haarlem – Weesp - Closing the Amsterdam metro ring - S-Bahn type connection between Amsterdam West and Hoofddorp - “High Quality PT” investments for, among other places, the A9-corridor and the provinces of Flevoland and Noord-Holland
Name *Alkmaar – Amsterdam Centraal*	
"busy" IC *Alkmaar – Amsterdam Centraal*	
"busy" sprinter *Amsterdam Centraal – Zaandam*	
BTM Amsterdam	

Table H-6: Corridor 12, name, capacity challenges and ambitions

# 12	**Ambitions** - Fast train service between Utrecht – Almere - ICs and Sprinters from Almere and Amersfoort to both *Amsterdam Zuid* and *Amsterdam Centraal* - Faster sprinters between Utrecht – Almere - New connection between the “Randstad” and Groningen/Leeuwarden (*Lelylijn*) - Extra trains between the “Randstad” area and Groningen/Leeuwarden - IC between Enschede – Zwolle – Amsterdam - S-Bahn type connection between Haarlem – Weesp - New connection between Almere and Amsterdam - New station *Staphorst* - “High Quality PT” investments for, among other places, the A9-corridor and the provinces of Flevoland and Noord-Holland
Name *Amsterdam Centraal – Meppel*	
"busy" IC *Amsterdam Centraal – Meppel*	
"busy" sprinter Almere - *Amsterdam Centraal*	
BTM Amsterdam, Almere, Lelystad, Zwolle	

Table H-7: Corridor 13, name, capacity challenges and ambitions

# 13	**Ambitions** - Expansion of the North-South Amsterdam metro line to Hoofddorp - Fast train service between Utrecht – Almere - IC+ between Den Haag – Schiphol – Amsterdam - ICs and Sprinters from Almere and Amersfoort to both *Amsterdam Zuid* and *Amsterdam Centraal* - Faster sprinters between Utrecht – Almere - S-Bahn type connection between Amsterdam West and Hoofddorp - “High Quality PT” investments for, among other places, Utrecht, Amersfoort and “Food-Valley” - “High Quality PT” investments for, among other places, the A9-corridor and the provinces of Flevoland and Noord-Holland
Name *Amersfoort Centraal – Schiphol Airport*	
"busy" IC *Amersfoort Centraal – Weesp – Schiphol Airport*	
"busy" sprinter *Hilversum – Weesp*	
BTM Amsterdam, Almere	

Appendix I Calculation of *the Lelylijn* and *Ijmeer* connection travel time

The travel time of the *Lelylijn* estimated by taking a reference travel duration and adapting it to the *Lelylijn* section using an estimated section length and equation *(8)*.

On the earlier mentioned *Lelylijn* website, it is claimed that the maximum speed is intended to be 200 km/h, which seems plausible given that the relative recently built *Hanzelijn* between Lelystad and Zwolle has the same maximum speed (*ProRail - Feiten En Cijfers*, 2012). Therefore, the high-speed section between Rotterdam *Centraal* and *Schiphol Airport* is used as a reference. The 2030 travel time is already in the Viriato database, and shows the use of ICNG rolling stock, which has a maximum speed of 200 km/h (as opposed to the maximum of 300 km/h allowed on that infrastructure). For the *Lelylijn*, the use of the same rolling stock is assumed. This section is 52 km, measured with the Google Maps measuring tool, and the travel time is 22 minutes.

The exact course of the *Lelylijn* section is unknown at the time of writing, therefore assumptions must be made. Between Lelystad and Emmeloord the line is assumed to follow the freeway A6, given the principle that building next to a highway is a desirable option in terms of available space, noise, and routing. After Emmeloord it follows the road N351 until southeast of Wolvega and splits of to join the existing section south of Heerenveen. See Figure I-1. Between Heerenveen and Groningen it is assumed to follow the freeway A7. See Figure I-2. Using the Google Maps measuring tool again, this gives 65 km for Lelystad – Heerenveen and 55 km for Heerenveen – Groningen.:

The acceleration and deceleration times are estimated at 2 minutes each, as a general deceleration and acceleration of 0,5 [m/s^2] is assumed which is well within the range of the ICNG rolling stock (Ministerium für Verkehr Baden-Württemberg, 2022). Assuming a constant change in velocity, the extra time lost due to acceleration and deceleration is equal to the time it takes for acceleration/deceleration, which is roughly 2 minutes at the mentioned acceleration. For the stopping time, 1 minute is used.

Using all the above, the input for equation *(8)* becomes:

$$T_{old} = 22\ [min], D_{old} = 52[km], T_{dec} = T_{acc} = 2\ [min], T_{stop} = 1\ [min]$$

Additionally, $D_{new} = 65\ [km]$ for the section Lelystad – Heerenveen and $D_{new} = 55\ [km]$ for the section Heerenveen – Groningen.

Applying the equation gives the travel times presented in Table I-1. This data is introduced in Viriato. For the stop in Heerenveen a one-minute stopping time is taken, leading to a total travel time between Lelystad and Groningen of 63 minutes.

Table I-1: Estimated travel times for the *Lelylijn* sections

Section	Distance [km]	Number of intermediate stations	Travel time [min]
Rotterdam – Schiphol	52	0	22
Lelystad – Heerenveen	65	1	33
Heerenveen – Groningen	55	1	29

