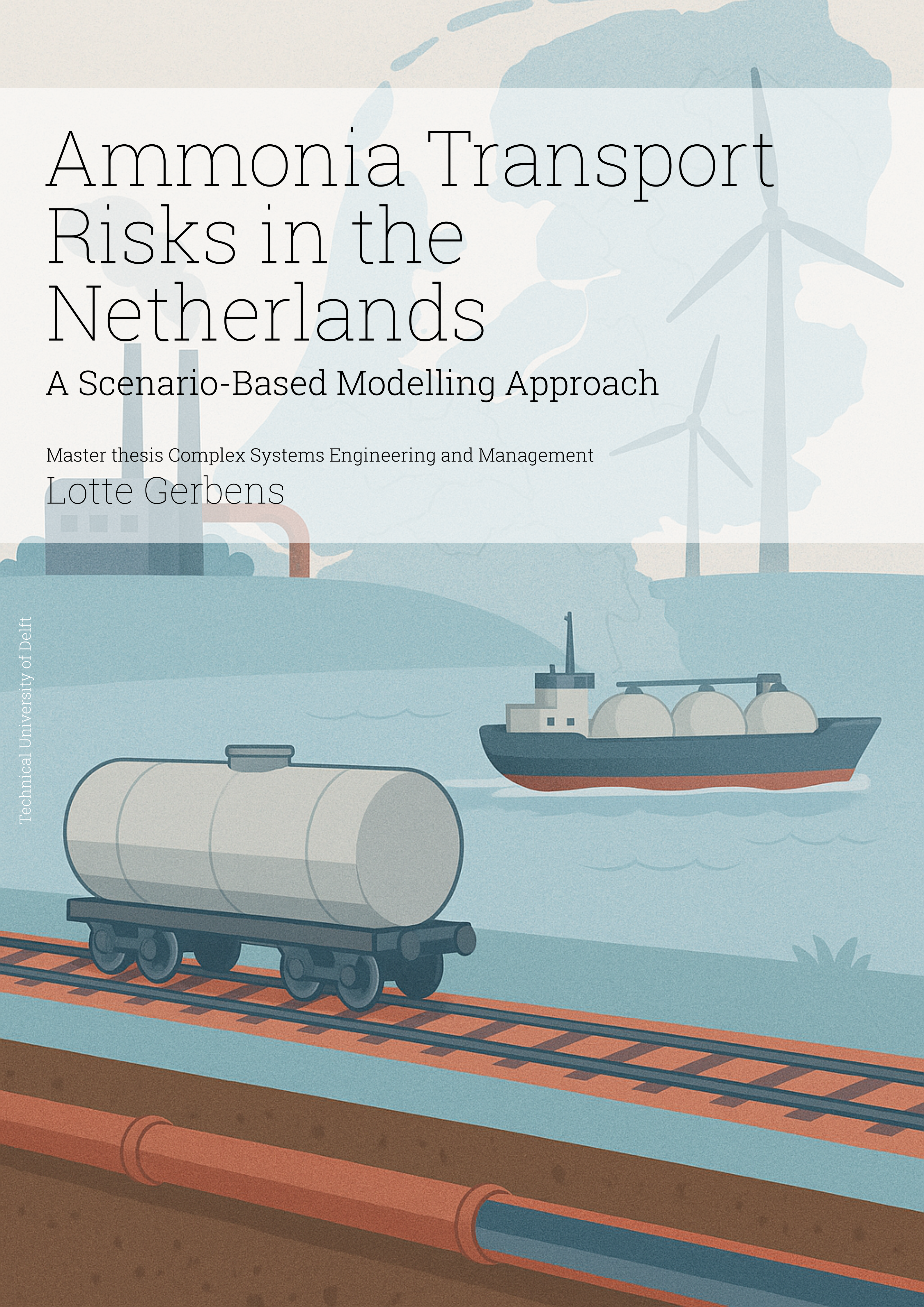
Ammonia Transport Risks in the Netherlands

A Scenario-Based Modelling Approach

Master thesis Complex Systems Engineering and Management

Lotte Gerbens



Technical University of Delft

Ammonia Transport Risks in the Netherlands

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by

Lotte Gerbens

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Acknowledgments

Dear reader,

Before you lies my Master thesis on the external safety risks of large-scale ammonia transport in the Netherlands. With this research, I hope to contribute to a safe and responsible energy transition—one of the most pressing challenges of our time. From a young age, I've been deeply fascinated by the natural world. I grew up with a love for nature and animals, and through the years I have gained a growing awareness of how vulnerable it is in the face of climate change. I still remember how captivated I was the first time I read ”A Life on Our Planet” by David Attenborough. His concluding words reinforced in me the conviction that I wanted to dedicate my academic and professional path to contributing to a sustainable future. Throughout my studies, I have therefore aimed to engage with the energy transition wherever possible—through coursework, projects, and now this thesis. In this research, I had the opportunity to work on a topic that is both technically complex and societally relevant: ensuring that the large-scale transport of ammonia, a promising hydrogen carrier, can take place in a safe and responsible way.

I would like to express my sincere gratitude to all those who supported me throughout the process of writing this thesis. First and foremost, I am grateful to my academic supervisors at TU Delft, Genserik and Jan Anne, for their valuable feedback, critical questions, and encouragement throughout the research process. Their guidance has been instrumental in shaping this thesis both methodologically and academically. I would also like to extend my heartfelt thanks to my supervisor at the RIVM, Suzanne, for the countless hours of support, expertise, and thoughtful input. You always made sure to have time for me and your patience, practical insights, and genuine enthusiasm for the topic made a significant difference in both the progress and enjoyment of this research. Lastly, I would like to thank my friends and family for their encouragement and support during the final phase of my studies.

Hopefully, you will read this thesis with as much pleasure as I had writing it.

Lotte B. Gerbens
Rotterdam, July 2025

Executive Summary

As ammonia gains attention as a sustainable hydrogen carrier in the European energy transition, the Netherlands faces a challenge: how to facilitate large-scale ammonia transport while safeguarding public safety. Ammonia's favourable transport properties, compatibility with existing infrastructure, and potential for green production make it a promising solution as a hydrogen carrier. Yet, ammonia is highly toxic and accidents during transport can result in devastating consequences for people and the environment. In anticipation of rising transport volumes, especially along industrial corridors such as Rotterdam–Chemelot, the Dutch government has committed to reducing risks where possible. To support risk-informed policymaking, this study evaluates the safety implications of transporting ammonia via pipelines, railways, and inland shipping under future projected transport volumes, using scenario-based modelling and multi-criteria evaluation.

The study is guided by the following research question: *What do scenario-based modelling with Safeti-NL and multi-criteria evaluation reveal about the relative safety and overall performance of ammonia transport via pipelines, railways, and inland shipping in the Netherlands?* To answer this question, a modelling-based approach is used, integrating desk research, scenario analysis, quantitative risk assessments (QRA) in Safeti-NL, GIS-based visualisation of the modeled risk and toxic effect zones, a multi-criteria analysis and expert consultations. To enable a structured comparison of the modalities, two contrasting locations were selected as example case studies: urban Breda and rural Moerdijk. Scenario development included both most probable and worst-case accidents. After initial risk quantification, tailored mitigation strategies were identified and modelled per modality to explore their mitigating potential. Finally, a multi-criteria analysis (MCA) was conducted to compare the three modalities not only in terms of human safety, but also on security, environmental impact, affordability, feasibility, adaptability, sustainability, and reliability.

The unmitigated risk assessments show significant variation between transport modalities. Rail transport exceeds the legal threshold for individual risk (PR 10^{-6}) in Breda and although its group risk remains moderate, it causes substantial toxic exposure zones. In Moerdijk this trend remains, though the 10^{-6} contour is very limited. Inland shipping performs better in terms of individual risk and shows no 10^{-6} exceedance in Breda, but in Moerdijk, this 10^{-6} contour is present and quite extensive, although the practical implications remain limited due to a large part of the contours falling in the waterway. However, group risk and effect distances are more significant for inland shipping than for rail transport. Pipeline transport shows the most severe individual risk exceedances, the highest group risk and largest effect zones in both locations. This is mostly due to the large volume and continuous release of ammonia during ruptures. The potential scale of accidents makes pipeline transport the most concerning modality in terms of collective risk.

After the implementation of mitigation strategies, safety performance improves across all modalities. For rail transport, measures such as reduced speed, ETCS, upgraded wagon design, and smaller tank wagons help reduce risk contours, but the PR 10^{-6} exceedance in Breda remains. Inland shipping benefits significantly from improved navigation and communication systems, underwater tank placement, smaller tanks and semi-cooled ammonia transport, resulting in compact risk and effect zones. In fact, the 10^{-6} contours are eliminated in both urban and rural contexts, with the 10^{-7} contour also disappearing in Breda, and the remaining contours are small and concentrated. Pipeline transport also benefits from mitigation through warning tape, supervision during work activities, shut-off valves and reduced pipeline diameter. This eliminates PR 10^{-6} contours in both locations. However, group risk remains above the orientation threshold in Breda, and its toxic effect zones are still the largest among all modalities.

The multi-criteria evaluation confirms that inland shipping performs best overall under mitigated conditions. It scores highest on safety, security, and adaptability. Its environmental risks are moderate: while the risk to surface water is high, the risk to soil and groundwater is minimal. Rail transport scores poorly on safety, feasibility, and reliability, and would require significant investment in new tank wagons and infrastructure to reduce existing capacity bottlenecks. Although pipelines perform well on sustainability and operational reliability, they score lowest on safety and adaptability. Their inflexibility, high investment costs, and extensive potential for lethal consequences in case of an incident limit their overall preference.

In addition to its practical value, this research also has an academic and societal contribution. Scientifically, it introduces a structured, scenario-based modelling approach for multimodal ammonia transport risk assessment, addressing a clear gap in existing literature. Most studies focus on a single transport mode, whereas this research offers a harmonised, spatially explicit comparison across pipelines, rail, and inland shipping. It provides new empirical insights and a replicable framework that future studies can adapt and extend. Societally, the study supports risk-informed policymaking by revealing where risks are concentrated, how they differ by modality and location, and which mitigation strategies are most effective. Translating technical risk outputs into visual and quantitative comparisons also helps bridge the gap between expert analysis and public understanding, which is essential for transparent and well-informed decisions in the energy transition.

This research is subject to several limitations. First, the analysis makes many assumptions, which could limit the realism of the results. For example, the study is based on projected transport volumes for 2033, while future demand is very uncertain. Second, the modelling focuses exclusively on preventive risk management, while reactive mitigating measures are excluded. Additionally, the research is limited to the Dutch context, while future ammonia flows are expected to serve wider European energy needs, which neglects the broader geopolitical and infrastructural reality. Also, except for the human safety criteria, none of the criteria were quantitatively assessed, which reduces objectivity. Finally, the MCA incorporates subjective expert judgement in weighting and scoring criteria, which further reinforces this limitation.

Based on the findings, it is recommended that policymakers prioritise inland shipping where navigable waterways are available, especially in light of its high safety performance and adaptability. Pipeline transport may become viable if routing avoids densely populated areas and safety investments are maximised from the design phase. Rail transport, by contrast, should only be considered where alternative modalities are unavailable. Across all modalities, location-specific safety assessments should guide zoning and infrastructure planning. The integrated use of QRA, GIS visualisation, and MCA in this study offers a replicable decision-support method for creating balanced ammonia transport networks.

