Mapping Out-of-Gauge Rail Freight Capacity

A Method for Identifying, Prioritising and Addressing UIC-Gauge Obstructions

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A Method for Identifying, Prioritising and Addressing UIC-Gauge Obstructions

by

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Cover: A measurement near Zwolle. Photo by ProRail

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ProRail TUDelft Ministerie van Defensie

Preface

I am proud to present the thesis report on mapping the possibilities for out-of-gauge rail freight transport. Between April 2025, when I started drawing up the design proposal, and now, the need for out-of-gauge transport has only increased. The changing geopolitical situation and reports from the Dutch government underline this statement. Being able to work on such a relevant topic was therefore a unique and valuable experience.

Although I would not want to have missed the recent period in which I worked on this thesis report, its completion also presented various challenges. From changing and formulating the design question to gaining insight on all relevant aspects related to the topic of interest. Grasping the core of the project was followed by the challenge of writing it down clearly and in a structured manner in a report that contributes to closing the research gap.

I am glad to have been able to learn so much in the last period. The educational moments are found in the academic skills, but also in what I have been able to learn in the workplaces of my graduation internship. Even before a train leaves the station, whether it is out-of-gauge or ‘normal’, a lot has already happened. I am grateful to have been able to witness a small part of this and it certainly has sparked my interest.

During the past period, I have been able to count on the support and input of various people. With sharp questions, genuine interest, and sometimes a (necessary) push in the right direction, they ensured that I stayed on track to complete my thesis. My sincere thanks go to various people within ProRail. I would especially like to thank René Koppert, who helped me find the internship and who, as my supervisor, helped and motivated me greatly throughout the process. I am also grateful for the support that I received within the Ministry of Defence, especially I would like to thank Natasja Bastein for her contribution. I could not have put this together scientifically without the support of Delft University of Technology, specifically Dr. Ir. van Binsbergen and Dr. Núñez Vicencio. Thank you for your knowledge, time, and interest.

Finally, I would like to thank my friends and family who followed my process with interest, contributed their ideas, and helped where possible. This support was provided not only during the course of this thesis but throughout my academic journey at Delft University of Technology.

A. (Arno) van der Pas
Delft, January 2026

Summary

This Master's thesis presents a reproducible, data-driven methodology to map and improve the out-of-gauge rail freight capacity in the Dutch rail network by systematically identifying, quantifying, prioritising and addressing UIC load gauge violations. The work is motivated by the ageing of infrastructure assets built under outdated design standards, increasing passenger and freight demand, and European interoperability requirements, and the strategic need to enhance network redundancy and resilience by enabling feasible diversion routes during disruptions.

The proposed approach leverages existing ProRail measurement and asset data stored in the Sigma application, including track alignment and geometry information and recorded violations of surrounding objects in the reference gauge. Data preprocessing consists of data cleaning, enrichment with manually obtained data, and quality filtering to remove measurements that are not relevant to out-of-gauge rail transport or contain measurement errors. The infrastructure margins are then calculated against the static gauging principles specified in NEN-EN 15273 (Gauging Methods), allowing the estimation of the remaining swept-envelope space available for rolling stock and cargo. The margins are made up of elements that take into account the lateral projection of railway track irregularities, curves including cant (deficit) and a factor representing dynamic effects. The first methodological module produces location-specific gauge possibilities and geospatial visualisations of violations. The gauge possibilities are calculated on the basis of what is possible based on the violations but also on the test gauges. These results support corridor-level diagnostics and reveal spatial clustering of infringements near nodes and along line sections.

To translate technical findings into actionable maintenance and investment decisions, in the second part a method derived from the bottleneck category and effect analysis is applied. Bottleneck categories are prioritised using a Bottleneck Priority Number (BNPN) that combines: (1) extend, represented by exceedance magnitude statistics; (2) observation, represented by observation frequency; and (3) detection, treated as constant because infringements are already detected in the underlying data set. It is also possible to work with scenarios when calculating the BNPN. This makes it possible to take into account the type of transport demand that exists at that moment. By integrating BNPN rankings with mapped violation outputs, the method distinguishes adjustments that can be carried out with minimal effort (this includes local relocations or minor asset adjustments) from redesign measures that require more time and supports staged mitigation planning. The outputs are structured to build a clearance database that can support the planning and re-routing decisions in both proactive and reactive situations. The ability to react quickly contributes to a more resilient rail network.

A case study is conducted to determine whether the developed method produces the desired results. After implementation, it appears that the requested output (including the decisive bottleneck, prioritisation, solution strategies) does indeed follow from the developed method. The result for the maximum width of the swept envelope depends on the height (h) of the train transport. Because h has a lower and upper limit, it is also possible to determine the limit values of the swept envelope. The case study also presents a strategy to resolve the observed bottleneck categories for the location of interest. Based on the BNPN score, a programme is proposed to solve a single but major bottleneck category (signs). Based on the geographical distribution, two other programmes are proposed. A programme to tackle station locations, as virtually all remaining gauge violations are located at and around stations. And a programme for resolving the gauge violations that are not tackled within the two proposed programmes. The order of the projects is determined on the basis of test gauges.
The case study shows that for the chosen location, the method works, and the required information is being delivered. However, its statistical relevance must be demonstrated through other case studies because currently a single case study has been conducted to test its effectiveness. Still, patterns can be identified in which signs are a significant problem and gauge violations are geographically concentrated around stations.

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Nomenclature

Abbreviations & Definitions

Abbreviation / Term	Definition
BS	Running Plane (bovenkant spoor).
BNPN	Bottleneck Prority Number.
Capacity	For this thesis, this is the number of train paths per unit of time (hours/days/year) available per railway line in the annual timetable.
Defined gauge	The total gauge width from the centre of the track to the infrastructure, including the vehicle width, vehicle margins and infrastructure margins.
Functionality	The quality of being suited to serve a purpose well. In the context of this thesis, what types of rail transport can a railway line accommodate. Increasing functionality results in railway lines being able to accommodate more, longer, heavier, and different types of trains.
Incidental Withdrawal	The occasional unavailability of infrastructure for the timetable. This may be due to major maintenance.
Node	A physical location is a railway network where it is possible to depart in more than two directions. According to this definition, Delft station is not a node (only the directions Rotterdam and The Hague), but Dordrecht, for example, is (directions Breda, Geldermalsen and Rotterdam).
Railway line	Railway tracks - including safety systems, substructure and superstructure - connection two nodes. Relevant established railway lines are given below.
Rapidity	The capacity to restore functionality in a timely manner, minimising losses and avoiding prolonged disruptions.
Redundancy	The extent to which parts of the transport system are substitutable. That is, are there alternative options (such as multiple routes) to ensure that functionality is maintained?
Resilience	The ability to continue functioning as a (transport) system despite (extreme) disruptions, to minimise the effects of such disruptions within the system, and to recover quickly from them.
Resourcefulness	The ability to diagnose and prioritise problems and to initiate solutions by identifying and mobilising resources.
Robustness	The ability to withstand (extreme) disruptions without significant degradation or loss of performance of the system.
RPN	Risk Priority Number.
Running Plane	Plane tangential to the running surface, as indicated with number 1 in [23] (see Figure 1). In Dutch, also known as ”Bovenkant Spoor (BS)”.
Swept Envelop	The exact gauge that needs to be kept free around for the vehicle en vehicle related motion.

Abbreviation / Term	Definition
Train pathway	This is the space included in the schedule to allow a train to travel from A to B. For example, there may be four passenger pathways and two rail freight pathways per hour between two cities. These paths are shown graphically in a time-distance diagram.
UIC-gauge	Standard reference gauges, laid down in standards.
Weekly Withdrawal	The planned and periodic (weekly or fortnightly) unavailability of the infrastructure for the timetable. This is for the purpose of carrying out preventive maintenance.
Railway lines	
Betuweroute	A (freight) railway line between Kijfhoek and Zevenaar-Border.
Betuwelijn	A (passenger) railway line between Geldermalsen and Elst.
Brabantroute	A mixed railway line between Roosendaal and Venlo.
Havenspoorlijn	A (freight) railway line connecting Rotterdam harbour with Kijfhoek.
MerwedeLingeLijn	A (passenger) railway line between Dordrecht and Geldermalsen.

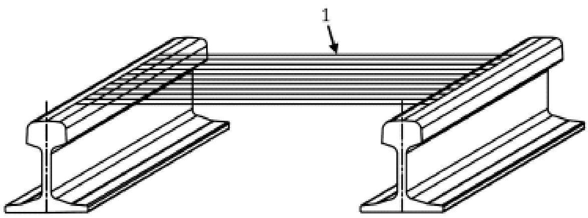


Figure 1: Visualisation of the Running Plane

Common sub- and superscripts

Index	Designation
a	Outside of the horizontal curve.
BN	Bottleneck.
cin	Refers to kinematic calculations.
constr	Constructed infrastructure.
CR	Reference gauge.
dyn	Refers to dynamic calculations.
i	Inside of the horizontal curve.
i/a	In- and outside of the curve.
inf	Refers to infrastructure properties.
lim	Limit value.
margin	Indicates the safety margin.
R	Recovery.
RM	Red Measurement Area, in Dutch ”Rode Meetgebied”.
SE	Stands for Swept Envelop.
st	Refers to static calculations.
th	Theoretical.
veh	Refers to Rolling Stock properties.

Symbols

Symbol	Definition	Unit
b	Half width of the chosen gauge.	[mm]
D	Cant.	[mm]
D^{BNPN}	Detection value, part of the Risk Priority Number calculation	[-]
h	Rolling Stock height, waggon including cargo.	[mm]
h_{c0}	Conventional value of roll centre height.	[mm]
I	Cant deficit.	[mm]
l	Track gauge. Distance between two rails.	[mm]
L	Conventional distance between the contact points of the wheels on the rails of the same track.	[mm]
O^{BNPN}	Occurrence value, part of the Risk Priority Number calculation	[-]
qs	Displacement due to the quasi-static roll taken into account by the infrastructure.	[mm]
r	Redundancy.	[-]
R	Horizontal curve radius.	[m]
s	Flexibility Coefficient.	[-]
S	Projection outside the reference gauge.	[mm]
S_{l}	Part of the lateral projection due to the effect of the track gauge widening.	[mm]
S_{R}	Part of the lateral projection due to the geometric overthrow in a curve of radius R.	[mm]
S^{BNPN}	Severity value, part of the Risk Priority Number calculation	[-]
T_{D}	Cross-level variation between two maintenance intervals.	[mm]
T_{osc}	Margin taking into account the vehicle oscillations due to track irregularities.	[mm]
T_{voie}	Lateral displacement of the track between two periods of maintenance.	[mm]
V	Velocity.	[km/h]
w	Weighing factor for scenario's.	[-]
x_{Sigma}	x-coordinate retrieved from Sigma.	[mm]

1 Introduction

1.1. Background

Rail freight transport on the Dutch rail network is divided into three categories in terms of gauges. These are regular rail freight transport, combined rail freight transport, and unique rail freight transport. Regular rail freight transport includes all freight trains that comply with the UIC gauge in use. Combined rail freight transport refers to trains for intermodal freight transport, where standard-size lorry trailers are placed on intermodal rail waggons. This combination makes the train higher than the UIC gauge. Three standard gauges (BP gauges) have been created for these trains that are higher. BP1-2-3 specifies the parts of the Dutch railway network on which these three BP gauges are allowed. The last category is unique rail freight transport and includes all freight trains that exceed the UIC and BP gauges. These trains are the out-of-gauge rail freight trains [10].

Each out-of-gauge train trip is scheduled individually. The route the train should take to reach its destination/border is determined, as well as any restrictions that need to be imposed. This is a manual process, and it takes several days to schedule an out-of-gauge train. It is not possible to adjust or reroute out-of-gauge trains during, for example, unforeseen situations. When this happens, diversion routes must be re-assessed for gauge violations and new exemptions must be obtained. The fact that the railway lines to be used must be assessed for each transport operation to determine whether the transport can take place is due to the fact that the decisive bottleneck for each railway line has not been recorded. Because this overview is missing, it is not possible to make quick adjustments during implementation. It is also difficult to get an idea of the possible routes for out-of-gauge rail freight transport. This affects the factors of “rapidity” and “redundancy”, which also contribute to resiliency.

However, the current state of the infrastructure makes it necessary to be able to respond and adjust quickly. In 2025, it was 80 years since the Netherlands was liberated and the Second World War ended. After the liberation, a period of *”Wederopbouw”* (reconstruction) started, and the restoration of the railway infrastructure began. Much of the infrastructure dates from that period, increasing the risk of failures. It is therefore not entirely unlikely that situations may arise in which rescheduling is required more due to disruptions.

Despite the ageing infrastructure and the resulting increased risk of parts of the railway network failing, the system as a whole must continue to function. One of the areas designated as essential for the Dutch society to continue to function is the railway network. Therefore, the National Coordinator for Counterterrorism and Security has designated the rail infrastructure as vital infrastructure [41]. It must continue to function, and this includes out-of-gauge rail freight transport. In the event of an exceptional situation, the Ministry of Defence, for example, must remain able to transport its out-of-gauge freight. In addition, the use of the railway network continues to increase. The Dutch National Railways (NS) intends to operate more than 1,500 additional trains under the new schedule for 2025 [38]. For freight transport, ProRail expects that 68 million tonnes of goods will be transported by rail by 2040 [21]. To put this in historical perspective: in 2024, 37.62 million tonnes were transported [6], compared to 18.19 million tonnes in 1986 [39]. Forecasts for out-of-gauge transport are currently unavailable.

To continue to deliver out-of-gauge capacity under these complex circumstances with an increased risk of railway infrastructure failure, it is necessary to map out the infrastructure possibilities for out-of-gauge rail freight transport. This should take into account where and how severe the infrastructure, parts of which were built in accordance with the 1938 Regulations for the Design, Construction and Erection of Steel Bridges (VOSB) [22], extends into the gauge.

There is a gap in the literature regarding the analysis of current infrastructure, especially for out-of-gauge rail freight transport. NEN EN standards specify how an infrastructure gauge can be calculated. However, these standards mainly use calculations based on the reference vehicle, whereas there is a need for a calculation method that takes the existing infrastructure as the basis. In relation to the calculation method, there is also no known method in the literature that prescribes how to search for bottlenecks at the link level. Various methods for ranking factors have been defined in the literature. For the issue at hand, this would involve adding a prioritisation to the bottlenecks to be resolved. No prioritisation method has been developed specifically for this particular need. There is a method, the Failure Mode Effect Analysis, which could serve as a basis for the need to prioritise the bottlenecks.

1.2. Design challenge

The missing methods mentioned above lead to the following design challenge:

Design a method to identify and prioritise structures in the UIC gauge and develop a strategy to resolve the identified obstructions.

To answer this question, the following sub-questions must be addressed:

1. How to identify and quantify bottlenecks for the operation of out-of-gauge rail freight transport on existing routes?
2. How to assess what is possible within the known gauge violations?
3. How can bottlenecks be compared with each other to ensure prioritisation of which bottleneck should be resolved first?
4. What results does the method provide when applied to the case study on the Betuweroute?

The desired solution is a method that indicates the maximum violation and what can still be driven as a result of that violation. The method must be structured in steps and ensure that data about what is possible is stored. This should result in the creation of a database that can be used to plan and reroute out-of-gauge freight trains. This addition should make the system more robust because it will be possible to respond more quickly to changing circumstances. A way is also sought to prioritise the bottlenecks so that they can be resolved in a substantiated manner. Resolving bottlenecks will increase the possibilities of out-of-gauge transport within the national network, which will also increase robustness.

1.3. Design approach

In order to contribute to closing the scientific gap, the following approach will be adopted. Three steps will be carried out, namely a literature study, the design of a method, and its application to a case study. Each step builds on the conclusions or results of the previous step.

During the literature study, the current Dutch rail freight transport system will be analysed and mapped. In addition, the regulations will be examined to determine the methods used to calculate the gauge. The system analysis and regulations will form the basis for answering sub-questions 1 and 2. Finally, the method that can be used as a basis for prioritisation and thus for answering sub-question 3 will be mapped out.

A method will be developed on the basis of what is known and what is missing in the literature. This method will be developed using the research by design method and combined with the System Engineering Spiral method. In developing the method, a number of scenarios will be considered for which the methods should be applicable. The scenarios are further elaborated in subsection 1.3.1.
The method designed is applied to a case study. This is to see whether the method works and thus answer sub-question 4. The case study is conducted for a situation in which there is congestion on

the Betuwe Route. The method is applied to assess whether there is an alternative route suitable for out-of-gauge rail freight transport. The application of the method should lead to the conclusion as to which gauge width can be used, what the decisive bottleneck is, and what a possible solution strategy might be.

The desired end state is a better understanding of the out-of-gauge possibilities and capacity within the current Dutch railway infrastructure and how these possibilities can be increased. The insights gained should ensure that it is possible to respond more effectively to demand for out-of-gauge rail freight transport, particularly when this needs to be done quickly. The ultimate goal, as already stated in section 1.1, is a more resilient railway network.

1.3.1. Scenario

In the near future, the need for out-of-gauge transport may increase significantly compared to the current situation. In such a situation, the scenarios outlined in Figure 1.1 are possible.

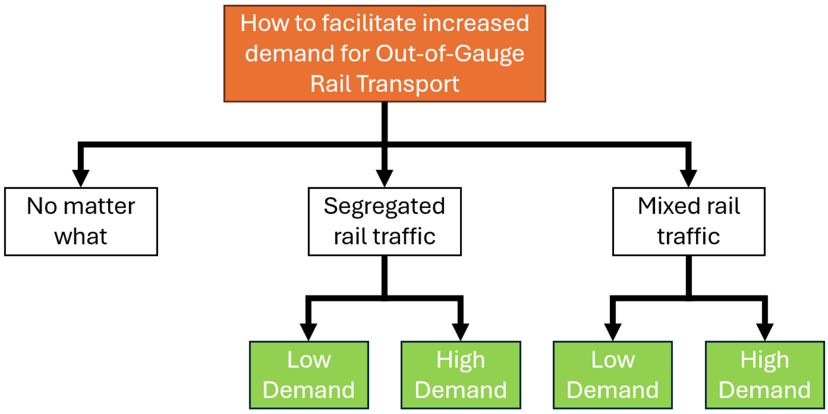


Figure 1.1: Scenario's for increased out-of-gauge traffic

The scenarios are based on three main scenarios. These scenarios were developed based on the urgency of out-of-gauge transport and the desired mix with passenger transport. Two scenarios also have sub-scenarios based on demand. The main scenarios are as follows.

- **No matter what:** In this scenario, there is no possibility of holding up transports or making adjustments to the infrastructure for the transports. In this scenario, passenger train transport is suspended and it is accepted that damage will be caused that might make it impossible to execute the normal schedule, but it still ensures that the necessary transport is carried out. This scenario only applies during an emergency situation. For this scenario, information is required on which structures along the track are susceptible to damage and which structures are actual bottlenecks. The bottlenecks in this scenario are structures along the railway line that cause unacceptable damage to the load or compromise safety. These include objects that are not easily falling or moving, such as platform structures, buildings, and bridges. Based on the data, a strategy can be developed to resolve the bottlenecks.
- **Segregated rail traffic:** In this scenario, passenger transport is temporarily suspended in order to prioritise out-of-gauge transport, freight and passenger flows are segregated. As soon as the demand for out-of-gauge transport (temporarily) decreases or completely disappears, passenger rail transport must be restarted. Damage that makes this impossible will not be tolerated. For this scenario, information is required on the critical bottlenecks on the route. Based on these data, a strategy can be developed to resolve the bottlenecks.
- **Mixed rail traffic:** For this scenario, out-of-gauge transport must be integrated into a schedule with the current passenger trains. This limits inconvenience to passengers. In addition to information about bottlenecks, as stated in the previous scenarios, this scenario also requires information about the possibilities of timetables and the capacity of waiting, stabling, and passing tracks.

The scenarios mentioned should be applied to the standard rail freight corridors, but also to other railway lines so that this infrastructure can also be used when rail pathways need to be rescheduled due to incidents on the main route and increasing the resiliency of the network.

Within segregated rail traffic and mixed rail traffic, sub-scenarios have been drawn up for high and low demand. The difference is characterised by whether, on the one hand, more train paths are taken into account to facilitate demand, and, with that, adjustments to block lengths and the train protection system. However, a higher demand also requires consideration of a simultaneous return flow, which places additional demands on the passing or side tracks. The passing tracks must then be long enough in both directions for a freight train, and the tracks on the route must be far enough apart.

This scenario can be applied in two ways.

1. Firstly, proactively, whereby the method is used to prepare (parts of) the network for a greater influx of out-of-gauge rail freight transport, so that there is sufficient redundancy to reroute in the event of a disruption.
2. A reactive manner, in which the method is used during disruptions on the planned main routes to search for possible alternative routes and what is possible for each scenario.

1.3.2. Scope

The aim of the thesis is to develop a method for mapping out the possibilities for out-of-gauge transport on the Dutch rail network based on the measurement data already available. This will clarify what is possible and, at the same time, which structures pose the greatest limitations for the width of the transport. The method to be developed will not only look at what is possible, but will also use information about the limiting structures to develop improvement strategies. The thesis focusses on the lateral component of out-of-gauge rail freight transport. The long-term effects on infrastructure and the environment are also beyond the scope of the thesis.

This scope provides details for the *No matter what* scenario and the *Segregated rail traffic - Low demand* scenario. These scenarios require data and solutions at the infrastructure level, which falls within the scope of the thesis. The remaining scenarios also require this information, but need more input due to the need for solutions for capacity allocation and timetabling. The latter falls outside the scope of this thesis, and further research will be required for these scenarios based on this thesis.

The method will be tested on a case-study which focusses on the Betuweroute, specifically on the first part of the Betuweroute, between Kijfhoek and Meteren. In chapter 4, we discuss in more detail why this location was chosen and what the scenario under consideration is.

1.4. Report structure

The context of Out-of-Gauge rail freight in the Netherlands is introduced in chapter 1. This chapter also defines the design challenge, sub-questions, and design approach. In chapter 2 the (in-depth) literature and regulatory framework are reviewed, including load-gauge concepts, gauging calculations, resilience, design methods, and FMEA-based decision support. The chosen methods and the designed methodology are presented in chapter 3. This includes data preparation and processing, clearance and gauge assessment, mapping of violations, and BNPN-based prioritisation with implementation of the scenario's. The method is applied to a Betuweroute-related case study (including a diversion option) in chapter 4. The chapter reports key bottlenecks and converts the rankings into mitigation strategies. The report concludes with contributions, limitations, and recommendations for implementation and future work in chapter 5. The appendices provide supporting figures, tables, and code.

2
Literature review

The literature review consists of three parts. The first part contains a description of the current rail freight system. The section covers the rail infrastructure in the Netherlands, how the corridors are organised, and which national and international requirements must be met. Part two provides in-depth information from the literature on two background themes, namely resilience and capacity. The purpose of this information is to provide insight into how the research relates to the overarching themes. The third part contains the literature on the applicable methods. The chapter concludes with a conclusion which states the differences between the various methods and where the research gap lies.

2.1. System description

The Netherlands has a railway network with a total length of 3.043 kilometres. 70% of this network has two or more tracks. There are 398 stations on this network. The network is shown in Figure 2.1.

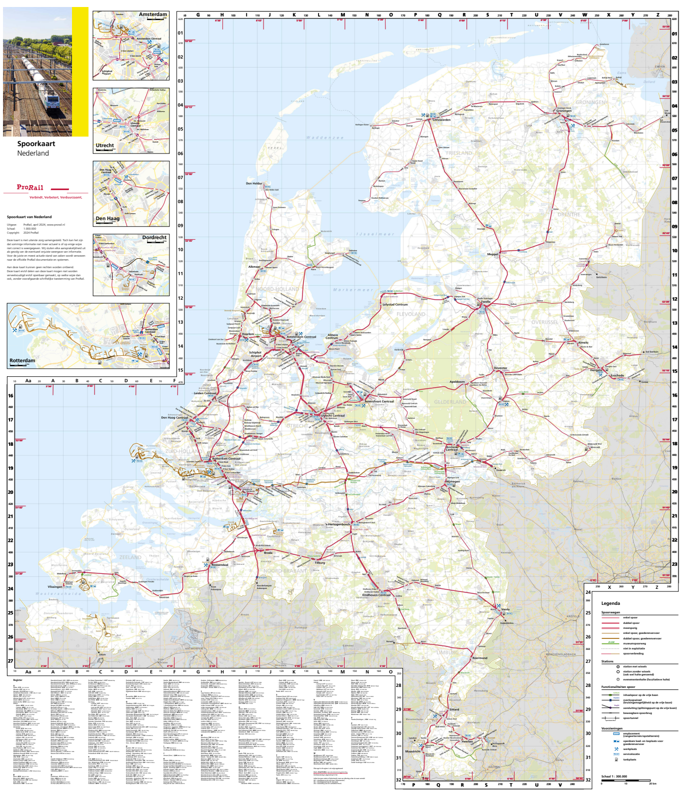


Figure 2.1: Dutch Railway Network

ProRail manages and uses various design regulations for the design of railways. This includes OVS00026 and OVS00056, mentioned in chapter 1. Twice a year, a railway line is scanned by a UFM measuring train (for track geometry, UIC-gauge, and superstructure). To check whether the infrastructure still complies with the regulations. The measurements are entered into Sigma, which can then be used to cheque whether there are objects within the UIC gauge. An example of an object detected in Sigma that is within the UIC gauge is given in Figure 2.2. In Sigma, you can view the contents of each cross-section, as shown in Figure 2.2, but it is not possible to obtain a total overview of the number of violations per section and to sort this further by category.

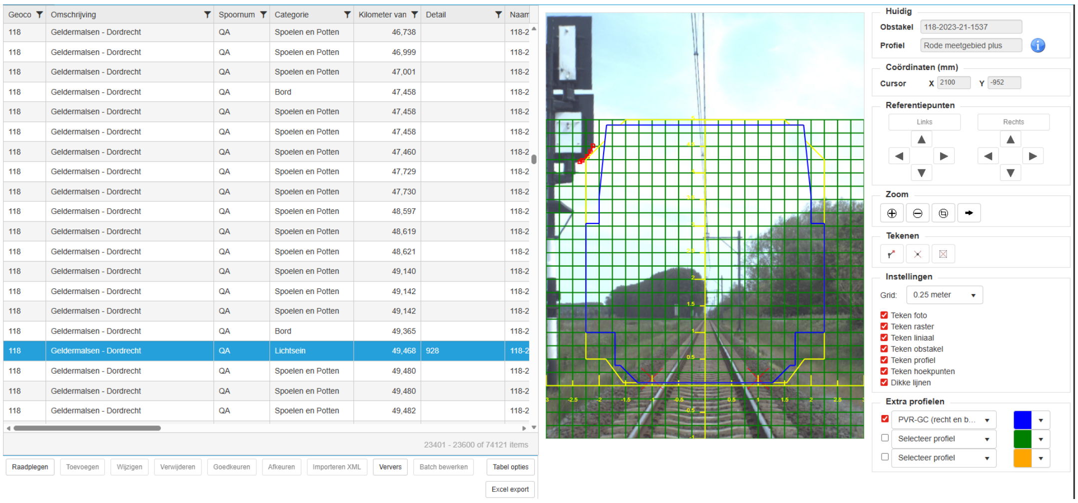


Figure 2.2: Example of how the data is presented in Sigma, in this case with a Signal within the UIC-gauge

The ideal situation is that all railways comply with these design regulations or adapt to these regulations during major maintenance. It appears that this is not possible due to limiting factors (existing buildings and engineering structures, narrow railway embankments, etc.), and that no major maintenance has yet been carried out on the tracks, or that a mistake has been made in the construction, and this has only been noticed too late. In practice, railways regularly deviate from regulations. Looking at OVS00026 (UIC gauge). If the Dutch railway network is assessed against the most recent UIC gauge (PVR-GC), including the “Red measurement area”, there are a total of 74.246 violations of the UIC gauge. This amounts to an average of one violation per 41 metres.

2.1.1. UIC-gauge

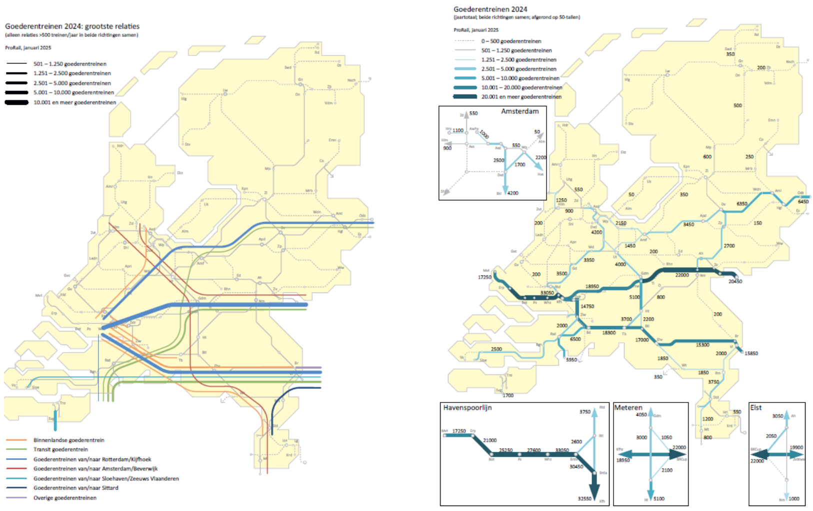
As indicated above, the current UIC design gauge in the Netherlands is ‘PVR-GC’. This gauge can also be viewed in Appendix E. In addition to the UIC gauge GC, three other gauges are also in use on Dutch railways, namely G2, NL-1 and NL-2 [10]. Newly built or rebuilt railway lines will have UIC gauge GC, which means that the other three profiles will eventually disappear. Vehicles that fit within the UIC-gauge can be transported without exemption. This means that anything lower than 4900 mm from the top of the track and narrower than 2000 mm wide from the centre line to 3550 mm above the track and from there tapering to a width of 1860 mm from the centre line can be transported [7].