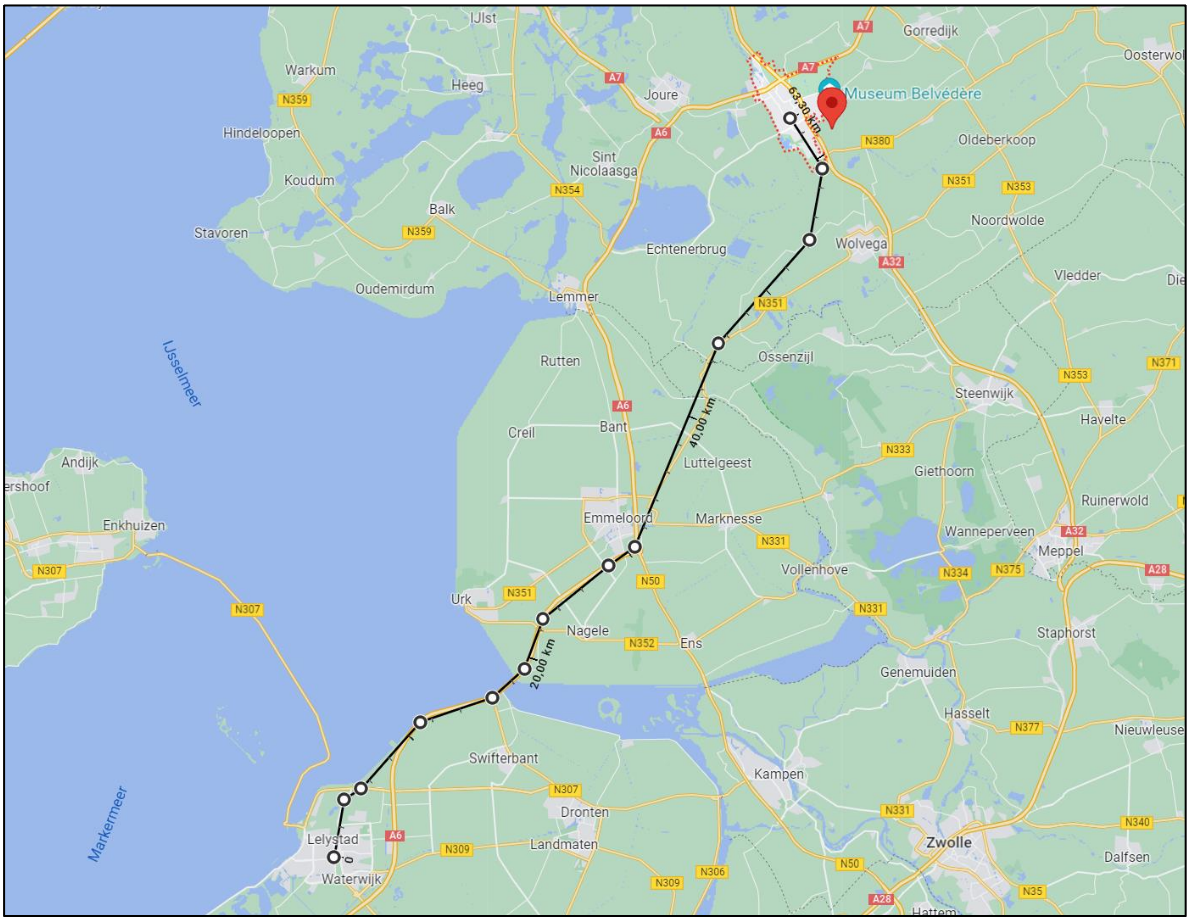


Figure I-1: Possible routing of the *Lelylijn* between Lelystad and Heerenveen. From: (*Google Maps*, n.d.)

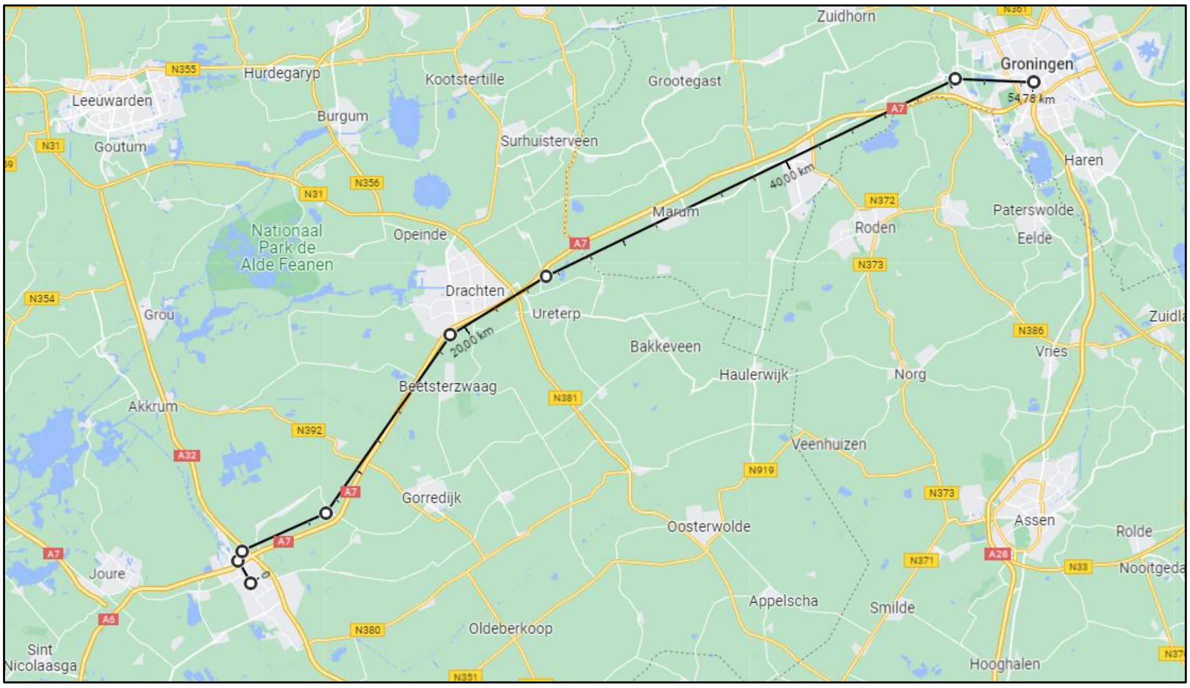


Figure I-2: Possible oruting of the *Lelylijn* between Heerenveen and Groningen. From: (*Google Maps*, n.d.)

The travel time for the *Ijmeer* connection is determined using equation *(8)* in three parts. For the section between station *Diemen Zuid* and *Ijburg* tram stop, and the section between the stop *Almere Pampus* and *Almere Centrum* station, two existing lines, namely line 50 and 52, from the GVB's (the BTM operator of the city of Amsterdam) metro network are used as a reference. This data is taken from the GVB website (GVB, 2014, 2022b) and presented in Table I-2 as D_{old} and T_{old}. The average is calculated and used for the two mentioned sections.

Table I-2: Amsterdam metro lines with line distance, total line travle time, and average distance and travel time

Line	$D_{old}\ [km]$	$T_{old}\ [h]$
50	20,1	0,62
52	9,5	0,23
Average	14,8	0,425

As this source gives the travel time that already includes braking, waiting, and accelerating at stops, $T_{acc} = T_{decc} = T_{stop} = 0$ is applied in the equation. Google Maps provides data on D_{new} for the new sections. Between the *Ijburg* tram stop and the *Almere Pampus* stop, the metro passes the water, where it is assumed that there are no stops, and the metro will be able to travel at full speed. Using line 52 as a reference (NOS nieuws, 2017), is 70 km/h. This can be introduced equation *(8)* as $T_{old}\ /\ D_{old}\ = 1/70\ [h/km]$. It must be noted that acceleration and deceleration times are neglected, which is deemed acceptable given the long distance over which this is calculated and the generally good braking and acceleration performance of metro systems. Moreover, the speed of 70 km/h is quite conservative. It is probable that for such a connection, a higher speed, of for instance 100 km/h is obtained. However, as this system is supposed to be integrated with the current GVB system, the use of 70 km/h is chosen. The resulting travel times and relevant input for equation *(8)* are presented in Table I-3.

Table I-3: Travel times for the *IJmeer* connection

From	To	$T_{old}\ /\ D_{old}\ [h/km]$	$D_{new}\ [km]$	$T_{new}\,[min]$
Diemen Zuid	*Ijburg*	0,0287	4	6,9
Ijburg	*Almere Pampus*	0,0143	10	8,6
Almere Pampus	*Almere Centrum*	0,0287	6	10,3