Future research should expand on this study by distinguishing between short- and long-term requirements in ammonia transport. Additionally, the application of this approach to other hazardous substances or European contexts would support cross-border policy alignment. Research on public perception and societal acceptance of ammonia transport options could provide further insights into policy feasibility. Lastly, validating mitigation effects in real-world pilot projects would strengthen the robustness of scenario-based planning.

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Introduction

This chapter introduces the research context and problem, explores relevant academic literature on hazardous materials transport and risk management, and identifies the knowledge gaps this thesis aims to address. It further defines the research objectives and scope, formulates the central research questions, and outlines the societal, scientific, and educational relevance of the study. The chapter concludes with a brief overview of the structure of this thesis.

1.1. Research Problem

Governments around the world are faced with the challenge of ensuring electricity security and meeting growing electricity uses while simultaneously cutting greenhouse gas emissions (IEA, 2022). The transition to renewable energy and the reduction of emissions have been demanded as a result of growing awareness of the negative effects fossil fuels have on the environment (Dolan et al., 2021). In response to the growing awareness of global warming, countries worldwide have pledged to take measures under the Paris Agreement (United Nations, 2015) to combat climate change. To be able to adhere to this agreement, energy carriers such as hydrogen have been proposed as green alternatives for energy storage and transport (Dolan et al., 2021). They can be widely used as a low-carbon energy carrier, supporting the gradual replacement of fossil fuels (Ong et al., 2024). This makes it essential for supporting the EU's goal of achieving carbon neutrality by 2050 (Ministerie van Klimaat en Groene Groei, 2024a). However, hydrogen itself faces transport and storage challenges, including low volumetric energy density and high costs (Ong et al., 2024). This has led to increasing interest in hydrogen carriers such as ammonia, which can store and transport hydrogen more efficiently (Acar and Dincer, 2020).

Ammonia is gaining international attention thanks to its efficient storage and transport of hydrogen, the potential for green production without CO_2 emissions and its compatibility with existing infrastructure (Sun et al., 2022). Additionally, once hydrogen is converted to ammonia, its energy density is increased, which makes long-distance transport more cost-effective (IRENA, 2023). However, as countries explore large-scale use of ammonia in energy systems, health and safety concerns are becoming increasingly prominent (Dolan et al., 2021). Accidents involving ammonia can result in extensive respiratory damage, permanent blindness and even major fatalities (Crolius et al., 2021). Additionally, accidents could cause significant environmental damage leading to soil toxicity, drinkwater pollution or mass die-offs of aquatic species (Anand and Barkan, 2006; Saat et al., 2014; Zhang et al., 2023). Therefore, analyzing and improving the safety of ammonia transport is a growing global concern, especially with its expected role in the energy transition (Kojima, 2024).

Risk assessments and mitigation strategies can support the safe integration of ammonia into national energy systems (Galeev et al., 2013). While the issue of safe ammonia transport is inherently international, safety policies and risk assessment practices vary considerably across countries. For example, although rail transport within Europe is governed by RID regulations, the Netherlands uses additional dedicated infrastructure policies such as the Basic Network Act (Ministerie van Infrastructuur en Waterstaat, n.d.). Furthermore, the Dutch approach to safety is shaped by legislation such as the 'Besluit kwaliteit leefomgeving' (Bkl) (The Environmental Quality Decree of the Netherlands) and the 'Besluit activiteiten leefomgeving' (Bal) (The Environment and Planning Act) (Rijksoverheid, 2024; Rijksoverheid, 2025), which mandates maximum allowable individual risk levels near the presence of hazardous materials. To be able to accurately model and assess these specific allowable risks, the Netherlands selected a customised version of the DNV risk tool Safeti as the national standard. This version – Safeti-NL – integrates extensive modifications to align with the Dutch safety requirements (Witlox and Worthington, 2007).

Given these national characteristics of allowable ammonia transport risks, this thesis focuses on the Netherlands specifically. In response to ammonia safety concerns, the Dutch government has committed to reducing risks for citizens by aiming to limit or phase out ammonia transport where possible (Ministerie van Klimaat en Groene Groei, 2024a). However, since ammonia is expected to play an increasingly important role in the energy transition, a complete phase-out of transport is very difficult. Instead, structured and location-specific risk assessments are necessary to determine how ammonia transport via several modalities can be made acceptably safe. Though ammonia can be transported via land (road and rail), water, and pipelines (Guo and Luo, 2022), road transport is only suitable for small-scale ammonia transport (Khaksar et al., 2024; TNO et al., 2022). Therefore, this study focuses explicitly on the safety risks of large-scale ammonia transport caused by accidental releases, through rail, inland shipping and pipeline transport. To assess the safety performance of each modality in a structured and comparable way, a scenario-based approach is used, defining both a most probable scenario and a worst-case scenario per modality. These scenarios are modelled in Safeti-NL at two representative locations to quantify their impact on safety.

1.2. Literature Exploration

Numerous studies have examined hazardous materials and their transportation. More specifically, they focus on transport risk assessments of specific modalities (Fang et al., 2017; Ovidi et al., 2020; Zhou and Chen, 2015; Vosooghi and Verma, 2025), general risk assessment (Mohri et al., 2022; Blišťanová et al., 2023), risk management (Liu et al., 2021; Guo and Luo, 2022; Polorecka et al., 2021; Kubas et al., 2022), and regulatory and policy challenges (Schipper et al., 2023).

This literature exploration has two main objectives. First, it establishes a conceptual foundation by clarifying key terms such as hazardous materials, transport risk assessment, the three transport modalities, and risk management. Second, it provides an overview of existing research on the transport of hazardous materials and the associated risks. This review ultimately aims to show the knowledge gaps in the current literature. The PRISMA flow diagram that presents the selection process of the literature, a structured overview of the selected articles, and a comparison between this study and the analysed publications can be found in Appendix A.

1.2.1. Hazardous Materials

Hazardous materials (hazmat) are substances that can cause harm to human health, property, or the environment (Mohri et al., 2022; Liu et al., 2021; Zhou and Chen, 2015; Polorecka et al., 2021). They are either flammable, explosive, toxic, or radioactive (Guo and Luo, 2022; Schipper et al., 2023; Mohri et al., 2022; Liu et al., 2021). The transportation of hazardous materials is a critical component of industrial supply chains but this activity also presents significant safety risks (Guo and Luo, 2022; Mohri et al., 2022; Ovidi et al., 2020), especially when transport routes pass through populated areas (Ovidi et al., 2020; Schipper et al., 2023). While hazmat transport accidents occur less frequently than other transportation-related incidents, their potential consequences are catastrophic (Mohri et al., 2022).

Hazardous materials often have distinct physical and chemical properties that influence the nature of risks in the event of a release. While these distinct properties often do not change across transport modes, emerging risks and their severity in case of an incident can vary significantly. This can be due to differences between transport modalities in, for example, transport volumes or release dynamics. Effective risk assessment should therefore account for both the substance and its transport method to ensure accurate evaluation of potential threats (Guo and Luo, 2022). However, most studies assess hazardous materials transport as a broad category, without distinguishing substance-specific risks and their transport modality. This generalized approach fails to capture important differences in hazardous properties, particularly for ammonia, whose primary hazard is toxicity rather than fire or explosion (Kubas et al., 2022; Polorecka et al., 2021). Although Kubas et al. (2022) and Polorecka et al. (2021) model ammonia risks, they do not evaluate how different transport modes influence these risks and the extent of their consequences. The lack of ammonia-specific transport risk assessments leaves uncertainty about how different transport methods influence ammonia-related incidents and what modality is preferred in terms of safety.

1.2.2. Risk Assessment of Transportation

The risk associated with hazardous materials transport is defined as the product of the probability and the consequence of an undesirable event (Mohri et al., 2022; Fang et al., 2017; Kubas et al., 2022; Schipper et al., 2023). Due to the dangerous nature of hazmat, it is important to not only determine the risk of an accident in terms of likelihood, but also by its severity (Liu et al., 2021). The extent of an incident is especially important when it occurs in densely populated or environmentally sensitive areas (Liu et al., 2021; Kubas et al., 2022). In the research, hazardous materials transport risks are assessed in three ways:

1. **Based on incident probability** – Focuses on how likely an accident is to occur (Liu et al., 2021);
2. **Based on population exposure** – Evaluates the number of people at risk if an incident occurs (Kubas et al., 2022; Liu et al., 2021; Ovidi et al., 2020; Vosooghi and Verma, 2025);
3. **Scenario-based** – Simulates potential leakage incidents to analyze their dispersion patterns and impacts, using the results to identify the most probable risks (Fang et al., 2017; Kubas et al., 2022; Ovidi et al., 2020; Polorecka et al., 2021).

Each of these methods provides valuable insights into hazardous materials transport risks. However, the studies apply them in isolation or combine two of the methods, rather than integrating all three into a single risk assessment approach. This fragmented approach limits the ability to assess the risks of hazardous materials transport accidents in a comprehensive manner.

1.2.3. The Three Transport Modalities

Hazardous materials can be transported via land (road and rail), water, and pipelines (Zhou and Chen, 2015; Guo and Luo, 2022; Ovidi et al., 2020; Blišťanová et al., 2023). Each mode presents unique risks and challenges, necessitating mode-specific risk assessment (Guo and Luo, 2022; Blišťanová et al., 2023). However, most studies focus on a single transport mode, primarily rail (Fang et al., 2017; Vosooghi and Verma, 2025; Ovidi et al., 2020), with limited research on pipelines (Zhou and Chen, 2015) and none specifically on inland shipping. While Schipper et al. (2023) provides an overview of all three transport modes, it lacks ammonia-specific focus and does not compare risk levels, trade-offs, or safety measures across modalities. This lack of cross-modal analysis prevents a comparative evaluation of their safety and effectiveness.

Rail transport currently plays a critical role in hazardous materials transportation, as many suppliers and customers of the chemical industry are primarily accessible via railway networks (Schipper et al., 2023; Fang et al., 2017). However, the potential for high-impact accidents is a concern (Fang et al., 2017; Blišťanová et al., 2023). The infrequent but severe nature of these incidents requires decision-makers to apply a risk-averse policy when transporting hazardous shipments (Vosooghi and Verma, 2025). This is particularly the case in countries like the Netherlands, where many major railway routes pass through densely populated areas (Ovidi et al., 2020). Despite strict regulations, railway transport remains vulnerable to infrastructure issues, human error, equipment failure, and adverse weather conditions (Blišťanová et al., 2023). As a result, accidents continue to pose significant health risks (Vosooghi and Verma, 2025).

Inland shipping, particularly in the Netherlands, is essential for hazardous materials transport (Schipper et al., 2023). However, it also presents significant safety risks, including human error and adverse environmental conditions (Blišťanová et al., 2023). Although inland shipping offers flexibility and can handle fluctuating demand, its potential hazards necessitate strict international and national regulations to prevent accidents and reduce environmental impact (Blišťanová et al., 2023).

Pipeline transport is considered the most safe, efficient and reliable method for transporting hazardous materials (Zhou and Chen, 2015). While pipelines have lower accident rates than other transport modes, failures can lead to severe environmental and safety consequences due to large-scale hazardous material releases (Zhou and Chen, 2015). In the Netherlands, pipelines account for the majority of hazardous materials transport (Schipper et al., 2023). However, they lack operational flexibility, as capacity cannot be easily adjusted to meet fluctuating demand and they are generally dedicated to specific substances (Schipper et al., 2023). This makes them well-suited for stable, large-scale transport but less adaptable than rail or inland shipping.