The PVR-GC is surrounded by the “red measurement area”. Objects must be placed outside this area, such as signs, signals, and poles for the catenary. It may be permissible to place a structure in the red measurement area. Then, this structure must be registered and it must be possible to remove them. This red measurement area is 2250 mm wide from the centre of the track and 5000 mm high from the top of the track. Trains (waggons + load), including safety margins, must remain within the red measurement area. Protruding beyond the red measurement area is not allowed. If the load is within the red measurement area, an exemption must be requested to be allowed to transport this load by train. The exemption is necessary because, as indicated, structures may have been placed in the red measurement area [7].

2.1.2. National rail freight corridors and link to international network

In 2024, 52,100 freight trains travelled in the Netherlands. Looking at the OD numbers as stated in Appendix B, there are four main border crossings, with more than 5,000 train movements per year, for rail freight transport. These border crossings are located in Roosendaal, Venlo, Zevenaar, and Oldenzaal. A total of 47,800 train movements (entering and leaving the network) per year take place at these border crossings. Looking at the origin and destination of the freight trains entering the Netherlands, it is noticeable that through Roosendaal mainly transit traffic enters or leaves the Netherlands. Of the 3,050 trains entering the Netherlands via Roosendaal, 2,550 go to one of the three other major border crossings. The numbers of trains in Appendix B also show that virtually all freight transport is transnational. The number of freight trains remaining within the Netherlands is very small.

In Figure 2.3 on the left, you can see how the flow of goods generally passes through the Netherlands and, on the right, how the freight trains are distributed across the network. This clearly shows that in the Netherlands, the flow of goods mainly takes place from east to west and vice versa. The port of Rotterdam being the most important starting point for rail freight transport.



(a) Flows of rail freight transport between connections

(b) Distribution of rail freight over the Dutch rail network

Figure 2.3: Rail freight flow through the Netherlands [6]

To facilitate the flow of goods, three rail freight corridors have been established in the Netherlands, also running east-west. These are the Brabant route, the Bad Bentheim route, and the Betuwe route. The routes are shown in Figure 2.4, with the Bad Bentheim route in red, the Betuwe route in blue, the Brabant route in orange, and Kijfhoek chosen as the starting location.

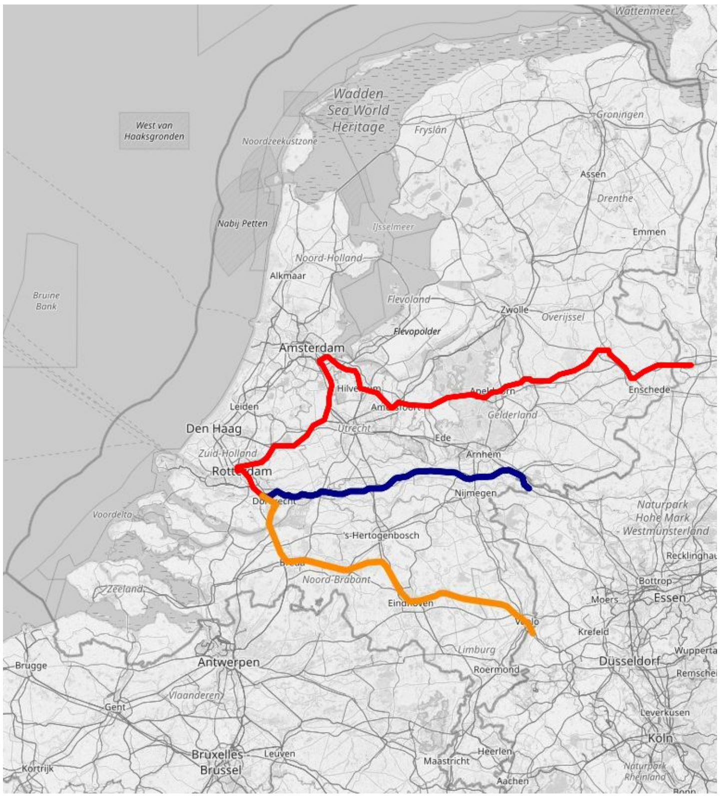


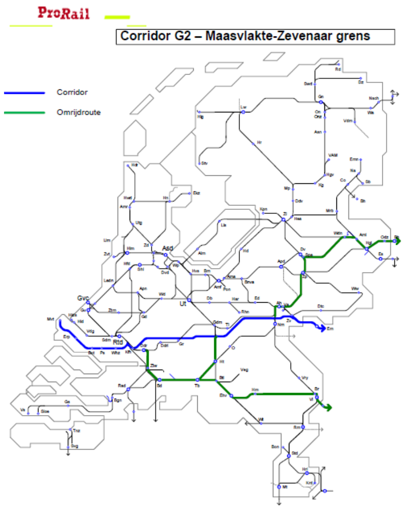
Figure 2.4: Dutch Rail freight Corridors

This suggests that the connection between the Port of Rotterdam and Germany can be established via three routes, thus providing a degree of redundancy. The three freight corridors are not identical and therefore do not have equal importance within the network. The Bad Bentheim and Brabant routes are combined with passenger transport, which means they have less capacity for freight transport. The Betuwe Route is the only route dedicated to rail freight transport. This is also reflected in the way freight transport is distributed throughout the network, with approximately 40% travelling the Betuwe Route [6], which is currently still limited by a lack of capacity on the German side of the border crossing.

There are also differences in international connections. The three freight corridors are included in two international corridors [18]. The Bad Bentheim Route is included in the core network of the North Sea-Baltic corridor for rail freight transport. The Betuwe Route is included in the core network of the North Sea – Rhine – Mediterranean rail freight transport network and can also be used for freight trains on the North Sea-Baltic corridor. The Brabant route is part of the extend core network of this corridor.

For all corridors in the Netherlands, including the three rail freight corridors, diversion routes have been established in the corridor book [4]. These are adjustment options for incidental withdrawals and to prevent work being scheduled on both the main route and the diversion route.

In Figure 2.5 an example is given of the diversion routes for a corridor, in this case the Betuwe Route. This shows that the diversion route mainly follows the Betuwe Route and, to a lesser extent, the Bad Bentheim route.



Corridor G2 Maasvlakte – Zevenaar Grens			
Btd Baanvak	Omrijdroute		Kaart nr
Mvt – Kfh	-		
Kfh - Brmet	Kfh-Ht-Brmet en/of Kfh – Tb – Ehv – Vlgr *Baanvak Zlw-Rsd en Ehv-Rm vrijhouden t.b.v. voldoende omrijdcapaciteit op de Brabantroute.*		59
Brmet - Zvo	Kfh – Tb – Ah – Zvo en/of Kfh – Tb – Ehv – Vlgr *Baanvak Zlw-Rsd en Ehv-Rm vrijhouden t.b.v. voldoende omrijdcapaciteit op de Brabantroute.*		60
Zvo - Zvgr	Kfh – Tb – Ehv – Vlgr *en Kfh-Ebtwa-Ah-Dvge-Odzg (alleen geldig overdag van 06.00-24.00 uur)* *Baanvak Zlw-Rsd en Ehv-Rm vrijhouden t.b.v. voldoende omrijdcapaciteit op de Brabantroute.*		61

Figure 2.5: Diversionroutes for the Betuwe route

2.1.3. TEN-T

As mentioned in subsection 2.1.2, national rail freight corridors are part of international rail freight corridors. These corridors are part of the TEN-T network (Trans-European Transport Networks). The TEN-T network consists of a core network, an extended core network, and a comprehensive network. The core network must be completed by 2030, the extended core network by 2040, and the comprehensive network by 2050 [18]. One of the objectives of the TEN-T network is to standardise the network and thus facilitate international freight transport. To do this, the core network infrastructure must meet several requirements by 2030. These are as follows:

1. Full electrification.
2. Track gauge of 1435 mm.
3. Train lengths of 740 m are possible. This is for 50% of the capacity or at least 2 pathways per hour per direction.
4. Axle loads of 22.5 tonnes are possible.
5. The P400 loading unit must be allowed as standard (as of 2040)*.
6. ERTMS as train protection.
7. Minimum speed of 100 km/h on 75% of the route between two terminals or a terminal and a national border.

*The P400 profile is a standard profile that applies to multimodal transport. It provides the space to transport a standard semi-trailer on a designated train waggon. ProRail has determined in BP1-2-3 [15] where this profile cannot be used.

In Europe, axle loads are specified in EN 15528 which is a coding system consisting of a letter for the axle loads and a number for the tonne-metre weight. The TEN-T requirement of 22.5 tonnes axle load corresponds to the load class ‘D’. In the Netherlands, load class ‘C’ (20 tonnes axle load) is the minimum that must be applied, C2 to be precise. Here, ‘2’ stands for a tonne-metre weight of $6.4 \text{tonnes}/\text{metre}$. Therefore, it is not evident that the Dutch railways meet this requirement. However, now there is a requirement that the load class D4 must be applied to all renovations and new construction of the Dutch railways. The ‘4’ corresponds to a tonne-metre weight of $8.0 \text{tonne}/\text{metre}$. This ensures that more and more parts of the network will meet this requirement [27].

According to the same TEN-T Regulation of the European Union, railway lines that are part of the diversion route of the TEN-T connections must also meet the same requirements, with the exception of the electrification requirement.

2.2. In-depth information

The following section provides more in-depth information on the topics of resilience and capacity.

2.2.1. Resilience

According to Tierney et al. [40], resilience reflects the concern for improving the capacity of physical and human systems to respond to and recover from extreme events. They identify four key attributes that define resilience. Robustness, Redundancy, Resourcefulness, and Rapidity. This is known as the R4 Resilience Framework. The meaning of the attributes can be found in Table 2.1.

Attribute	**Meaning**
Robustness	The ability to withstand (extreme) disruptions without significant degradation or loss of performance of the system.
Redundancy	The extent to which parts of the transport system are substitutable. That is to say, are there alternative options (such as multiple routes) to ensure that functionality is maintained?
Resourcefulness	The ability to diagnose and prioritize problems, and to initiate solutions by identifying and mobilising resources.
Rapidity	The capacity to restore functionality in a timely manner, minimising losses and avoiding prolonged disruptions.

Table 2.1: R4 Resilience Framework by Tierney and Bruneau [40]

The impact of a disruption and the length of time it lasts create a loss triangle, as shown in Figure 2.6. At time t_0 shown on the graph, an extreme event occurs. The degree to which the system function is not forced to zero at that point represents the robustness of the system. Over time, the system function recovers until t_R it is fully restored. Increasing resilience, which is equivalent in the diagram to reducing the loss triangle, can be accomplished through redundancy (ex ante) measures or resourcefulness (ex post) actions [16].

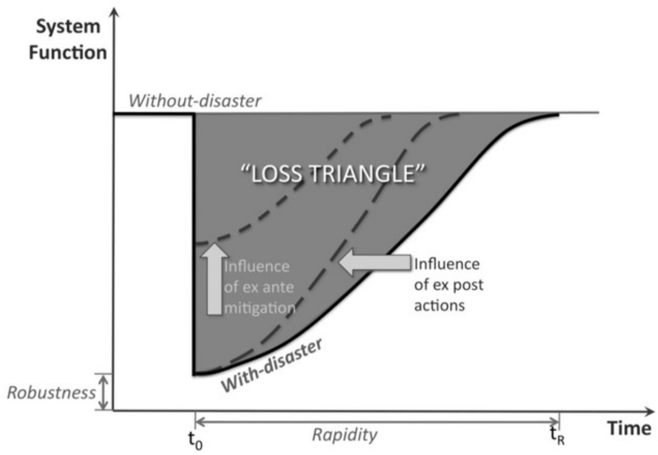


Figure 2.6: Resilience Concept [16]

Zhou et al. [42] distinguish two phases in the measurement of resilience. The Disruption Phase, where Robustness and Redundancy influence the immediate impact on the transport system. Followed by the Recovery Phase, where Resourcefulness and Rapidity determine how quickly the system can recover. This is shown in Figure 2.7.

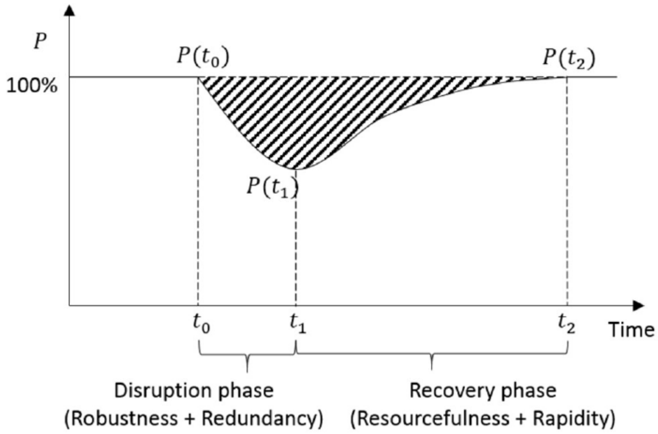


Figure 2.7: Two phases of resilience measurement [42]

2.2.2. Capacity

Meirich et al. state that the capacity on the track is influenced by three different factors: Infrastructure, Train Runs (mixing ratio), and Accepted Level of Quality [30], which is visually represented in Figure 2.8. In a broader way, the three factors are "Infrastructure", "Traffic", and "Operations". The factors of "Traffic" and "Operations" are outside the scope of the thesis, as stated in subsection 1.3.2

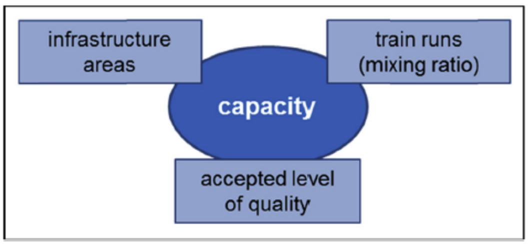


Figure 2.8: Factors impacting railway capacity [30]

In their paper on the assessment of Railway Capacity, Abril et al. determined various parameters within the three factors that influence capacity. For the infrastructure section, the parameters are given in Table 2.2 [1].

Parameter	Meaning
Block and signalling system	The type of signalling system (fixed or moving) and the corresponding parameters of block section lengths, train speeds, and train lengths determine how short the distance between trains can be and thus the capacity.
Single/Double tracks	Two tracks usually have around four times more capacity than a single track; however, a four-track line rarely increases capacity by more than 50% over a double line.
Definitions of lines/routes	In assessing the line capacity, the railway line itself must be defined, namely the list of stations and halts along the line and their characteristics.
Network Effects	A single line cannot be considered as a fully independent part of the whole network due to crossing and overlapping lines.
Track Structure & Speed	The condition of the rails, ties, and ballast dictate the weight and type of equipment that can be used on the line, as well as the speeds allowed on the line.
Length of the subdivision	If the length of the subdivision increases, so does the transit time of trains. Resulting in a lower capacity.

Table 2.2: Infra parameters influencing capacity [1]

2.3. Methods

This section cites the literature on the methods applicable for this thesis research. These are various calculation methods for the gauge calculation, techniques for executing the scenarios, and various methods for prioritisation.

2.3.1. Design methods

Various methods are available in the literature for realising a product, in this case a method. Based on the available information and the desired solution, four system engineering methods have been considered as the design method: Waterfall Model, Feedback Model, V-model, and Spiral Model.

The Waterfall Model represents the most linear and sequential interpretation of the systems engineering. It typically progresses through information planning, conceptual study, basic design, detailed design, construction, implementation, usage, and maintenance, with each phase formally completed before the next begins. Within a systems engineering context, this model emphasises early requirements stability and extensive upfront specification. Its principal strength lies in its clarity and simplicity of management. The Waterfall Model disadvantage is the rigidity. It assumes that requirements can be fully captured at the outset and that late-stage changes are exceptional [3].

The Feedback Model introduces explicit iterative feedback loops between phases, recognising that learning occurs throughout system development. Roozenburg and Eekels emphasise feedback loops between analysis, synthesis, simulation, and evaluation, reflecting a more realistic representation of engineering practice under uncertainty. In systems engineering projects, this feedback-orientated approach improves adaptability and supports progressive refinement of the system requirements. Its principal advantage is its ability to respond to uncertainty and partial knowledge. However, the absence of a strongly formalised structure can also be a weakness. Without disciplined configuration control and clear decision gates, frequent iteration can cause the goal to be lost sight of [33].

The V-Model can be understood as a refinement of the Waterfall approach that explicitly couples development phases with corresponding verification and validation activities. The decomposition of the system on the left side of ”V” is mirrored by integration and verification on the right, ensuring traceability between requirements, design elements, and test cases. Nevertheless, the V-Model largely inherits the limitations of linear lifecycle models. Although iterations can be introduced, they are not central to the structure of the model [19].

The Spiral Model further extends iterative principles by embedding feedback and risk assessment into each development cycle. Development proceeds through a series of cycles, each consisting of requirements analysis, design, test, and production. Relaxes the rigidity of phase sequencing. Relative to the other methodologies, the Spiral Model offers adaptability for large-scale systems, though at the cost of increased management complexity and reduced standardisation [19].

The methodologies differ primarily in how they balance control against iterative learning. Linear models, like the Waterfall, Feedback and V-model, prioritise predictability and control, while feedback-driven and spiral approaches, like the Spiral Model, emphasise adaptability and continuous validation.

In addition to the design methods, there are also different ways of conducting research while designing a method. The two methods under consideration are Research by Design and Research through Design. Research by Design defines knowledge as emerging directly from design activities, using iterative prototyping and reflective documentation. Research through Design, by contrast, emphasises the production of knowledge through reflection on the design process itself [20].

2.3.2. Gauge calculation

NEN EN 15273 describes the calculations used to determine the gauge. The UIC gauges are also calculated on the basis of these calculations.

NEN EN 15273-1 [23] sets out the common rules for rolling stock and infrastructure. NEN EN 15273-2 [24] deals with calculating the reference gauge of rolling stock, NEN EN 15273-3 [25] deals with the construction gauge of the infrastructure, and NEN EN 15273-4 [26] focusses on the defined UIC gauges.

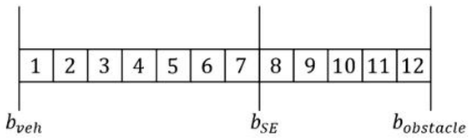
In Figure 2.9, the various gauges used are visualised. The image is not scaled and is for illustrative purposes only. The gauges used are as follows.

- b_{CR} is the width of the reference gauge, which is determined in consultation with the railway undertaking and the infrastructure manager. The railway undertaking deducts the rolling stock margins from this gauge to determine the maximum construction gauge. The infrastructure manager adds the infrastructure margins to this to determine the minimum infrastructure gauge. The UIC has laid out a number of gauges in standards, including the Dutch gauge GC, which is specified in OVS00026 and laid down as a UIC gauge in NEN-EN 15273-4.
- b_{veh} is the maximum construction gauge for the railway undertaking. The railway undertaking may not design or build rolling stock larger than this gauge. Therefore, the actual train is also smaller than this gauge.
- b_{inf} is the minimum distance at which structures must be placed to ensure that they do not enter the reference gauge.
- An additional margin can be added on top of b_{inf}. Together with b_{inf}, this forms the red measurement area, b_{RM}. The red measurement area is therefore not only the red area in Figure 2.9. The red measurement area makes it possible to run trains (including rolling stock margins) that do not fall within b_{CR}.

Figure 2.9: illustrative explanation of the different gauges

For out-of-gauge rail transport, the gauges must be calculated for the widths and heights that are travelled. The vehicle with load then has a width b_{veh}. The rolling stock margins are added to this to calculate the Swept Envelope, b_{SE}. In an out-of-gauge situation, there is no b_{CR}, but this is b_{SE}. Infrastructure margins are added to b_{SE} to arrive at a minimum b_{inf}. To be able to carry out the transport, the constructed infrastructure gauges $b_{\mathrm{inf}}^{\mathrm{constr}} \geq b_{\mathrm{inf}}$.

Annex E of NEN EN 15273-1 describes the absolute gauging process. The absolute gauging process was developed to allow the maximum physical dimensions of the rolling stock to be achieved.Figure 2.10 from Annex E clearly shows how the margins are constructed.



Key

b_{SE}	swept envelope semi-width	6	movements due to suspension flexibility
b_{veh}	vehicle semi width	7	lateral wheelset movements
$b_{obstacle}$	infrastructure profile semi-width	8	clearance
1	vehicle construction tolerances	9	other relevant infrastructure effects
2	vehicle maintenance tolerances	10	infrastructure measurement tolerances
3	vehicle measurement tolerances	11	infrastructure installation tolerances
4	other relevant vehicle effects	12	infrastructure track tolerances
5	geometric overthrow		

Figure 2.10: Absolute gauge calculation

The determination of the swept envelope of the rolling stock, elements 1 to 7, is the responsibility of the owner of the rolling stock. The infrastructure gauge consists of elements 8 to 12 and is the responsibility of the infrastructure manager.

Since one of the sub-questions is to determine what is possible within the existing infrastructure, the minimum distance between b_{SE} and b_{obstacle} is examined. The report will refer to b_{inf} instead of b_{obstacle}.

For the calculation of b_{inf}, NEN EN 15273-3 provides three options: calculation based on a dynamic calculation, a kinematic calculation, or a static calculation. The dynamic calculation is the most accurate because it takes into account time-dependent behaviours such as vibrations and resonance due to track-vehicle interaction. This also requires more calculations and modulation of the force.
The kinematic gauge takes into account the relative movement of the rail vehicle. This takes into account the effect of how the rolling stock reacts to track irregularities such as cant, gauge widening, and so on. This requires data input from the rolling stock that will be operating on the railway line. However, this method does not take dynamic effects into account. The kinematic calculation method is the standard calculation method for the gauging method.
The static gauge calculation looks at the immobile rail vehicle. This is purely the shape of the vehicle and fixed values cant deficit and track irregularities. It is the fastest calculation, but also the least accurate. An exception to this are rail vehicles with a low flexibility coefficient [s], lower than s_{lim}. For these types of vehicles, the static calculation method may also be applied. The various variables, but especially Σ_{j}, do include terms to take into account dynamic effects.

The formula for calculating b_{inf} can be done with Equation 2.1 for the kinematic calculation method, with Equation 2.2 for the dynamic calculation method, or with Equation 2.3 for the static method [25].

$$b_{\mathrm{inf}}^{\mathrm{cin}} = b_{\mathrm{CR}}^{\mathrm{cin}} + S_{\mathrm{i/a}} + qs_{\mathrm{i/a}}^{\mathrm{cin}} + \Sigma_{\mathrm{j}}^{\mathrm{cin}} \tag{2.1}$$

$$b_{\mathrm{inf}}^{\mathrm{dyn}} = b_{\mathrm{CR}}^{\mathrm{dyn}} + S_{\mathrm{i/a}} + \Sigma_{\mathrm{j}}^{\mathrm{dyn}} \tag{2.2}$$

$$b_{\mathrm{inf}}^{\mathrm{st}} = b_{\mathrm{CR}}^{\mathrm{st}} + S_{\mathrm{i/a}} + \Sigma_{\mathrm{j}}^{\mathrm{st}} \tag{2.3}$$

The effects of curves on the infrastructure are included in $S_{\mathrm{i/a}}$, the formula is given in subsection 3.2.1 as Equation 3.4. Σ_{j} is the sum of the allowances to cover the random phenomena. These are calculated differently for each calculation method, for the static calculation The allowances Σ_{j} shall be sufficient to cover all quasi-static and dynamic displacements of the rolling stock, the dissymmetry, and the movements caused by track irregularities that are not included within the static reference gauge. [23] The formulas are given in NEN-EN 15273-3 and subsection 3.2.1 contains the formula for Σ_{j} of the calculation method used in the methodology. $qs_{\mathrm{i/a}}$ takes into account quasi static effects. b_{CR} is the half-width of the clearance gauge of the vehicle.

NEN15273-1, Annex G shows the compatibility between static and kinematic defined gauges. The defined gauge is the total gauge width from the centre of the track to the infrastructure, including the vehicle width, vehicle margins, and infrastructure margins. The standards are drawn up in such a way that the kinematically calculated defined gauge corresponds to the statically calculated defined gauge, as long as the flexibility coefficient stays below the set value for s_{lim}. The effects that are included in the vehicle margins in the kinematic calculation method are incorporated into the infrastructure margins in the static calculation method. Annex G shows through calculations that the defined gauges for both calculation methods ultimately have the same outcome. [23]

The required values for the different variables are given in table A.1 in Annex A of NEN-EN 15273-3 [25]. The relevant values are given in Table 2.3. For T_{voie}, there is a value for ballasted track and ballastless track. Since Dutch railways are ballasted, with the exception of the HSL-Zuid, the value for ballasted track has been selected. For T_{osc}, a value can be selected for “good track quality” and “other track quality.” Because the focus is on rail connections that are in use and, therefore, maintained, the value “good track quality” has been chosen.

Table 2.3: Values from NEN-EN 15273-3

Symbol	Value [mm]
T_{voie}	25
$T_{\text{D}}(V \leq 80\text{km/h})$	20
$T_{\text{D}}(V > 80\text{km/h})$	15
L	1500
T_{osc}	7

Not all values can be found in Annex A. Some variables remain. These are listed in Table 2.5, including the corresponding value and the source from which it originates. For the value s_{lim}, the values used are those specified in NEN-EN 15273-4 for the GC-gauge, the current design standard in the Dutch rail network, as mentioned in subsection 2.1.1. The value s is the flexibility coefficient [-] and therefore reflects something about the properties of the vehicle. Taking the limit value, a conclusion can still be drawn about the size of the infrastructure margin without having the vehicle properties. However, it must be known whether the s-value does not exceed the limit value before transport is carried out.

The three calculation methods also use cant (D) or cant deficit (I). Both can be provided as a measured value.

If no information is available on the cant, an estimate of the maximum cant deficit can be made on the basis of the design specifications (OVS00056-4.1). The design specification stipulates that the cant can be calculated in mm using Equation 2.4.

$$D_{\text{th},V} = \frac{11.8 \times V^2}{R} \tag{2.4}$$

The same design regulation also states that for mixed passenger and freight train traffic, cant is only applied if $D_{\text{th},V} > 40\text{mm}$. These regulations have been included in Table 2.4.

Table 2.4: Applied Cant for Mixed Traffic [mm]

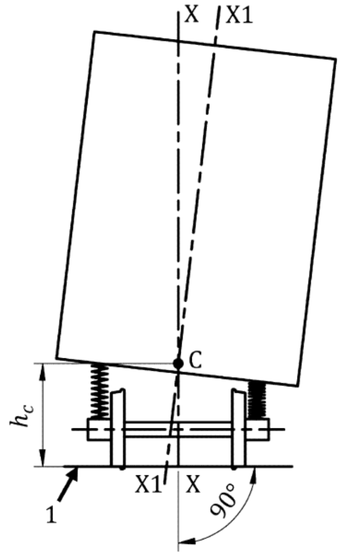
Condition	Standard Value	Exceptional Value
$D_{\text{th},V} \leq 40$ mm	$D = 0$	$D = 0$
$D_{\text{th},V} > 40$ mm	$(0.4 \times D_{\text{th}}) \leq D < (D_{\text{th}} - 20)$	$(0.2 \times D_{\text{th}}) \leq (D < 0.4 \times D_{\text{th}})$

This means that in situations with mixed rail traffic, $D_{\text{th},V} = I$ for $D_{\text{th},V} \leq 40mm$. Furthermore, the minimum cant to be applied is 20 mm, which also fits within the boundaries specified in Table 2.4, which can be seen as the minimum cant applied to estimate the maximum cant deficit. This results in $(I = D_{\text{th},V} - 20, forD_{\text{th},V} > 40\text{mm})$. This calculation is limited in the maximum value that it can assume. According to the regulations, there must be no cant deficit exceeding 120 mm. Therefore, this is the maximum value that can be taken as an estimate of I.

Table 2.5: Other values

Symbol	Value [mm]	Source
s_{lim}	0,3	NEN-EN 15273-4 [26]
I_{max}	120	OVS00056-4.1 [8]

One of the variables on which the margin depends is h_{c0}. h_{c0} is the conventional value of the roll centre height. This height is determined by the type of suspension, how it is positioned, and the type of load. The visualisation of how the height of the roll centre can be determined is given in Figure 2.11. Where X1 is the twisted centre line of the superstructure of the train (load + loading deck) relative to the centre line “at rest”, represented by X. Where X and X1 intersect is the roll centre height, h_{c0} [23].



Key

1 running plane

Figure 2.11: Visualisation of the Roll centre height

2.3.3. Failure mode and effect analysis (FMEA)

Dev Sharma et al states that FMEA is a systematic method of identifying and preventing system, product, and process problems before they occur. Focusses on preventing problems, improving safety, and increasing customer satisfaction. Formally FMEA was introduced in the late 1940s by the US military Forces. In 1960s it was used by the aerospace industry as a design methodology, with obvious reliability and safety requirements. In the late 1960s, Ford Motor Company introduced FMEA to the automotive industry for safety and regulatory consideration. They also used it to improve production and design.