Appendix J Netvisio netgraph of the case study network, colored by system

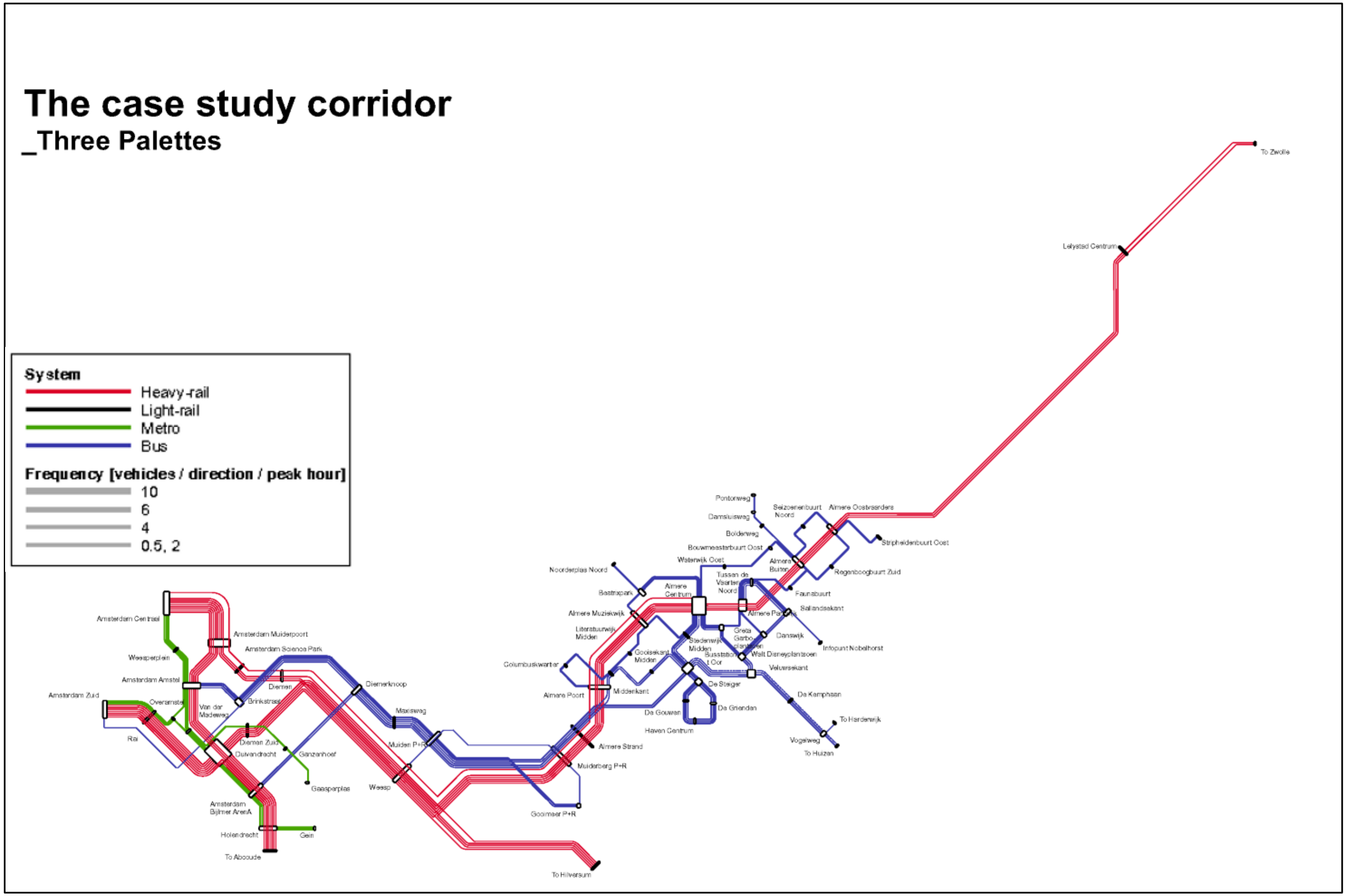


Figure J-1: Graphical service network representation of the case study made with Netvisio. Blue: bus, red: heavy-rail, green: metro

Appendix K TD-Diagrams and netgraphs

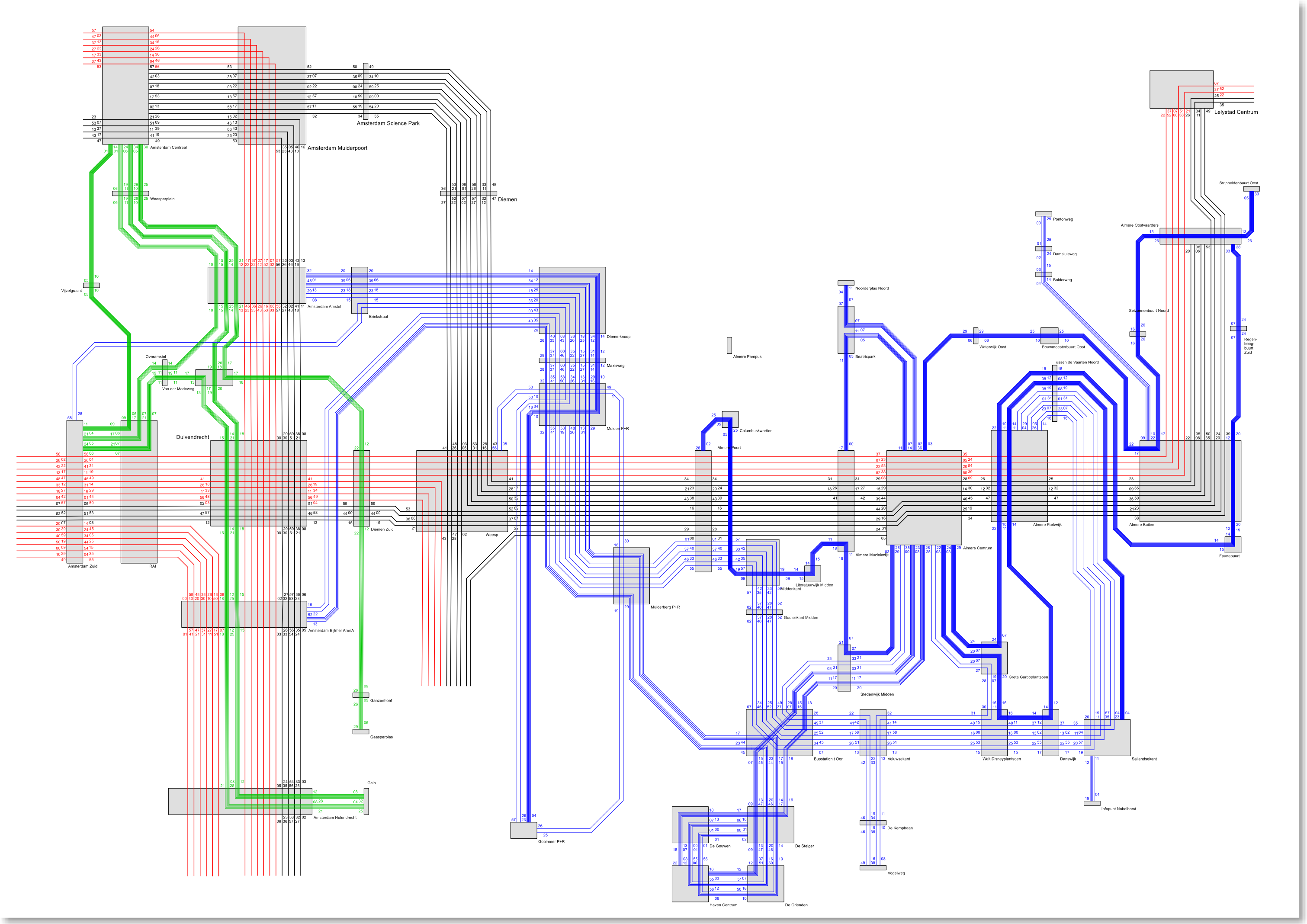


Figure K-1: Netgraph V0

V0-1: V0 Amsterdam Zuid - Lelystad

daily

Trains from scenario: 'ami_V0b'.