1.2.4. Risk Management

A crucial aspect of hazardous material transport is risk management, especially for substances such as ammonia, where rapid intervention is essential to minimise human harm (Liu et al., 2021).

Most risk assessment models focus on preventive planning, selecting optimal transport routes and safety measures based on risk minimisation and population exposure (Kubas et al., 2022; Guo and Luo, 2022; Blišťanová et al., 2023). According to Polorecka et al. (2021), this is because preparing for future crises is generally considered more effective than attempting to manage all potential hazards once they occur. As a result, reactive capabilities — in particular, the speed and effectiveness of emergency response — are often underrepresented in quantitative risk models (Liu et al., 2021). Nonetheless, literature highlights that faster intervention can significantly reduce both casualties and environmental damage, stressing the importance of including response time in risk assessments (Liu et al., 2021; Guo and Luo, 2022).

Despite its relevance, the effect of reactive measures across transport modalities is difficult to quantify. Metrics such as emergency arrival time, resource availability, and coordination quality are difficult to accurately determine (Kubas et al., 2022; Liu et al., 2021; Polorecka et al., 2021). Still, the importance of coordinated emergency response should not be overlooked. Hazmat incidents require the participation of multiple stakeholders, including emergency services, crisis managers, infrastructure operators, and policymakers (Polorecka et al., 2021; Kubas et al., 2022). The effectiveness of these interventions depends not only on technical readiness, but also on real-time information sharing, clear decision protocols, and established cross-agency coordination (Kubas et al., 2022).

1.2.5. Academic Knowledge Gap

From the current state of research, several critical knowledge gaps emerge:

1. There is limited ammonia-specific research in hazardous materials transport studies. Although general hazmat risk assessments exist, few studies explicitly focus on ammonia and its unique transport risks.
2. Integrated risk assessment approaches are absent. Existing studies do not combine incident probability, population exposure, and scenario-based analysis into a comprehensive methodology. This limits the ability to fully capture the complexity of ammonia transport risks and develop holistic safety strategies.
3. There is a lack of comparative risk assessments across transport modalities for ammonia. Most existing research focuses on single-mode risk assessment, leaving uncertainty about how ammonia-related risks differ between inland shipping, railways, and pipelines.

1.3. Research Objectives and Research Questions

This section outlines the scope and context of the research, formulates the objectives that the study aims to achieve, and introduces the research questions developed to meet these objectives.

1.3.1. Research Scope & Context

The following focus points define the scope of this study:

1. **Focus on ammonia:** This research focuses on the hazardous properties and risks of ammonia transport.
2. **Comparison of transport modalities:** The study evaluates pipelines, rail transport, and inland shipping for ammonia transportation in the Netherlands. Road transport is excluded, as it is considered unsuitable for large-scale ammonia distribution (TNO et al., 2022).
3. **Transport risks:** The results presented in this study are limited to the risks from accidental releases of ammonia during transportation only and do not include the risks during loading and unloading activities.
4. **Focus on toxic cloud formation:** This study examines the toxic cloud formation of ammonia transport incidents, as ammonia is not flammable or explosive under normal conditions (NIPV, 2024). Additionally, Safeti-NL only supports toxic cloud dispersion modeling for ammonia, making it the most appropriate focus for quantitative risk assessment.
5. **Focus on the Netherlands:** This study focuses on the Netherlands, as risk assessment frameworks and policies for hazardous materials transport differ significantly across countries, and national tools like Basisnet and Safeti-NL are not compatible with international systems.
6. **Futuristic perspective:** As current volumes of ammonia transport in the Netherlands are still minimal, this study adopts a forward-looking perspective. The modelled transport flows reflect the projected demand related to the expected growth of ammonia due to the energy transition in 2033 (Kraan et al., 2024).
7. **Standardised comparison:** To enable a uniform and meaningful comparison between rail transport, inland shipping, and pipelines, each modality is modelled as if it were solely responsible for transporting the entire projected volume of ammonia. This approach ensures makes it possible to isolate the influence of transport mode characteristics on the resulting risks and effects.
8. **Human health consequences:** This research mainly examines the safety of ammonia transport accidents in terms of public health, as this is the primary domain that may experience severe negative impacts in the event of a hazardous release. However, it does address security, environmental, economic and operational criteria in the multi-criteria assessment.

1.3.2. Research Objectives

The objective of this study is to quantify and compare the safety risks of ammonia transport via railways, inland shipping, and pipelines in the Netherlands. By integrating scenario-based risk modelling and multi-criteria evaluation, the research aims to provide insight into the relative risks, consequences, and overall performance of each transport modality. Specifically, the study aims to:

- Identify the most significant health risks associated with ammonia releases and determine under which conditions these releases occur in each transport modality;
- Apply scenario-based risk modelling to quantify and compare the dispersion behaviour and risk levels of ammonia transport incidents across modalities;
- Quantify and compare the risks and consequences of ammonia transport for human health across different modalities and locations;
- Evaluate which risk and consequence mitigation strategies are available per modality and analyse their individual and combined effects;
- Compare the three modalities using a multi-criteria assessment to determine which performs best overall in the Dutch context.

1.3.3. Research Questions

In line with the research objectives, this research is guided by the following research question:

What do scenario-based modelling with Safeti-NL and multi-criteria evaluation reveal about the relative safety and overall performance of ammonia transport via railways, inland shipping, and pipelines in the Netherlands?

To address the main research question, the following sub-questions are formulated. Each sub-question builds on the outcomes of the previous one, creating a logical progression toward the main research question.

1. *What are the health risks associated with ammonia releases, under which conditions can these releases occur in railways, inland shipping, and pipelines, and which factors influence its dispersion?* (Desk research, quantitative risk assessment, exploratory expert consultations)
2. *How can scenario-based modelling with Safeti-NL be used to quantify and compare the dispersion behaviour and risk levels of ammonia releases across different transport modalities?* (Desk research, scenario analysis, quantitative risk assessment, exploratory expert consultations)
3. *What are the quantified risks and consequences of ammonia transport via railways, inland shipping, and pipelines, and how do these differ between modalities?* (Desk research, scenario analysis, quantitative risk assessment, GIS-based impact assessment, exploratory expert consultations)
4. *What risk and consequence mitigation strategies are possible for each transport modality and what is their expected individual and combined impact on the risks and consequences of ammonia transport incidents?* (Desk research, scenario analysis, quantitative risk assessment, GIS-based impact assessment, exploratory expert consultations)
5. *Based on a multi-criteria assessment, which ammonia transport modality performs best overall in the Dutch context?* (Desk research, multi-criteria analysis, exploratory expert consultations)

1.4. Relevance

This section describes the relevance of this research from three perspectives. It highlights the societal relevance of studying ammonia transport risks, identifies its contribution to the scientific domain, and explains how the topic aligns with the learning objectives and interdisciplinary focus of the MSc Complex Systems Engineering and Management (COSEM).

1.4.1. Societal Relevance

Ammonia is a toxic substance that poses significant risks to both public health and the environment in the event of a release. As ammonia is expected to play an increasing role in the energy transition as a hydrogen carrier, its large-scale transport is likely to grow substantially (Ministerie van Klimaat en Groene Groei, 2024a). Ensuring the safe movement of ammonia is therefore critical to protecting communities, maintaining public trust, and achieving national climate goals.

This research contributes to that effort by identifying and quantifying the safety risks of ammonia transport via rail, inland shipping, and pipelines. Through scenario-based modelling and multi-criteria evaluation, the study highlights which transport modalities present the greatest potential health risks and which offer the most balanced performance. These insights can help national and regional policymakers make well-informed decisions about, for example, infrastructure investment and necessary transport regulations.

Moreover, as the Netherlands is expected to serve as a European import and transit hub for ammonia, enabling its safe handling and distribution could deliver significant economic benefits. Facilitating the use of ammonia as a hydrogen carrier also supports the transition away from fossil fuels by enabling clean energy storage and transport (Dolan et al., 2021).

In addition, ammonia poses unique emergency response challenges, as toxic cloud formation leaves responders and residents with few options for action in the event of an accident (TNO et al., 2022). By modelling the dispersion behaviour and potential effect zones of ammonia releases, this research provides valuable information for local authorities, emergency services, and the general public. It supports emergency preparedness and the identification of spatial safety gaps. In doing so, this study contributes directly to the protection of people while enabling the responsible advancement of energy infrastructure.

1.4.2. Scientific Relevance

Although considerable research has been conducted on the transport of hazardous materials, few academic studies offer a multimodal, in-depth risk analysis focused specifically on ammonia. Existing literature predominantly examines single-mode scenarios—most often rail transport—while pipeline and inland shipping receive far less attention. Moreover, ammonia pipelines are an emerging field of interest, with limited computational modelling data available (TNO et al., 2022).

This research directly addresses these gaps by providing a comprehensive, empirical comparison of ammonia transport risks across rail, inland shipping, and pipeline modalities. Through the use of harmonised scenarios, standardised locations, and consistent modelling assumptions, this study enables a one-to-one comparison of individual risk, group risk, and toxic effect zones per modality. In addition, it quantifies the effect of multiple mitigation strategies per modality—something rarely done in existing literature—offering new insights into the effectiveness of preventive and consequence-reducing measures.

By integrating scenario-based risk modelling with multi-criteria analysis, this thesis also contributes methodologically. This introduces a structured exemplary approach for comparing transport modalities not only on safety, but also on security, environmental, economic, and operational criteria. This framework is replicable for other substances or locations in the Netherlands, and may serve as a basis for further empirical and academic exploration. In doing so, the study expands the scientific knowledge base on substance-specific, modality explicit risk assessments, and offers an applied modelling approach that future research can adopt, refine, and extend.

1.4.3. MSc Program Relevance

This thesis aligns closely with the COSEM program, as it contains several of its core elements. Firstly, the research explores ammonia transport as a complex socio-technical system. A complex system is an unpredictable system involving multiple stakeholders with diverse perspectives, where dynamic interactions between actors and external environmental factors require an interdisciplinary approach to understanding and managing the system's behavior (Judge et al., 2022). Firstly, the system of ammonia transportation is unpredictable as it involves large uncertainties. Examples are accident probabilities, long-term transport policies, and ammonia's role in the energy transition, making decision-making complex (Ministerie van Klimaat en Groene Groei, 2024a). Secondly, it involves multiple actors, including national and regional government agencies, emergency responders, policymakers, and industry stakeholders. All these stakeholders have diverging interests in and opinions on safety, regulation, the environment and associated risks. Thirdly, the research is interdisciplinary as it integrates technical, institutional, governance, and environmental aspects, requiring a holistic approach. Therefore, ammonia transport is a complex system.

Additionally, this research can be characterised as a socio-technical system study, as it involves both sociological and technical dimensions. The sociological dimension arises from the risks ammonia transport poses to communities and the environment, as well as from the interactions between stakeholders involved in its regulation. The technical dimension encompasses the infrastructure, transport features, and mitigating measures that determine how ammonia is moved, stored, and controlled. These two dimensions are closely interrelated: technical decisions influence societal exposure and vulnerability, while societal norms and stakeholder concerns shape technical priorities and acceptable risk levels. This mutual interaction underlines the need to study ammonia transport as an integrated socio-technical system. This approach lies at the core of the COSEM programme.