There are three types of FMEA, namely:

1. Concept FMEA
2. Design FMEA
3. Process FMEA

As the name suggests, the Concept FMEA (CFMEA) is applied during the concept phase of a product. It focusses on possible failure mechanisms within or between the functions proposed in a concept proposal. The CFMEA differs from other FMEA's in that it is applied to products that are yet to be realised [35].

The Design FMEA (DFMEA) is used to identify and analyse potential failure modes and their associated causes for product design. It is a verification activity that can help avoid a large percentage of product design problems before the design is finalised. When dealing with new generations of a product including design changes based on existing ones, design FMEA of previous generations can be used as a reference for such design modifications [29].

Process FMEA (PFMEA) focusses on the failure modes that occur during the production process. There are two variants of the PFMEA, namely for assembly and for manufacturing. The manufacturing PFMEA focusses more on potential errors in (sub)products required in the assembly process. The assembly PFMEA, on the other hand, focusses more on errors in the assembly of the earlier sub-products.

The basic process is the same for the different types of FMEA. The requirements that the product must meet or the reasons why the previous product failed are identified. The failure modes are identified, and an RPN value is calculated for each failure mode. This value is calculated based on Severity (S), Occurrence (O) and Detectability (D). The severity is a value that indicates how serious the impact of a failure mode is. The occurrence, as the name suggests, gives a value for the frequency with which the failure mode occurs in the system under investigation. The detectability gives a value for how easy it is to detect the failure mode in the system. All these values are measured on the same scale, for example, from 1 to 10, where a high score is bad. When calculating the RPN, the three values are multiplied to produce a score. The failure mode with the highest score has the highest priority for resolution [35].

A flow chart visualising the design FMEA is given in Figure 2.12.

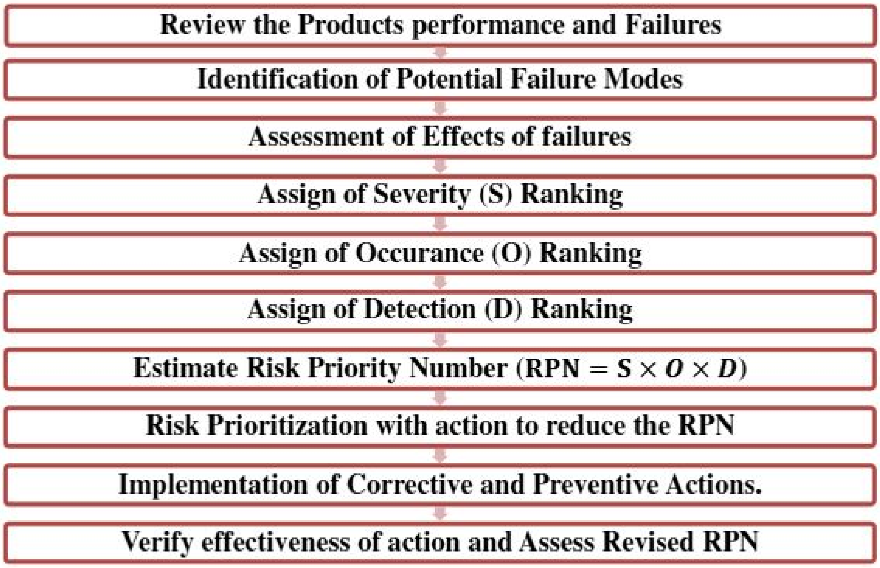


Figure 2.12: Flow chart design FMEA [17]

2.4. Conclusion

The system description of the literature review shows that European agreements clearly specify the requirements that railways must meet for freight transport. Regulations specify which gauges must be facilitated on the Dutch railways. The Dutch Infrastructure Manager (ProRail) also knows what the diversion routes are for in-gauge transport and where gauge violations occur within the network. The statistics used show that rail freight transport is mainly international. In the literature review, it describes how Dutch rail freight corridors are connected to international rail freight corridors.

To choose a design methodology, the Waterfall Model, V-model, Feedback Model, and Spiral Model were reviewed. Linear models such as the Waterfall Model provide limited flexibility and are less suited to problems characterised by uncertainty and evolving constraints. The iterative Spiral Model, incorporating structured feedback, is better aligned with complex design challenges. The V-model offers regular verification and validation, and the Feedback Model offers regular feedback loops, but also offers less flexibility due to their linear characteristics.

For gauge assessment, NEN EN 15273 defines static, kinematic, and dynamic calculation methods based on reference profiles. Where there is little to no information available in the literature, but which is necessary for the design challenge, is a calculation method that looks at the infrastructure. This means how the detected gauge violations are converted into (im)possibilities for out-of-gauge transport.

Finally, no suitable method was identified to prioritise bottlenecks. Although Failure Mode and Effect Analysis shows conceptual similarities, it does not adequately address the network-based and infrastructural nature of railway bottlenecks. In general, the literature lacks an integrated approach that transforms infrastructure-based gauge violations into operational possibilities and supports systematic bottleneck prioritisation, which forms the research gap addressed in this thesis.

3 Methodology

In section 2.3, a number of options are given for the methods that can be applied (in part). To solve the design challenge, choices will have to be made about which methods to apply and why. The choices are listed in order of application and are linked to the general structure of the methodology. The method itself was developed by applying the Spiral Model, combined with the Research by Design method. The design challenge consists of two parts: gauge calculation and bottleneck prioritisation. This is supplemented by the fact that the gauge calculation, in particular, depends on various variables. Due to this complexity, the Spiral Method, with its adaptability for large-scale systems, is used as the design method. With this complexity, the various variables, and the current research gap, it became clear that the research results must come from design. This resulted in the Spiral Model being combined with the research by design method.

3.1. General methodology

Manual data cleansing and data enrichment were chosen to modify the data set. This method was chosen because it is necessary to visually determine whether a violation is relevant and how far it extends into the gauge [32]. An example of the information used for the data cleansing is given in Figure 2.2.

Based on the adjusted data set, the infrastructure assessment is carried out in phase 1. The main component is the calculation of the maximum applicable gauge based on the violations. The input for this is what is given in NEN-EN 15273-1 Annex G about the compatibility between the kinematic and static calculation methods, the observation that the flexibility coefficient of freight trains remains below the s_{lim}-value ($s_{\mathrm{lim}} < 0.3$) [37] [28] and the availability of the parameters required for the static calculation. Based on these three points, it was decided to use the static calculation method as the basis for the designed method. Based on the static calculation method, a method is devised to calculate the maximum gauge based on the infrastructure. This phase also introduces test gauges. Phase 1 outputs the number of violations of the red measurement area, the violations of the various gauges, and indicates which violation is the largest and constitutes the decisive bottleneck.

In phase 2, the bottleneck categories identified in phase 1 are prioritised. The results of the method can serve as the basis for a redesign of the investigation railway line. The Design FMEA (DFMEA) is most applicable to this situation. It was therefore decided to use this method as the basis for prioritising bottlenecks. The DFMEA is adapted to meet the desired solution to the design challenge. The method is supplemented by the application of scenarios. The outcome of this phase is a prioritisation based on Bottleneck Priority Numbers (BNPN) and possible solution strategies based on BNPN, geographical distribution, and speed of implementation. The chosen methods are listed in Table 3.1.

Table 3.1: Overview of applied methods

Applied methods	
Design Method	Spiral Model + Research by Design
Data set modifying	Manual cleansing + Manual Data enrichment
Gauge calculation method	Static gauging method
Prioritisation method	DFMEA (only as a basis)

One step that is not carried out in the method but is included in this thesis is the feedback loop to the desired solution. This is done in the thesis in chapter 5 where the question of whether there is a solution to the Design Challenge is answered. The process can be summarised in the block diagram shown in Figure 3.1.

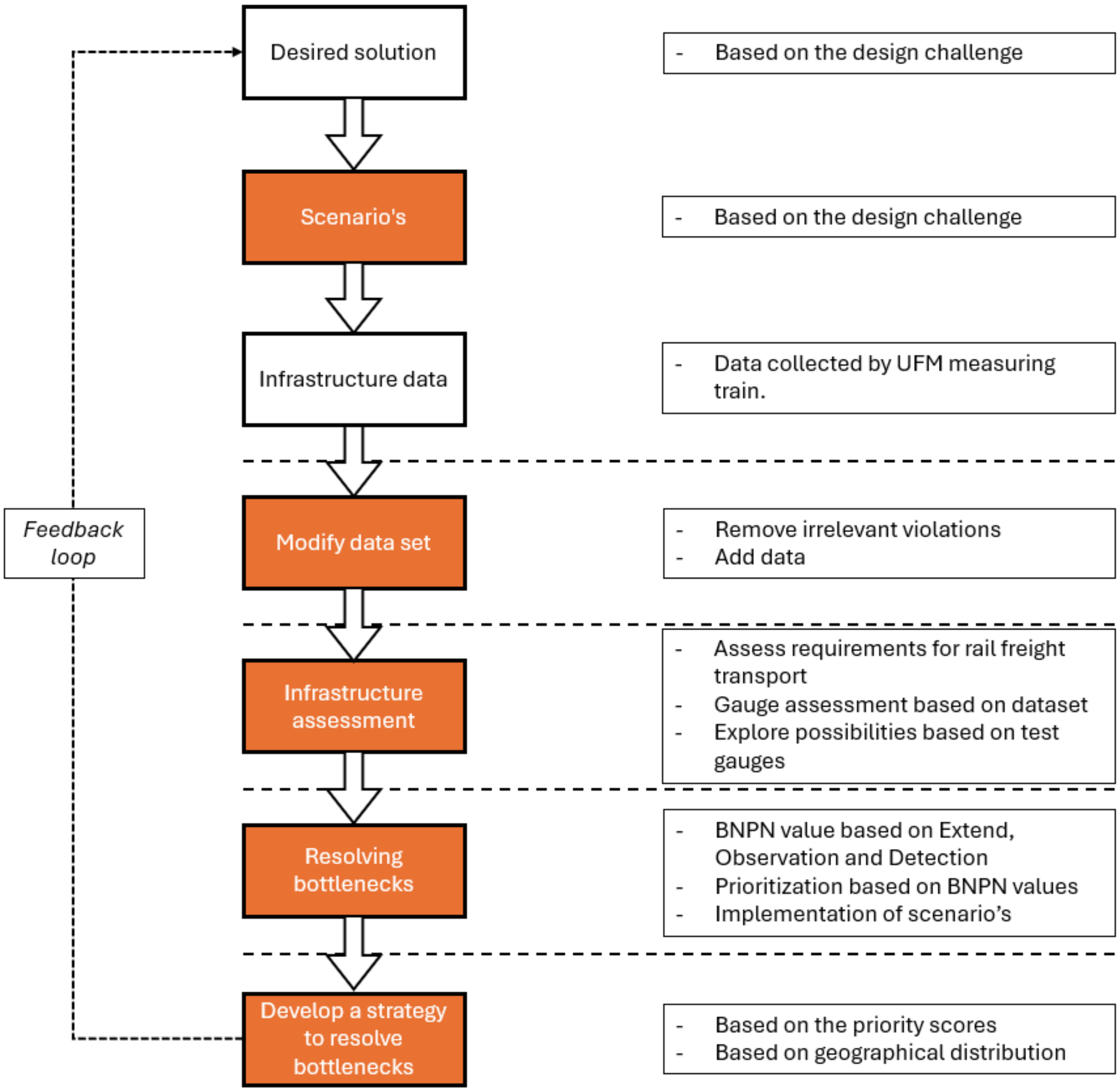


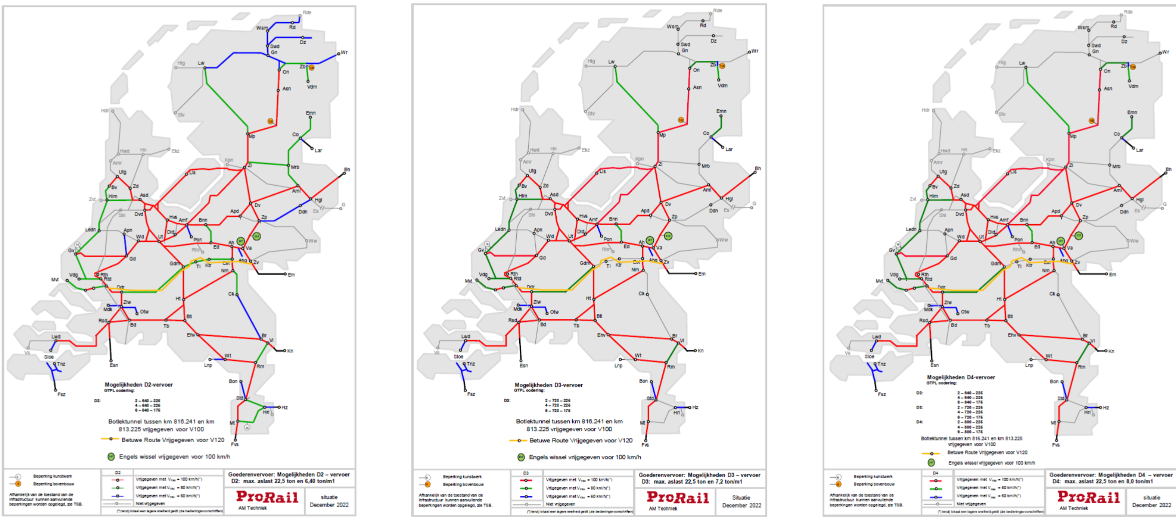
Figure 3.1: Schematic representation of the design method

3.2. Infrastructure assessment

The first optional step is to determine the alternative routes available. This must be done for the section of the rail freight corridor that is out of service. The diversion route must meet the following indicators:

- Sufficient loading capacity for rail freight transport.
- Physical connection to the rest of the network.
- Compliance with current TEN-T requirements.
- Within a reasonable distance, both in terms of distance and time, from the closed railway line.

The GVS00094 is used to determine whether the load bearing capacity is sufficient. Figure 3.2 shows which parts of the Dutch railway infrastructure comply with the load bearing class "D" requirement.



(a) D2 **(b)** D3 **(c)** D4

Figure 3.2: Infrastructure suitable for D2 [left], D3 [center] and D4 [right][5]

The figure shows that load class D is permitted on many parts of the network. The different colours indicate that speed restrictions are in place. In blue sections, the maximum speed is $60\mathrm{km/h}$, in green sections it is $80\mathrm{km/h}$, in red sections it is $100\mathrm{km/h}$, and in yellow sections (Betuwe Route) the maximum speed is $120\mathrm{km/h}$.

Physical connection to the rest of the network means whether it is possible with the existing infrastructure to resume the planned original route, and if so, how. For example, if a freight train has to change direction at a station, the infrastructure must be in place to park the train there and move the locomotive to the other side through a bypass track. Switches must also be in place to get to the planned connecting track. This assessment is done visually based on the most up-to-date overview of the rail infrastructure in RailMaps [11].

The identified routes are then analysed to determine whether they meet the design requirements for the UIC-gauge. Where the infrastructure does not meet the requirements, it is assessed what is needed to ensure compliance or what is possible without modifications.

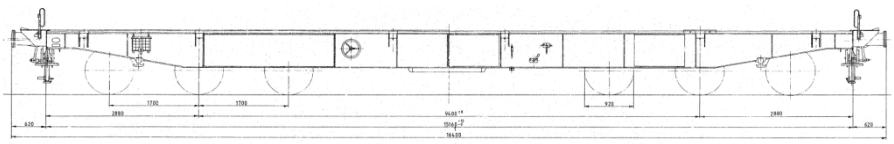
3.2.1. Gauge assessment

To assess the available gauge, data on the structures surrounding the railway infrastructure that are within the UIC gauge are required. Data are required on where the structures are located along the track, how far the structures extend into the gauge, and what type of structures they are. This information is needed to ultimately analyse whether the problem lies in a type of structure that is located along the entire route or whether part of the route has not been designed in accordance with regulations and different types of structures have been built within a short distance in the UIC gauge. This will determine whether a solution for a particular structure needs to be implemented for the entire route or whether a redesign of a particular location needs to be implemented.

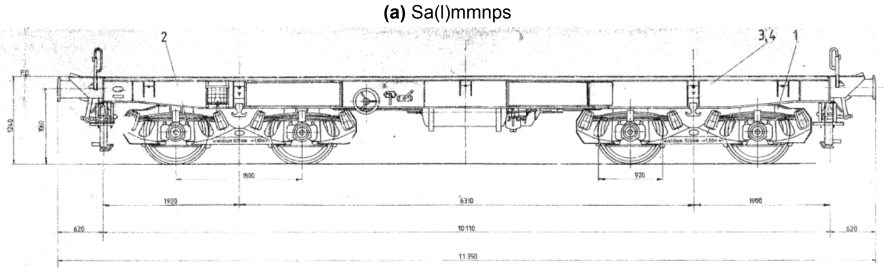
Furthermore, data are required on how far the structures extend into the UIC gauge. There are two reasons for this. Firstly, the structure that extends farthest into the UIC gauge is decisive and therefore constitutes the bottleneck. This decisive bottleneck is needed to determine what (out-of-gauge) transport is possible in the current situation. In addition, the extent of the UIC gauge exceedance can be used to prioritise the obstacles to be resolved. Minor violations are less of a priority to resolve than major violations.

For railways in the Netherlands, these data are collected by the Infrastructure Manager and are available in Sigma [13]. In Sigma, the measurements that are periodically carried out with the UFM measuring train are checked against a selected (UIC-)gauge. The programme then provides information on which structures are located at which (Rijksdriehoek)coordinates within the selected (UIC-)gauge. The list of violations in the Dutch railway network can then be downloaded as an xlsx-file. This makes it possible to analyse and process the data.

Before loading the violations on the previously selected route, it is necessary to determine which violations are relevant. If the infrastructure is tested against a UIC gauge, violations that are not relevant can also be detected. For example, when assessing the infrastructure on the red measurement area, objects close to ground level are also detected as violations. In the scenario in which this method is to be applied, out-of-gauge rail freight transport is considered. This concerns flat freight waggons such as Sa(l)mmnps or Slmmnps. These are waggons that both have a floor height of 1240 mm; see Figure 3.3 for an example of these waggons. In this scenario, all low-lying structures, such as coils and pots, switch controls, and platform edges, are omitted and excluded from further processing.



(a) Sa(l)mmnps



(b) Slmmnps

Figure 3.3: Sa(l)mmnps and Slmmnps flat waggons

The data set available for this thesis does not include any data on the dimensions of the violation. This means that for now, Sigma must be manually checked to determine which violations are problematic. For example, the system indicates obstacles in the “category ”other”” and it must be determined whether or not these constitute an obstacle to (out-of-gauge) freight transport. The obstacle “light signal” can be a signal on a pole (obstructive) or a ground signal (non-obstructive). The same applies to signs.

The extent of the violation within the UIC gauge must then be determined manually. This can be done by placing the cursor at that point, after which Sigma will provide the x and y-coordinates. The x-coordinate can be used to determine the extent of the violation. Because the origin in Sigma is at the centre of the track, the total violation must be calculated. This can be done using the simple formula given in Equation 3.1. Because this has to be done manually, there is a risk of errors. subsection 5.2.2 explains how the method can be used with more precision.

$$x_{\mathrm{BN},ij} = b_{\mathrm{RM}} - |x_{\mathrm{Sigma},ij}| \tag{3.1}$$

Structures on the left side of the gauge have a negative x-coordinate. In the calculation, it was therefore decided to use the absolute value for x_{sigma} so that only positive values are obtained for $b_{\text{BN},ij}$. The advantage of performing the calculation in this way is that as soon as negative values are obtained for $b_{\text{BN},ij}$, the structure is outside the red measurement area and therefore cannot be a bottleneck. These violations can be removed in a data processing application.

The cleaned and supplemented data set is further processed. This is to achieve two goals. The first goal is to generate an overview of what violations there are and how many there are. What are the extreme values per violation category? The maximum, minimum, and median are calculated for each category. The median is chosen because it is less sensitive to outliers and therefore provides a better picture of the extent of most violations. This is done to find the decisive bottleneck for each category, but also for the total selected trajectory. This can be used for further use in the FMEA. The second goal is to plot the violations on a map. This is to visually see whether there are clusters of violations or whether it is a problem along the entire route. This is used for the solution strategies.

3.2.2. Infrastructure margins

In order to answer the sub-question in section 1.2 about what is possible within the known violations, it must be determined what format of out-of-gauge rail transport can be operated. This is done on the basis of NEN EN 15273, as mentioned in subsection 2.3.2. This involves varying the absolute gauging method. As mentioned earlier, the absolute gauging method uses the dynamic calculation method. This is effective and desirable when calculating the kinematic gauge for smaller networks or completely enclosed situations, such as in narrow rail tunnels. An example where this dynamic method pays off is for metro networks. The dynamic method is not desirable for calculating what is possible on (parts of) the national network, and, if desired, extended to an international network. The computing power and time required are not proportional to the goal of quickly assessing what out-of-gauge rail freight transport is possible. Because the focus is on infrastructure and the possibilities for out-of-gauge rail transport, little information is available about rolling stock. Kinematic calculation methods require information on rolling stock characteristics.

Based on the standard, Equation 3.2 is formulated to calculate the maximum swept envelope on the chosen route i, $b_{\text{SE},i}$.

$$b^{\text{st}}_{\text{SE},i} = b_{\text{RM}} - \max[\,x_{\text{BN},ij}] - b^{\text{st}}_{\text{inf.margin}} \tag{3.2}$$

With $\max[\,x_{\text{BN},ij}]$ the maximum violation of an object j along the chosen route i. The different terms are visualised in Figure 3.4.

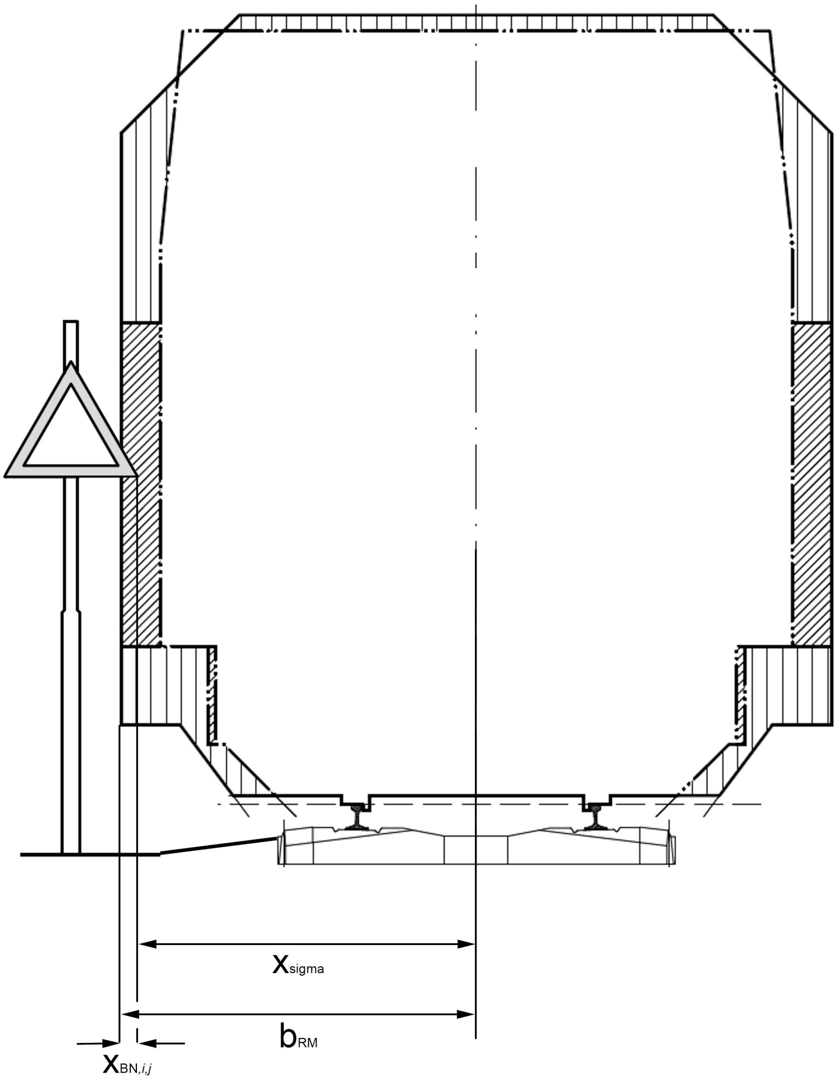


Figure 3.4: Visualisation of the maximum swept envelop calculation (figure adapted from standard)

The calculation of $b_{\text{inf.margin}}$ is based on Equation 2.1, but in order to apply the formula in Equation 3.2, $b^{\text{st}}_{\text{CR}}$ has been omitted. This results in the formula given in Equation 3.3.

$$b^{\text{st}}_{\text{inf.margin}} = S_{\text{i/a}} + \Sigma^{\text{st}}_{\text{j}} \tag{3.3}$$

with

$$S_{\text{i/a}} = S_{\text{l}} + S_{R,\text{i/a}} \tag{3.4}$$

and

$$\begin{aligned} \Sigma_{\text{j}} = T_{\text{voie}} + \frac{T_{\text{D}}}{L} \times h + \frac{T_{\text{D}}}{L} \times s \times (h - h_{\text{c0}})_{>0} + \tan(1^{\circ}) \times (h - h_{\text{c0}})_{>0} \\ + \frac{T_{\text{osc}}}{L} \times s \times (h - h_{\text{c0}})_{>0} + \frac{s}{L} \times D \; or \; \frac{I \times (h - h_{\text{c0}})_{>0}}{1000} \end{aligned} \tag{3.5}$$

With the formulas given in subsection 2.3.2 the following value can be calculated for S_l (lateral projection of track widening):

$$S_\mathrm{l} = \frac{l - l_\mathrm{norm}}{2} = \frac{l_\mathrm{max} - l_\mathrm{norm}}{2} = \frac{1465 - 1435}{2} = 15[\mathrm{mm}] \tag{3.6}$$

$$S_R, i/a\,[\mathrm{mm}] = \begin{cases} R = \infty, & S_{R,i} = S_{R,a} = 45, \\ \infty > R \geq 250\,\mathrm{m}, & S_{R,i} = S_{R,a} = \left(\frac{3.75}{R} + 0.045\right) \times 1000, \\ 250\,\mathrm{m} > R \geq 150\,\mathrm{m}, & S_{R,i} = \left(\frac{50}{R} - 0.140\right) \times 1000, \quad S_{R,a} = \left(\frac{60}{R} - 0.180\right) \times 1000. \end{cases} \tag{3.7}$$

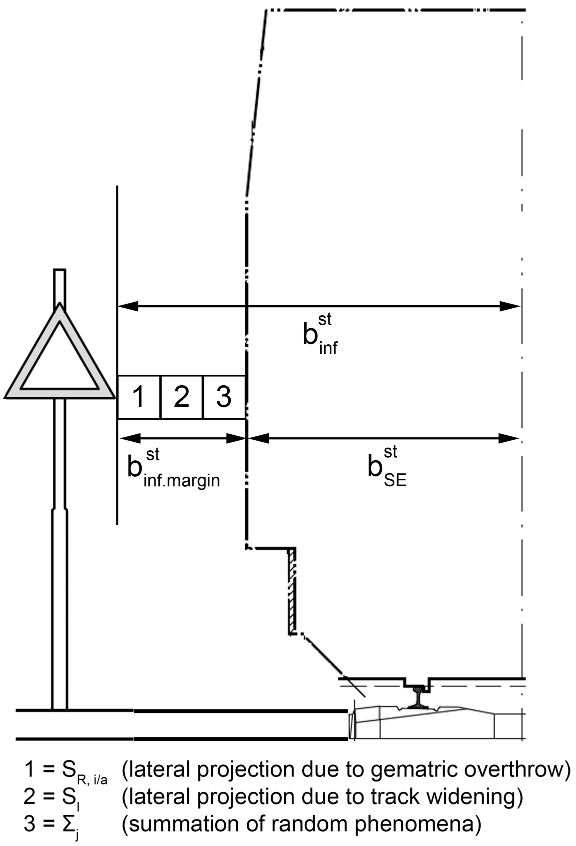


Figure 3.5: Explanation $b^{\mathrm{st}}_{\mathrm{inf.margin}}$(figure adapted from standard)

3.2.3. Test-gauges to explore the possibilities

During gauge assessment, as it currently takes place in subsection 3.2.1, structures are detected based on the maximum lateral use of the red measurement area. The infrastructure margin ($b^{\mathrm{st}}_{\mathrm{inf.margin}}$) depends on the height of the train. When considering what is possible in the lateral direction, given the detected structures, the answer will depend on the height of the train.

To develop solution strategies, there is also the possibility to examine which bottlenecks apply to certain standard-format out-of-gauge gauges, from now on called test-gauges. These test-gauges can be drawn either on the basis of the expected format of out-of-gauge rail freight transport or on the basis of out-of-gauge gauges that the infrastructure manager wishes to offer. The test gauges provide an answer that indicates more clearly whether or not a train can run within that gauge.

For now, it has been decided to draw up three test-gauges and to examine which and how many violations occur for each of these gauges. In this case, it was decided to divide the available space for the swept envelope, as required by the standard, into three equal parts. This means that half the width of the static reference profile (1575mm [26]) serves as a basis. The area within this gauge would be in-gauge transport and, therefore, should already be available. Half the width of the red measurement area minus the infrastructure margin serves as the maximum width. It was decided to divide the distance between these two limits into three approximately equal parts. The heights of the test gauges have been chosen in the same way. However, no absolute margin is known here, as this falls outside the scope, but it has been decided to keep 50mm free up to the height of the red measurement area, which is 5000mm. The height of the static reference profile is 4650mm.