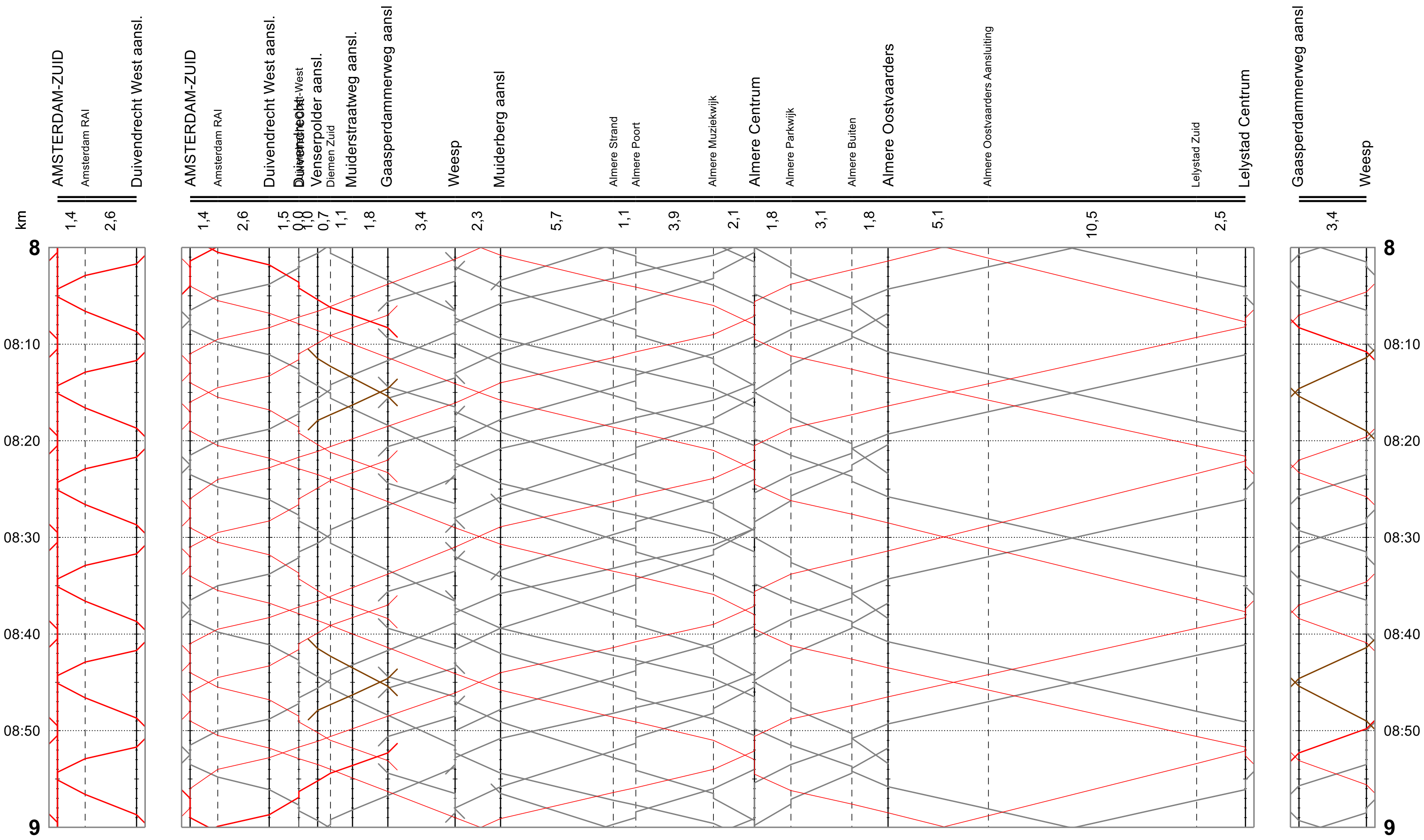


Figure K-2: TD-diagram V0 *Amsteredam Zuid - Lelystad Centrum*

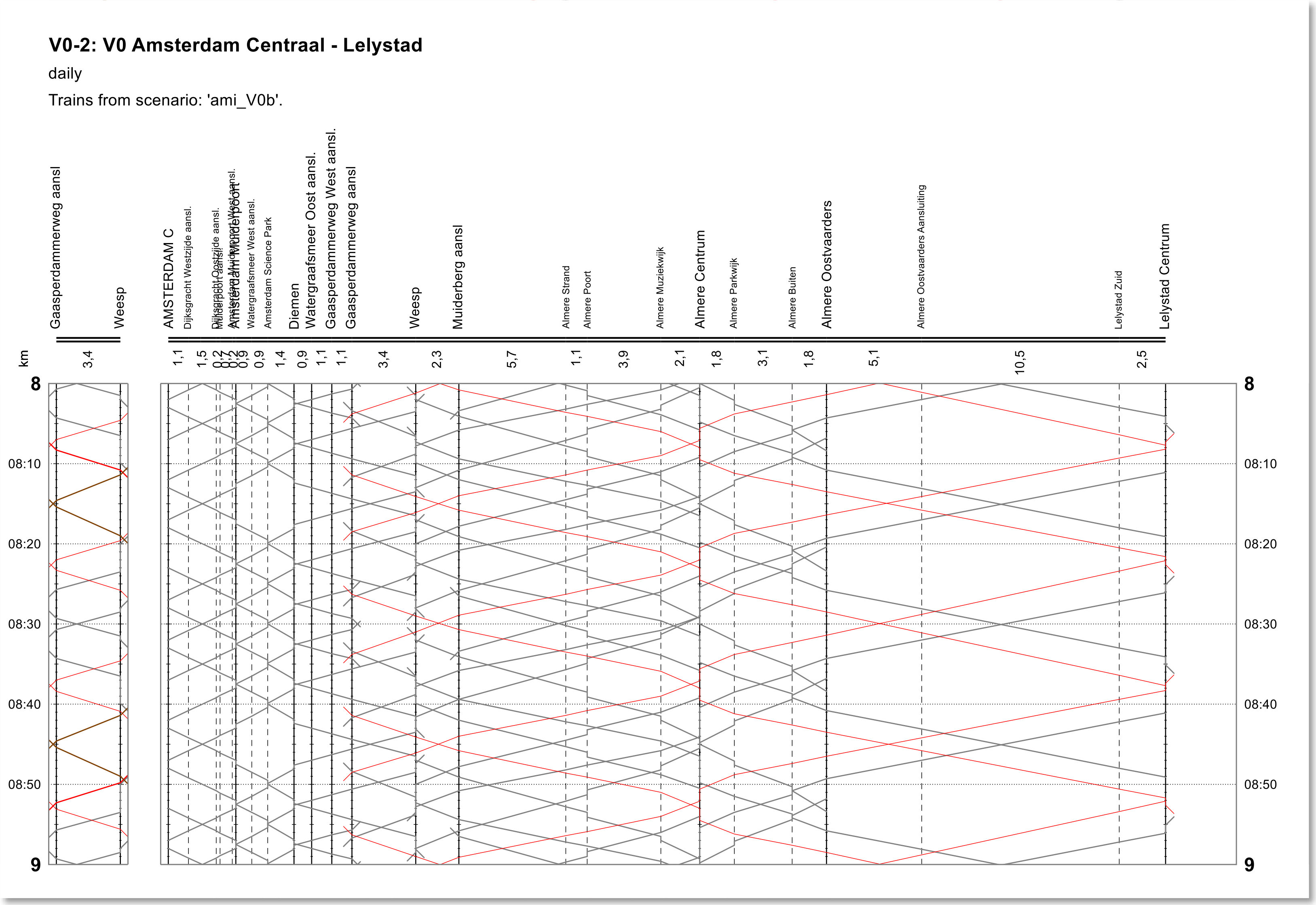


Figure K-3: TD-diagram V0 *Amsterdam Centraal - Lelystad Centrum*