Moreover, this research aims to explore which interventions are most effective in containing ammonia risks and consequences. This aligns closely with COSEM's core aspect of designing interventions in complex socio-technical systems. While this study will not produce a concrete design, it will provide data-driven recommendations meant to inform stakeholders on potential interventions they could support. Lastly, the research subject of this thesis aligns closely with the Energy Track within the COSEM program. The promotion of renewable energy is a core aspect of the wider energy transition towards sustainable energy supply, and ammonia as a hydrogen carrier represents a significant aspect in the switch to renewable energy. Therefore, by studying the transport risks of ammonia, research is conducted on a topic closely related to the core principles of the COSEM Master Program and Energy Track.

1.5. Thesis Outline

This thesis is structured into nine chapters. Chapter 1 introduced the problem context, described the research objectives, and formulated the central research question and sub-questions. It also included a literature exploration that highlights knowledge gaps in the risk assessment of ammonia transport. Chapter 2 presents the methodology, outlining the modelling approach, data collection methods, scenario development, and the selection of representative case study locations. Chapter 3 identifies the main risks associated with ammonia transport, distinguishing between different transport modalities and analysing the release and dispersion behaviour of ammonia. Chapter 4 describes how these risks are quantified using the Safeti-NL modelling tool, detailing the model assumptions, scenario setup, and simulation process. Chapter 5 presents the results of the quantitative risk assessment, focusing on individual risk contours, group risk, and toxic effect zones, and discusses their implications for human health across different scenarios and locations. Chapter 6 introduces and evaluates mitigation strategies, modelling their effects on both risk and consequence outcomes. Chapter 7 compares the three transport modalities in a broader decision-making context using a multi-criteria analysis (MCA), incorporating safety, security, environmental, economic, and strategic criteria. Chapter 8 offers a discussion of the findings by comparing them to the literature explored in this Chapter, situating the results in academic and societal context, and addressing the limitations. Finally, Chapter 9 concludes by answering the research questions and offering actionable recommendations for stakeholders and potential for future research.

2

Methodology

This chapter outlines the research approach used to quantify and compare the risks associated with ammonia transport in the Netherlands. It also describes the data sources and collection methods that support a comprehensive and consistent evaluation. In addition, the chapter explains the selection of a representative transport route along which all three modalities—rail transport , inland shipping, and pipeline transport—are modelled. Finally, it presents the research flow diagram, which provides a visual overview of the methodological steps followed in this study.

2.1. Research Approach

In this research, a modelling approach is adopted. Through modelling, an extensive range of parameters can be examined across diverse scenarios, helping the identification of important uncertainties within a system (Riddel et al., 2019). Varying inputs, such as leak sizes, weather conditions, or population densities, across different scenarios reveals how these parameters influence risks. Consequently, identifying which parameters have the greatest influence on risk allows stakeholders to prioritise their mitigation efforts.

Within external safety, risks are often quantified through numerical probability values, indicating the likelihood of accidents in combination with their potential impact on human life (TNO et al., 2022). Therefore, this study adopts a quantitative risk modeling approach. Rather than developing new theoretical insights or hypotheses, this research aims to provide practical, evidence-based insights for risk mitigation and prevention in ammonia transport through simulation. According to Robinson (2004), simulation is ”experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for the purpose of better understanding and/or improving that system”. Central to this approach is the use of Safeti-NL, a software tool for Quantitative Risk Assessment (QRA). It simulates accident scenarios to enhance understanding of ammonia transportation risks. This improved understanding can, in turn, support more effective implementation and mitigation strategies.

In the Netherlands, Safeti-NL is the nationally supported and recommended tool for modelling risks associated with the transport of hazardous substances. According to experts from the National Institute for Public Health and the Environment (RIVM), it is currently the most advanced and actively maintained quantitative risk assessment (QRA) software available. They note that earlier tools, such as RBMII, were previously used for rail and inland shipping, but are now outdated, no longer maintained, and incompatible with current scientific standards. Another alternative, the NIPV Scenario Book (NIPV, n.d.), is aimed primarily at supporting operational emergency services and focuses only on the most probable scenarios and not on worst-case scenarios, making it less suitable for a broader safety analysis.

Safeti-NL, in contrast, allows users to define both worst-case and most-probable scenarios, customise input parameters, and perform dispersion and risk analyses within dedicated modelling environments tailored to specific transport modalities. It also supports comparison across these modalities by enabling consistent input structures for pipeline, shipping, and rail transport. These features make it particularly well-suited for the comparative risk analysis conducted in this research. While the model contains some default assumptions and parameters defined by RIVM in Modules I, III and V (RIVM, 2025a; RIVM, 2025b; RIVM, 2025c), this study goes far beyond standard application by tailoring inputs to specific locational context and transport modalities of interest. Many assumptions and parameters have been supplemented with literature and manually adjusted, which can be found in Appendix B.

This research approach also has some limitations. Firstly, scenario modeling is limited to the possibilities included in Safeti-NL. Therefore, the level of detail in environmental or technical variables like extreme weather events or system operations may be simplified. Second, while default parameter values provide consistency, they may not fully reflect local or future-specific conditions. Lastly, the quantified risks generated by Safeti-NL need to be translated into practical insights. Misunderstanding of the results could lead to inadequate conclusions. Nevertheless, the modelling approach provides a robust way to quantify ammonia transport risks systematically.

2.2. Data Types and Collection

This research uses multiple methods to collect data to answer the formulated research questions. The data types and associated collection methods are provided in this section.

2.2.1. Desk Research

Desk research is conducted to analyse existing knowledge on ammonia transport risks and regulatory frameworks. Desk research is defined as the study of academic literature as well as professional literature, such as policy documents or internal documentation of organizations (Guerin et al., 2018). To this end, a literature review was conducted in Chapter 1 by almost exclusively using academic literature. A combination of the two types of literature was used to formulate an answer to all sub-questions.

The academic literature examines hazardous material transport risks and risk assessment techniques. It draws from peer-reviewed journal articles retrieved from Scopus and Google Scholar. The professional literature focuses on regulations and safety guidelines relevant to ammonia transport safety in the Netherlands. This includes an examination of Dutch and European transport regulations, legal risk thresholds and risk mitigation strategies. Documents and regulations are sourced from institutions such as RIVM, several Ministries such as the Ministry of Climate Change and Green Growth, and the Dutch government. The collected academic literature was systematically categorized and analyzed using Excel to identify important themes, research gaps, and other relevant findings in current ammonia transport.

2.2.2. Scenario Analysis

In the context of this study, scenario analysis is used to evaluate the potential risks and consequences of ammonia transport accidents across railways, inland shipping, and pipelines. The analysis will simulate different accident scenarios to assess the risks associated with ammonia leaks and ruptures, and their potential impact on human health. Unlike traditional risk assessments, scenario analysis is a forward looking "what if" approach (IBM, 2025). It is a method used to assess how a system responds to an unexpected event and can be utilized to explore changes in system performance in a theoretical most probable case or worst-case scenario (Balaman, 2018). This helps to understand the full range of possible outcomes. Additionally, it allows for the exploration of uncertainties and interactions between risk factors, such as hazard severity, exposure levels, and vulnerability of affected areas (Riddell et al., 2019).

Each scenario will differ in terms of extent of the leakage (e.g. leak with small or large diameter, or even ruptures) and the event probability of each scenario, which will be further elaborated in Sections 4.2 and 4.4. This in turn will impact the extent of both the risk and consequences for each scenario. The results will be used to quantify the transport risks per modality using Safeti-NL. To ensure a systematic and reliable approach, scenarios will be developed based on data from RIVM, expert consultations, and academic literature, providing a comprehensive view of the parameters that influence the potential ammonia transportation risks.

2.2.3. Quantitative Risk Assessment

Quantitative Risk Assessments (QRAs) are performed when hazardous substances are present on transport routes in quantities that, if released, could lead to direct fatalities among local residents (RIVM, 2009). QRAs will allow for more efficient prioritization of mitigation or prevention measures that can reduce the calculated risk (Bubbico, 2018). This study applies a QRA to compare the ammonia transport risks across railways, inland shipping, and pipelines using Safeti-NL, a specialized risk assessment tool. The effectiveness of the QRA depends on the use of appropriate generic data in the analysis, the level of detail of the hazard identification process to identify a set of failure scenarios, and the use of reliable consequence models (Hassan et al., 2010)

The QRA methodology adopted for this study was based on the common approach used in the transportation industries. The methodology adopted is illustrated in the flow chart as shown in Figure 2.1, which includes the following steps (Bubbico et al., 2016; Hassan et al., 2010). First, the three transport modalities are defined (Chapter 1), then all potential hazards for the system are identified (Chapter 3). Third, both the failure frequencies and scenario probabilities are estimated for all the identified scenarios and the risks for the defined system are quantified (Chapter 4). Finally, the risks are assessed against a criterion to determine whether they are within acceptable limits or whether further analyses are needed to identify ways to reduce the risks (Chapter 5). Chapter 6 proposes new ways to reduce the identified risks.

The results of a QRA are both individual and societal, as individual risk contours (PR) and the magnitude of the societal risk (GR) are calculated (RIVM, 2009). It assesses the likelihood and severity of hazardous material accidents through scenario simulations, providing a data-driven evaluation of ammonia transport risks. Therefore, it can be used to demonstrate the risk caused by transport and to provide the competent authorities and emergency responders with relevant information to enable decisions on the acceptability of risk related to the transport route (RIVM, 2009; Uijt de Haag and Ale, 2005). Integrated with scenario analysis and expert insights, this approach ensures a comprehensive assessment of ammonia transport safety.

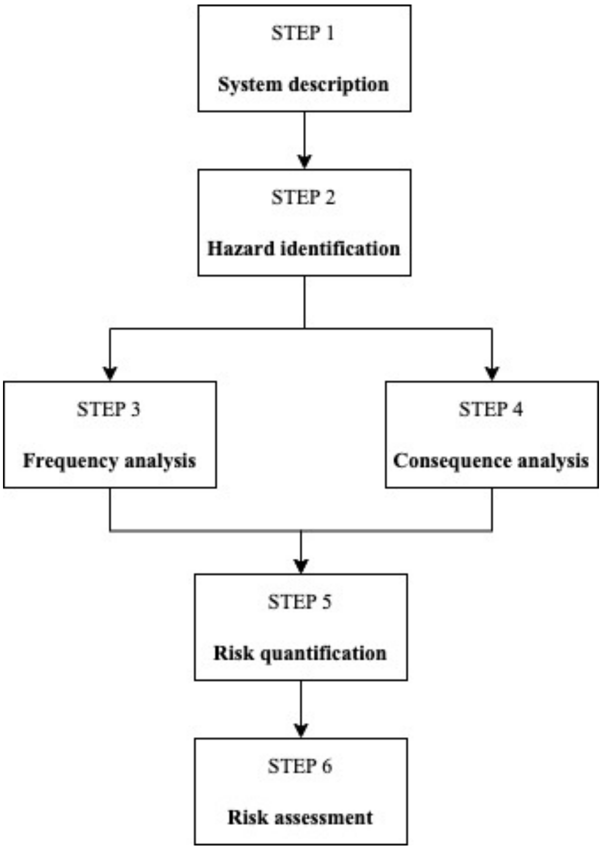


Figure 2.1: Flow diagram of the steps in the QRA methodology

2.2.4. GIS-Based Impact Assessment

A Geographic Information System (GIS)-based impact assessment is conducted to analyze the spatial distribution of ammonia transport risks and their potential effects on human health. GIS technology is used for mapping of data with a spatial reference (Gunasekera, 2004). This study utilises Quantum GIS (QGIS) to visualize individual risk contours and estimate the extent of the consequences in surrounding areas. Geospatial datasets, such as the transport routes, and the toxic risk and effect contours from Safeti-NL are imported into QGIS for spatial analysis. The created risk and effect maps will delineate ammonia impact zones to estimate exceedances of risk and exposure levels. This GIS-based approach enhances risk and consequence visualization, ensuring a comprehensive spatial analysis of ammonia transport hazards.