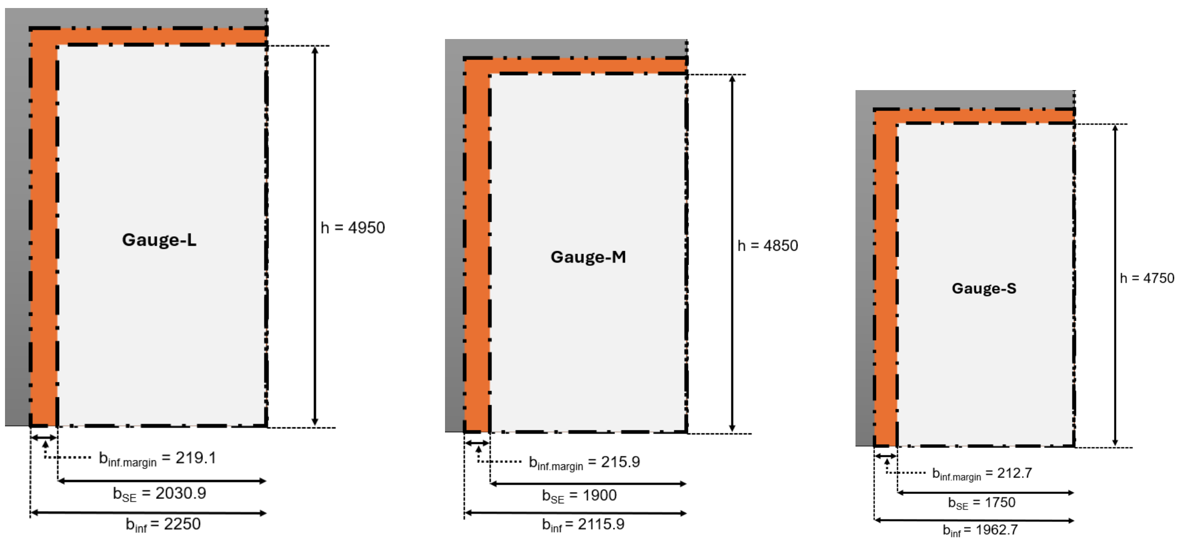
The test gauges are called Gauge-L (Large), Gauge-M (Medium), and Gauge-S (Small). Gauge-L uses the maximum available space in the red measurement area. The $b^{\text{st}}_{\text{inf}}$ is based on a selected height of $h = 4950mm$. If Equation 3.3 is applied and $V = V_{\max} = 100\text{km/h}$ is used, then it follows that $b_{\text{SE}} = 2030.9\text{mm}$ with an infrastructure margin $b^{\text{st}}_{\text{inf.margin}} = 219.1\text{mm}$.
For Gauge-M, $b^{\text{st}}_{\text{SE}} = 1900\text{mm}$ and $h = 4850\text{mm}$ are used. This results in a $b^{\text{st}}_{\text{inf.margin}} = 215.9\text{mm}$ and a $b^{\text{st}}_{\text{inf}} = 2115.9\text{mm}$. Gauge-S is based on $b^{\text{st}}_{\text{SE}} = 1750\text{mm}$ and $h = 4750\text{mm}$. This gives $b^{\text{st}}_{\text{inf.margin}} = 212.7\text{mm}$ and $b^{\text{st}}_{\text{inf}} = 1962.7\text{mm}$. The values for the three test gauges, which correspond to the widths indicated in Figure 2.9 and Figure 3.5, are listed in Table 3.2.

Table 3.2: Out-of-Gauge test gauges

Gauge	$b^{\text{st}}_{\text{SE}}$	h	$b^{\text{st}}_{\text{inf.margin}}$	$b^{\text{st}}_{\text{inf}}$
Gauge-L*	2030.9	4950	219.1	2250
Gauge-M	1900	4850	215.9	2115.9
Gauge-S	1750	4750	212.7	1962.7

*$b^{\text{st}}_{\text{SE}}$ for gauge-L is not rounded because it needs to meet the width of the red measurement area.

The dimensions shown in the table are also visualised in Figure 3.6.



(a) Gauge-L **(b)** Gauge-M **(c)** Gauge-S

Figure 3.6: Visualisation of the various test gauges. Not to scale, dimensions in mm

3.2.4. Data preprocessing and analysis procedure

The data preprocessing and analysis procedure follows a sequential workflow in which raw measurement data are transformed into a structured and interpretable dataset for the evaluation and prioritisation of gauge violations. The procedure is implemented computationally; the complete implementation is provided in Appendix A.

The workflow starts with the import of raw spreadsheet data originating from Sigma, the ProRail application used to manage railway alignment data and geometric characteristics related to obstacles and violations. The raw data set contains a large number of descriptive and administrative attributes for each recorded violation. As a first preprocessing step, non-essential and redundant attributes are removed to reduce complexity and to ensure that subsequent analyses are based solely on relevant parameters.

Next, manual data cleansing is performed. This involves removing the violation categories that are not relevant to out-of-gauge rail freight transport, as specified in subsection 3.2.1. Individual violations that are irrelevant are first recorded in a separate data set, so that they can then be processed in a single data cleansing step with the created data set as input.

The data set is manually enriched by adding the $x_{\mathrm{BN},ij}$ values. These values are observed manually in Sigma, recorded per structure name, and then added to the data set. This also involves a data cleansing step. If a detected violation is outside the red measurement area, it is removed from the data set. These false positives are stored in a separate data set so that, if desired, something can be said about the accuracy of the provided data.

For each remaining violation, additional parameters are calculated to be used for the infrastructure margin calculation. This includes the values I, S, and Σ_j for different speeds. The formulas given earlier are used for this. Further enrichment of the data set is done with the addition of the outcome from the gauge calculation. For this purpose, the added values and statistical calculation method as previously provided are utilised. The modified data set is then analysed again using filtering and visualisation capabilities, showing the violations that are relevant to the assessment.

The prioritisation of violation categories is performed using the analytical framework described in section 3.3. First, this analysis is conducted for the entire red measurement area corresponding to gauge-L, as defined in subsection 3.2.3. For this purpose, the relevant formulas are applied using the modified data set. Based on these inputs, the exposure, occurrence, and detectability scores, denoted E^{BNPN}, O^{BNPN}, and D^{BNPN}, are calculated. The summary statistics, including maximum, minimum, and median values per bottleneck category, are then derived and used to compute the overall BNPN score. These results are presented for the selected geocode.

The same procedure is subsequently applied to the two additional test gauges considered in this study. First, the values of $b^{\mathrm{st}}_{\mathrm{inf.margin}}$ and $b^{\mathrm{st}}_{\mathrm{inf}}$ are determined based on the selected values of h and $b^{\mathrm{st}}_{\mathrm{SE}}$. This is achieved by calculating Σ_{j} for the selected parameters and substituting these values into Equation 3.3. The value of $b^{\mathrm{st}}_{\mathrm{inf}}$ is then obtained using Equation 3.8.

$$b^{\mathrm{st}}_{\mathrm{inf}} = b^{\mathrm{st}}_{\mathrm{SE}} + b^{\mathrm{st}}_{\mathrm{inf.margin}} \tag{3.8}$$

To determine which violations remain applicable for the test gauges and to quantify their magnitude, the calculation defined in Equation 3.9 is applied.

$$x_{\mathrm{test-gauge},ij} = (-b_{\mathrm{RM}}) + x_{\mathrm{BN},ij} + b^{\mathrm{st}}_{\mathrm{SE}} + b^{\mathrm{st}}_{\mathrm{inf.margin}} \tag{3.9}$$

Here, $x_{\mathrm{test-gauge},ij}$ represents the test gauge violation of structure j on the railway line i. If $x_{\mathrm{test-gauge},ij} \leq 0$, the structure, although previously a violation of gauge-L, no longer constitutes a violation of the smaller test gauge. This approach is valid because, according to the applicable regulations, test gauges, including the margins, may not exceed the red measurement area.

Violations for which $x_{\mathrm{test-gauge},ij} \leq 0$ are excluded from further analysis. These exclusions are logged separately to allow quantification of the reduction in both the number and types of violations. The BNPN prioritisation calculations are then repeated for the remaining violations, and the resulting scores are stored and presented in tabular form.

Finally, the procedure concludes with an integrated visualisation step in which the processed data set is filtered according to user-defined selections, enriched with geocoded coordinates and severity scores, and visualised on an interactive map. Each violation is displayed with relevant contextual information, allowing comprehensive spatial analysis. The visual outputs are also stored as stand-alone files to facilitate sharing and further inspection.

In summary, the analysis procedure consists of the following main steps:

- Data import and preprocessing, including cleaning and merging with additional data sets.
- Spatial and categorical filtering to allow for targeted inspection of violations.
- Calculation of margins, test gauge violations, and prioritisation scores.
- Visualisation and tabulation of results for interpretation and comparison.

The general workflow of the analysis procedure is summarised in the flow chart shown in Figure 3.7.

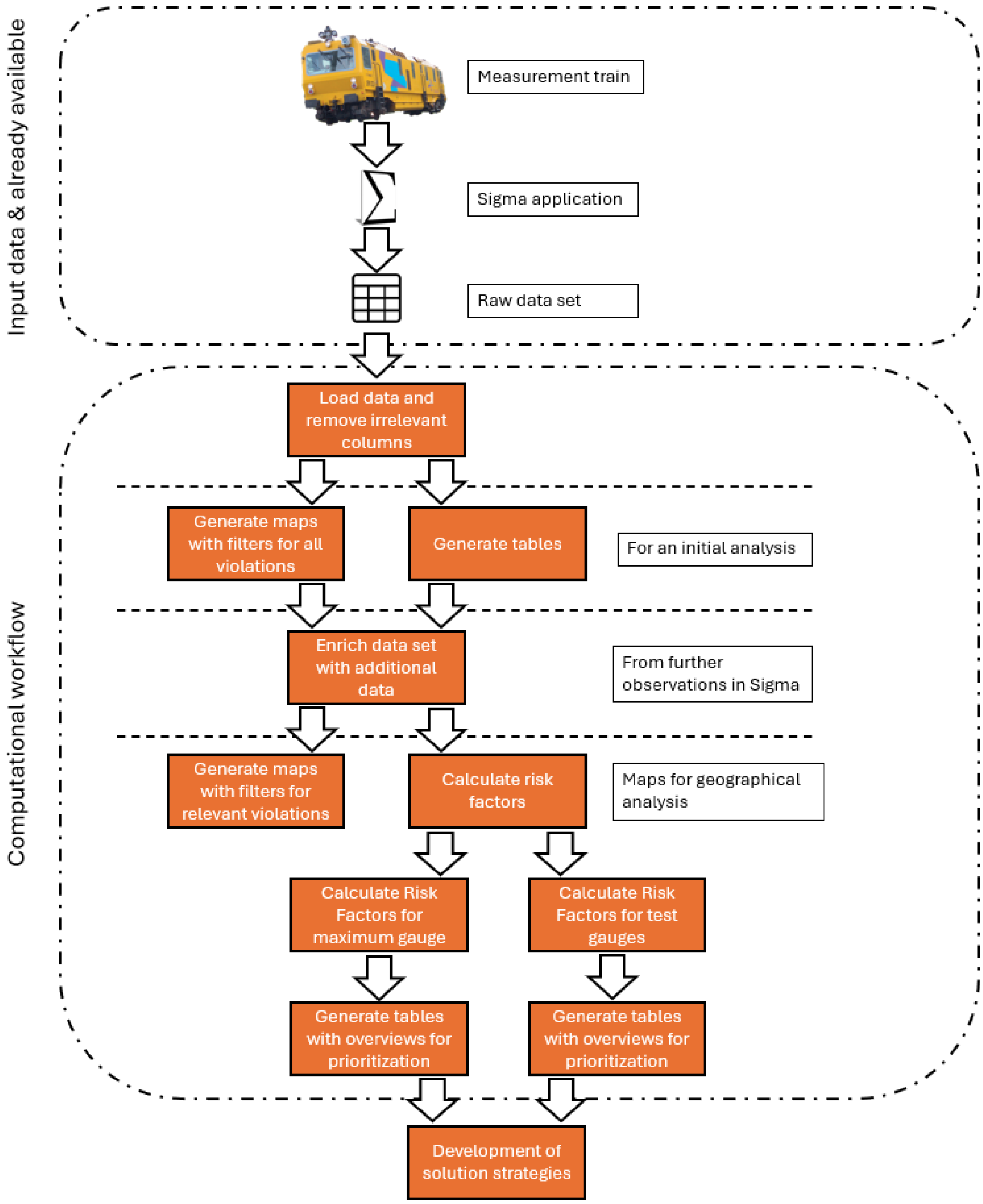


Figure 3.7: Flow chart of the data analysis procedure

3.3. Resolving bottlenecks

The implemented data analysis as described in subsection 3.2.4 provides an overview of:

1. The total number of violations on a railway line.
2. The number of violations per type on a railway line or in total for the network.
3. An overview of the extreme values and the median for each type of violation.
4. The locations where the violations occur.
5. How far do the violations extend into the red measurement area of a railway line.
6. The maximum landing/vehicle width that can be accommodated on a railway line.

The data have a strong similarity to the input required to perform an FMEA, but there are also differences. For example, the detection value (D) always has the highest score because the structures are always measured; they are not hidden along the track. In order to prioritise the different categories of bottlenecks, it was decided to use the design FMEA as the basis for the developed method, as further explained in subsection 3.3.1. In subsection 3.3.3, it is mentioned how solution strategies can be formulated.

3.3.1. Prioritisation of bottlenecks

The Design FMEA prioritises the various Failure Modes using the Risk Priority Number (RPN), which is calculated based on Severity, Occurrence, and Detection. In order to prioritise the various bottleneck categories, it was decided to calculate a Bottleneck Priority Number (BNPN). The BNPN is calculated based on Extent (instead of Severity for the RPN), Observation (instead of Occurrence for the RPN), and Detection.

The values for E^{BNPN}, O^{BNPN} and D^{BNPN} are determined on the basis of the available data, as no formulas have been given in the literature to perform an infrastructure assessment. The superscripts $^{\mathrm{BNPN}}$ have been included to clarify the difference between cant (D) and energy or Young's modulus (E). The BNPN score must represent a number of elements. One of these is that it shows that the bottleneck category to which the decisive bottleneck belongs is given a high priority score. Furthermore, the frequency of violations must be taken into account, but, for example, a violation that occurs 100 times but only protrudes 2 mm in the gauge is given a lower priority than a bottleneck category that occurs 10 times but protrudes 200 mm in the gauge.

It is decided to include the property of the maximum exceedance of the bottleneck category (j) in the gauge of a railway line (i) in the Extend value ($E_{i,j}^{\mathrm{BNPN}}$). This calculation also takes into account the median value of the bottleneck category. This involves looking at the ratio of the violation that occurs in relation to the maximum that can occur on the railway track. The formula is given in Equation 3.10.

$$E_{i,j}^{\mathrm{BNPN}} = \frac{\max[\,x_{\mathrm{BN},ij}] + \mathrm{med}[\,x_{\mathrm{BN},ij}]}{\max[\,x_{\mathrm{BN},i}] + \max[\,\mathrm{med}[\,x_{\mathrm{BN},ij}]]} \tag{3.10}$$

Here, $\max[\,x_{\mathrm{BN},i}]$ is the maximum violation on the selected track i. $\mathrm{med}[\,x_{\mathrm{BN},ij}]$ is the median of a bottleneck category j along track i and $\max[\,\mathrm{med}[\,x_{\mathrm{BN},ij}]]$ is the maximum median of all bottleneck categories on track i.

For the Observation value $O_{i,j}^{\mathrm{BNPN}}$ Equation 3.11 is applied.

$$O_{i,j}^{\mathrm{BNPN}} = \frac{\Sigma \mathrm{violations}_j}{\Sigma \mathrm{violations}_i} \tag{3.11}$$

Here, the sum of the violations of bottleneck category j is divided by the sum of all violations along the route i. In this way, it is taken into account how often a particular violation occurs along the track.

For the Detection value, the current input does not allow for a distinction to be made between the different bottleneck categories. As indicated earlier, this is because all bottleneck categories are detected equally well. The value is deliberately not removed from the formula. This is because a fixed value, provided that $D^{\mathrm{BNPN}} > 0$, does not affect the outcome and offers the possibility of expanding the weighing method in the future should other bottleneck categories, such as overhanging trees, be included. For now, Equation 3.12 has been chosen for D^{BNPN}.

$$D_{i,j}^{\mathrm{BNPN}} = 1 \tag{3.12}$$

3.3.2. Scenario integration

The scenarios introduced in chapter 1 are applied in the calculation of the BNPN value. In the final calculation, given in Equation 3.13, a weighing factor w_j is added. This weighing factor, which is unique for each bottleneck category, reflects the extent to which the bottleneck category is an actual bottleneck in the chosen scenario. For example, in the *No matter what* scenario, damage to the infrastructure is accepted, but this damage must not be counterproductive. If, for example, the damage caused causes the train to derail, it is not effective to carry out that transport. In that case, the weighing factor will have a value that prevents the bottleneck category from decreasing in priority. The impact caused by the damage assigned to the bottleneck category is thus captured in the weighing factor w_j. This also varies by type of freight. A robust freight can withstand more than a fragile freight.

Determining the weighting factors for a specific freight requires further research and will not be carried out within this thesis. w_j is included in Equation 3.13, but will be omitted in the implementation of the case study due to a lack of values for the weighing factor.

The BNPN value is calculated by multiplying Equation 3.10, Equation 3.11 and Equation 3.12 with w_j, resulting in Equation 3.13.

$$BNPN_{i,j} = \left(E_{i,j}^{\mathrm{BNPN}} \times O_{i,j}^{\mathrm{BNPN}} \times D_{i,j}^{\mathrm{BNPN}}\right) \times w_j \tag{3.13}$$

The bottleneck category with the highest BNPN is the category with the greatest impact on the maximum width of out-of-gauge rail freight transport. This category has the highest priority for resolution. In subsection 3.2.3, three test gauges are described. For the first gauge (gauge-L), the process of calculating the BNPN score is described in the text above. This process is repeated in the same way for the other two gauges (gauge-M and gauge-S).

3.3.3. Developing solution strategies

The solution strategy is primarily based on the calculated BNPN values. This is because the bottleneck category with the highest BNPN value represents the greatest obstacle to out-of-gauge rail freight transport. One of the possible solution strategies that arises from this is to resolve the bottleneck strategies one by one based on the BNPN score.

However, this may not necessarily be the most obvious solution strategy. Two other aspects are also taken into account when determining the strategy, namely geographical distribution and speed of implementation. The geographical distribution may reveal that several bottlenecks of different categories are clustered at certain locations. The identified location can then be adjusted several times for each bottleneck category or once for all bottlenecks. The latter is expected to cause the least disruption to passengers. Another possibility is that a bottleneck category does not have the highest BNPN score but is resolved earlier due to its speed of implementation. This allows the bottleneck category to be resolved while a more complex design is drawn up for the other bottleneck categories and/or locations. This could involve relocating structures located between stations that do not require major construction plans and permits, while simultaneously redesigning station locations to remove platform obstacles. An initial estimate of how quickly a solution can be implemented can be provided by subject matter experts.

The three test gauges that have been set up are also included in the development of the solution strategy. Based on the geographical distribution of the bottlenecks for the various test gauges, certain locations may contain only bottlenecks for the larger gauges. These locations may be given lower priority in the solution strategy than locations where there are bottlenecks for all test gauges.

3.4. Key findings

A method has been developed that achieves the following points. The method ensures that measurement data and manual observations are converted into a cleaned data set containing the relevant violations (cleaning of the data set) and how far they extend into the gauge (addition to the data set). A detection in the maximum applicable gauge is converted into a concrete bottleneck. Based on this data set and the NEN standards, the maximum reference gauge that fits the current infrastructure is then calculated.
An interesting finding based on the parameters specified in NEN EN 15273 relates to speed. The current procedure within ProRail is to reduce the speed of out-of-gauge transport that passes through a bottleneck location. Looking at the standard, it should be noted that one variable depends on speed (T_{D}) and that it decreases with higher speeds. This implies that, according to the standard used, it is more favourable to travel at higher speed than to slow down. In order to resolve the bottlenecks, a prioritisation is made based on BNPN scores, which are calculated on the basis of the cleaned-up data set. The scores are used for the maximum gauge, but also for two other test gauges.

Returning to the scenarios as set out in subsection 1.3.1, the method provides information on the following points.

- For the *No matter what* scenario, it indicates which structures need to be cleared in order to carry out out-of-gauge transport or what will be damaged as a result of this out-of-gauge transport.
- For the *Segregated rail traffic scenario - Low demand*, it also indicates what needs to be cleared in order to carry out the out-of-gauge transport, but sets a stricter limit for what is still permitted, as damage to the infrastructure will not be tolerated.
- For the adjustment situation, it also provides a method for finding an alternative route.

4 Case study

The case study is being conducted to determine whether the proposed method is effective and produces the desired results. To this end, the scenario described in subsection 1.3.1 is being further expanded. The Case Study examines a situation in which there is a major disruption on the Betuwe Route between Kijfhoek and Meteren, making it impossible for train traffic in both directions for an extended period of time.

The Betuweroute is an exception in the Dutch railway network. This is a dedicated rail freight line that was opened in 2007. This railway line has been fully equipped and designed to transport freight, including oversized freight (provided that it falls within the out of gauge limitations), without restrictions, both now and in the future. Once the third track in Germany and the connexion at Meteren have been completed, the Betuwe Route should free up space on the rest of the network for more passenger trains. The Betuwe Route should facilitate by far the most freight routes in 2030. This can be seen in Appendix D.

This unique addition enhances the efficiency of the network, but also poses a threat. After all, in the event of a failure of the Betuweroute, freight traffic will have to be handled by the rest of the network, which will have more passenger trains running on it in the future than is currently the case.

During the case study, gauge violations were used as they were known in Sigma on 15 November 2025.

4.1. Assumptions

In order to carry out the case study, a number of variables must be assumed in order to arrive at results. These assumptions are as follows.

- As no data are available on the flexibility coefficient of the possible freight trains, the s_{lim} value is applied. For gauge-GC, this is 0.3 $[-]$.
- No values have been provided for the cant or the cant deficit. Therefore, it has been assumed that the most unfavourable situation applies. This involves calculating the theoretical cant required ($D_{\text{th},V}$) according to OVS00056-4.1. Where this is less than 40mm, based on Table 14 of the OVS, it is assumed that the infrastructure does not contain any cant, so the theoretical cant is also equal to the cant deficit $(I = D_{\text{th},V}, for D_{\text{th},V} \leq 40\text{mm})$. For a $D_{\text{th},V} > 40$, it is assumed that only the minimum cant is applied, which is 20 mm according to the regulation. This results in $(I = D_{\text{th},V} - 20, for D_{\text{th},V} > 40\text{mm})$. The maximum cant deficit is limited to 120mm, which is the maximum allowed cant deficit according to the regulation.
- As mentioned in subsection 3.3.2, there is no information available on w_j. Therefore, no quantitatively expressed outcome is given for the various scenarios when prioritising the bottleneck categories. However, the way in which the scenarios can influence the outcome is mentioned.

- The height of the roll centre, h_{c0}, must be between the top of the loading floor and the top of the wheel of a flat freight waggon. The exact height is unknown, but for now it is assumed to be exactly halfway between the top of the loading floor and the top of the wheel of a Sa(I)mmnps or Slmmnps waggon. In both cases, $h_{c0} = h_{\text{wheel}} + \frac{h_{\text{floor}} - h_{\text{wheel}}}{2} = 920 + \frac{1240-920}{2} = 1080\text{mm}$ measured from the top of the rail.
- To apply the test gauges (gauge-L, gauge-M, and gauges), the parameters associated with the speed $V = 100\text{km/h}$ are used.
- In Sigma, the infrastructure is assessed against the UIC gauge currently in use, the gauge-GC including the red measuring area, which is 4500 mm wide. This also includes a section of red measurement area near the ground, which is not relevant for the scenario of out-of-gauge rail freight traffic. This scenario assumes the use of flat waggons with a loading floor that is 1240 mm above the running plane, which is the case when using Slmmnps or Sa(I)mmnps waggons. Only the margin around the waggon and the red measurement area from the top of the waggon are relevant. In Figure 4.1, the complete red measuring area for UIC-gauge GC is shown on the left, and the gauge relevant to the scenario is shown on the right.

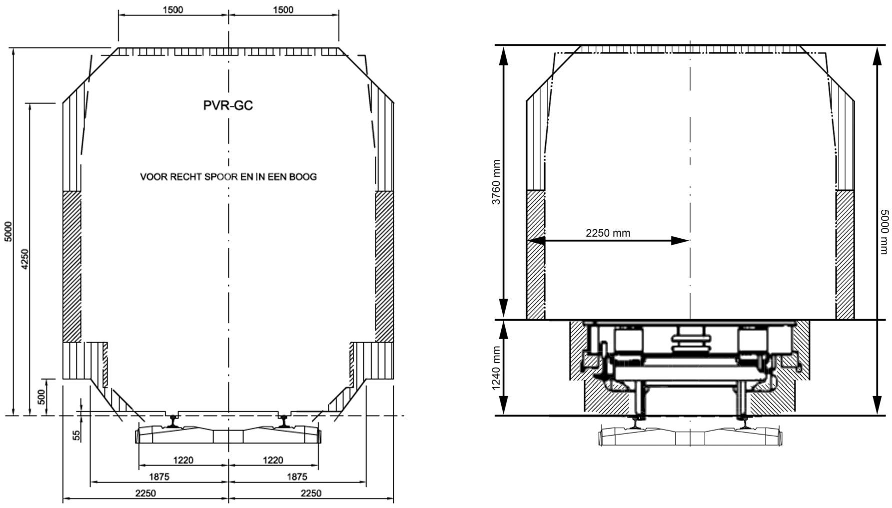


Figure 4.1: Comparison between the complete GC-gauge (left) and relevant GC-gauge (right)

4.2. Analysis of the existing rail (freight) network around the Betuweroute

Looking at the rail network as shown in Figure 2.1, it is possible to identify a number of alternative routes from Kijfhoek to Geldermalsen or another alternative connection to the Betuweroute. The options that are geographically close by are as follows:

- Via Dordrecht, Breda to Tilburg and then to Den Bosch and Geldermalsen. This route uses the Brabant route, which, due to a blockage on the Betuwe route, will already be using all its capacity for rail freight transport, as can be seen in Appendix D.
- Via Rotterdam, Utrecht and Geldermalsen. However, this route uses the Bad Bentheim route, which will also be fully operational in the event of a disruption.
- Via the Merwede Linge Line. Currently not included in any of the freight corridors. This makes the Merwede Linge Line an interesting option to consider as a possible alternative route. The characteristics of this railway line are discussed in more detail below.

The Merwede Linge Line is a largely single-track route between Dordrecht and Geldermalsen. The railway line runs almost parallel to the Betuwe Route, as can be seen in Figure 4.2 and therefore meets the requirement that it is reasonably close to the original route. In ProRail's systems, the Merwede Linge Line has geocode 118.

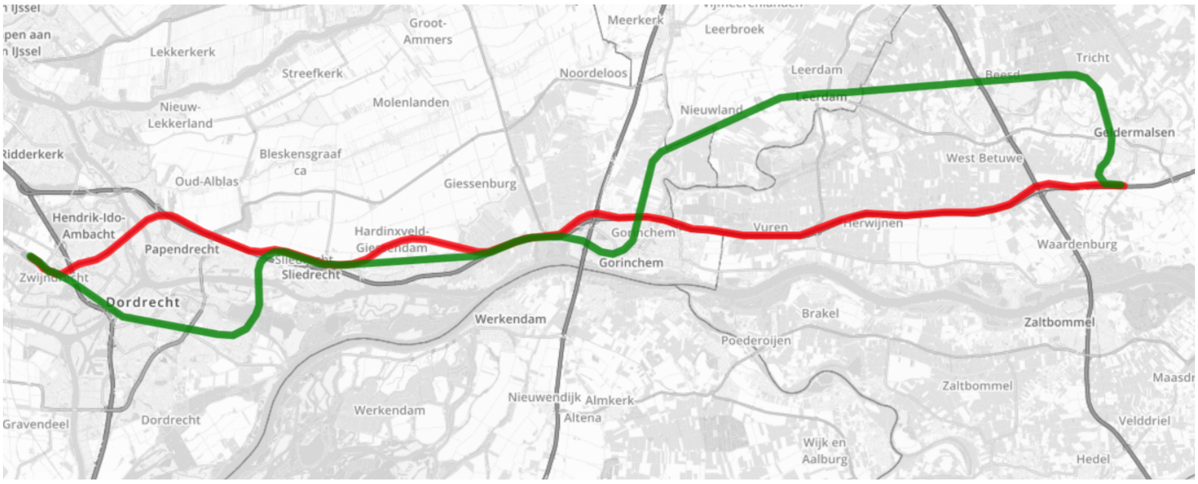


Figure 4.2: Merwede Linge Line (Green) and the Betuweroute (red)

In Dordrecht, there are switches to connect to the rest of the railway network. To the north (Kijfhoek/Rotterdam), this can be done in one go, but to the south, trains must turn around in Dordrecht. Geldermalsen also has switches to connect to the rest of the railway network. Here, trains can continue southbound (Den Bosch) and it is possible to connect to the Betuwe Route eastbound (Arnhem). The direction of Utrecht is possible if a turnaround is made in Geldermalsen. It is not possible to continue eastward (Elst) from Geldermalsen via the Eastern Betuwe Line (this is not the Betuwe Route freight line). The necessary switches are not located in Geldermalsen. This does meet the requirement that the railway line is connected to the rest of the network.