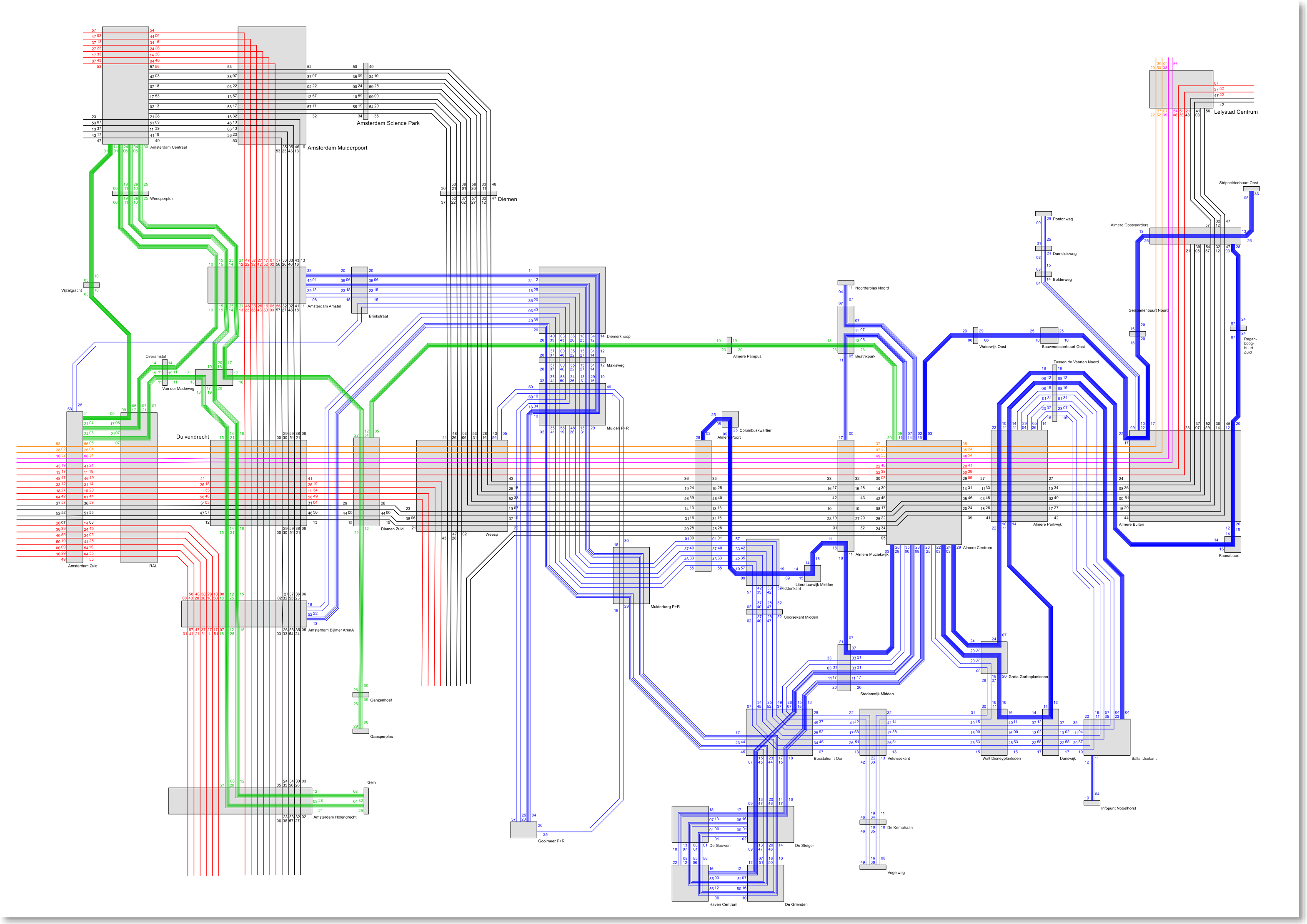
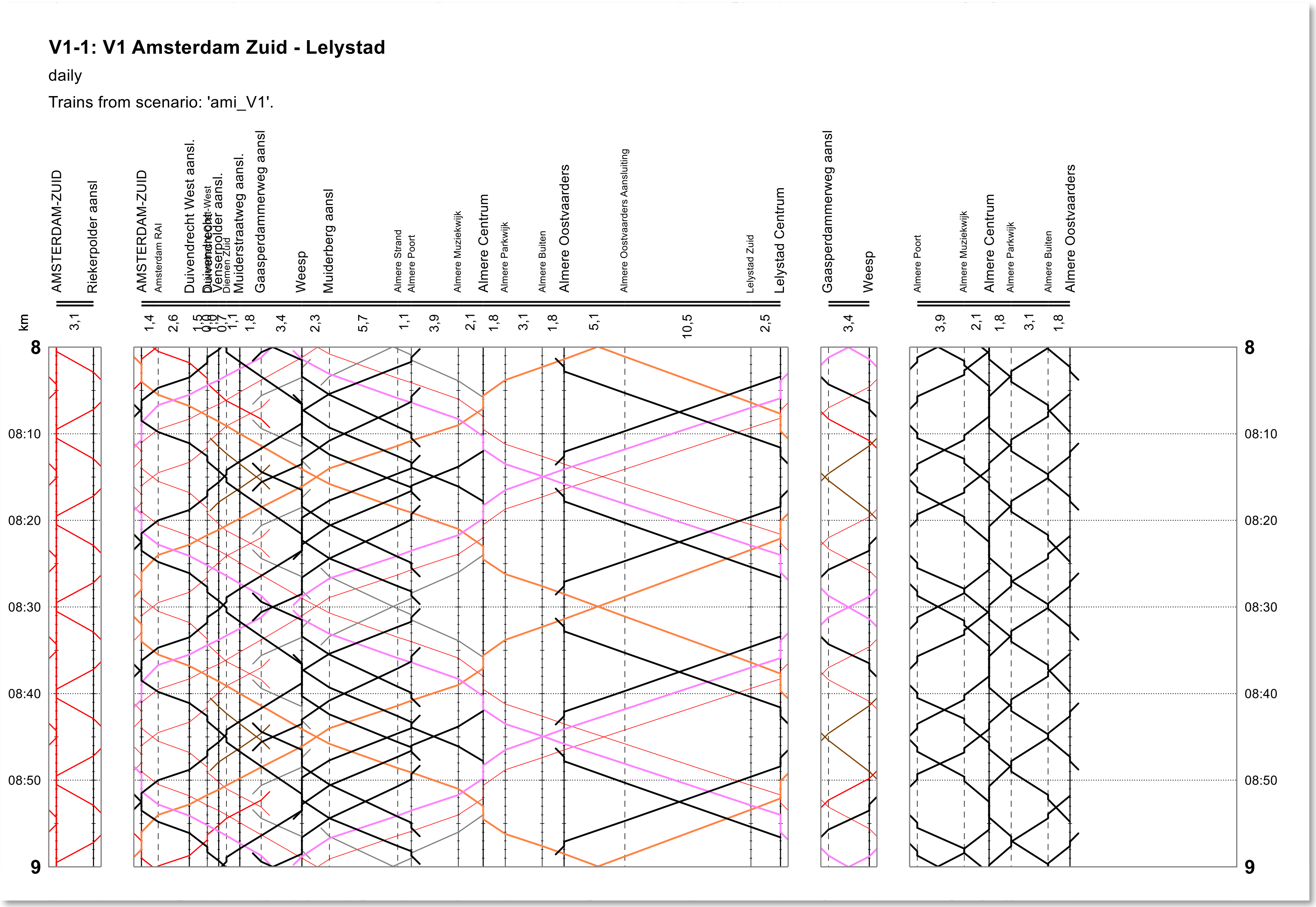


Figure K-4: Netgraph V1



V1-1: V1 Amsterdam Zuid - Lelystad

daily

Trains from scenario: 'ami_V1'.