2.2.5. Multi-Criteria Analysis

To compare the transport modalities not only in terms of safety, but also on aspects such as security, environmental impact, and costs, this research incorporates a Multi-Criteria Analysis (MCA). MCA is a decision-support tool that facilitates structured comparisons across heterogeneous criteria that cannot easily be expressed in the same unit (Stratelligence, 2024). This makes it particularly suitable for evaluating public policy challenges that involve trade-offs between diverse societal values.

In this study, the MCA is used to illustrate how different risk and performance dimensions can be integrated into a single comparative framework. It is important to note that both the scores and the relative weights of the criteria have been assigned by the researcher, based on scenario modelling results, desk research, and exploratory expert input. As such, the MCA should not be interpreted as an empirical assessment, but rather as an example of how an MCA can be applied to generate a holistic performance comparison between transport modalities.

The criteria definitions, scoring method, normalisation procedure, weighting, and ranking approach are explained in detail in Chapter 7 (Multi-Criteria Assessment). This chapter applies the MCA to the fully mitigated versions of all three modalities to determine which alternative performs best under optimised conditions.

2.2.6. Exploratory Expert Consultation

In addition to formal methods, several informal expert consultations were conducted throughout the research process. These conversations were held with professionals familiar with ammonia transport, Safeti-NL modelling, and safety regulations surrounding hazardous materials transport. While not recorded or systematically analysed, these interactions served as a valuable source of contextual insight. It helped the verifications of assumptions, refinement of scenario parameters, and the creation of a better understanding of the practical meaning of risk and consequence outcomes.

These informal exchanges took place in the form of email correspondence and short meetings. As such, they complemented the structured desk research and modelling work by grounding the research in current real-world perspectives.

2.3. Selection of Transportation Route

To accurately analyse and compare the risks of ammonia transport via rail, inland shipping, and pipelines, it is necessary to define a realistic transport route where all three modalities are in use. The transportation of ammonia often entails bulk movement between production facilities like Dutch ports, and end users like chemical clusters, often over long distances via different modes of transportation (Schipper et al., 2023; Shikder et al., 2024). This study focuses specifically on the Rotterdam–Chemelot transport corridor. Rotterdam functions as the primary import and production hub for ammonia, receiving shipments via maritime transport, while Chemelot is one of the largest industrial users in the Netherlands, processing ammonia for chemical production (Schipper et al., 2023).

Both inland shipping and railway transport currently connect Rotterdam to Chemelot, facilitating the movement of ammonia and other chemical products (Provincie Limburg, 2022). Although Chemelot is already connected to a pipeline network, this infrastructure is not intended for ammonia transport. In fact, ammonia is currently not transported via pipelines over public land anywhere in the Netherlands (Riemersma, 2024). In the future, however, the Delta Rhine Corridor project aims to introduce new pipelines along this route, expanding the infrastructure for ammonia transport (Chemelot, 2021). As a result, this corridor is expected to eventually integrate rail, inland shipping, and pipelines, making it well-suited for a direct risk comparison under real-world conditions. Additionally, population densities along the Rotterdam–Chemelot route vary significantly. This enables the examination of risk differences in both urban and rural areas.

Although this corridor forms the reference frame for the analysis, the entire route is not fully modelled due to computational limitations, such as the extensive time required to simulate multiple detailed scenarios across the full length of the route. In addition, the lack of consistent high-resolution spatial data along the entire corridor and the diminishing added value of modelling every segment in similar environmental conditions contributed to the decision to model only representative locations. Instead, two hypothetical yet representative locations along the route are selected to facilitate scenario development: Breda as an urban setting and Moerdijk as a rural setting. These locations are used illustratively to explore how risks may vary between different environmental and population contexts. Their selection does not imply that such ammonia transport scenarios currently occur or are planned at these exact sites. The rationale behind their selection and their use in the scenario-based analysis are further explained in Section 4.2.

2.4. Research Flow Diagram

To visualize the structure and process flow of this thesis project a research flow diagram was made. It encompasses four phases, which flow from one to the other, and each phase includes one or multiple chapters. It also includes the research methods that will be used for answering the sub-questions, the data analysis tools that will help analyze the information gathered via these research methods, and lastly an overview of the main in- and outputs of each chapter is provided.

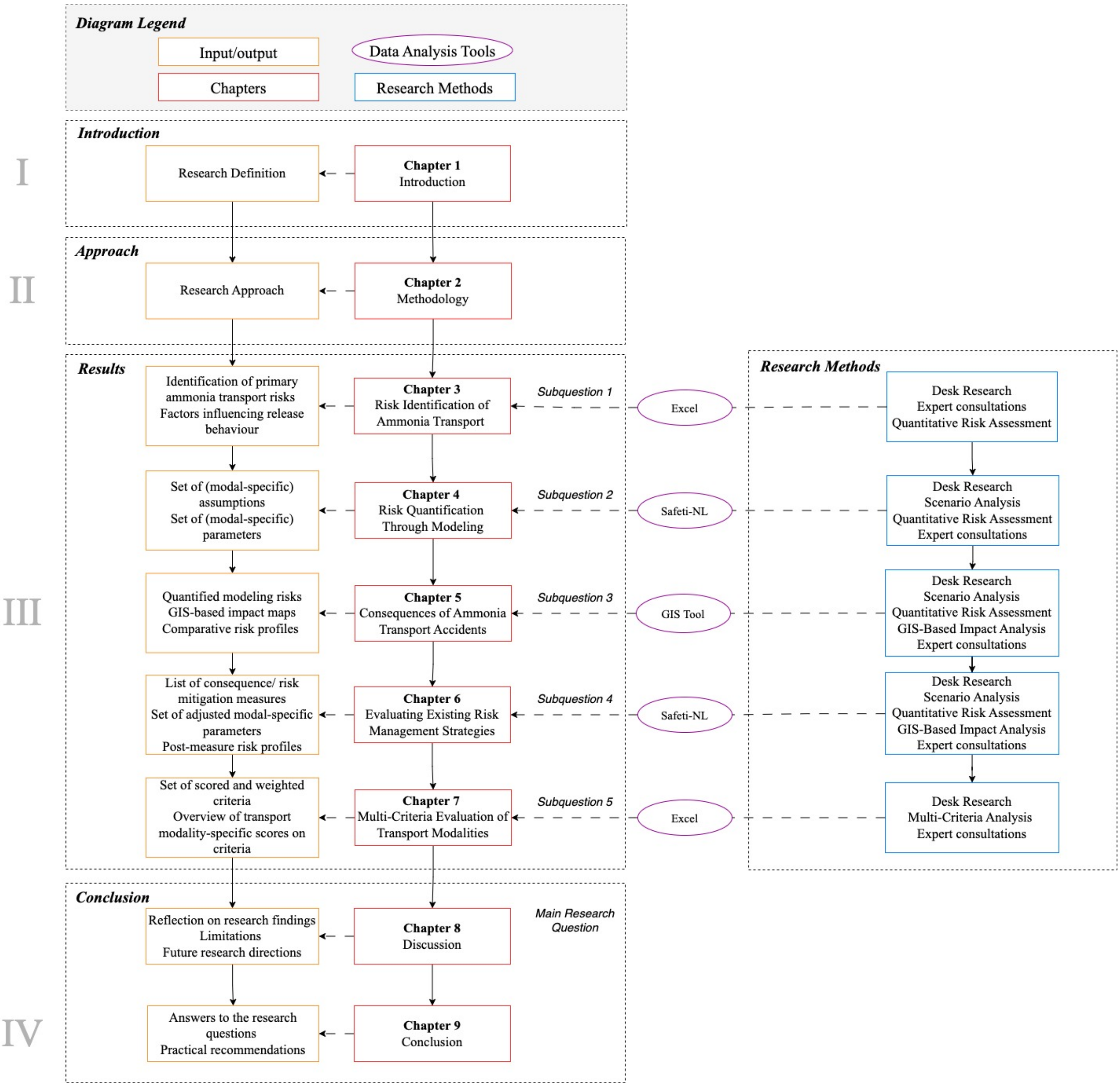


Figure 2.2: Research Flow Diagram

3

Risk Identification of Ammonia Transport

Before ammonia transport risks can be quantified or mitigated, it is essential to understand the nature of the hazards involved and the conditions under which they may materialise into risks. To that end, this chapter addresses sub-question 1, by identifying the hazardous properties of ammonia and its primary risks. In addition, it discusses both unintentional and intentional causes of ammonia release from railways, inland ships, and pipelines, and analyses how the substance behaves once released into the environment.

3.1. Ammonia Hazards and Risks for Human Health

The following section first describes the hazards of ammonia, which are the inherent properties that make it dangerous to humans. Then the risks are identified, defined as the likelihood of a hazard causing harm and the severity of the consequences if that harm occurs under specific transport or accident conditions (Kirschner, 2024).

Ammonia is a colourless gas with a pungent odour that poses several inherent hazards to human health. It is classified as H331: Toxic if inhaled and H314: Causes severe skin burns and eye damage (Mahieu et al., 2025). These classifications reflect ammonia's highly toxic and corrosive nature which presents severe health risks upon inhalation (Crolius et al., 2021). Additionally, its high solubility enables it to rapidly dissolve into moisture-rich tissues such as those in the eyes, respiratory tract, and skin, intensifying its harmful effects upon contact (Crolius et al., 2021).

The actual risk emerges when people are exposed to ammonia under certain conditions, such as when a spill or leakage occurs during a transport accident. If the risk of exposure is realized, the consequences can be severe and, in some cases, fatal (Crolius et al., 2021). Ammonia is particularly dangerous to humans in terms of negative consequences, making them the most vulnerable target in the event of exposure (Kubas et al., 2022). The extent of human exposure following an ammonia release depends on proximity to the spill, wind direction, and local population density. Large-scale accidents near residential areas, transportation hubs, and industrial zones significantly increase the risk (Guo and Luo, 2022).

The most immediate and severe risk occurs through inhalation (Mahieu et al., 2025). Inhalation can cause irritation of the nose and throat, leading to coughing, chest tightness, headaches, fever, and rapid heartbeat (Crolius et al., 2021; UK Health Security Agency, 2024). The damage depends on factors such as concentration, duration of exposure, and depth of inhalation (UK Health Security Agency, 2024). Prolonged exposure may result in cell death, potentially compromising vital organs or obstructing airways and blood flow (Crolius et al., 2021). In high concentrations, inhalation can cause death due to fatal damages to organs such as the lungs and heart (Close et al., 1980; Mahieu et al., 2025; UK Health Security Agency, 2024). However, even at a lower concentration these vital organs may be irreversibly damaged in elderly people (Mahieu et al., 2025). Long-term health effects include persistent airway obstruction, chronic cough, elevated blood pressure, and kidney damage (Close et al., 1980; Crolius et al., 2021).