The load class can be found in GVS00094 [5] and can be seen in Figure 3.2. This shows that the Merwede Linge Line has been approved for the transport of weight class C4 with a maximum speed of 100 km/h or for weight class D4 with a speed restriction of 80 km/h. This also meets the third requirement that the infrastructure is suitable for the weight of freight trains and load class D4 also complies with the TEN-T requirement for axle loads.
The Merwede Linge Line also meets the following TEN-T requirements that have not yet been mentioned:

- Fully electrified
- Track gauge of $1435\mathrm{mm}$
- Kijfhoek and Geldermalsen are suitable for $740\mathrm{m}$ trains, but there are no facilities for $740\mathrm{m}$ trains on the line itself. This means that they must continue without stopping. [12]

However, the Merwede Linge Line does not meet the requirements of ERTMS as a train protection system, a minimum speed of $100\mathrm{km/h}$ ($100\mathrm{km/h}$ only for axle loads less than 22.5 tonnes), and the applied gauges do not permit the P400 loading unit. Although the latter will only be a requirement from 2040 onwards, it can be expected that structures will be placed in the corners during gauge assessment.

The distances between the timetable points on the Merwede Linge Line, the number of tracks at these locations, and the travel times between the timetable points are given in Appendix C. The two-track stations used for crossing trains are marked in yellow.

4.3. Gauge assessment

The second step is to determine the available gauge, as indicated in subsection 3.2.1. To do this, data on all violations were extracted from Sigma. First, the unfiltered data set was examined. This resulted in the violations mentioned in Table 4.1.

Table 4.1: Overview of the unfiltered violations on railway track 118

Categories	Number
Coils and Pots	302
Signs	158
Fencing	90
Platform Edge	67
Contact Wire	60
Engineering Structure	52
Platform Obstacle	44
Overhead Line	38
Light Signal	31
Other	13
Switch Control	10
Level Crossing Installations	9
Control Box	9
Pole	7
Total	**890**

All violations are plotted on the map and can be seen in Figure 4.3.

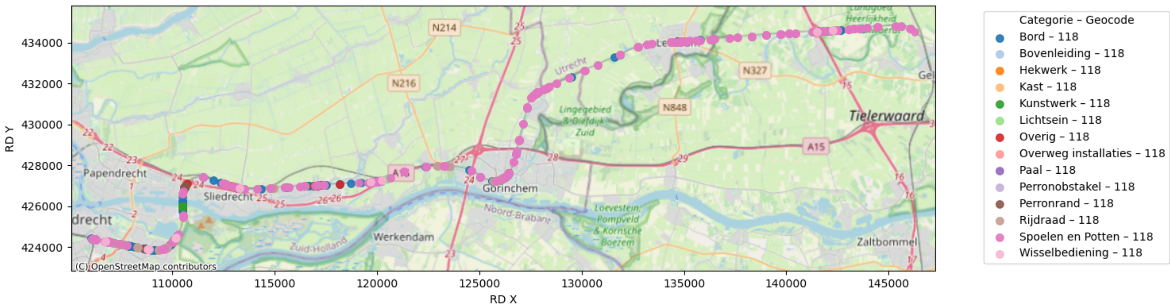


Figure 4.3: Unfiltered violations on railway track 118

4.3.1. Data preparation

The 890 violations were reviewed in Sigma, with the aim of cleaning up the data set and removing all violations that are not relevant to the case study and/or scenario. In subsection 3.2.1, it is indicated which categories are not relevant. This means that all *Coils and Pots, Platform Edges, Switch Controls* , and *Control Boxes* are removed from the data set.

All *Engineering Structures*, except three violations, in this section of the track are extensions of the edges of the platform. This meant that this category also remained below the gauge that should be kept clear. The three remaining violations belong to *Fencing* and were moved to that category.

The elements belonging to the overhead line were found to hang higher than 5000 mm from the running plane and are located outside the gauge. This meant that violations in the categories *Contact Wire* and *Overhead Line* could be removed from the data set.

In the category *Other*, there were 12 violations that were just above the running plane and are therefore not relevant to this case study. The remaining structure in the *Other* category belongs to the *Platform Obstacles* category and has therefore been moved to that category.

In the *Signs* category, 58 small signs were found to be low to ground, below 1240 mm in relation to the running plane, and there were 4 ground light signals. The 62 violations have been removed from the data set. In total, 609 violations have been removed, leaving 281 violations remaining.

The next step was to determine how far the objects were from the centre track. This was noted for each violation *Name*. These data were merged with the existing list of violations. Upon determining the distance, it also became apparent that objects that were outside the red measurement area were registered. An overview of structures that are not located within the red measurement area is listed in Table 4.2.

Table 4.2: Number of removed violations that are outside the red measurement area

Categories	Number
Signs	17
Fencing	24
Platform Obstacle	26
Light Signal	9
Level Crossing Installations	2
Pole	4
Total	**82**

With the removal of these 82 entries, the data set has been completely cleaned up and there are 199 violations that actually affect how wide the load can be at most.

4.3.2. Infrastructure margins

With the cleaned-up data set, it is possible to see what can currently be transported on the Merwede Linge Line. The map showing the remaining violations is provided in Figure 4.4.

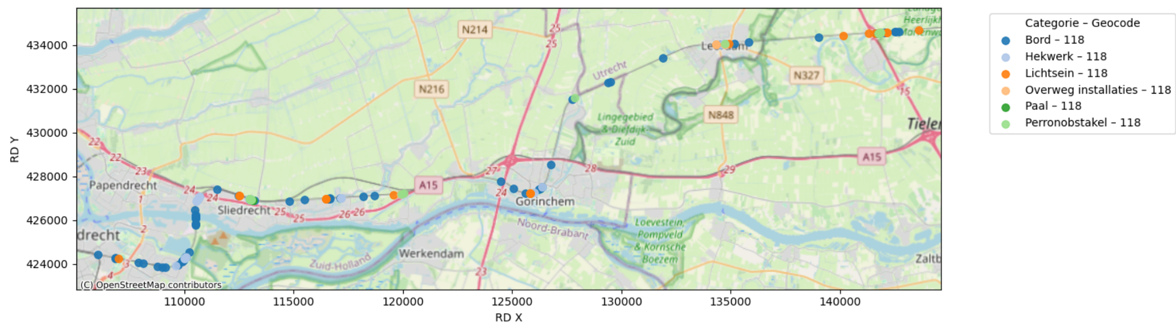


Figure 4.4: Violations witg affect on railway line 118

The decisive violation, the bottleneck, is the one with the highest violation. The maximum bottleneck is a sign on a straight section of the track ($R = 9000\text{m} \rightarrow \infty$) and extends 472 mm into the gauge. To determine the maximum kinematic vehicle width that may pass there, Equation 3.2 must be used.

Using the numbers from section 4.1, $b_{\text{inf.margin.st}}$ can be calculated using Equation 2.3. The final margin depends on h, where $h_{\text{min}} \leq h \leq h_{\text{max}}$ and h cannot be lower than the floor height of the waggon used and the height cannot exceed the maximum gauge height permitted in Dutch railways, which is 5000 mm from the running plane [7]. Therefore, $b_{\text{inf.margin.st}}$ also lies within a certain range.

$$b^{\text{st}}_{\text{inf.margin.min}} = (15+45)+25+\frac{15}{1500}\times 1240+\frac{15}{1500}\times 0.3\times 160+\tan(1^\circ)\times 160 + \frac{7}{1500}\times 0.3\times 160+\frac{0\times 160}{1000} = 100.9\text{mm} \tag{4.1}$$

$$b^{\text{st}}_{\text{inf.margin.max}} = (15+45)+25+\frac{15}{1500}\times 4950+\frac{15}{1500}\times 0.3\times 3870+\tan(1^\circ)\times 3870 + \frac{7}{1500}\times 0.3\times 3870+\frac{0\times 3870}{1000} = 219.1\text{mm} \tag{4.2}$$

The maximum and minimum values of $b_{\text{inf.margin.st}}$ are entered in Equation 2.3 together with $b_{\text{RM}} = 2250\text{mm}$. 2250mm is from the centre of the track.

4.3.3. Outcome gauge assessment Merwede Linge Line

The decisive bottleneck is a sign near Sliedrecht station. This sign protrudes 472mm into the gauge from the edge of the red measurement area.
The swept envelope from the centre of the track of a train on the Merwede Linge Linge, as a result of the decisive bottleneck, may have a maximum value in the range of $1559\text{mm} < b_{\text{SE}}^{\text{st}} < 1677\text{mm}$. In total, the static swept envelope can therefore be between 3114mm and 3354mm wide. To put this into perspective, this is partially less than the static gauge width 3150mm for the UIC-gauge GC (1575mm from the centre of the track), which should be available according to the design regulations [26].
The results of the assessment of the test gauges are included in Table 4.3.

Table 4.3: Test-gauge assessment results

	Violation count							
	Total	Sign	Fencing	Light Signal	Level Crossing Installation	Pole	Platform Obstacle	Max Violation
Gauge-L	**199**	83	70	18	7	3	18	472
Gauge-M	**66**	34	14	7	2	1	8	338
Gauge-S	**12**	7		2	2		1	185

As indicated above, the decisive bottleneck extends within the static reference gauge. Therefore, it can be expected that violations will occur for each test gauge, and resolve strategies must be implied.

The distribution of detected violations is also shown in Figure 4.5. The far left shows the edge of the red measurement area, and the far right shows the edge of the static UIC gauge GC. This orientation corresponds to that of Figure 2.9, where the left edge is b_{RM} and the right edge is b_{CR}. Between them, the numbers of violations are shown per 5 millimetres. The continuous vertical lines indicate the test gauges, while the dot-dashed vertical lines indicate the test gauges with margins. The edge of gauge-L, including the margin, is the edge of the red measurement area.
Everything to the right of a solid line corresponding to a test gauge indicates that the detected structure is guaranteed to be within the gauge and will be hit if that width is transported. Detected structures between the dot-dashed and solid lines of a test gauge are within the infrastructure margin (b_{inf}). There is a chance that these structures will be hit if the transport uses that gauge. If detected violations are to the left of the broken line (or outside the red measurement area), they will not be hit.

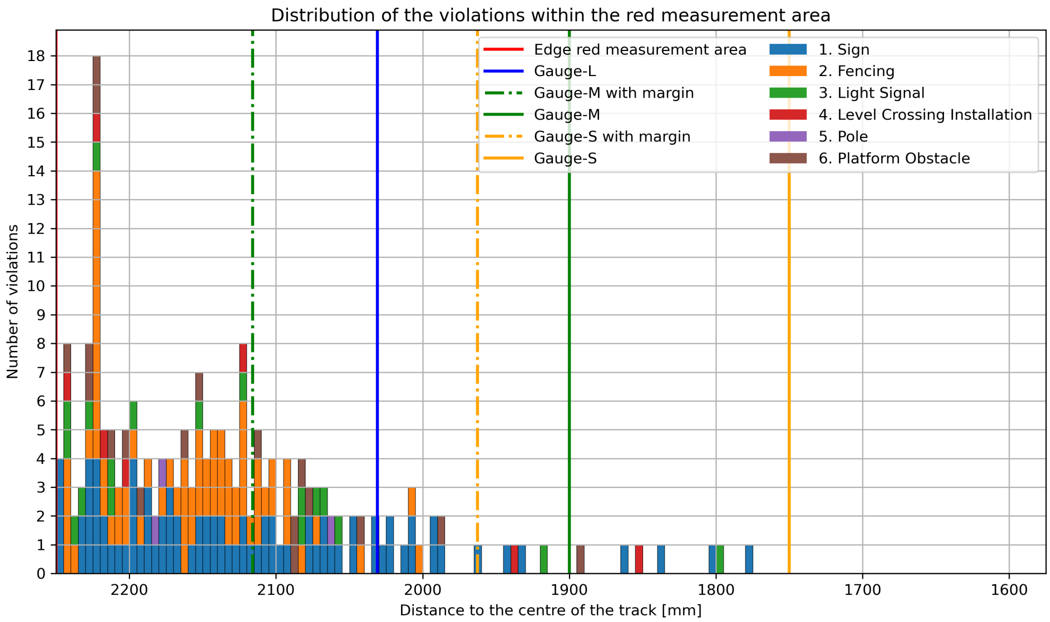


Figure 4.5: Distribution of the violations within the red measurement area

It should be noted that if the extra space for out-of-gauge rail transport, the space added to the static reference gauge but without the $b^{\mathrm{st}}_{\mathrm{inf.margin}}$, is reduced by 28.7% between gauge-L and gauge-M, the number of violations decreases by 66.8%.

With the current rolling stock used on the Merwede Linge Line, the Stadler GTW 'Spurt', this restriction is not a problem. This type of train has a material width of 2950 mm (half width is 1475 mm) and a material height of 4300 mm [2]. At the location of this sign, with the above rolling stock height, a $b_{\mathrm{SE.st}} = 1579\mathrm{mm}$ is available. This means that there can still be a margin of 104 mm on the rolling stock for the characteristics of the vehicle. This margin is in addition to the infrastructure margin of 198 mm.

4.4. Bottleneck category prioritization

The remaining obstruction categories, bottleneck categories, are listed in Table 4.4, including the input necessary to prioritise the bottleneck category. In this case, the table shows the values for test-gauge L, but the same data are also available for test-gauges M and S.

Table 4.4: Overview of bottleneck categories and statistical values

bottleneck categories	Count	Maximum	Minimum	Median
Sign	83	472	1	110.0
Fencing	70	250	8	96.5
Light Signal	18	455	6	77.6
Level Crossing Installations	7	400	9	50.0
Pole	3	186	69	75.8
Platform Obstacle	18	357	10	95.31

The number of violations per test gauge is also shown in Figure 4.6. For each bottleneck category, the number of violations is shown and how these decrease as the test gauge becomes smaller. The total number of violations is also shown in black. The observation made in subsection 4.3.3, namely that the number of violations decreases rapidly with a small gauge, is also visible in this graph.

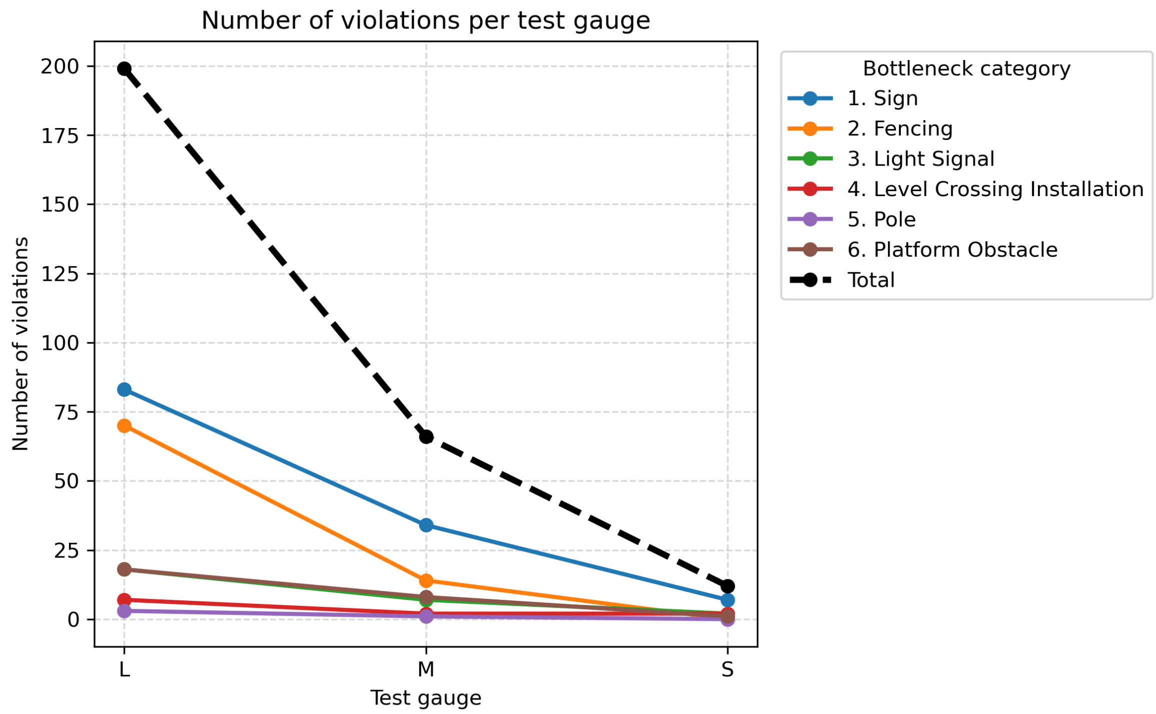


Figure 4.6: Number of violations per test gauge

4.4.1. BNPN ranking

Using the statistics available per test-gauge for the various categories of bottlenecks and the formulas set out in section 3.3, extend, observation, and detection can be calculated. With these values will lead to an BNPN score per bottleneck category. The results are given in Table 4.5 for gauge-L, in Table 4.6 for gauge-M, and in Table 4.7 for gauge-S. Bottleneck categories are listed in priority order.

Table 4.5: Categories Sorted by BNPN for test-gauge L

Category	Extend	Observation	Detection	BNPN
Sign	1.00	0.42	1	0.42
Fencing	0.60	0.35	1	0.21
Light Signal	0.92	0.09	1	0.08
Platform Obstacle	0.78	0.09	1	0.07
Level Crossing Installations	0.77	0.04	1	0.03
Pole	0.45	0.02	1	0.01

The BNPN score indicates that signs are the most serious bottleneck category along the route. This is understandable, as signs are both the most common bottleneck category along the Merwede Linge Line and also contain the decisive bottleneck.

Table 4.6: Categories Sorted by BNPN for test-gauge M

Category	Extend	Observation	Detection	BNPN
Sign	0.75	0.52	1	0.39
Light Signal	0.66	0.11	1	0.07
Platform Obstacle	0.46	0.12	1	0.06
Fencing	0.25	0.21	1	0.05
Level Crossing Installations	0.87	0.03	1	0.03
Pole	0.20	0.02	1	0.01

Signs remain the bottleneck category with the highest BNPN score, in part because the decisive bottleneck for gauge-M also remains the sign, and signs continue to have a high count. However, it can be seen that the fencing is falling in priority, because the number of counts is falling (from 70 to 14).

Table 4.7: Categories Sorted by BNPN for test-gauge S

Category	Extend	Observation	Detection	BNPN
Sign	0.98	0.58	1	0.57
Light Signal	0.94	0.17	1	0.16
Level Crossing Installations	0.62	0.17	1	0.10
Platform Obstacle	0.48	0.08	1	0.04

For gauge-S, it is noticeable that the number of bottleneck categories has decreased from six to four. Fencing and poles are no longer included in the gauge.

In Figure 4.7, the BNPN scores of the various gauges per bottleneck category are plotted on a bar chart. The chart also clearly shows that the bottleneck category ‘signs’ has the highest priority and also increases in priority for the smallest gauge.

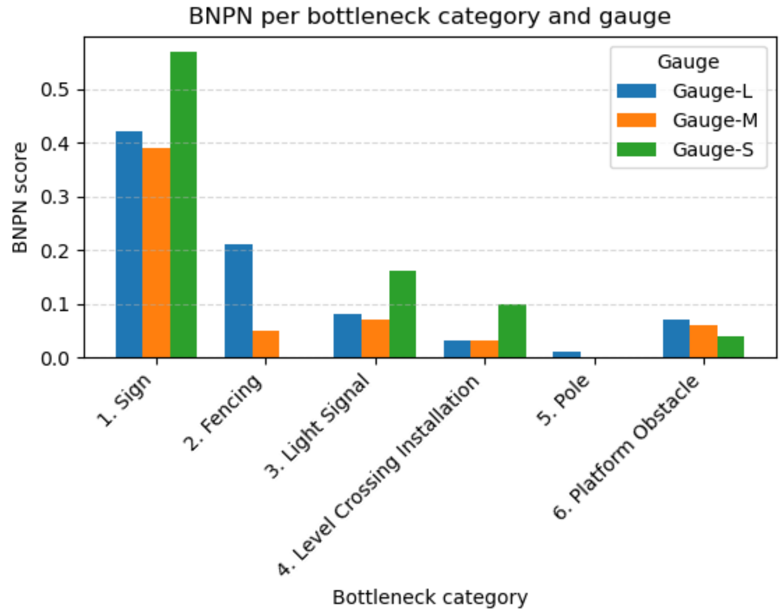


Figure 4.7: BNPN scores per bottleneck category

4.4.2. Geographical distribution

In Appendix F, the maps show how the violations are geographically distributed along the rail line for gauge-L for each bottleneck category.

In section 4.4, it appears that the signs have the highest BNPN score for each bottleneck category. In Figure 4.8, Figure 4.9 and Figure 4.10, the maps show how signs are distributed along the railway line.

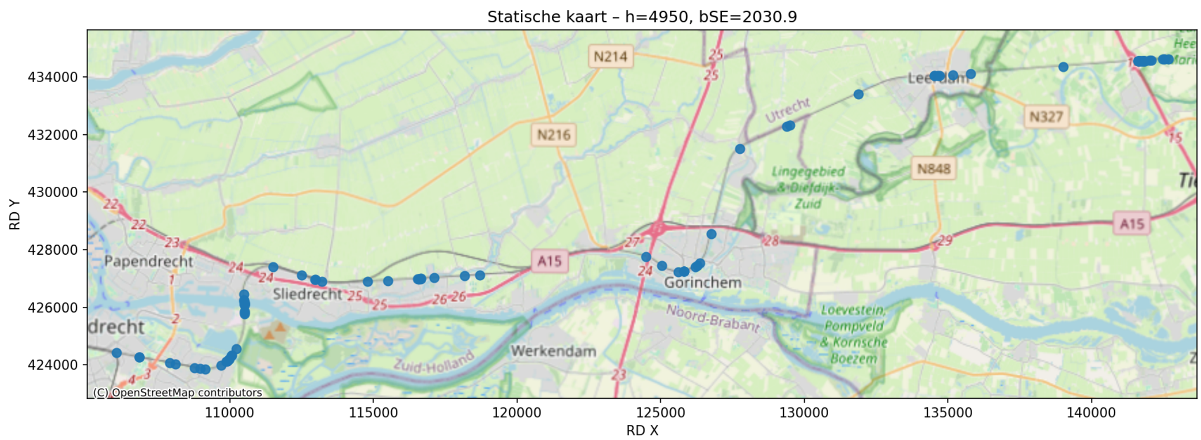


Figure 4.8: Geographical distribution of the bottleneck category signs for gauge-L

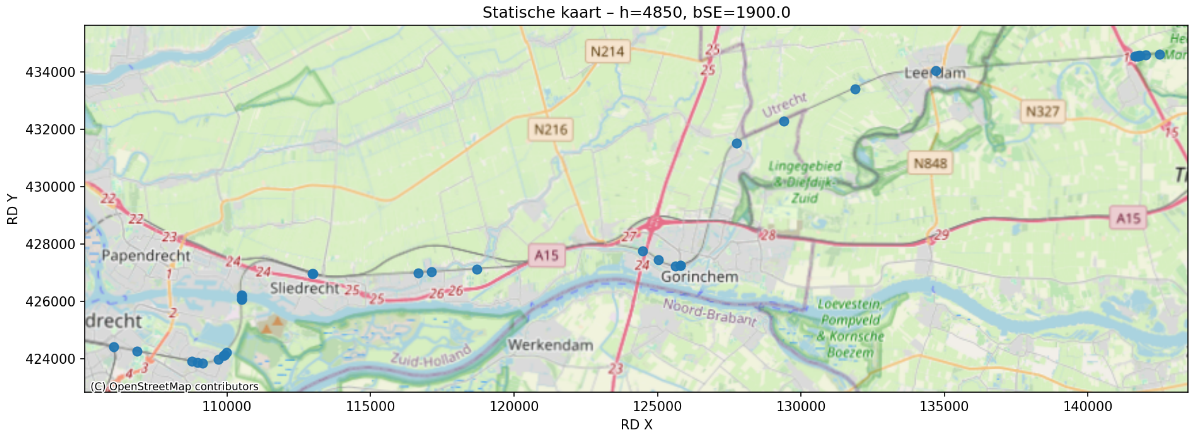


Figure 4.9: Geographical distribution of the bottleneck category signs for gauge-M

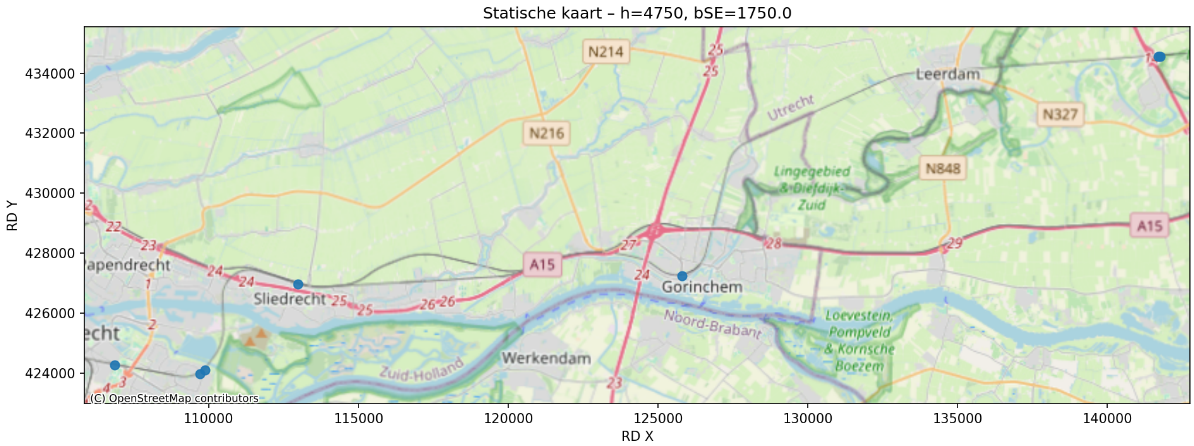


Figure 4.10: Geographical distribution of the bottleneck category signs for gauge-S

Taking into account the geographical distribution, it can be seen that this bottleneck category occurs on the entire railway line. For none of the test gauges can the bottleneck category signs be linked to a (station) area or other characteristic location on the railway line.

It is noticeable that the remaining bottleneck categories are mainly, if not entirely, clustered around the station areas. This is not illogical, as four of the seven bottleneck categories (Fencing, Platform Obstacle, Level Crossing Installations, Pole) relate to station installations.

For gauge-L, there are still three (groups of) violations that cannot be linked to a station area. The three exceptions to this are two light signals that are not located near a station and the *Wantij Railway bridge*, where there is fencing inside the gauge.
For gauge-M, these three violations are eliminated. The number of stations that need to be modified is also reduced from eight to seven. For gauge-S, it goes back to three stations.

The distribution of the other bottleneck categories can be seen in Figure 4.11 for gauge-L, in Figure 4.12 for gauge-M and in Figure 4.13 for gauge-S.