Figure K-5: TD-diagram V1 *Amsterdam Zuid - Lelystad Centrum*

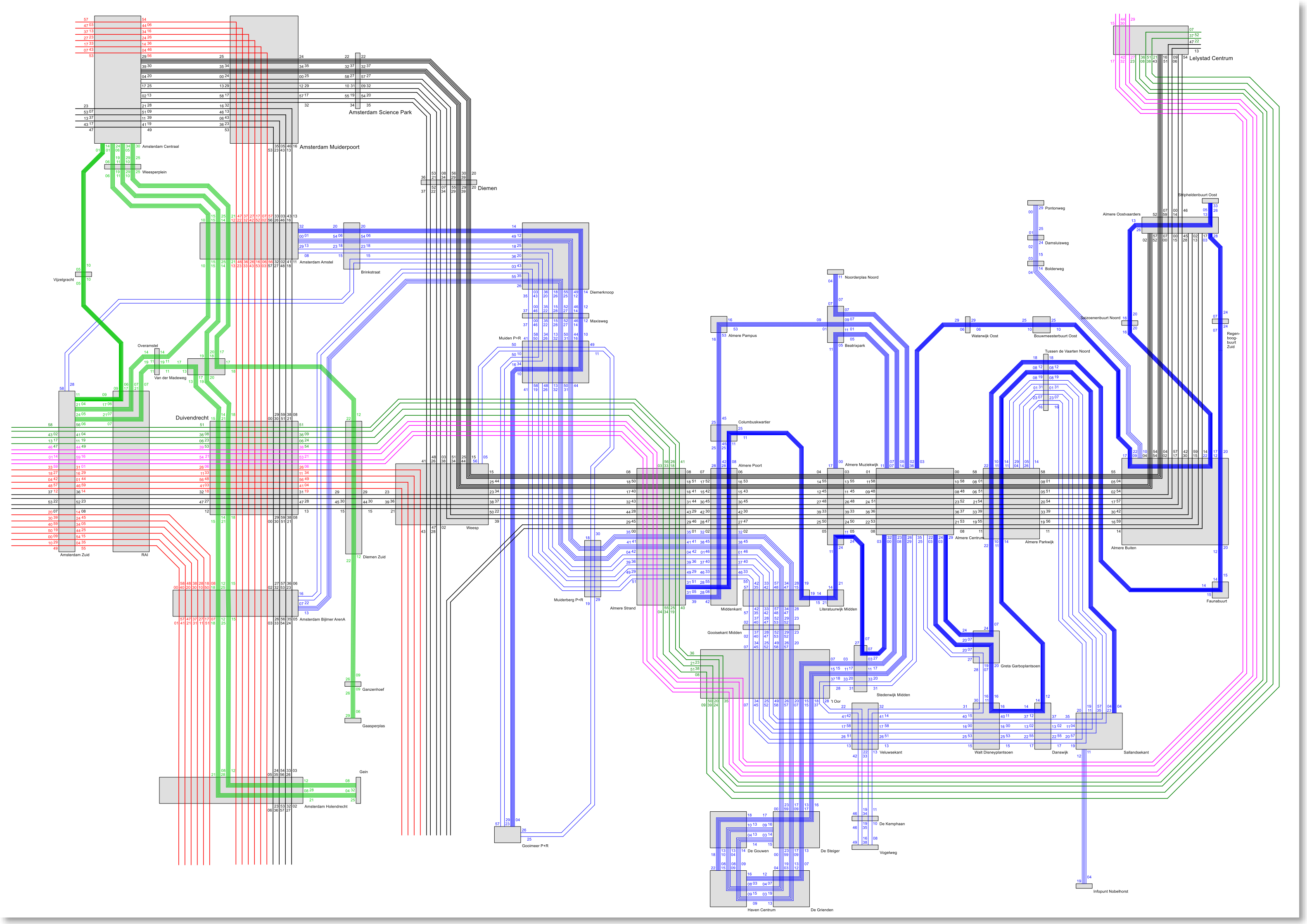


Figure K-6: Netgraph V2

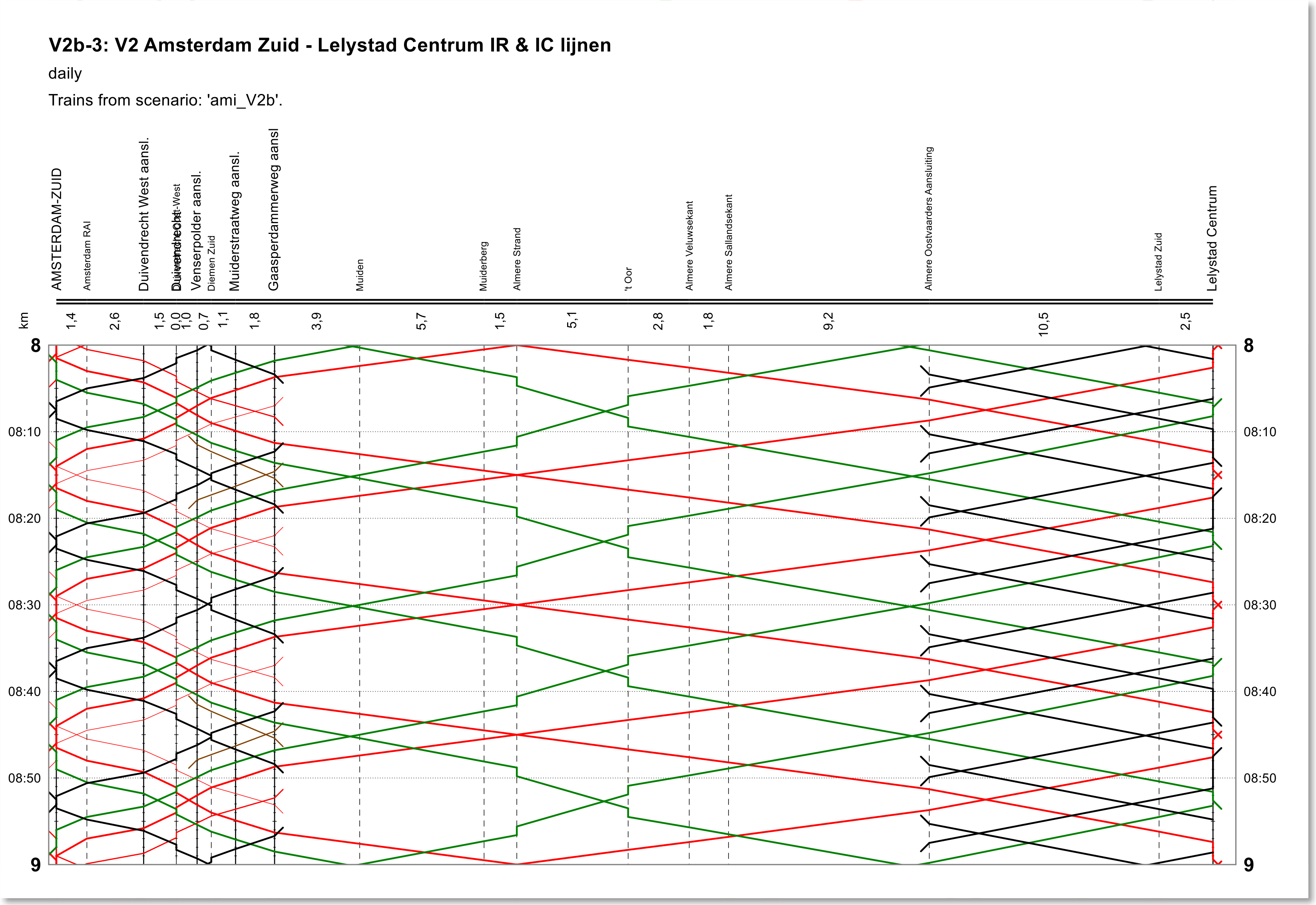


Figure K-7: TD-diagram V2 *Amstrerdam Zuid - Lelystad Centrum*