In addition to inhalation, simple skin contact could also cause extensive health consequences. Ammonia's high solubility in water enables it to extensively and quickly damage the skin and eyes (Crolius et al., 2021). Dermal contact can lead to chemical burns and deep tissue damage (Mahieu et al., 2025). Similarly, ocular exposure can cause irreversible damage such as permanent blindness (Close et al., 1980; Crolius et al., 2021). These presented risks clearly demonstrate that ammonia poses a significant threat to human health in the event of exposure. Understanding these properties of ammonia is essential to appreciate the severe consequences that can result from its release. Therefore, the following section explores the types of transport incidents that may lead to ammonia releases.

3.2. Accident Causes related to Hazmat Transportation

The following sections describe the main safety risks for rail transport, inland shipping, and pipeline transport. Accident causes are defined as accidental and unintended events that could lead to dangers, risks, injuries, and fatalities (Reniers and Zamparini, 2013). They represent the conditions under which a loss of containment could occur and which should therefore be aimed at preventing.

3.2.1. Rail Transport

Although the probability of the release of hazardous material from a train is generally low, the consequences can be severe, especially when transport routes pass through densely populated areas (Hassan et al., 2010; Ovidi et al., 2020). The main causes of railway accidents involving ammonia transport include mechanical and equipment failures, management failures, human errors, and external factors (Guo and Luo, 2022; Shikder et al., 2024).

Mechanical and equipment failures are the leading cause of ammonia transport accidents in trains, often stemming from defective components, aging infrastructure, or loose closures on tank wagons (Shikder et al., 2024). These issues can result in leaks, and therefore, the dispersion of ammonia (Riemersma, 2024). Derailment due to structural failures in rail tracks can be seen in the Viareggio LPG train disaster in 2009, where a freight train derailed due to mechanical failures. This led to a major explosion and subsequent fire, resulting in many injuries and fatalities (Ovidi et al., 2020). While ammonia has a much lower risk of ignition compared to LPG, its toxicity makes uncontrolled releases highly dangerous. Therefore, the integrity of tank wagons is crucial in preventing ammonia release during transport (Riemersma, 2024). Management failures are another critical factor, with improper handling of ammonia, inadequate preparation for transport, and over-pressurisation contributing to incidents (Shikder et al., 2024).

Human errors, including mistakes in railway operations, such as ignoring signals, improper braking, and incorrect cargo handling, have also been identified as significant contributors to accidents (Ovidi et al., 2020). A notable example is the Tilburg train collision in 2015, where signal misinterpretation and the lack of automatic train protection led to an incident involving hazardous materials. It could have resulted in a major disaster had the structural damage been more severe (Ovidi et al., 2020). Lastly, external factors such as track defects, vandalism, and extreme weather events can also cause ammonia rail transport accidents (Shikder et al., 2024).

3.2.2. Inland Shipping

While inland waterway transport is often considered an effective method for moving dangerous goods, accidents involving ammonia can result in severe personal injury, environmental contamination, and financial losses (Huang et al., 2021; Riemersma, 2024). Due to the limited route accessibility of inland shipping, the transport cycle is relatively long and prone to operational uncertainties (Huang et al., 2021). However, despite these uncertainties, the likelihood of serious incidents remains low, although the potential consequences can be severe. This makes inland shipping a typical example of a low-probability, high-consequence transport modality (Huang et al., 2021). In the Netherlands, risk analyses for the transport of hazardous materials via shipping focus exclusively on tank ships, as container-based ammonia transport is considered to have an extremely low probability of failure (RIVM, 2017).

The causes of accidents in inland shipping can be divided into human failures, technical faults, weather conditions, and operational causes (Bačkalov et al., 2023). Human error, which is responsible for 70%–80% of all inland waterway transport incidents in Western Europe, is the main cause (Bačkalov et al., 2021). These failures include fatigue, failure to follow established procedures, abuse of alcohol, misjudgment of navigational conditions, lack of communication, and insufficient situational awareness (Bačkalov et al., 2023). Given the critical role of human decision-making in inland shipping, even minor lapses in concentration can escalate into serious accidents, particularly in high-traffic or constrained waterways.

Technical faults are another major cause of ammonia transport accidents. Mechanical failures, such as machinery malfunctions or navigational equipment failures, can disrupt safe operation (Bačkalov et al., 2023). This could lead to vessel collisions, loss of control, or accidental releases of ammonia. Furthermore, incident prone weather conditions such as strong winds, fog, ice, and water level fluctuations, can impact vessel maneuverability and increase the risk of groundings, collisions, or loss of control (Bačkalov et al., 2021). Low water levels during dry periods can increase the risk of grounding accidents, while strong river currents during floods can make navigation more difficult (Bačkalov et al., 2021; Hendriks, 2021). Lastly, failures during inland shipping can also stem from operational deficiencies. These arise from circumstances encountered during transportation, such as inadequate waterway maintenance or poorly managed interactions with other vessels (Bačkalov et al., 2023).

Collisions between vessels represent one of the greatest risks in ammonia transport by water. Inland waterways are congested environments, where large sea-going vessels frequently interact with smaller inland tankers. If a fully loaded sea tanker collides with an inland ammonia tanker, the structural impact can breach cargo tanks, leading to uncontrolled ammonia leaks (De Looij and Wieme, 2011). The severity of a leak is determined by the location of the rupture relative to the waterline. Releases occurring above the waterline result in the formation of toxic vapor clouds, whereas underwater breaches lead to dissolution in water, decreasing airborne toxicity risks but causing significant ecological damage (De Looij and Wieme, 2011; Riemersma, 2024). Studies have shown that the effect range of underwater ammonia leaks is much smaller than that of atmospheric releases, making the location of the breach an important determinant of accident severity (De Looij and Wieme, 2011).

3.2.3. Pipeline Transport

Pipeline transportation is generally regarded as a safer alternative to other transport modes due to its lower accident frequency and the limited number of fatalities historically recorded (Bubbico et al., 2016). However, loss of containment incidents do occur, and while rare, they can lead to severe consequences including environmental contamination, property destruction, and human casualties (da Cunha, 2016; Bonvicini et al., 2015). The greatest risk associated with ammonia transport via pipelines is the uncontrolled release of ammonia (Riemersma, 2024). In more populated areas, the higher interaction with human activities can significantly increase the likelihood of damages to the pipeline and of materials release (Bubbico et al., 2016; Bubbico, 2018). Contrary, when pipelines traverse rural regions, environmental damage and pollution become primary concerns following an accident (Bubbico et al., 2016).

The causes of pipeline failures can be broadly categorised into third-party activity, corrosion, mechanical failure, operational/human error, natural hazards, and equipment failure (Bubbico et al., 2016; RIVM, 2025c). Among these, third-party activity—primarily excavation work—is the leading cause of pipeline incidents (Bubbico et al., 2016; Crolius et al., 2021; da Cunha, 2016; RIVM, 2025c). Construction activities, roadworks, and farming operations often lead to accidental punctures, cracks, or gouges in pipelines, which can result in either immediate failure or a delayed failure due to fatigue or corrosion (Bubbico et al., 2016). Incidents such as the Oaxaca ammonia pipeline rupture due to roadworks in 2013, which resulted in nine fatalities and the evacuation of approximately 1,500 residents, highlight the dangers associated with third-party interference (Crolius et al., 2021).

The second most common causes are mechanical failure and corrosion (Bubbico et al., 2016; Crolius et al., 2021; RIVM, 2025c). Corrosion, particularly stress corrosion cracking (SCC), occurs when ammonia interacts with susceptible materials, leading to structural degradation and potential rupture (Mora-Mendoza et al., 2016). The 1981 ammonia pipeline failure in Ice, England, was attributed to excessive water infiltration, accelerating corrosion and causing a minor leak (Crolius et al., 2021). Ammonia is especially corrosive to copper, brass, and zinc alloys, making material selection critical for preventing structural deterioration over time (Crolius et al., 2021). Additionally, equipment failure, including valve malfunctions, pump failures, and improper welding, can contribute to accidents (Bubbico, 2018).

Natural hazards, such as earthquakes, landslides, and extreme weather events, can also compromise pipeline integrity (RIVM, 2025c). These events, though less frequent, have the potential to cause sudden ruptures or expose buried pipelines to additional risks, particularly in geologically unstable areas (da Cunha, 2016). Finally, human errors during maintenance, repair, or operation can lead to accidental releases. For instance, improperly closed valves, incorrect pressure settings, or procedural mistakes during pipeline start-up have been linked to past failures (Bubbico et al., 2016).

3.3. Terrorism and Cybersecurity in Ammonia Transport

This section addresses security risks, defined as threats arising from intentional human actions, contrary to the unintentional accident causes discussed in Section 3.2. Security is concerned with the prevention of and protection against deliberate actions that aim to inflict mass casualties, disrupt vital services, or generate economic and societal instability (Reniers and Zamparini, 2013; Stratelligence, 2024). In the context of ammonia transport, two types of intentional threats are especially relevant: terrorism and cybersecurity risks (Ministerie van Klimaat en Groene Groei, 2024a). Due to its toxicity and the large volumes in which ammonia is transported, any targeted attack could have catastrophic human and environmental consequences.

The transport sector has historically been a common target for terrorism. Between 1970 and 2010, approximately 6% of all terrorist attacks worldwide targeted transportation means and infrastructure (Reniers and Zamparini, 2013). The hazardous materials sector, including ammonia transport, is considered particularly vulnerable due to the potential for mass casualties in the event of an attack. However, the actual risk level varies between transport modes due to differences in infrastructure accessibility, since modes with more publicly accessible or exposed infrastructure offer more opportunities for malicious interference.

The increasing digitisation of the transport sector also introduces new vulnerabilities. In the Netherlands, digitalisation of transport infrastructure plays a growing role in optimisation and cost efficiency (Transport en Logistiek Nederland, 2020). However, this digital transformation also exposes critical systems to cybercrime (Transport en Logistiek Nederland, 2020). Again, the extent of risks to which cybercrime can lead depends on the modality, as the degree of centralisation, automation, and interconnectivity differs between rail transport, inland shipping and pipeline transport.

An important distinction between safety threats as discussed in section 3.2 and the security threats presented in this section is methodological. Safety risks can be estimated with statistical and probabilistic models, while security threats—given their strategic, intentional nature and very low frequency—require different tools, such as cost-benefit analyses or game theory (Reniers and Zamparini (2013)). Therefore, since security risks lack empirical data, are very unpredictable and cannot be quantified in a similar manner to safety risks, they are not included in the quantitative modelling in this research. This high level of uncertainty is confirmed in a research done by Stratelligence, 2024 in which interviewees admit that the likelihood and severity of such events are difficult to assess and that effective mitigation remains highly uncertain.

Despite the fact that security risks cannot be easily quantified and are not included in the quantitative analysis, these risks should not be ignored. As ammonia transport volumes increase and infrastructure becomes more digitally integrated, deliberate threats must be addressed in future policy, planning, and risk mitigation frameworks. Therefore, although not included in the quantitative comparison of this research, terrorism and cybersecurity are critical components of a comprehensive ammonia transport strategy. Thus, they are included in the multi-criteria analysis done in Chapter 7.