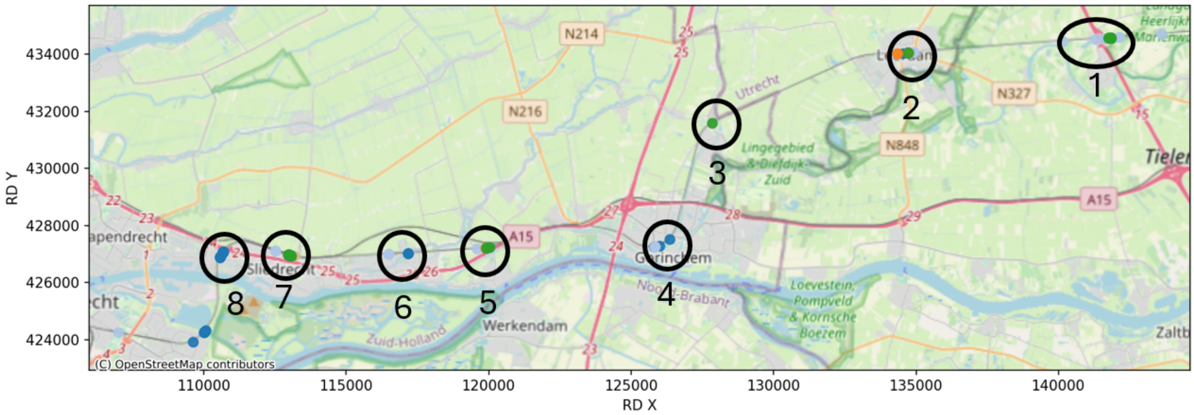


Figure 4.11: Geographical distribution of the other bottleneck category for gauge-L.
1. Beesd - 2. Leerdam - 4. Gorinchem - 5. Boven-Hardinxveld - 6. Hardinxveld-Giessendam - 7. Sliedrecht - 8. Sliedrecht Baanhoek

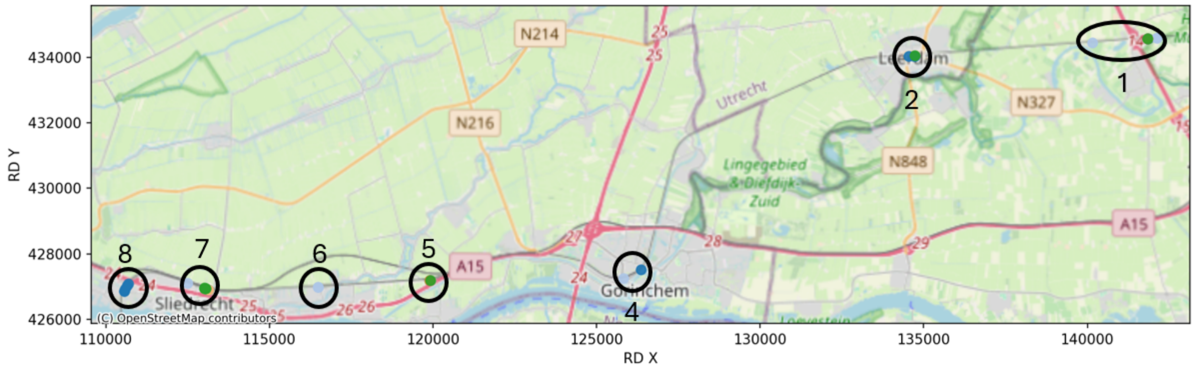


Figure 4.12: Geographical distribution of the other bottleneck category for gauge-M.
1. Beesd - 2. Leerdam - 3. Arkel - 4. Gorinchem - 5. Boven-Hardinxveld - 6. Hardinxveld-Giessendam - 7. Sliedrecht - 8. Sliedrecht Baanhoek

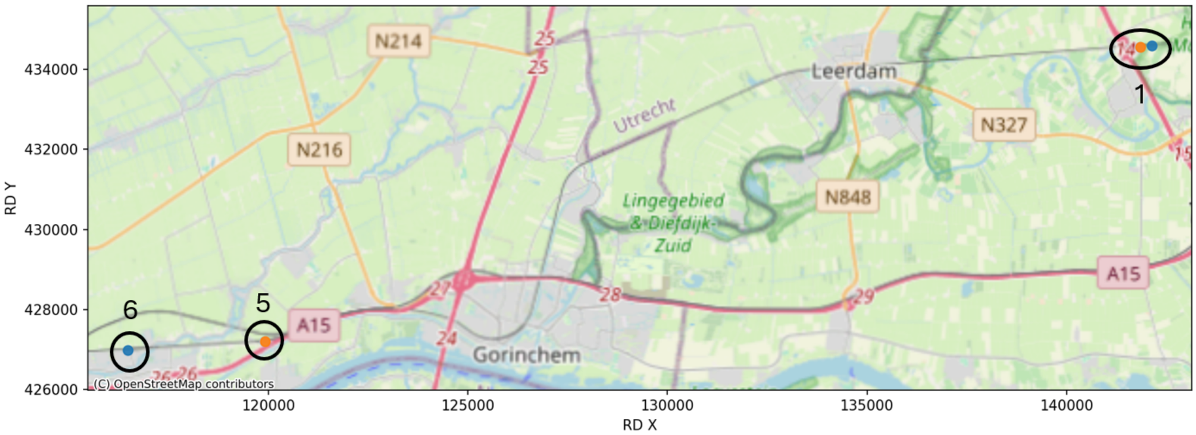


Figure 4.13: Geographical distribution of the other bottleneck category for gauge-S.
1. Beesd - 5. Boven-Hardinxveld - 6. Hardinxveld-Giessendam

4.4.3. Bottleneck category resolve strategies

Based on the calculated BNPN scores and the fact that the scenarios are not actively used in the case study, the following prioritisation startegy has been established:

1. Relocating signs
2. Station approach
3. Remaining issues

When implementing the strategy in this order, the bottleneck category with the highest BNPN score is addressed first. After completion of the entire project, it is possible to use the full width (gauge-L) for out-of-gauge transport, whereby the test gauges can be released from small to large during the project. The BNPN shows that relocating the signs is by far the highest priority for all three test-gauges. An additional advantage is that, based on subject matter experts, this project is relatively quick and easy to implement. No technical installations need to be moved or rewired for signs. The train safety system does not need to be modified. Signs must be positioned in such a way that they comply with sight lines as specified in OVS69133-2 v019 [9]. This work can be carried out during the standard weekly withdrawals on the Merwede Linge Line, which means that there will be no impact on passengers. In short, this project will resolve the decisive bottleneck and 42% of violations (for gauge-L) with minimal work and no inconvenience to passengers. In this way, the three elements mentioned in subsection 3.3.3 that influence the determination of the resolve strategy have been taken into account, namely the BNPN value, the geographical distribution and the speed of implementation.

The second project involves the redesign of the stations. This involves relocating the structures on the platform in such a way as to ensure that all gauge violations are resolved. There are various design regulations for the layout of stations. Care must be taken to ensure that the modifications made for the transport of out-of-gauge rail freight do not result in other design regulations being violated and new violations arising that could potentially endanger passengers. The designs must therefore be worked out with precision, which takes time. Creating new designs for unique stations is not within the scope of the project. This project includes, among other things, the relocation of light signals and level crossing installations. This requires cabling to be modified and rerouted. Modifying the underground infrastructure is more work compared to the relocation of signs in the first project, but it does not require any modifications to the train safety system, which reduces the time and complexity of the project. The final redesign of the stations will determine how long the projects for each station will take and what the disruption for passengers will be. If not all stations are tackled at the same time, the next step in the implementation process will be to prioritise which station will be modified first. The maximum out-of-gauge rail freight transport to be carried out is determined by the largest gauge violations. The recommendation here is to first resolve the station with the largest violation. This prioritisation can be seen in Table 4.8. In addition, the stations in the orange cells have violations for all three test gauges, while the stations marked in yellow have violations for gauge-M and gauge-S. The last station must be addressed to eliminate the last violations around the stations for gauge-L.

Table 4.8: Stations arranged based on maximum bottleneck

Station name	Maximum Violation [mm]	Categories
Hardinxveld-Giessendam	455	Light Signal
Boven-Hardinxveld	400	Level Crossing Installations
Beesd	357	Platform Obstacle
Sliedrecht-Baanhoek	242	Fencing
Sliedrecht	208	Platform Obstacle
Leerdam	172	Platform Obstacle
Gorinchem	170	Light Signal
Arkel	97	Platform Obstacle

In Appendix C it can be seen that seven of the ten intermediate stations on the Merwede Linge Line are double-tracked. The station projects can be scaled down if it is decided to examine the geographical distribution of bottlenecks at the local level and modify only one of the two tracks and prepare it for out-of-gauge rail freight transport. For example, at Sliedrecht station, a platform roof is located in the red measurement area, which constitutes an obstacle for gauge-M and gauge-L. This roof is only in the gauge of the southern track. The northern track is not affected by this and, looking at the number of violations for gauge-L at Sliedrecht station, there are 28 on the southern track and four on the northern track. The number of modifications to be implemented for the northern railway track is lower than for the southern railway track. Therefore, it is expected that the scope of the station project will be reduced when a track is made suitable for out-of-gauge rail freight transport.

The third programme, which has the lowest priority, is to resolve the three remaining violations. These are two light signals and the fencing on the *Wantij Railway Bridge*. The first light signal is located just outside Geldermalsen and extends 130 millimetres into the gauge, which is less than the maximum value of the different bottleneck categories, so this signal is not likely to be the decisive bottleneck. This light signal is also located 1.8 kilometres from Beesd station, which allows it to be included in the station project. The other signal is located just before Dordrecht and extends 11 millimetres into the gauge, which is also unlikely to be the decisive bottleneck. The fence on the railway bridge extends between 15 and 44 millimetres in the gauge. To solve this bottleneck, relatively complex work needs to be carried out on a bridge that crosses the water, is movable, and has only a single track. The work is expected to take a relatively long time with minimal gauge being freed up. In short, these three points must be resolved in order to eliminate all violations. Resolving these violations will take a relatively long time and only create the space required for the largest gauge (gauge-L). For gauge-M and gauge-S, the points in this programme do not even need to be addressed.

In section 4.1 it is stated that the scenarios are not included in the calculation of the BNPN values for the case study because there are no values for the weighting factor. However, an indication can be given of how the scenarios may influence the results once values for the weighting factor are known. For the *No matter what* scenario, damage to infrastructure is tolerated, provided it is not counterproductive. Subject matter experts indicate that, in the event of a calamity, signs may be run over. When transporting a robust load, this will result in a low weighing factor. This will reduce the BNPN value of the bottleneck category “Signs”. As a result, the category may drop in priority, which may mean that this bottleneck category will not be resolved, or will be resolved later or in a different way. The choice is determined by the new BNPN value. In the *Segregated rail traffic - Low demand* scenario, damage to the infrastructure is not accepted in connection with the safety of train passengers. The BNPN values and prioritisation will then correspond more closely to those currently calculated.

4.5. Conclusion

The outcome of the case study is that the current maximum gauge is in the range of $1559\text{mm} < b_{\text{SE}}^{\text{st}} < 1677\text{mm}$. Here, the lower limit applies in the cases where the waggon and its load together have a height of 4950mm from the running plane. The upper limit applies in situations where the combination of waggon and load is not much higher than the height of the flat waggon. The consequence of this is that out-of-gauge rail freight transport is not possible on the Merwede Linge Line. Based on BNPN scores, geographical distribution, test gauges, and scenarios, a strategy has been drawn to resolve bottleneck categories in phases.

The above results were obtained by applying the method as schematically represented in Figure 3.1. The case study started with modifying the data set, resulting in usable input data. The next step was the “Infrastructure assessment”, in which the bottlenecks within the case study area were identified and quantified. Based on the decisive bottleneck, calculations were performed to determine the maximum amount of out-of-gauge rail freight that can be transported. For the “Resolving bottlenecks” step, a BNPN value was calculated for each bottleneck category. Subsequently, these values were applied in the final step, in which a resolving strategy was developed. With the exception of the full implementation of the scenarios, the method was applied to the case study, and the results are in line with the desired solution as stated in chapter 1. The case study demonstrates that the method is applicable and yields meaningful results within the scope of the Merwede Linge Line

An observation during the case study is that there are almost 10% measurement errors in the data set, even though all irrelevant violations have already been removed. This leads to the conclusion that only initial assumptions can be made on the basis of the raw data set and further cleansing is necessary.

5

Conclusion and Discussion

The aim of this thesis is to develop a method to determine the possibilities of out-of-gauge rail freight transport on the Dutch rail network. After studying the literature, a method was developed. The method was then tested in a case study. This chapter returns to the design challenge of chapter 1 and the answer to it. The chapter concludes with a discussion and recommendations for further research.

5.1. Conclusion

In order to answer the design challenge, four sub-questions have been formulated. The results of these will first be discussed, followed by the answer to the design challenge.

1. How to identify and quantify bottlenecks for the operation of out-of-gauge rail freight transport on existing routes?

The quality of the Dutch railway infrastructure is mapped using measurement trains. These measurements result in a data set that contains all violations of the GC gauge, including the red measurement area. This is used as a basis for identifying bottlenecks. The first filter to determine which violations are actually bottlenecks is based on which gauge actually has to pass over the railway line. For out-of-gauge transport, these are flat waggons, which means that all violations close to the ground are not bottlenecks. All of these violations have been removed from the data set. The method then includes a step in which the remaining violations are manually reviewed. This involves checking whether the identified violation actually affects the gauge. If this is not the case, those measurements are removed. The remaining violations are therefore all within the gauge and will ultimately form a bottleneck. This answers the first part of the sub-question.

In the same manual analysis, the distance of each violation, the bottlenecks, from the centre of the track is examined. This data is stored in a separate file. Once this distance has been determined for each bottleneck, the data is added to the data set and, at the same time, the extent to which the violation protrudes into the red measurement area is calculated. This is the width of the red measurement area from which the distance of the object from the centre of the track is subtracted. This gives the actual violation per bottleneck. In this way, the bottlenecks, together with the sum of the number of bottlenecks, can be quantified.

2. How to assess what is possible within the known gauge violations?

To determine what is possible with the existing bottlenecks along the railway line, it is necessary to know what margin must be taken into account. For this purpose, the formulas for the static gauging method are used. In the NEN-EN 15273 standard, these formulas are used to calculate how far the structures must be from the reference gauge. In this method, these formulas are used in reverse, to calculate a gauge from the structures. The formulas below are used for this purpose. These formulas originate from NEN-EN 15273 and have been adapted where necessary to the scenario of this thesis.

$$b^{\mathrm{st}}_{\mathrm{SE},i} = b_{\mathrm{RM}} - \max[\,x_{\mathrm{BN},ij}] - b^{\mathrm{st}}_{\mathrm{inf.margin}} \tag{5.1}$$

$$b^{\mathrm{st}}_{\mathrm{inf.margin}} = S_{\mathrm{i/a}} + \Sigma^{\mathrm{st}}_{\mathrm{j}} \tag{5.2}$$

$$S_{\mathrm{i/a}} = S_{\mathrm{l}} + S_{R,\mathrm{i/a}} \tag{5.3}$$

$$\begin{aligned}\Sigma_{\mathrm{j}} = T_{\mathrm{voie}} + \frac{T_{\mathrm{D}}}{L} \times h + \frac{T_{\mathrm{D}}}{L} \times s \times (h - h_{\mathrm{c0}})_{>0} + \tan(1^{\circ}) \times (h - h_{\mathrm{c0}})_{>0} \\ + \frac{T_{\mathrm{osc}}}{L} \times s \times (h - h_{\mathrm{c0}})_{>0} + \frac{s}{L} \times D \text{ or } \frac{I \times (h - h_{\mathrm{c0}})_{>0}}{1000}\end{aligned} \tag{5.4}$$

Depending on the height of the out-of-gauge transport to be driven, the lateral projection of the irregularities of the track depends on the height of the transport. This gives the infrastructure manager a range within which the width of the transport can lie, with low loads being allowed to be wider. In order to arrive at more concrete results, three test gauges with a selected height and width have also been introduced. The infrastructure margin can then be added to this. Next, we examine whether these would fit within the existing violations.
Together, this ensures that, on the basis of the violations, a range is given for what could be transported as out-of-gauge rail transport. With the help of test gauges, the possibilities become clearer.

3. How can bottlenecks be compared with each other to ensure prioritisation of which bottleneck should be resolved first?
To compare the bottlenecks, a method based on Failure Mode Effect Analysis is used. Based on the calculation of the Risk Priority Number (RPN), a calculation has been made for the Bottleneck Priority Number (BNPN). Bottleneck categories can be prioritised on the basis of the BNPN value.
For each bottleneck category, a value is calculated for Extend, Observation, and Detection. These parameters are given a score between 0 and 1. For Extend, the maximum exceedance and the median value of the bottleneck category are compared with the maximum exceedance of all bottleneck categories and the maximum median value of the bottleneck categories. This takes into account the effect of the maximum violation (which is the determining bottleneck), but also the impact of many relatively high violations. Observation takes into account how often a bottleneck category occurs on the railway line. The number of violations in that bottleneck category is divided by the total number of violations. Detection usually indicates the effect of how well a bottleneck category can be detected. For the gauge violations currently measured, detection is equally good for all of them. Therefore, each bottleneck category has the value “1”. Finally, a weighting factor is also added. This factor w_j takes into account the effect of the bottleneck category on the applicable scenario. A low value of w will apply if the bottleneck category has a limited influence on the way out-of-gauge rail freight transport must take place in the chosen scenario.
These values are multiplied together to give an BNPN score. The bottleneck category with the highest priority is the one with the highest BNPN score. Next, the geographical distribution of the violations is examined. A certain grouping of different bottleneck categories may have a common cause, such as the presence of a station or a bridge. This means that the bottleneck categories must be resolved by addressing the common cause. BNPN scores are also calculated for test gauges. This is ultimately used as input to support the prioritisation of the bottleneck categories to be resolved.
In short, the method created that calculates a BNPN score can be used to prioritise bottleneck categories. What has been devised in the method is effective. Only the application of the scenarios has not been tested in the case study. Based on the geographical distribution, it is possible to determine which bottleneck categories can be combined. By calculating the BNPN scores for the test gauges, these values can be used to substantiate the choice of prioritisation or to make changes.

4. What results does the method provide when applied to the case study?
The method concludes that out-of-gauge transport is not possible at the case study location, the Merwede Linge Line. There is a sign that extends into the reference gauge of the static GC gauge. Transport larger than this gauge is considered out-of-gauge, so this is an expected outcome. Calculating

BNPN scores indicates that signs have the highest priority for all test scenarios; this bottleneck category occurs most frequently and also has the bottleneck with the highest violation. The analysis of the geographical distribution of the violations then shows that the remaining bottlenecks, with a few exceptions, are located around stations. The use of test gauges shows that the aforementioned exceptions that are not located at stations only affect the maximum test gauge. This supports the recommendation that resolving these remaining issues should be given the lowest priority. The method produces the expected results for the case study. Only the scenarios have not been applied in the case study because additional research is required for this. An observation that was not taken into account, but was observed during the case study is that the number of violations decreases by 66.8% if the gauge is reduced by 28.7% between test gauges L and M.

The conclusions of the sub-questions lead to a solution to the Design Question.

Design a method to identify and prioritise structures in the UIC gauge and develop a strategy to resolve the identified obstructions.

A method has been designed to identify bottlenecks based on observations made by the measurement train. This method is implemented in a data processing application that combines the data and calculates the necessary parameters. It is also possible to assign an BNPN score to bottleneck categories based on the calculated parameters, which in turn form the basis for a strategy to resolve the bottleneck categories. The results are linked to the scenarios described in the introduction. For *No matter what* scenario, in which the out-of-gauge trains must run, the outcome of the method gives a list of structures that will be damaged. The effects of this need to be further researched. In order to implement the *Segregated rail traffic* scenario, in which passenger rail transport must be able to run again once the peak of out-of-gauge trains has passed, the method provides a list of issues to be resolved.
The method developed shows a pattern of violations that are largely located at the edge of the red measurement area and tend to cluster around stations. The signs are an exception to this.

5.2. Discussion and recommendations

When reading this report, it should be taken into account that various assumptions have been made. These assumptions form the basis for a discussion that will lead to recommendations for further research.

5.2.1. Discussion

In terms of gauge violations, the thesis focused primarily on lateral exceedances of a single track. This approach did not take into account the effect and consequences of double tracks. The method does not include anything that maps the possible overlap of red measurement areas or calculates the margin that should be between two passing trains. For the scenarios for which the method is currently designed, this is less relevant but it does come into play in other scenarios where there are return flows or other trains that need to be passed.
Due to the focus on the lateral component, the vertical component of out-of-gauge transport has not been further investigated. In the Netherlands, this is covered largely in BP 1-2-3, but this does not take into account loads that are wider than the reference gauge. As a result, the effects of high- and wide out-of-gauge transport have not been sufficiently described or tested.
For the method developed to prioritise bottlenecks, a conscious decision was made to use a method that does not take costs into account. This is because it is assumed that the transports will be required to run. However, the maintenance and new construction of rail infrastructure is paid for from public funds or partly by consumers who pay for train tickets and/or transport costs for the product. It is therefore appropriate to manage these expenditures responsibly. Costs are currently not mentioned in the various programmes. This is also the case for the benefits. This will have to be done when the improvement programmes are further elaborated.
The method was tested on a case study involving a single railway line. This gives $n = 1$, which means that only very limited statistically relevant statements can be made. However, it can be used to identify certain patterns and investigate them further in follow-up studies. It is therefore appropriate to exercise restraint in drawing conclusions from the findings.
During the development of the method and the execution of the case study, certain choices were made, such as the choice for static calculation, or values were assumed for certain variables, such as the

flexibility coefficient s. The choices and assumptions that have been made provide grounds for further research. This is to see whether the method can be refined using other techniques or whether other values for variables would yield a more realistic outcome. The recommendations for further research are included in the following subsection 5.2.2.

5.2.2. Recommendations

Based on this thesis, recommendations can be made for further research within three fields. These include recommendations within the scientific field, recommendations for the infrastructure manager to improve the quality of the results, and a final recommendation for railway undertakings to be able to calculate more accurately how much space is needed in the gauge.

Scientific recommendation

In the developed method, all calculations are performed based on the static gauging method. This is done on the basis that the flexibility coefficient does not exceed the value of s_{lim}. For the situation in the thesis, this is a reasonable assumption because freight waggons have rigid suspension. A gauging method that takes into account the interaction between infrastructure and rolling stock as a result of suspension is the kinematic calculation method. This calculation method is also standard within ProRail, for example, for drawing up design regulations.

It is advisable to investigate further whether the kinematic gauging method can be incorporated into the developed method. The advantage is that interoperability with the current design specifications would be achieved. Because the gauging method depends on more and more complex variables, the calculation time increases. In order to choose a suitable gauging method for the design question of this thesis, it is advisable to also investigate whether the kinematic calculation method actually offers greater accuracy. The terms in $\Sigma_{\mathrm{j}}^{\mathrm{st.}}$ already create a realistic approximation. If the kinematic calculation method does indeed improve quality, it will be possible to calculate more accurately what fits on the railway line, but data on the rolling stock must also be available for this.

During the course of the thesis, it also became apparent that there is no information available about the effect of allowing trains to run that cause damage to the infrastructure. This refers to damage in the form of knocking over signs or other structures near the railway tracks. The effect on freight, infrastructure, and subsequent trains is not known. The time required to perform initial repairs when damage is caused to an entire railway line or corridor is also unknown. This research could potentially be carried out in collaboration with the infrastructure manager. The results can be used to apply the scenario in the developed method, but also to gain knowledge on the resilience of the network in terms of robustness and rapidity.

Infrastructure manager recommendation

The recommendation for the infrastructure manager, ProRail, is to expand the current violation data set with additional data. Both the implementation of the method developed in this thesis and the actual scheduling of out-of-gauge trains rely on a manual determination of gauge exceedances. For the method developed, this only needs to be done once per violation, with new manual processing required if there are new violations or changes to the violation. To schedule out-of-gauge trains, the effect of each violation they encounter is currently determined for each journey to be scheduled. This manual step in the process can be eliminated. This can be done by modifying the measuring train so that it also measures the distance to the edge of the structure along the track. If it is not possible to measure this distance at the “source” itself or if these modifications are too costly, it is also possible to set up a Neural Network Machine Learning model for this analysis. Once this model has been trained, it can quickly process the images taken by the measurement train and extract the distance to the edge of the structure. Both adjustments mean that the data set can be supplemented with the data on violations immediately after new measurements have been taken. This provides a continuously updated overview of what can and cannot be transported.

As it is not always feasible, it has not been included as a recommendation. However, it should be noted that the problem of gauge violations would be significantly reduced if construction was consistently carried out in accordance with the specified design regulations and if the infrastructure manager were to ensure that this was the case. If this were to happen, the problem would be reduced to locations where the old infrastructure has been constructed according to the old guidelines, as discussed in chapter 1.

Railway undertaking recommendation

The recommendation for the railway undertaking is to create, where possible, a database of common out-of-gauge combinations with corresponding vehicle and load characteristics. Currently, variables such as s_{lim} and h_{c0} are assumed to have a specific value. If the scientific recommendation is adopted, additional characteristics of the vehicle and the load will be added. Additional data on rolling stock and load can confirm the assumptions or provide new values that must be used. This is not possible for everything; there will always be unique combinations that occur only once or a few times. However, there are also out-of-gauge loads that are transported more frequently. Examples include the transport of materials and equipment for (railway) construction, as well as military transport of armoured vehicles that are larger than the reference gauge. For these categories, railway undertakings could establish fixed swept envelopes and also determine h_{c0} for the combination of load and waggon. If the dimensions of the swept envelope and other relevant properties are made known to the infrastructure manager, they can calculate and establish the corresponding infrastructure margins. This, combined with the recommendation for the infrastructure manager, makes it possible to determine where a number of standard out-of-gauge gauges can be used. This also allows a kind of BP1-2-3 to be drawn for gauges that are wider than the reference gauge.

This has the advantage that the routes for these rail transports can be planned more quickly. It also helps train traffic control when they need to divert these trains.

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A

Python code infrastructure analysis

```python
#General
import numpy as np
import pandas as pd
import matplotlib
import matplotlib.pyplot as plt
import plotly.express as px
import ipywidgets as widgets
import os
import math
from ipywidgets import interact, widgets, VBox, HBox, Output, Dropdown

#Map
import osmnx as ox
import geopandas as gpd
import contextily as ctx
import folium
import pyproj
import plotly.express as px
from shapely.geometry import Point
from pyproj import Transformer
from ipyleaflet import Map, TileLayer, CircleMarker, LayerGroup
from folium.plugins import MarkerCluster
from IPython.display import display
from IPython.display import HTML

#Violations file
bestand = "obstakels.xlsx"
df = pd.read_excel(bestand)

#Filter spreadsheet
df = df.drop(columns=["Opmerking", "Proces status", "Kwaliteit", "ID", "Subcode", "Datum opname", "Referentiemal", "Eigenaar", "Organisatie"], errors="ignore")
df['RD X'] = pd.to_numeric(df['RD X'], errors='coerce')
df['RD Y'] = pd.to_numeric(df['RD Y'], errors='coerce')

## New cell

output = Output()

def toon_categorieen(change):
    output.clear_output()
    geocode = change['new']
    df_filtered = df[df['Geocode'] == geocode]
    categorie_counts = df_filtered['Categorie'].value_counts()
    tabel = categorie_counts.reset_index()
    tabel.columns = ['Categorie', 'Aantal']
    with output:
        display(tabel)

```

```
geocode_dropdown = Dropdown(
    options=sorted(df['Geocode'].dropna().unique()),
    description='Geocode:',
    style={'description_width': 'initial'},
    layout={'width': '50%'}
)

geocode_dropdown.observe(toon_categorieen, names='value')

print("de␣geo-code␣voor␣de␣Merwede␣Linge␣Lijn␣is␣118")

alle_geocodes = sorted(df["Geocode"].dropna().unique())
alle_categorieen = sorted(df["Categorie"].dropna().unique())

geocode_widget = widgets.Dropdown(
    options=alle_geocodes,
    description="Geocode:",
    style={'description_width': 'initial'}
)

categorie_checkboxes = [
    widgets.Checkbox(value=True, description=c)
    for c in alle_categorieen
]
categorie_box = VBox(categorie_checkboxes)

output = Output()

geocode_cache = {g: df[df["Geocode"] == g] for g in alle_geocodes}
VBox([geocode_dropdown, output])

## New cell

print("de␣geo-code␣voor␣de␣Merwede␣Linge␣Lijn␣is␣118")

alle_geocodes = sorted(df["Geocode"].dropna().unique())
alle_categorieen = sorted(df["Categorie"].dropna().unique())

geocode_widget = widgets.SelectMultiple(
    options=alle_geocodes,
    description="Geocode(s):",
    style={'description_width': 'initial'}
)

categorie_checkboxes = [
    widgets.Checkbox(value=True, description=c)
    for c in alle_categorieen
]
categorie_box = VBox(categorie_checkboxes)

output = Output()

def plot_geocode(change=None):
    with output:
        output.clear_output()

        geselecteerde_geocodes = list(geocode_widget.value)
        geselecteerde_cats = [cb.description for cb in categorie_checkboxes if cb.value]

        if not geselecteerde_geocodes:
            print("Selecteer␣minstens␣één␣geocode.")
            return

        subset = df[df["Geocode"].isin(geselecteerde_geocodes)]
        if geselecteerde_cats:
            subset = subset[subset["Categorie"].isin(geselecteerde_cats)]

        if subset.empty:
            print("Geen␣data␣om␣te␣plotten␣(controleer␣je␣filters).")
            return