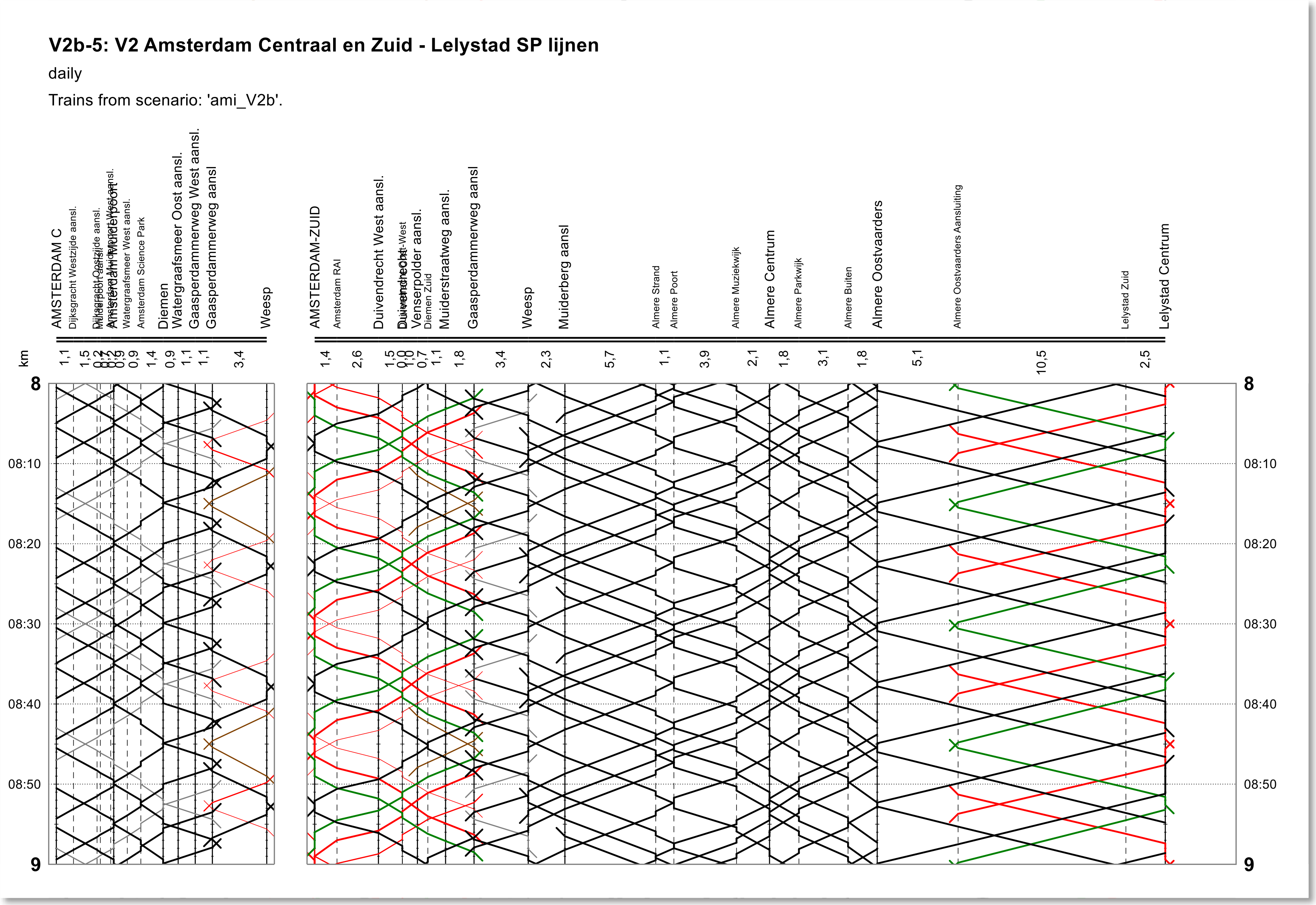


Figure K-8: TD-diagram V2 *Amsterdam Centraal - Lelystad Centrum*

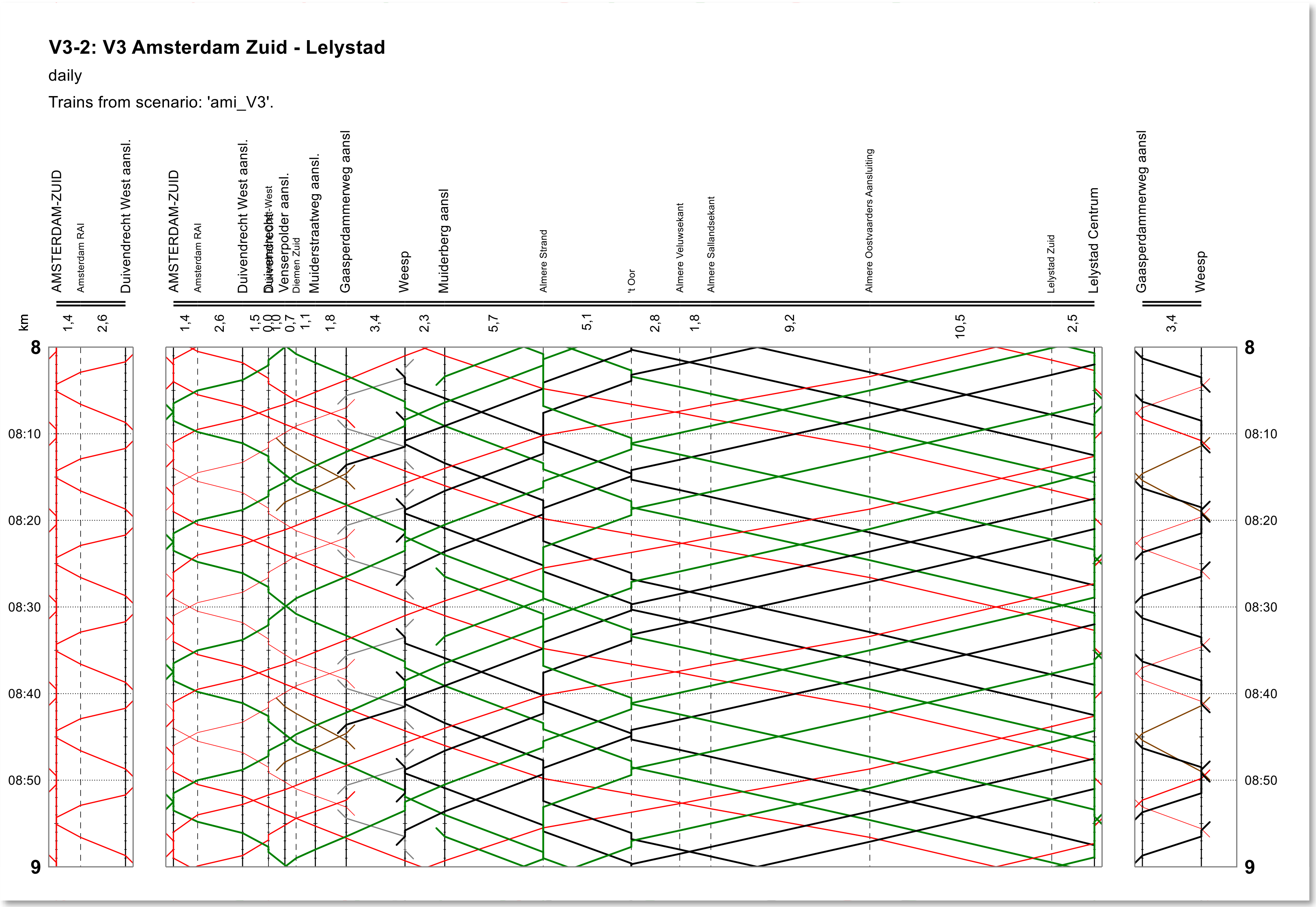