3.4. Release and Dispersion Behaviour of Ammonia

Once ammonia is released, several aspects influence whether it remains confined to the immediate surroundings or broadly disperses, greatly affecting the health risks and consequences. These determining factors are introduced in this section. These parameters are then specified in Chapter 4, after which the resulting impacts on health risks and consequences are presented in Chapter 5.

The behaviour of ammonia post-release depends on its physical and chemical properties (Bubbico et al., 2016). At ambient temperature, it is a gas that is lighter than air (Crolius et al., 2021; NIPV, 2024; Shikder et al., 2024). To facilitate transport, ammonia is liquefied by pressurizing it to 6 bar at 10°C ('warm' ammonia) (NIPV, 2024; Riemersma, 2024). As 10°C is far above its boiling point, ammonia undergoes flashing upon its release—a process where stored energy causes instantaneous vaporization (Hassan et al., 2009). Flashing leads to dense, low-lying aerosol clouds, which initially suppresses vertical mixing and allows ammonia to travel along the ground before gradually dispersing (Crolius et al., 2021). This effect is particularly dangerous in urban areas, where ammonia can be trapped between buildings, increasing human exposure risks (Bubbico et al., 2016). The behaviour of an ammonia release also depends on how the containment system fails. According to Bubbico et al., 2016 the nature of the release is categorized based on the size and extent of the failure:

- **Leak:** A puncture or small hole, which can either be a long-duration leak or a short-lived spill. Detection time can range from seconds to several hours, affecting the total release volume.
- **Catastrophic rupture:** A sudden, violent failure of a large section of the containment system, which leads to the immediate release of a large amount of ammonia. This is mostly a short-term, high impact spill.

Once released, there are multiple factors that affect the way ammonia disperses. For leaks, its position relative to the ground can significantly change the speed of dispersion (RIVM, 2025b). Moreover, wind speed and atmospheric stability also greatly influence airborne dispersion. Strong winds dilute ammonia faster, but transport it over greater distances, while stable conditions trap it near the ground, increasing local exposure risks (Bubbico et al., 2016). Terrain and obstacles such as hills, valleys, vegetation and buildings can also influence ammonia dispersion, as turbulence generation slows the toxic cloud down (Crolius et al., 2021; Teng et al., 2025). In waterborne transport, ammonia's solubility in water plays a major role in dispersion. If an underwater leak is created, only a small amount will enter the atmosphere to spread further (De Looij and Wieme, 2011).

Determining the factors that influence ammonia's behaviour following a release is essential for accurate risk modelling. The factors discussed above, such as ambient temperature, wind conditions, terrain, and ammonia's physical properties, are incorporated as key input parameters in the modelling process given in Chapter 4. Furthermore, the two types of containment failure described here, namely leaks and catastrophic ruptures, form the basis for the scenario development presented in the quantitative risk assessment in Chapter 4. These scenarios are tailored to reflect realistic release events for each transport modality and serve as the basis for evaluating risk outcomes in the next phase of this research.

4

Risk Quantification through Modeling

This chapter describes the quantitative risk assessment (QRA) process applied in this study. It addresses sub-question 2, which explores how scenario-based modelling with Safeti-NL can be used to quantify and compare the dispersion behaviour and risk levels of ammonia releases across different transport modalities. First, the key concepts and risk metrics relevant to QRA are introduced. Subsequently, the reference scenarios for each transport modality are given. The assumptions and input parameters used for quantifying the risks associated with each modality are then presented, which are based on standard, unmitigated conditions. This means that no technical or operational risk reduction measures have yet been applied. Finally, the process of risk calculation is outlined. These inputs form the basis for comparison, and their outputs will be presented in Chapter 5.

4.1. Concepts and Safety Indicators in Safeti-NL

This section introduces the main concepts in quantitative risk assessments and elaborates what indicators determine the level of safety in the risk assessment. QRA models like Safeti-NL rely on a set of input values that reflect how likely certain incidents are to occur, and what the consequences may be. The accuracy and relevance of these indicators are crucial for meaningful interpretation of risk outputs.

4.1.1. Main Concepts in QRA

Two of the most influential input parameters in Safeti-NL are the Event Probability and the Failure Frequency. These variables quantify, respectively, the chance that a specific scenario will unfold given a loss of containment, and how often such failures are expected to happen within a given timeframe. These concepts form the basis for consequence modelling and risk contour generation. This subsection elaborates on how these parameters are determined and applied within the context of Safeti-NL.

4.1.1.1. Event Probability

The event probability (EP) determines the frequency at which a particular release scenario is expected to occur (RIVM, 2025b). Though the term ‘probability’ might suggest a statistical chance between 0 and 1, in this application it is not used as a probability but as a frequency indicator to represent the scenario frequency in units of [1/km·year]. For rail transport and inland shipping, to model each scenario accurately, the EP field in Safeti-NL is filled with the value of the Scenario Frequency (Fs). The Fs value reflects both the general likelihood of a system failure and the specific conditions under which a particular release may occur. It is calculated using the following formula (RIVM, 2025b):

$$\text{Scenario Frequency } (F_s) = F_b \cdot P_u \cdot P_v \cdot f_m \cdot N_s$$

Where:

- F_b = basic accident frequency [1/vehicle·km]
- P_u = probability of a relevant release
- P_v = probability of relevant consequence
- f_m = model scenario fraction
- N_s = annual intensity [vehicles/year]

This formulation ensures that all relevant elements influencing the likelihood of a scenario are captured in a single value. Because Safeti-NL multiplies EP by FF to calculate total risk, and because all scenario-specific information is already included in EP for rail and shipping, FF is set to 1 to avoid double-counting. This approach allows all relevant frequency inputs to be scenario-specific, without having to define a separate FF profile for every route, substance, or transport configuration.

4.1.1.2. Failure Frequency

The Failure Frequency (FF) represents how often a transport system is expected to experience a failure, such as a rupture or leak, per kilometre of route per year [1/km·year] (RIVM, 2025c). For rail transport and inland shipping, the failure frequency is set at 1 per kilometre per year in Safeti-NL, following the approach advised in Module III (RIVM, 2025b). This is not an actual failure rate, but a modelling convention that shifts all scenario-specific frequency data to the EP field. This setup simplifies the modelling of dynamic transport flows, where the number of movements, types of incidents, and transported substances can vary over time.

By contrast, pipeline transport uses a different approach. This is because the failure frequency for pipeline transport is determined differently than for rail transport and inland shipping (RIVM, 2025c). Since pipelines are fixed assets, their transport routing and volume are constant and can therefore be embedded within the FF. In this case, the actual failure frequency is entered in the FF field, and the EP is set to 1. This ensures that the scenario frequency is determined solely by the predefined FF value. This distinction reflects how Safeti-NL handles dynamic versus static transport modalities. For pipelines, the transport volume and routing are constant, and therefore embedded in FF. For rail and shipping, which involve variable traffic volumes and routing, EP carries the full frequency definition.

4.1.2. Safety Indicators in QRA

In QRAs conducted using Safeti-NL, three risk metrics are calculated to ensure a full overview of ammonia risks and its spatial consequences: individual risk, group risk, and effect zones. Each of these indicators reflects a different aspect of risk and plays a distinct role in national and regional safety policy and land-use planning. These metrics are automatically calculated by Safeti-NL for each scenario and provide insights into both the severity and spatial extent of risk.

4.1.2.1. Individual Risk (PR-contours)

As described in Article 5.6 of the Besluit kwaliteit leefomgeving (Bkl), individual risk is defined as the annual probability that an unprotected person, continuously present at a specific location, will die as a result of a hazardous incident (Rijksoverheid, 2024). It is location-specific and visualised using individual risk contours, which represent lines of equal risk around a hazardous source. These so-called PR-contours can be drawn at various probability levels, such as 10^{-6}, 10^{-7} and 10^{-8}. The 10^{-6} contour is particularly important in Dutch policy, as it marks the maximum allowable individual risk for land uses such as housing and schools (Atlas Leefomgeving, 2024b). The PR-contours are influenced by both the likelihood of an accident occurring, and the volume of release in case of an ammonia incident.

4.1.2.2. Group Risk (FN-curves)

Group risk refers to the annual probability that ten or more people may die as a direct result of an unusual incident occurring within an attention zone (Informatiepunt Leefomgeving, n.d.). Therefore, the group risk is influenced by the people in the vicinity of a risk (Ovidi et al., 2020). In contrast to the individual risk, it is not possible to visualize the group risk with contours around the risk source, so it cannot be represented spatially. Instead, it can be represented in a graph that plots the numbers of victims (N) on the x-axis, against the cumulative probability that such a group will become a victim of an accident (F) on the y-axis, also called an FN-curve (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieu, 2007). FN-curves are assessed against a predefined orientation value line, which represents the acceptability threshold for group risk. This line should preferably not be exceeded at any point of the graph; however, it serves as an indicative threshold rather than a legally binding limit (Boot, 2013).

4.1.2.3. Effect Zones

Effect zones represent the spatial extent of physical harm resulting from the dispersion of hazardous substances, such as toxic gas clouds. Unlike individual or group risk, effect zones do not express probabilities, but rather the distance over which certain health thresholds are exceeded. These thresholds are based on intervention values such as the LBW (Life-Threatening Value), AGW (Alarm Threshold Value), and VRW (Public Information Value), which relate to degrees of severity ranging from mild irritation to lethality (Mahieu et al., 2025). These values are further elaborated in 5.4.1. They are not used in spatial planning or as regulatory tools, but are rather indicators for emergency planning (RIVM, n.d.-c). The effect zones and their associated health thresholds, represented by contours, are derived from scenario-based dispersion modelling in Safeti-NL and are used to visualise where harmful concentrations may occur following a release.

The attention zone is a special kind of effect zone. Similar to effect zones, they are based on the effects of a scenario, rather than their probabilities (RIVM, n.d.-a). Attention zones are defined in Dutch policy as areas where additional protection may be needed to ensure that people inside buildings are not harmed during incidents involving hazardous substances (Informatiepunt Leefomgeving, n.d.). More specifically, the attention zones are based on a dose-based LBW concentration, which calculates the accumulated LBW dose over time instead of a fixed concentration in a given moment (RIVM, n.d.-b). In practical terms, they can be determined using the effect zones contours and tables generated in Safeti-NL. The effect and attention zones also serve a different purpose. While effect zones provide intervention values for emergency responders, attention zones are used in spatial planning to define areas where specific protective measures or planning restrictions may apply (Atlas Leefomgeving, 2024a; RIVM, n.d.-c).

4.2. Scenario Development for Modeling

To conduct a realistic risk analysis, this study uses a structured approach to define relevant accident scenarios, both in terms of physical setting and technical failure type. The development of modelling scenarios is structured into two parts: (1) the selection of representative urban and rural locations along the previously identified industrial transport corridor (Rotterdam-Chemelot), and (2) the definition of a set of most probable and worst-case release scenarios per transport modality. This allows for consistent and comparable modelling of ammonia transport risks in the Dutch context.