```

```
        fig, ax = plt.subplots(figsize=(15,15))
        ax.set_aspect('equal')

        pad = 1000
        xmin, xmax = subset["RD X"].min(), subset["RD X"].max()
        ymin, ymax = subset["RD Y"].min(), subset["RD Y"].max()
        ax.set_xlim(xmin - pad, xmax + pad)
        ax.set_ylim(ymin - pad, ymax + pad)
        ctx.add_basemap(
            ax,
            crs="EPSG:28992",
            source=ctx.providers.OpenStreetMap.Mapnik
        )

        cmap = plt.colormaps['tab20']
        unieke_categorieen = sorted(subset["Categorie"].unique())
        categorie_kleuren = {cat: cmap(i % 20) for i, cat in enumerate(unieke_categorieen)}
        markers = ['o', 's', '^', 'D', 'x', 'P', '*', 'v', '<', '>']
        unieke_geocodes = sorted(subset["Geocode"].unique())
        geocode_markers = {g: markers[i % len(markers)] for i, g in enumerate(unieke_geocodes)}

        for (cat, geo), data_gc in subset.groupby(["Categorie", "Geocode"]):
            ax.scatter(
                data_gc["RD X"],
                data_gc["RD Y"],
                label=f"{cat} - {geo}",
                s=45,
                alpha=0.9,
                marker=geocode_markers[geo],
                color=categorie_kleuren[cat],
                zorder=6
            )

        ax.set_title(f"Locaties voor Geocode {geselecteerde_geocodes} (RD met kaart, gelijke schaal)")
        ax.set_xlabel("RD X")
        ax.set_ylabel("RD Y")

        ax.legend(title="Categorie - Geocode", bbox_to_anchor=(1.05, 1), loc="upper left")
        plt.tight_layout()
        fig.savefig("plots/plaatje.png")
        plt.show()

geocode_widget.observe(plot_geocode, names="value")
for cb in categorie_checkboxes:
    cb.observe(plot_geocode, names="value")

ui = HBox([VBox([geocode_widget, categorie_box]), output])
display(ui)

plot_geocode()

## New cell

overschrijding_df = pd.read_excel("overschrijding.xlsx")
remove_df = pd.read_excel("remove.xlsx")
remove_df.rename(columns=lambda x: x.strip(), inplace=True)
df118 = df.merge(
    overschrijding_df[['Naam', 'b_inf']],
    on='Naam',
    how='left'
)

if "naam" in remove_df.columns:
    remove_df.rename(columns={'naam': 'Naam'}, inplace=True)

namen_verwijderen = remove_df['Naam'].astype(str).str.strip().unique()
df118 = df118[~df118['Naam'].astype(str).str.strip().isin(namen_verwijderen)]

kolommen_verwijderen = [
```

```
    'argument', 'Datum␣opname', 'Referentiemal', 'Eigenaar', 'Organisatie',
    'Opmerking', 'Proces␣status', 'Kwaliteit'
]

df118 = df118.drop(columns=kolommen_verwijderen, errors="ignore")

categorie_filter = [
    "Spoelen␣en␣Potten",
    "Wisselbediening",
    "Rijdraad",
    "Perronrand",
    "Bovenleiding"
]

mask_geocode_118 = (df118['Geocode'] == 118) | (df118['Geocode'] == "118")
mask_categorie = df118['Categorie'].isin(categorie_filter)
df118 = df118[~(mask_geocode_118 & mask_categorie)]
df118.loc[df118['Naam'] == "118-2023-21-1433", "Categorie"] = "Perronobstakel"
df118.loc[df118['Categorie'] == "Kunstwerk", "Categorie"] = "Hekwerk"
df118['b_inf'] = pd.to_numeric(df118['b_inf'], errors='coerce')
df118['Overschrijding'] = 2250 - df118['b_inf'].abs()
verwijderd = df118[df118['Overschrijding'] < 0][['Naam', 'Categorie', 'Overschrijding']]
verwijderd.to_excel("Overschrijding_negatief_log.xlsx", index=False)
df118 = df118[df118['Overschrijding'] >= 0]
df118['Boogstraal␣(H)'] = pd.to_numeric(df118['Boogstraal␣(H)'], errors='coerce')
df118['Binnenzijde'] = df118['Binnenzijde'].astype(str).str.strip().str.upper()
tan_1deg = math.tan(math.radians(1))  # tan(1 graad)
boog = df118['Boogstraal␣(H)']

mask_i100_case1 = (df118['Binnenzijde'] == "ONWAAR") & (boog >= 2950) & (boog < 9000)
mask_i100_case2 = (df118['Binnenzijde'] == "ONWAAR") & (boog < 2950)

i100 = pd.Series(0.0, index=df118.index)

const_num = 11.8 * (100.0**2)  # 11.8 * 100^2
valid_case1 = mask_i100_case1 & (boog > 0) & (boog.notna())
i100.loc[valid_case1] = const_num / boog.loc[valid_case1]


valid_case2 = mask_i100_case2 & (boog > 0) & (boog.notna())
i100.loc[valid_case2] = (const_num / boog.loc[valid_case2]) - 20.0
i100.loc[valid_case2] = i100.loc[valid_case2].clip(upper=120.0)

df118['I_100'] = i100.fillna(0.0)
df118['I_100'] = pd.to_numeric(df118['I_100'], errors='coerce').fillna(0.0)

threshold_i80 = 1888
mask_i80_case1 = (df118['Binnenzijde'] == "ONWAAR") & (boog >= threshold_i80) & (boog < 9000)
mask_i80_case2 = (df118['Binnenzijde'] == "ONWAAR") & (boog < threshold_i80)

i80 = pd.Series(0.0, index=df118.index)
valid_i80_case1 = mask_i80_case1 & (boog > 0) & (boog.notna())
valid_i80_case2 = mask_i80_case2 & (boog > 0) & (boog.notna())

i80.loc[valid_i80_case1] = const_num / boog.loc[valid_i80_case1]
i80.loc[valid_i80_case2] = (const_num / boog.loc[valid_i80_case2]) - 20.0
i80.loc[valid_i80_case2] = i80.loc[valid_i80_case2].clip(upper=120.0)

df118['I_80'] = i80.fillna(0.0)
df118['I_80'] = pd.to_numeric(df118['I_80'], errors='coerce').fillna(0.0)

s_r = pd.Series(np.nan, index=df118.index)
mask_boog_9000 = boog == 9000

s_r.loc[mask_boog_9000] = 45.0

mask_boog_other = (boog.notna()) & (boog > 0) & (~mask_boog_9000)
s_r.loc[mask_boog_other] = ((3.75 / boog.loc[mask_boog_other]) + 0.045) * 1000.0

df118['S_R'] = s_r
```

```
df118['S_R'] = pd.to_numeric(df118['S_R'], errors='coerce')

df118['S'] = df118['S_R'] + 15.0

I100 = df118['I_100'].astype(float).fillna(0.0)
I80 = df118['I_80'].astype(float).fillna(0.0)

df118['\\Sigma_j_100_min'] = (
    25.0
    + (15.0 / 1500.0) * 1240.0
    + (15.0 / 1500.0) * 0.3 * 160.0
    + (tan_1deg * 160.0)
    + (7.0 / 1500.0) * 0.3 * 160.0
    + (I100 * 160.0)
)

df118['\\Sigma_j_100_max'] = (
    25.0
    + (15.0 / 1500.0) * 5000.0
    + (15.0 / 1500.0) * 0.3 * 3920.0
    + (tan_1deg * 3920.0)
    + (7.0 / 1500.0) * 0.3 * 3920.0
    + (I100 * 3920.0)
)

df118['\\Sigma_j_80_min'] = (
    25.0
    + (20.0 / 1500.0) * 1240.0
    + (20.0 / 1500.0) * 0.3 * 160.0
    + (tan_1deg * 160.0)
    + (7.0 / 1500.0) * 0.3 * 160.0
    + (I80 * 160.0)
)

df118['\\Sigma_j_80_max'] = (
    25.0
    + (20.0 / 1500.0) * 5000.0
    + (20.0 / 1500.0) * 0.3 * 3920.0
    + (tan_1deg * 3920.0)
    + (7.0 / 1500.0) * 0.3 * 3920.0
    + (I80 * 3920.0)
)


df118['S'] = pd.to_numeric(df118['S'], errors='coerce')

df118['b_SE_min_80'] = 2250.0 - df118['\\Sigma_j_80_max'] - df118['S'] - df118['
    Overschrijding']
df118['b_SE_max_80'] = 2250.0 - df118['\\Sigma_j_80_min'] - df118['S'] - df118['
    Overschrijding']
df118['b_SE_min_100'] = 2250.0 - df118['\\Sigma_j_100_max'] - df118['S'] - df118['
    Overschrijding']
df118['b_SE_max_100'] = 2250.0 - df118['\\Sigma_j_100_min'] - df118['S'] - df118['
    Overschrijding']

df118.to_excel("case_study.xlsx", index=False)
print("Eindbestand opgeslagen als: case_study.xlsx (met nieuw berekende kolommen)")

## New cell

df_cs = pd.read_excel("case_study.xlsx")

waarde_kolom = "Overschrijding"
cat_kolom = "Categorie"
geo_kolom = "Geocode"

geocodes = np.sort(df_cs[geo_kolom].dropna().unique())

def analyse_geocode(geocode):
    df_sub = df_cs[df_cs[geo_kolom] == geocode]

```

```
    if df_sub.empty:
        print("Geen data voor deze geocode.")
        return

    agg = df_sub.groupby(cat_kolom)[waarde_kolom].agg(
        aantal='count',
        maximum='max',
        minimum='min'
    ).reset_index()

    medians = df_sub.groupby(cat_kolom)[waarde_kolom].apply(lambda x: np.median(x.dropna())).reset_index(name='median')
    agg = agg.merge(medians, on=cat_kolom, how='left')

    max_of_maxima = agg['maximum'].max(skipna=True)
    max_of_medians = agg['median'].max(skipna=True)
    denominator = (0 if np.isnan(max_of_maxima) else max_of_maxima) + \
                  (0 if np.isnan(max_of_medians) else max_of_medians)

    totaal_aantal = len(df_sub)

    def extend_fn(row):
        if np.isnan(row['maximum']) or np.isnan(row['median']) or denominator == 0:
            return np.nan
        return (row['maximum'] + row['median']) / denominator

    agg['Extend'] = agg.apply(extend_fn, axis=1)
    agg['Observation'] = agg['aantal'] / totaal_aantal
    agg['Detection'] = 1
    agg['BNPN'] = agg['Extend'] * agg['Observation'] * agg['Detection']

    display(agg)

    print(f"--- INFO VOOR GEOCODE: {geocode} ---")
    print(f"max_of_maxima     = {max_of_maxima}")
    print(f"max_of_medians    = {max_of_medians}")
    print(f"denominator       = {denominator}")
    print(f"Totaal aantal rijen: {totaal_aantal}")

interact(analyse_geocode, geocode=Dropdown(options=geocodes, description="Geocode"));

## New cell

alle_geocodes = sorted(df118["Geocode"].dropna().unique())
alle_categorieen = sorted(df118["Categorie"].dropna().unique())

geocode_widget = widgets.SelectMultiple(
    options=alle_geocodes,
    description="Geocode(s):",
    style={'description_width': 'initial'}
)

categorie_checkboxes = [
    widgets.Checkbox(value=True, description=c)
    for c in alle_categorieen
]
categorie_box = VBox(categorie_checkboxes)

output = Output()

def plot_geocode(change=None):
    with output:
        output.clear_output()

        geselecteerde_geocodes = list(geocode_widget.value)
        geselecteerde_cats = [cb.description for cb in categorie_checkboxes if cb.value]

        if not geselecteerde_geocodes:
            print("Selecteer minstens één geocode.")
            return

```

```
        subset = df118[df118["Geocode"].isin(geselecteerde_geocodes)]
        if geselecteerde_cats:
            subset = subset[subset["Categorie"].isin(geselecteerde_cats)]

        if subset.empty:
            print("Geen data om te plotten (controleer je filters).")
            return

        fig, ax = plt.subplots(figsize=(15,15))
        ax.set_aspect('equal')

        pad = 1000
        xmin, xmax = subset["RD X"].min(), subset["RD X"].max()
        ymin, ymax = subset["RD Y"].min(), subset["RD Y"].max()
        ax.set_xlim(xmin - pad, xmax + pad)
        ax.set_ylim(ymin - pad, ymax + pad)
        ctx.add_basemap(
            ax,
            crs="EPSG:28992",
            source=ctx.providers.OpenStreetMap.Mapnik
        )

        cmap = plt.colormaps['tab20']
        unieke_categorieen = sorted(subset["Categorie"].unique())
        categorie_kleuren = {cat: cmap(i % 20) for i, cat in enumerate(unieke_categorieen)}
        markers = ['o', 's', '^', 'D', 'x', 'P', '*', 'v', '<', '>']
        unieke_geocodes = sorted(subset["Geocode"].unique())
        geocode_markers = {g: markers[i % len(markers)] for i, g in enumerate(unieke_geocodes)}
        for (cat, geo), data_gc in subset.groupby(["Categorie", "Geocode"]):
            ax.scatter(
                data_gc["RD X"],
                data_gc["RD Y"],
                label=f"{cat} - {geo}",
                s=45,
                alpha=0.9,
                marker=geocode_markers[geo],
                color=categorie_kleuren[cat],
                zorder=6
            )

        ax.set_title(f"Locaties voor Geocode {geselecteerde_geocodes} (RD met kaart, gelijke schaal)")
        ax.set_xlabel("RD X")
        ax.set_ylabel("RD Y")
        ax.legend(title="Categorie - Geocode", bbox_to_anchor=(1.05, 1), loc="upper left")
        plt.tight_layout()
        fig.savefig("plots/plaatje_opgeschoond.png")
        plt.show()

geocode_widget.observe(plot_geocode, names="value")
for cb in categorie_checkboxes:
    cb.observe(plot_geocode, names="value")

ui = HBox([VBox([geocode_widget, categorie_box]), output])
display(ui)
plot_geocode()

## New cell

alle_geocodes = sorted(df118["Geocode"].dropna().unique())
alle_categorieen = sorted(df118["Categorie"].dropna().unique())

geocode_widget = widgets.SelectMultiple(
    options=alle_geocodes,
    description="Geocode(s):",
    rows=8,
    style={'description_width': 'initial'}
)

categorie_checkboxes = [
```

```
    widgets.Checkbox(value=True, description=c)
    for c in alle_categorieen
]
categorie_box = VBox(categorie_checkboxes)

output = Output()
proj_rd2wgs = pyproj.Transformer.from_crs("EPSG:28992", "EPSG:4326", always_xy=True)

def plot_geocode_plotly(change=None):
    with output:
        output.clear_output()
        geselecteerde_geocodes = list(geocode_widget.value)
        geselecteerde_cats = [cb.description for cb in categorie_checkboxes if cb.value]
        if not geselecteerde_geocodes:
            print("Selecteer␣minstens␣één␣geocode.")
            return

        subset = df118[df118["Geocode"].isin(geselecteerde_geocodes)]
        if geselecteerde_cats:
            subset = subset[subset["Categorie"].isin(geselecteerde_cats)]

        if subset.empty:
            print("Geen␣data␣om␣te␣plotten.")
            return

        lons, lats = proj_rd2wgs.transform(
            subset["RD␣X"].values, subset["RD␣Y"].values
        )

        subset = subset.copy()
        subset["lat"] = lats
        subset["lon"] = lons
        subset = subset.sort_values("Overschrijding")

        fig = px.scatter_map(
            subset,
            lat="lat",
            lon="lon",
            color="Overschrijding",
            color_continuous_scale="YlOrRd",
            size=[12] * len(subset),
            opacity=1.0,
            hover_data={
                "Naam": True,
                "Categorie": True,
                "Geocode": True,
                "Overschrijding": True,
                "lat": False,
                "lon": False
            },
            zoom=12,
            height=700
        )

        fig.update_layout(
            map_style="open-street-map",
            margin=dict(l=0, r=0, t=0, b=0)
        )

        fig.show()

geocode_widget.observe(plot_geocode_plotly, names="value")
for cb in categorie_checkboxes:
    cb.observe(plot_geocode_plotly, names="value")

ui = HBox([VBox([geocode_widget, categorie_box]), output])
display(ui)

plot_geocode_plotly()

## New cell
```

```python

V = 100

h_list   = [4950, 4850, 4750]
bSE_list = [2030.9, 1900, 1750]

T_voie = 25
T_D = 15
L = 1500
h_c0 = 1080
s = 0.3
T_osc = 7
tan_1deg = math.tan(math.radians(1))

kolommen_basis = [
    "Geocode", "Categorie", "Kilometer van", "Naam",
    "Boogstraal (H)", "Binnenzijde", "RD X", "RD Y",
    "Overschrijding", "I_100", "S"
]

main_output_excel = f"assessment_MULTI_V={V}.xlsx"
removed_output_excel = "remove_test-gauge.xlsx"
removed_rows = []

results_assessments = {}
results_bnpn = {}

with pd.ExcelWriter(main_output_excel, engine="openpyxl") as writer:

    for h, bSE in zip(h_list, bSE_list):
        print(f"Verwerken voor h={h}, bSE={bSE}...")

        df_ass = df118[kolommen_basis].copy()
        delta_h = (h - h_c0)

        df_ass["Sigma_J"] = (
            T_voie
            + ((T_D / L) * h)
            + ((T_D / L) * s * delta_h)
            + (tan_1deg * delta_h)
            + ((T_osc / L) * s * delta_h)
            + ((df_ass["I_100"] * delta_h) / 1000)
        )

        df_ass["b_inf"] = df_ass["S"] + df_ass["Sigma_J"]

        df_ass["violation"] = -2250 + df_ass["Overschrijding"] + bSE + df_ass["b_inf"]

        removed = df_ass[df_ass["violation"] < 0].copy()
        kept    = df_ass[df_ass["violation"] >= 0].copy()

        if not removed.empty:
            removed["h"] = h
            removed["bSE"] = bSE
            removed_rows.append(removed)

        df_sub = kept.copy()
        cat_kolom = "Categorie"
        waarde_kolom = "violation"

        agg = df_sub.groupby(cat_kolom)[waarde_kolom].agg(
            aantal='count',
            maximum='max',
            minimum='min'
        ).reset_index()

        medians = df_sub.groupby(cat_kolom)[waarde_kolom].median().reset_index(name='median')
        agg = agg.merge(medians, on=cat_kolom, how='left')

        max_of_maxima = agg["maximum"].max()
        max_of_medians = agg["median"].max()
```

```
        denominator = max_of_maxima + max_of_medians if not np.isnan(max_of_maxima + max_of_medians) else 0

        totaal_aantal = len(df_sub)

        def extend_fn(row):
            if denominator == 0:
                return np.nan
            return (row["maximum"] + row["median"]) / denominator

        agg["Extend"] = agg.apply(extend_fn, axis=1)
        agg["Observation"] = agg["aantal"] / totaal_aantal
        agg["Detection"] = 1.00
        agg["BNPN"] = agg["Extend"] * agg["Observation"] * agg["Detection"]

        kept = kept.round(2)
        agg  = agg.round(2)

        sheet_name = f"h={h}_bSE={bSE}"
        bnpn_sheet_name = f"BNPN_h={h}_bSE={bSE}"

        kept.to_excel(writer, sheet_name=sheet_name, index=False)
        agg.to_excel(writer, sheet_name=bnpn_sheet_name, index=False)

        results_assessments[(h, bSE)] = kept.copy()
        results_bnpn[(h, bSE)] = agg.copy()

        print(f"  -> Verwijderd: {len(removed)} | Bijgehouden: {len(kept)}")

if removed_rows:
    df_removed_all = pd.concat(removed_rows, ignore_index=True)
    df_removed_all.to_excel(removed_output_excel, index=False)
    print(f"Verwijderde rijen opgeslagen in: {removed_output_excel}")
else:
    print("Geen negatieve violations. remove_test-gauge niet aangemaakt.")

def show_bnpn(change=None):
    display(output_bnpn)
    output_bnpn.clear_output()
    with output_bnpn:
        key = bnpn_dropdown.value
        h, bSE = key
        display(results_bnpn[(h, bSE)])

bnpn_dropdown = widgets.Dropdown(
    options=[(f"h={h}, bSE={bSE}", (h, bSE)) for h, bSE in zip(h_list, bSE_list)],
    description="BNPN sheet:"
)

output_bnpn = widgets.Output()
bnpn_dropdown.observe(show_bnpn, names="value")

display(widgets.VBox([bnpn_dropdown, output_bnpn]))

## New cell

h_bSE_options = [f"h={h}_bSE={bSE}" for h, bSE in zip(h_list, bSE_list)]
h_bSE_widget = widgets.Dropdown(
    options=h_bSE_options,
    description="h & bSE:",
    style={'description_width': 'initial'}
)

alle_geocodes = sorted(df118["Geocode"].dropna().unique())
geocode_widget = widgets.SelectMultiple(
    options=alle_geocodes,
    description="Geocode(s):",
    rows=8,
    style={'description_width': 'initial'}
)
```

```python
alle_categorieen = sorted(df118["Categorie"].dropna().unique())
categorie_checkboxes = [widgets.Checkbox(value=True, description=c) for c in alle_categorieen
    ]
categorie_box = VBox(categorie_checkboxes)

output_map = Output()

def plot_geocode_plotly(change=None):
    with output_map:
        output_map.clear_output()

        sel = h_bSE_widget.value
        if sel is None:
            print("Selecteer een h & bSE paar.")
            return

        h_str, bSE_str = sel.split("_bSE=")
        h = int(h_str.replace("h=", ""))
        bSE = float(bSE_str)


        try:
            df_ass = results_assessments[(h, bSE)].copy()
        except KeyError:
            print("Geen vooraf berekend resultaat.")
            return

        codes = list(geocode_widget.value)
        if codes:
            df_ass = df_ass[df_ass["Geocode"].isin(codes)]

        cats = [cb.description for cb in categorie_checkboxes if cb.value]
        if cats:
            df_ass = df_ass[df_ass["Categorie"].isin(cats)]

        if df_ass.empty:
            print("Geen data na filtering.")
            return

        lons, lats = proj_rd2wgs.transform(df_ass["RD X"].values, df_ass["RD Y"].values)
        df_ass["lat"] = lats
        df_ass["lon"] = lons

        # Plot
        subset = df_ass.sort_values("Overschrijding")
        fig = px.scatter_map(
            subset,
            lat="lat",
            lon="lon",
            color="Overschrijding",
            color_continuous_scale="YlOrRd",
            size=[12] * len(subset),
            opacity=1.0,
            hover_data={
                "Naam": True, "Categorie": True,
                "Geocode": True, "Overschrijding": True
            },
            zoom=12,
            height=700
        )
        fig.update_layout(map_style="open-street-map", margin=dict(l=0,r=0,t=0,b=0))
        global last_map_figure
        last_map_figure = fig
        fig.show()

h_bSE_widget.observe(plot_geocode_plotly, names="value")
geocode_widget.observe(plot_geocode_plotly, names="value")
for cb in categorie_checkboxes:
    cb.observe(plot_geocode_plotly, names="value")
```

```
ui = VBox([h_bSE_widget, HBox([geocode_widget, categorie_box]), output_map])
display(ui)

## New cell

def export_last_map_html(filepath="kaart_export.html"):
    """
    Slaat de laatst getoonde kaart op als standalone HTML file.
    """
    try:
        last_map_figure.write_html(filepath, include_plotlyjs="cdn", full_html=True)
        print(f"Kaart␣succesvol␣geëxporteerd␣naar:␣{filepath}")
    except NameError:
        print("Er␣is␣nog␣geen␣kaart␣gemaakt.␣Maak␣eerst␣een␣kaart␣via␣de␣UI.")

filename = f"kaart_h={h}_bSE={bSE}.html"
export_last_map_html(filename)
```

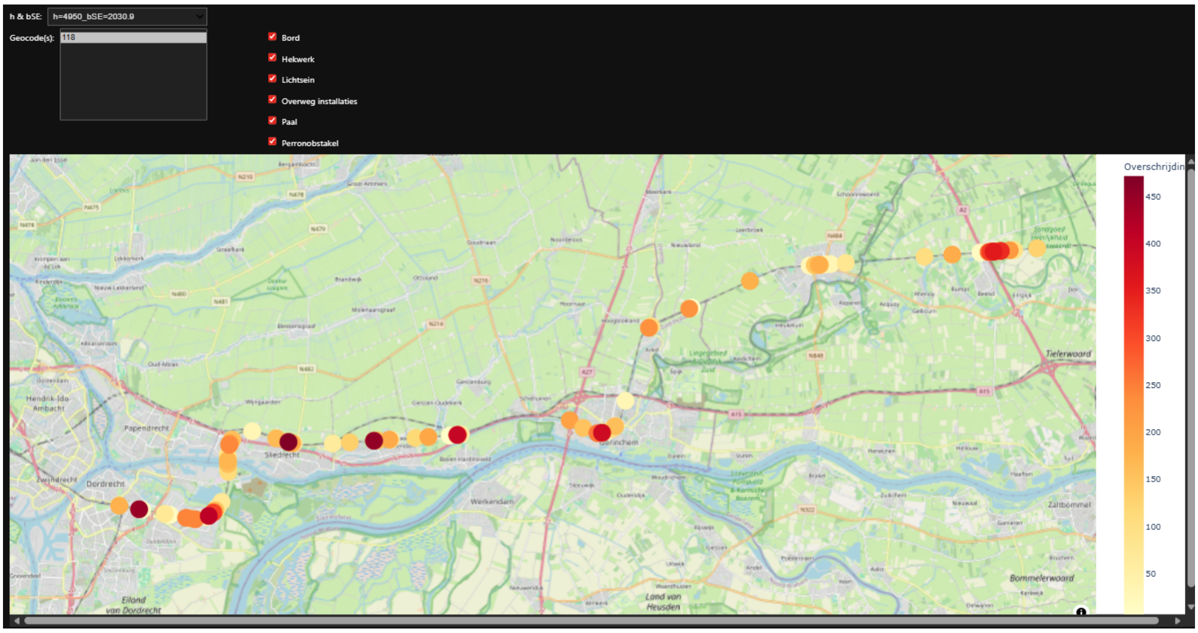


Figure A.1: Generated map

```
## New cell

h_bSE_options = [f"h={h}_bSE={bSE}" for h, bSE in zip(h_list, bSE_list)]
h_bSE_widget_static = widgets.Dropdown(
    options=h_bSE_options,
    description="h␣&␣bSE:",
    style={'description_width': 'initial'}
)

alle_geocodes = sorted(df118["Geocode"].dropna().unique())
geocode_widget_static = widgets.SelectMultiple(
    options=alle_geocodes,
    description="Geocode(s):",
    rows=8,
    style={'description_width': 'initial'}
)

alle_categorieen = sorted(df118["Categorie"].dropna().unique())
categorie_checkboxes_static = [
    widgets.Checkbox(value=True, description=c) for c in alle_categorieen
]
categorie_box_static = VBox(categorie_checkboxes_static)

```

```python
output_static_map = Output()

def plot_static_map(change=None):
    with output_static_map:
        output_static_map.clear_output()

        sel = h_bSE_widget_static.value
        if sel is None:
            print("Selecteer eerst een h & bSE-paar.")
            return

        h_str, bSE_str = sel.split("_bSE=")
        h = int(h_str.replace("h=", ""))
        bSE = float(bSE_str)

        try:
            df_ass = results_assessments[(h, bSE)].copy()
        except KeyError:
            print("Geen vooraf berekend resultaat voor dit h & bSE-paar.")
            return

        selected_geocodes = list(geocode_widget_static.value)
        if selected_geocodes:
            df_ass = df_ass[df_ass["Geocode"].isin(selected_geocodes)]

        selected_categories = [cb.description for cb in categorie_checkboxes_static if cb.value]
        if selected_categories:
            df_ass = df_ass[df_ass["Categorie"].isin(selected_categories)]

        if df_ass.empty:
            print("Geen data over na filtering.")
            return

        fig, ax = plt.subplots(figsize=(15, 15))
        ax.set_aspect("equal")

        pad = 1000
        xmin, xmax = df_ass["RD X"].min(), df_ass["RD X"].max()
        ymin, ymax = df_ass["RD Y"].min(), df_ass["RD Y"].max()
        ax.set_xlim(xmin - pad, xmax + pad)
        ax.set_ylim(ymin - pad, ymax + pad)

        ctx.add_basemap(
            ax,
            crs="EPSG:28992",
            source=ctx.providers.OpenStreetMap.Mapnik
        )

        cmap = plt.colormaps["tab20"]
        unieke_cat = sorted(df_ass["Categorie"].unique())
        cat_colors = {cat: cmap(i % 20) for i, cat in enumerate(unieke_cat)}

        markers = ['o', 's', '^', 'D', 'x', 'P', '*', 'v', '<', '>']
        unieke_geo = sorted(df_ass["Geocode"].unique())
        geo_markers = {g: markers[i % len(markers)] for i, g in enumerate(unieke_geo)}

        legend_entries = []
        for (cat, geo), sub in df_ass.groupby(["Categorie", "Geocode"]):
            sc = ax.scatter(
                sub["RD X"],
                sub["RD Y"],
                label=f"{cat} - {geo}",
                s=45,
                marker=geo_markers[geo],
                color=cat_colors[cat],
                alpha=0.9,
                zorder=6
            )
            legend_entries.append(sc)