Figure K-9: TD-diagram V3 *Amsterdam Zuid - Lelystad Centrum*

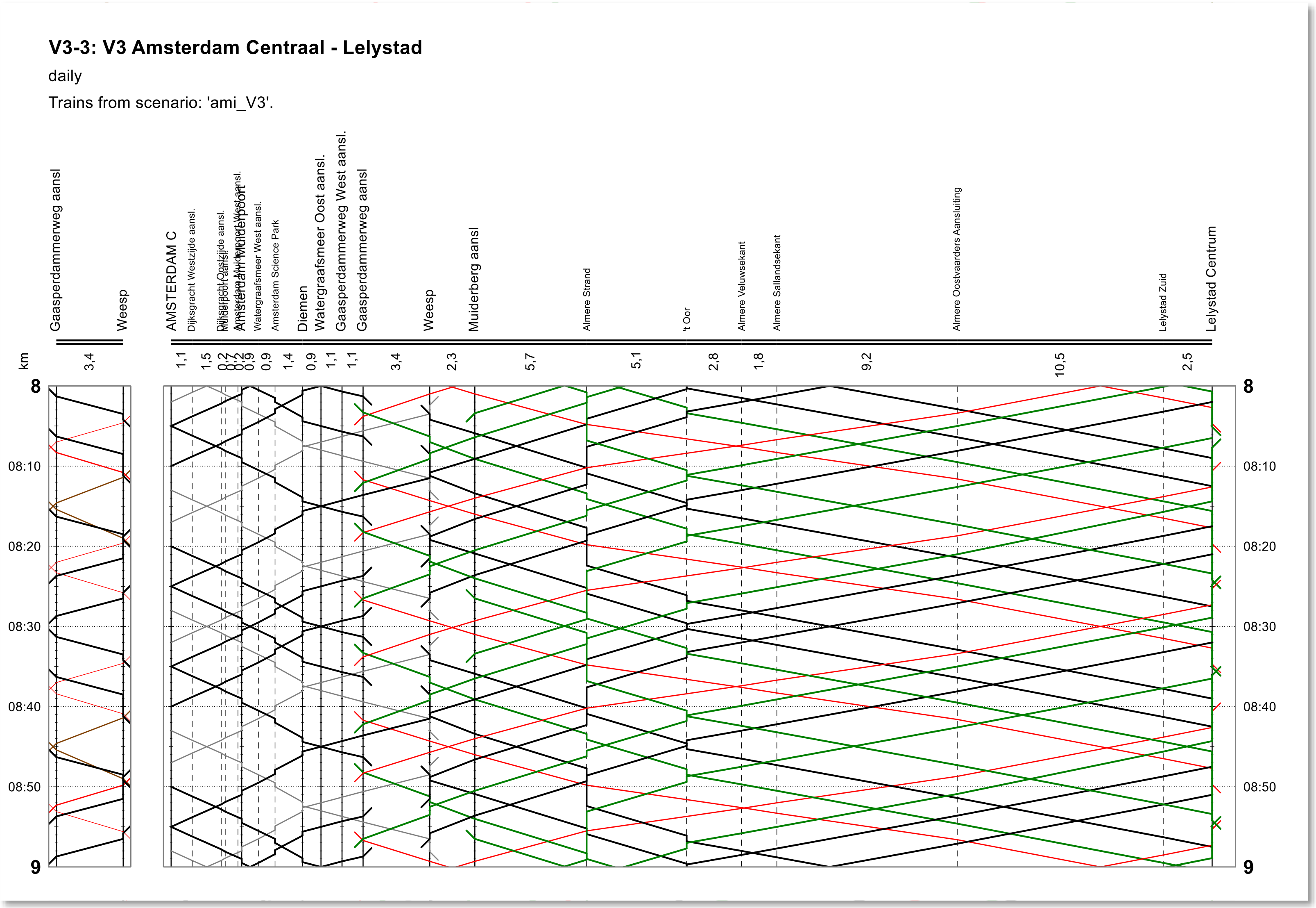


Figure K-10: TD-diagram V3 *Amsterdam Centraal - Lelystad Centrum*

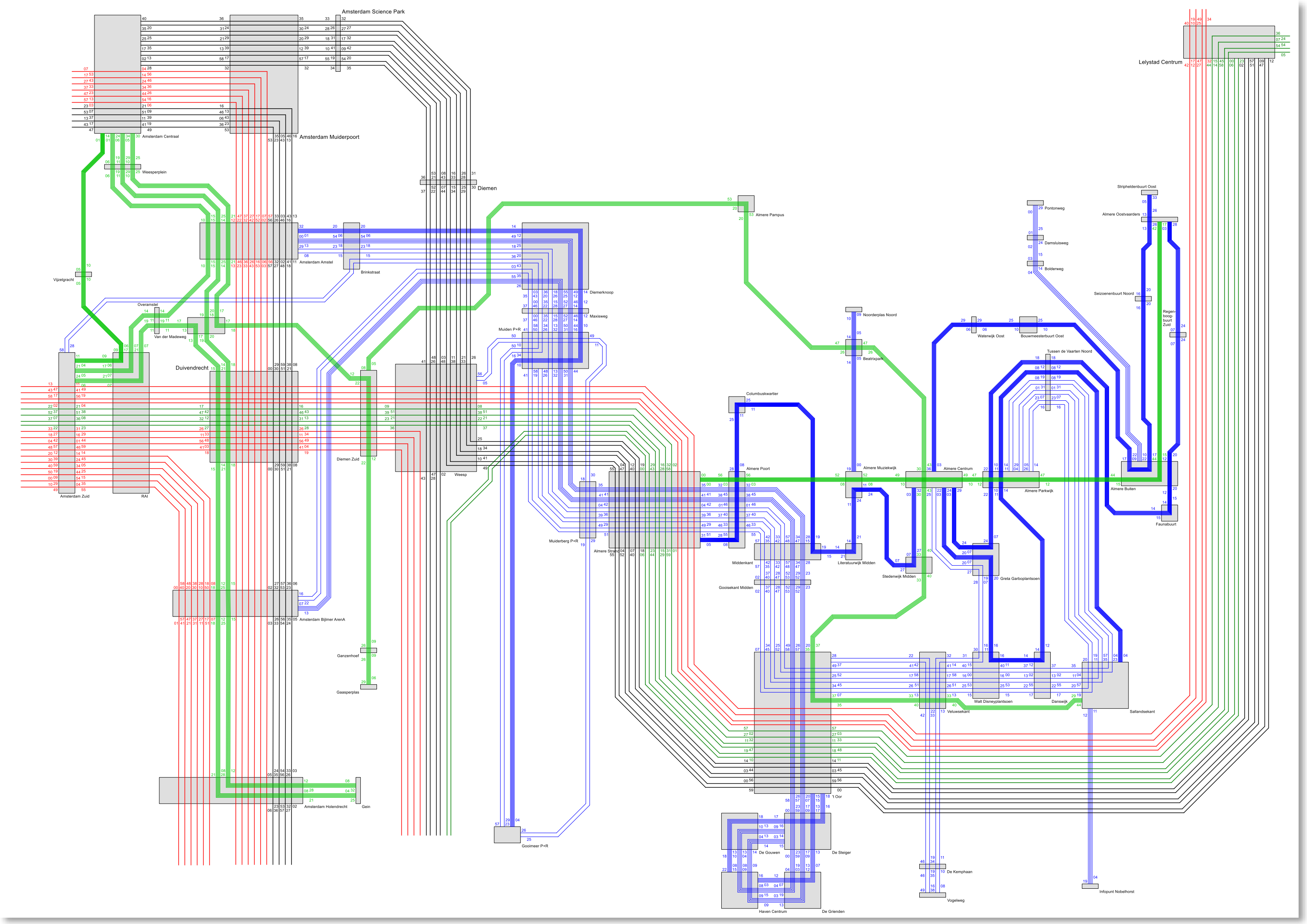


Figure K-11: Netgraph V3