```

```python
        ax.set_title(f"Statische kaart - h={h}, bSE={bSE}")
        ax.set_xlabel("RD X")
        ax.set_ylabel("RD Y")
        ax.legend(title="Categorie - Geocode", bbox_to_anchor=(1.05, 1), loc="upper left")
        plt.tight_layout()

        save_path = f"plots/static_map_h{h}_bSE{bSE}.png"
        fig.savefig(save_path, dpi=150)
        print(f"Kaart opgeslagen als: {save_path}")

        plt.show()

h_bSE_widget_static.observe(plot_static_map, names="value")
geocode_widget_static.observe(plot_static_map, names="value")
for cb in categorie_checkboxes_static:
    cb.observe(plot_static_map, names="value")

ui_static = VBox([
    h_bSE_widget_static,
    HBox([geocode_widget_static, categorie_box_static]),
    output_static_map
])
display(ui_static)

plot_static_map()

## New cell

gauge_map = {
    (4950, 2030.9): "Gauge-L",
    (4850, 1900):   "Gauge-M",
    (4750, 1750):   "Gauge-S",
}

gauge_colors = {
    "Gauge-L": "#1f77b4",  # blauw
    "Gauge-S": "#ff7f0e",  # oranje
    "Gauge-M": "#2ca02c",  # groen
}

category_rename_map = {
    "Bord": "1. Sign",
    "Hekwerk": "2. Fencing",
    "Lichtsein": "3. Light Signal",
    "Overweg installaties": "4. Level Crossing Installation",
    "Paal": "5. Pole",
    "Perronobstakel": "6. Platform Obstacle",
}

all_categories = sorted(
    {
       category_rename_map.get(cat, cat)
        for df in results_bnpn.values()
        for cat in df["Categorie"]
    }
)

bnpn_plot_data = {}

for (h, bSE), df in results_bnpn.items():
    gauge_name = gauge_map[(h, bSE)]

    df_plot = df.assign(
        Categorie=df["Categorie"].replace(category_rename_map)
    )

    series = (
        df_plot
        .set_index("Categorie")
        .reindex(all_categories)["BNPN"]
    )
```

```
    bnpn_plot_data[gauge_name] = series

x = np.arange(len(all_categories))
bar_width = 0.25

fig, ax = plt.subplots()

for i, gauge in enumerate(["Gauge-L", "Gauge-M", "Gauge-S"]):
    ax.bar(
        x + i * bar_width,
        bnpn_plot_data[gauge].values,
        width=bar_width,
        color=gauge_colors[gauge],
        label=gauge
    )

ax.set_xlabel("Bottleneck category")
ax.set_ylabel("BNPN score")
ax.set_title("BNPN per bottleneck category and test gauge")

ax.set_xticks(x + bar_width)
ax.set_xticklabels(all_categories, rotation=45, ha="right")

ax.grid(axis="y", linestyle="--", alpha=0.5)

ax.legend(
    title="Gauge",
    loc="upper right",
    frameon=True
)

plt.subplots_adjust(bottom=0.40)
plt.savefig("plots/BNPN_graph.png")
plt.show()

## New cell

gauge_order = ["Gauge-L", "Gauge-M", "Gauge-S"]

gauge_label_map = {
    "Gauge-L": "L",
    "Gauge-M": "M",
    "Gauge-S": "S",
}

all_categories = sorted(
    {
        category_rename_map.get(cat, cat)
        for df in results_assessments.values()
        for cat in df["Categorie"]
    }
)

violation_counts = {
    cat: [] for cat in all_categories
}
total_counts = []

for gauge in gauge_order:
    # juiste (h, bSE) bij deze gauge zoeken
    key = next(
        k for k, v in gauge_map.items()
        if v == gauge
    )

    df = results_assessments[key].copy()
    df["Categorie"] = df["Categorie"].replace(category_rename_map)

    # totaal aantal violations voor deze gauge
    total_counts.append(len(df))
```

```

    # aantallen per categorie
    counts_per_cat = df["Categorie"].value_counts()

    for cat in all_categories:
        violation_counts[cat].append(counts_per_cat.get(cat, 0))

x = np.arange(len(gauge_order))

fig, ax = plt.subplots(figsize=(8, 5))

for cat, values in violation_counts.items():
    ax.plot(
        x,
        values,
        marker="o",
        linewidth=2,
        label=cat
    )

ax.plot(
    x,
    total_counts,
    marker="o",
    linewidth=3,
    linestyle="--",
    color="black",
    label="Total"
)

ax.set_xlabel("Test␣gauge")
ax.set_ylabel("Number␣of␣violations")
ax.set_title("Number␣of␣violations␣per␣test␣gauge")

ax.set_xticks(x)
ax.set_xticklabels([gauge_label_map[g] for g in gauge_order])

ax.grid(True, linestyle="--", alpha=0.5)
ax.legend(
    title="Bottleneck␣category",
    bbox_to_anchor=(1.02, 1),
    loc="upper␣left",
    frameon=True
)

plt.tight_layout()
plt.savefig("plots/violations_per_gauge.png", dpi=300)
plt.show()

## New cell

df = pd.read_excel("case_study.xlsx")

df["b_inf_abs"] = pd.to_numeric(df["b_inf"], errors="coerce").abs()
df = df.dropna(subset=["b_inf_abs", "Categorie"])
df["Categorie_EN"] = df["Categorie"].replace(category_rename_map)

bin_edges = np.arange(1575, 2250 + 5, 5)
bin_centers = (bin_edges[:-1] + bin_edges[1:]) / 2
categories = sorted(df["Categorie_EN"].unique())
cmap = plt.get_cmap("tab10")
category_colors = {
    cat: cmap(i % 10) for i, cat in enumerate(categories)
}

counts_per_category = {}

for cat in categories:
    values = df.loc[df["Categorie_EN"] == cat, "b_inf_abs"]
    counts, _ = np.histogram(values, bins=bin_edges)
    counts_per_category[cat] = counts
```

```python

plt.figure(figsize=(10, 6))

bottom = np.zeros(len(bin_centers))

for cat in categories:
    plt.bar(
        bin_centers,
        counts_per_category[cat],
        width=5,
        bottom=bottom,
        color=category_colors[cat],
        edgecolor="black",
        linewidth=0.3
    )
    bottom += counts_per_category[cat]

plt.xlim(2250, 1575)
y_max = int(bottom.max())
plt.yticks(np.arange(0, y_max + 1, 1))

plt.axvline(2250, color="red", linewidth=2)
plt.axvline(2030.9, color="blue", linewidth=2)
plt.axvline(2115.9, color="green", linestyle="-.", linewidth=2)
plt.axvline(1900, color="green", linewidth=2)
plt.axvline(1962.7, color="orange", linestyle="-.", linewidth=2)
plt.axvline(1750, color="orange", linewidth=2)

line_handles = [
    Line2D([0], [0], color="red", linewidth=2, label="Edge red measurement area"),
    Line2D([0], [0], color="blue", linewidth=2, label="Gauge-L"),
    Line2D([0], [0], color="green", linewidth=2, linestyle="-.", label="Gauge-M with margin"),
    Line2D([0], [0], color="green", linewidth=2, label="Gauge-M"),
    Line2D([0], [0], color="orange", linewidth=2, linestyle="-.", label="Gauge-S with margin"),
    Line2D([0], [0], color="orange", linewidth=2, label="Gauge-S"),
]

category_handles = [
    Patch(facecolor=category_colors[cat], label=cat)
    for cat in categories
]

plt.legend(
    handles=line_handles + category_handles,
    ncol=2,
    loc="upper right",
    columnspacing=1.5,
    handlelength=2.5
)

plt.grid(True, axis="both")
plt.xlabel("Distance to the centre of the track [mm]")
plt.ylabel("Number of violations")
plt.title("Distribution of the violations within the red measurement area")
plt.tight_layout()

plt.savefig("plots/b_inf_violations_histogram.png", dpi=300)
plt.show()
```

B

Freight trains per connection

Appendix II of the document ‘Development of rail freight in the Netherlands - 2024 compared to 2023’ [6] contains the number of freight trains running between the connections. These numbers are summarised and included in Table B.1. On the vertical are the origins and on the horizontal the destinations.

	Amsterdam	Beverwijk	Blerick	Eijsden	Oldenzaal	Noord-NL	Roosendaal	Rotterdam	Sittard	Sloe	Tilburg	Venlo	Zevenaar	Zwaluwe	Overig	Totaal
Amsterdam	X	150			50			400				150	250		50	1050
Beverwijk	150	X		250	50							50	350		50	900
Blerick			X					1050				700	50		25	1825
Eijsden		250		X		100			150						25	525
Oldenzaal	50	100			X	150	500	1450		50	250			200	500	3250
Noord-NL				100	150	X									50	300
Roosendaal					500		X	350				1350	700	50	100	3050
Rotterdam	350		1050		1500		200	X	250	200	300	3850	8200	650	550	17100
Sittard				200				250	X	100		750	100		350	1750
Sloe					100			150	100	X		650	150		25	1175
Tilburg					200			300		50	X		50		25	625
Venlo	150		700				1350	3800	650	500		X		50	100	7300
Zevenaar	250	350	50				750	8300	100	200	50		X	100	150	10300
Zwaluwe					150		50	600				50	150	X	25	1025
Overig	50	25	25	25	500	50	50	500	300	50	25	100	150	25	X	1925
Totaal	1000	875	1825	575	3200	300	2900	17200	1550	1150	625	7650	10150	1075	2025	**52100**

Table B.1: Number of freight trains per connection in 2024

C

Merwede Linge Line

Timetable Point	Full Name	Number of tracks	Kilometre Marker	Distance to next point [km]	Travel time [min] (V=80 km/h)	Travel time [min] (V=100 km/h)
Ddr	Dordrecht	2	93.67	2.87	2.15	1.722
Ddrs	Dordrecht Stadspolder	2	90.80	1.52	1.14	0.912
Wijb	Wantijbrug	1	89.28	0.18	0.14	0.108
Ddria	Dordrecht Industrieaansluiting	1	89.10	1.68	1.26	1.008
Bmbr	Baanhoekbrug	1	87.42	0.97	0.73	0.582
Sdtb	Sliedrecht Baanhoek	1	86.45	2.68	2.01	1.608
Sdt	Sliedrecht	2	83.77	2.55	1.91	1.530
Hbzm	Hardinxveld Blauwe Zoom	1	81.22	1.39	1.04	0.834
Gnd	Hardinxveld-Giessendam	2	79.83	2.99	2.24	1.794
Bhvd	Boven-Hardinxveld	2	76.84	6.44	4.83	3.864
Gr	Gorinchem	2	70.40	4.64	3.48	2.784
Akl	Arkel	1	65.76	0.31	0.23	0.186
Mkbr	Merwedekanaalbrug	1	65.45	7.00	5.25	4.200
Ldm	Leerdam	2	58.45	5.37	5.32	4.254
Bsd	Beesd	2	51.36	4.03	4.03	3.222
Gdm	Geldermalsen	2	45.99	–	–	–
Totaal:				47.68	35.76	28.608

Table C.1: Train timetable and track information

D

Railfreight paths & demand

D.1. Rail freight capacity in 2030

The following formula is used to calculate capacity in the year 2030:

$$C_{\text{freight}} = \sum_{i=1}^{j} (H_{i,\text{week}} \times N_{i,\text{hour}} \times 2) \times W_{\text{year}} \tag{D.1}$$

With C_{freight} the capacity for rail freight trains in $[\frac{trains}{year}]$, $H_{\text{i, week}}$ the number of operating hours per week in $[\frac{hours}{week}]$ for the chosen rail freight corridor and $N_{i,\text{hour}}$ the number of trains per day per hour in $[\frac{pathways}{hour}]$ for the chosen rail freight corridor. The capacity is multiplied by two to represent the fact that the train pathways are bidirectional. This is then multiplied by the number of weeks per year W_{year}.

The railway may be used 24 hours a day, 7 days a week. Weekly withdrawals are included in the annual service schedule for maintenance and inspections of the railway. For each night, it is indicated which parts of the network are withdrawn from the timetable, and the numbers and duration vary per part of the network [14]. In the basic timetable for 2026, the Betuwe Route is withdrawn from the timetable for 8 hours one night a week. The Brabant Route is withdrawn from the timetable for 4 hours on four nights. The Bad Bentheim route is also withdrawn from the timetable for four nights for four hours. How the weekly withdrawals will be allocated in 2030 is still unknown, but planning specialists do not expect any major changes in this regard.

It should also be noted that as soon as the weekly withdrawal starts, all trains must be off the track, and as soon as the weekly withdrawal ends, the trains must pass through the corridor again. To give an indication of the period before and after the withdrawal, the length of the corridor is taken and divided by the speed. A speed of 100 km/h is used (TEN-T requirement). The data can be found in the Table D.1 below. The operating hours per week are rounded to whole hours.

Weekly available operating hours							
i	**Name**	**Length [km]**	**Clearing time [hour]**	**Number of weekly withdrawals**	**Duration of each withdrawal**	**hours a week with no train traffic**	$H_{\text{i, week}}$ **(rounded)**
1	Betuweroute	113	01:08	1	08:00	157:44	157
2	Brabantroute	149	01:30	4	04:00	140:00	140
3	Bad Bentheimroute	256	02:35	4	04:00	131:20	131

Table D.1: Weekly available operating hours

The number of train pathways per day varies by railway track and is included in the basic hour pattern [12]. Any increases in freight train pathways towards 2030 are included in the project documents. The train pathways for the three main rail freight corridors are listed in Table D.2. All rail freight pathways are bidirectional.

Freight train pathways		
i	*Track name*	*Pathways (bidirectional)*
1	Betuweroute	8
2	Brabantroute	2
3	Bad-Bentheimroute	2

Table D.2: Freight train pathways per track [12]

In total, this gives a capacity $C_{\text{freight}} = 186.992$ of freight trains per year for 2030. In Table D.3 it is given how the rail freight paths are distributed on the three main freight tracks.

Total freight train pathways 2030		
i	*Track name*	*Pathways per year*
1	Betuweroute	130.624
2	Brabantroute	29.120
3	Bad-Bentheimroute	27.248

Table D.3: Freight train pathways per track for the year 2030 [12]

D.2. Rail freight capacity and transport in 2024

In the current situation (2024), there is as much capacity available for rail freight transport as is planned for 2030. The only difference is the distribution of train paths across the network. Due to restrictions in the Sophia Tunnel, restrictions that have been partially lifted, [36] there are currently six bidirectional rail freight pathways per hour. Currently, there are four freight trains per hour in both directions via the Brabant route. As soon as the connecting curve under construction at Meteren [34] is complete, the number of freight train paths on the Brabant route will be reduced to two per hour in each direction. This means that $C_{\text{freight, 2024}} = 183.456$ freight trains for that year, the distribution over the network is given in Table D.4

Total freight train pathways 2024		
i	*Track name*	*Pathways per year*
1	Betuweroute	97.968
2	Brabantroute	58.240
3	Bad-Bentheimroute	27.248

Table D.4: Freight train pathways per track for the year 2024 [12]

Appendix B contains the table showing the number of freight trains that ran between the various connections. In 2024, a total of 52.100 freight trains were operated. [6] also provides information on how many trains have travelled on the Betuweroute. In 2024, 18.950 freight trains travelled between Kijfhoek and Meteren. This is 36,4% of the total number of freight trains operating in the Netherlands, using 19,3% of the capacity on the track that houses 53,4% of the national capacity.

D.3. Rail freight demand in 2030

The IMA 2021 [31] outlines high and low expectations for rail freight transport in the Netherlands in 2030. These figures are needed to determine how much train traffic should be diverted in the event of long-term disruption. The IMA includes, among other things, a high- and low-scenario scenario for the year 2030, based on population and employment growth. This provides the forecasts for rail freight in that year. It also includes the number of train journeys expected on the segments of the Betuweroute. The IMA was written in 2021 and is based on the WLO scenarios (Prosperity and Living Environment Scenarios) from 2015. In the period that followed, various developments took place that influenced the outcome of those forecasts and were not (fully) taken into account when drawing up the forecasts. These include the COVID-19 pandemic, the wars in Ukraine and Gaza, and the changing political situation in the Netherlands and internationally. Instead, it is recommended to look at the number of trains that ran in 2022. That year saw the highest number of freight trains in the past ten years, and in the years that followed, rail freight transport did not come close to reaching those levels again. The year 2022 does not provide a good prediction for the number of trains on the Betuweroute (the section between Kijfhoek and Meteren) because the third track in Germany was not yet ready in 2022. Therefore, it was decided to look at the percentages expected on the Betuweroute in 2030 and apply the average of these (50, 59%) to the scenario of 2022.

This provides the numbers shown in Table D.5 for the expected number of freight trains in 2030.

Total freight train demand 2030 $\left[\frac{\text{trains}}{\text{year}}\right]$			
Scenario:	2030 Low	2030 High	2022 based
Total demand:	76.200	82.200	61.500
Demand Betuweroute:	39.000	41.100	31.113

Table D.5: Freight train demand for 2030

D.4. Conclusion

Based on Table D.3 and Table D.5, it is possible to calculate how many freight trains cannot run if the Betuweroute is unavailable. The Equation D.1 can then be used in reverse to determine how many rail freight pathways are required per hour. The operating hours per week vary per railway line. For the calculation, it was decided to use 4 withdrawals per week of 4 hours, as this is the most common situation, with a clearing time of one and a half hours before and after. This results in 28 hours per week of withdrawal from the timetable and 140 operating hours per week. The additional pathways required based on these figures are listed in Table D.6.

Required additional pathways/hour	
Scenario:	**Additional pathways**
2030 Low	3
2030 High	4
2022 based	1

Table D.6: Additional freight pathways required per hour

E

OVS00056v007 information

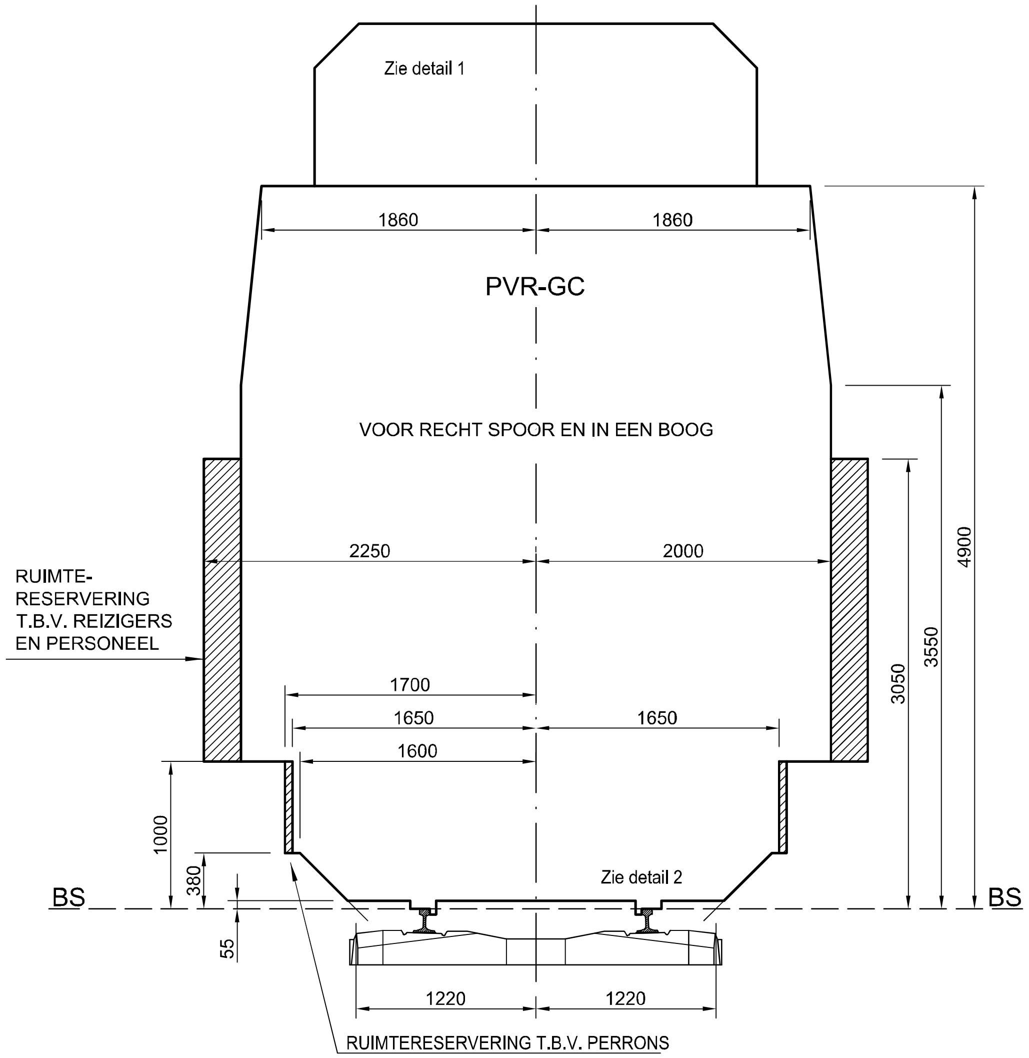
This appendix contains the most relevant information from the design regulation on the UIC-gauge (OVS00026v007)

Bijlage 1a Profiel van Vrije Ruimte – GC

(kinematisch referentieprofiel GC)

Maten in mm

Voor detail 1 ruimte voor stroomafnemer zie bijlage 1b

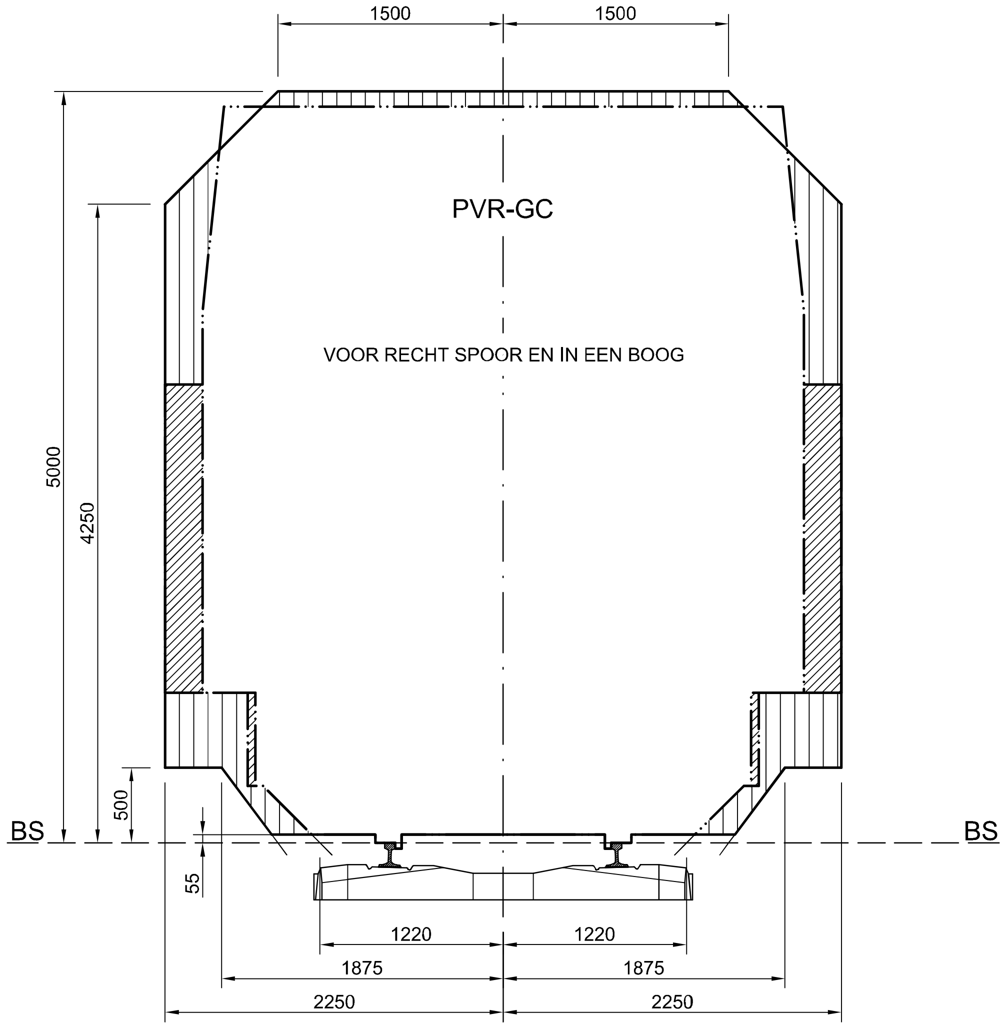


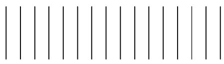
Voor detail 2, ruimte voor de wielflens zie bijlage 1c

Van toepassing voor bogen met R ≥ 250 m.
Voor R < 250 is art 5.2, Tabel 1 van toepassing.

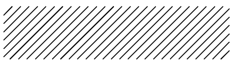
Bijlage 4a Profiel van het Rode Meetgebied rondom PVR–GC

Maten in mm





Rode Meetgebied



Ruimte reservering, deze ruimte behoort ook tot het Rode Meetgebied

F

Gauge violations per categories

This appendix contains the maps on which the violations are plotted per bottleneck categorie.

Figure F.1: Geographical distribution of the bottleneck categorie Signs

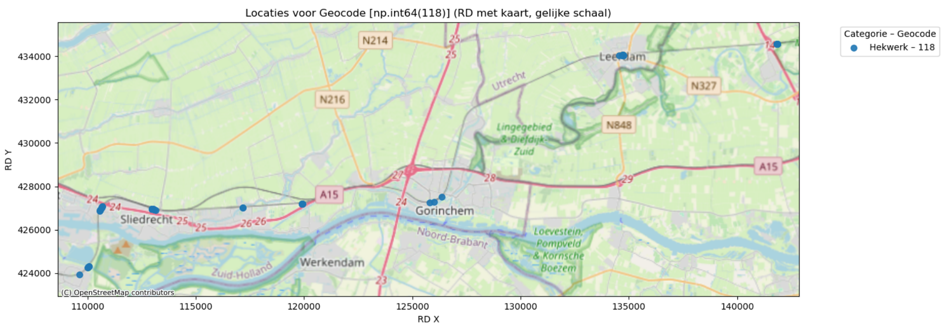


Figure F.2: Geographical distribution of the bottleneck categorie Fencing

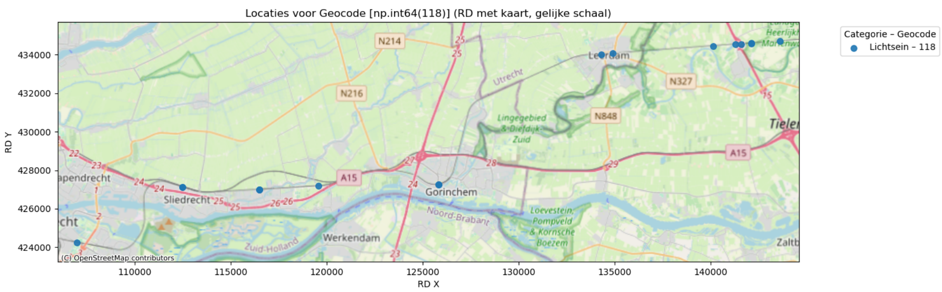


Figure F.3: Geographical distribution of the bottleneck categorie Light Signals

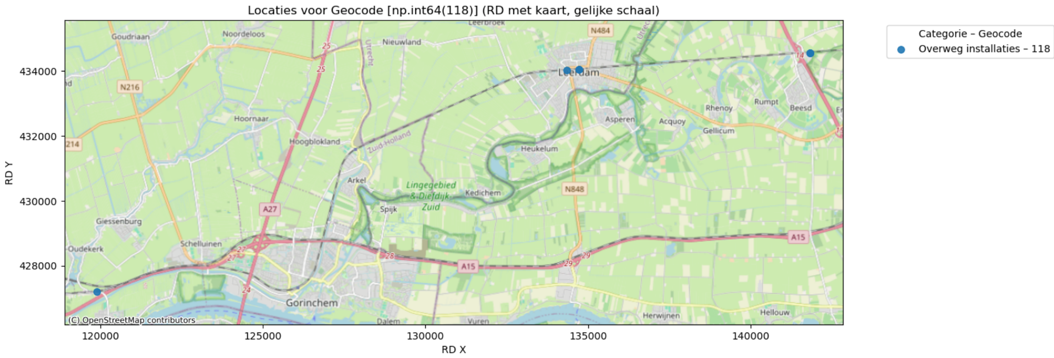


Figure F.4: Geographical distribution of the bottleneck categorie Level Crossing Installations

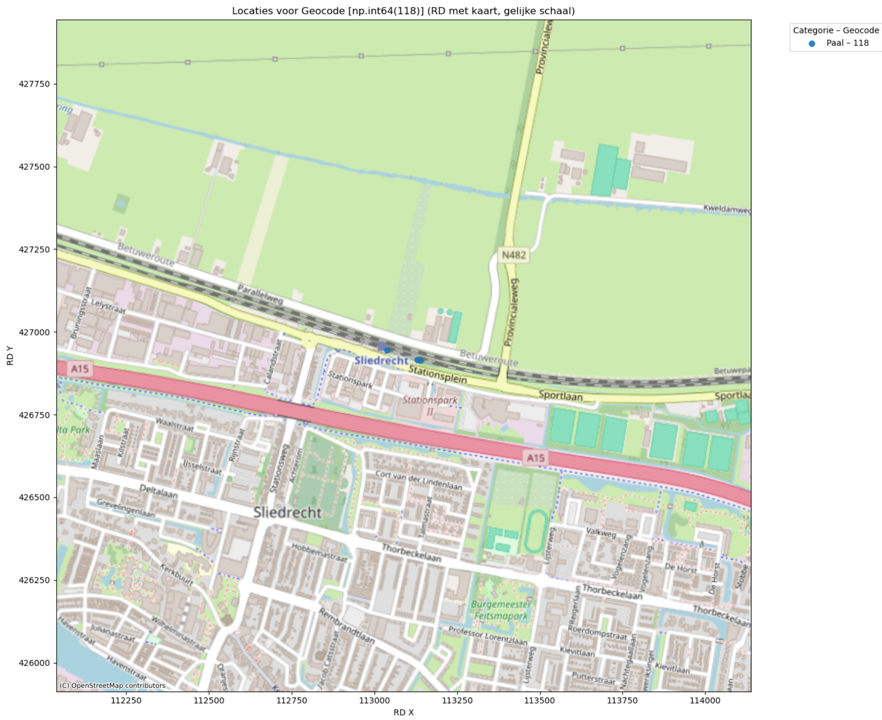


Figure F.5: Geographical distribution of the bottleneck categorie Pole

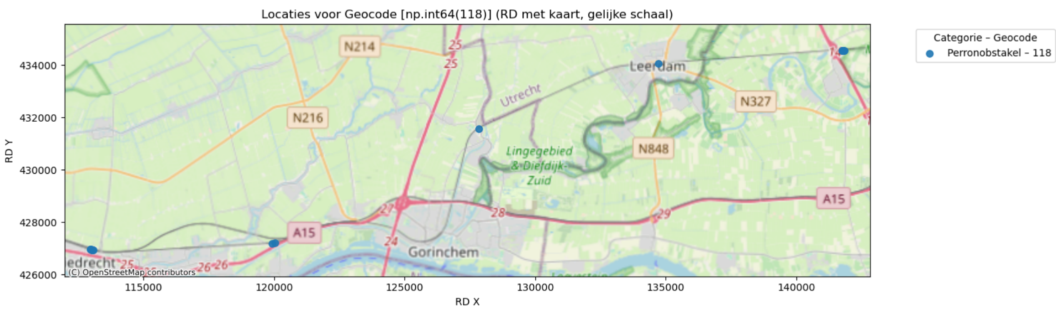


Figure F.6: Geographical distribution of the bottleneck categorie Platform Obstacle