4.2.1. Location Selection along Transport Route

The scenario development is based on ammonia transport from the Port of Rotterdam to Chemelot, an industrial corridor that currently accommodates both rail transport and inland shipping, and is expected to serve future pipeline transport under the proposed Delta Rhine Corridor (Chemelot, 2021). Selecting such a route is necessary, as Safeti-NL requires a physical context for modelling transport pathways and release locations. Drawing on RIVM's guidelines for transport risk analysis (RIVM, 2017), it is justified to model along an indicative transport corridor, as incident probability, population exposure and environmental characteristics vary by route. However, due to both time constraints and technical limitations of the Safeti-NL software, such as processing capacity and the level of detail required for route-based calculations, two specific locations along this corridor are selected for modelling. Rather than using arbitrary or generic points, real-world and illustrative locations were chosen. This approach increases the reliability and contextual validity of the risk estimates generated in Safeti-NL. To capture both human health risks and environmental consequences, two contrasting types of locations were selected: one urban and one rural.

For the urban environment, Breda was selected. This location is particularly well suited for estimating population exposure and assessing human health impacts due to its high residential density. Moreover, Breda is of special interest from a safety policy perspective: it is the first city along the Basisnet route (for rail transport of hazardous substances) where the individual risk (PR) exceeds the threshold of 10^{-6} per year, as shown in Figure 4.1 (Informatiepunt Leefomgeving, 2024). This elevated risk level continues along the corridor towards other densely populated areas, making Breda a representative case study for cumulative urban transport risks.

Figure 4.1: PR-contour exceedances railway Basisnet in the Netherlands

For the rural environment, Moerdijk was selected. The planned Delta Rhine Corridor is expected to run through Moerdijk, reinforcing the relevance of this location as a potential ammonia transport hub and thus as a case study (Ministerie van Klimaat en Groene Groei, 2024b). Moreover, in contrast to Breda, Moerdijk is sparsely populated, which allows for an insightful comparison of how population density influences both the individual and group risk contours. Additionally, the physical environment differs considerably: where Breda is characterised by urban structures and tall buildings that can affect ammonia dispersion, Moerdijk's open landscape with low vegetation provides fewer obstacles, thereby enabling a clear assessment of the influence of environmental roughness on gas dispersion. Finally, rail infrastructure and inland waterways in rural settings often differ in track types and navigability classes compared to urban areas, making Moerdijk and Breda valuable reference points for understanding how such infrastructural differences affect accident probabilities and dispersion behaviour.

Inland waterways are classified according to CEMT classes, which represent the reference vessel for a given waterway, defined by its type, length, width, loaded draught, and air draft. For safety reasons, significant transport volumes of hazardous substances only occur on the following waterway classes (Rijkswaterstaat, 2008; Uijt de Haag and Ale, 2005): Navigability Class IV, Navigability Class V and Navigability Class VI. The higher the class, the higher the incident probability. For railway infrastructure the likelihood of a major accident depends on the complexity of the track, as for an open track without switches, the probability of an accident is lower than in complex areas with many switches. Therefore, there's a distinction between three different types of track (Uijt de Haag et al., 2020). Type A - open track without switches (no switch within 500 m), Type B - open track with switches (at least one switch within 500 metres), and Type C - complex situations (sections where switches are located within 500 metres and the width of the track bundle exceeds 25 metres). The urban location (Breda) has Navigability Class IV and track type C, while the rural location (Moerdijk) has Navigability Class VI and track type A.

4.2.2. Scenario Selection

Scenario analysis is a useful tool to understand how the severity of ammonia releases can vary and to gain insight into the implications of different types of accidents. In order to conduct a structured and comparable risk analysis across all three transport modalities, two distinct release scenarios are defined per modality: the most probable scenario and the worst-case scenario. These scenarios are designed to represent a realistic range of accident severity, with each scenario varying in parameters such as release size and failure frequency. The selected hole diameters for each scenario are based on recommendations from RIVM (2025b) and RIVM (2025c), and were validated in close consultation with domain experts to ensure practical relevance and consistency across modalities. This approach allows for capturing both frequently occurring, lower-impact incidents as well as rare but catastrophic events.

The most probable scenario represents the highest-likelihood event with relatively limited consequences. It typically involves a small release from a minor leak.

- **Rail transport:** Continuous release through a 75 mm hole during 1800 s.
- **Inland shipping:** Continuous release through a 75 mm hole during 1800 s.
- **Pipeline transport:** Continuous release through a 20 mm hole during 1800 s.

The worst-case scenario reflects the largest credible release, generally low in probability, but extremely high in consequence. This scenario is often the basis for emergency planning and effect zone definition.

- **Rail transport:** Catastrophic rupture of a tank car.
- **Inland shipping:** Continuous release from a 150 mm hole during 1800 s.
- **Pipeline transport:** Breach leading to continuous outflow during 1800 s.

The scenarios show that not all modalities have the same failure types. For example, accidents in inland shipping cannot lead to catastrophic ruptures, but only allow continuous release instead of instant release, while this is possible for rail and pipeline transport (RIVM, 2025b). Another notable aspect is that the worst-case scenario for rail transport does not specify a release duration. This is because the rail tank ruptures instantaneously and empties rapidly—well within 1800 seconds—making it unnecessary to define a specific time frame. In contrast, inland shipping involves a continuous release from a non-pressurised tank, likely exceeding 1800 seconds. For pipelines, the release may also persist beyond 1800 seconds due to the length of the upstream pipe segment, which continues to drain until empty.

The value of 1800 seconds is used as the modelling duration in Safeti-NL and is therefore set as the maximum release duration in scenarios where the outflow is expected to continue beyond that time. By using a consistent typology of scenario severity across modalities rather than constricting to identical technical failure types like exact hole sizes, the modelling retains realism. Moreover, it still reflects the specific characteristics of each transport system, while still allowing for meaningful comparisons in terms of risk outcomes.

4.3. Modeling Assumptions

To accurately model ammonia dispersion in Safeti-NL, a clear and consistent set of assumptions must be defined for each transport modality. These assumptions delineate the system boundaries and allow for a structured and comparable modelling approach across scenarios. While several assumptions are based on official modelling standards outlined in RIVM Modules I, III, and V (RIVM, 2025a; RIVM, 2025b; RIVM, 2025c), most were determined through exploratory expert consultations.

It is important to note that many of these assumptions reflect simplified or idealised conditions which may not fully capture the complexity of real-world situations. While necessary for feasibility and comparability, they also impose limitations on the scope and realism of the outcomes. These limitations are acknowledged and further discussed in Section 8.3. The following sections present first the general assumptions—applicable across all transport modalities—and then the mode-specific assumptions for rail, inland shipping, and pipeline transport.

4.3.1. General Assumptions

This section outlines the general assumptions that apply across all transport modalities. These include assumptions about ammonia's physical state, the nature of the release, population exposure, location setup, and the structure of the scenarios. They provide a consistent basis for modelling and ensure that results are comparable across different scenarios and transport modes.

Table 4.1: Overview of general assumptions for modeling

Assumptions
Ammonia state at release is as toxic gas.
Ammonia is assumed to be transported in pressurised form.
No flammable or explosive behaviour is considered.
Accident scenarios occur at predefined representative locations.
Population presence is static and based on current datasets.
No risk-reducing measures are in place for calculations.
Worst-case and most probable scenarios are mutually exclusive; there are no cascading or domino effects.
All scenarios are caused during transportation, not during loading/unloading, etc.

4.3.2. Mode-Specific Assumptions

In addition to the general assumptions applied across all transport modalities, each mode also requires specific assumptions to reflect their unique operational characteristics. They also form the basis for accurately defining realistic and representative release scenarios in Safeti-NL.

4.3.2.1. Rail Transport

Table 4.2: Overview of rail-specific assumptions for modeling

Assumptions
Transport is assumed to take place in dedicated tank wagons.
Both instantaneous and continuous releases are modelled.
Accident scenarios include leaks and catastrophic ruptures.
Effect and risk calculations are performed using Safeti-NL's standard rail transport configuration.
Track type for the urban location is classified as Type C, while the track type for the rural location is classified as Type A.

4.3.2.2. Inland Shipping

Table 4.3: Overview of inland shipping-specific assumptions for modeling

Assumptions
Transport is assumed to occur in dedicated tankers, not in (tank) containers.
Only continuous releases are modelled (no instantaneous failures).
Catastrophic rupture of the tank is not considered, based on typical vessel design and policy guidance.
Effect and risk calculations are performed using Safeti-NL's standard inland shipping configuration.
Navigability class for the urban location is classified as IV, while Navigability class for the rural location is classified as VI.

4.3.2.3. Pipeline Transport

Table 4.4: Overview of pipeline-specific assumptions for modeling

Assumptions
The pipeline is assumed to be operational and continuously transporting ammonia.
Both instantaneous and continuous releases are modelled.
Scenarios include leaks and breaches.
The pipeline is assumed to be entirely underground.
Effect and risk calculations are performed using Safeti-NL's standard pipeline transport configuration.
Safeti-NL's long pipeline configuration is used for modelling.

4.4. Model Parameters

The risks are calculated in accordance with the Environmental Safety Calculation Regulations (RVO) (RIVM, 2025a; RIVM, 2025b; RIVM, 2025c). The RVO specifies the parameters that must be entered into the calculation program. The scenario, model parameters and modeling method in the RVO are generally applicable for a risk calculation of hazardous substances.

Some model parameters, specifically for a QRA in the Netherlands, have been taken directly from the RVO and/or Safeti-NL 9.2, and some were collected through desk research. A full overview of the model parameters used in this study and whether they were retrieved from the RVO or different sources, is included in Appendix B.

4.4.1. General Parameters

To accurately model the dispersion of ammonia in Safeti-NL, a set of model parameters is required. First, a set of general parameters must be defined and applied consistently across all cases. These parameters, summarized in Table 4.5, were established primarily through desk research and exploratory expert consultations. Appendix B.1 provides a detailed explanation of how each parameter was determined. This section presents the general modelling parameters that are true for all three transport modalities.

Table 4.5: Overview of general parameters for modelling

Parameter	**Value**
Total amount of ammonia [kg]	6.27×10^9
Transport temperature [ºC]	9.8
Release duration [s]	1800
Meteorological conditions	D5 and F1.5
Release location urban	Breda
Release location rural	Moerdijk
Population distribution urban surroundings [people]	188,834
Population distribution rural surroundings [people]	990
Weather station urban	Gilze-Rijen
Weather station rural	Rotterdam
Surface roughness length urban [m]	3.0 (City centre with high and low rise buildings)
Surface roughness length rural [m]	0.1 (Low crops; occasional large obstacle)

4.4.2. Mode-Specific Parameters

Although certain parameters are applied consistently across all modes (see Section 4.4.1), others are specific to the characteristics and operating conditions of rail, inland waterway and pipeline transport. The table below summarizes the mode-specific parameters used in the modelling process. These parameters help ensure that risk modelling reflects realistic transport conditions and supports meaningful comparison across modalities. Again, some parameters are retrieved from Module I, III and V, published by RIVM (RIVM, 2025a; RIVM, 2025b; RIVM, 2025c) and some are retrieved from desk research. A full overview of the parameters and their sources can be found in Appendices B.2, B.3, and B.4.

4.4.2.1. Rail Transport

Table 4.6: Mode-specific modeling parameters rail transport

Parameter	**Value**
Vessel type	Pressure vessel
Tank capacity [kg]	50,000
Elevation [m]	Catastrophic rupture: 2.5; Leak: 1.0
Tank head [m]	3.0
Specified condition	Temperature/bubble point
Type of surface	Dry soil
Day/Night transport ratio	0.29 / 0.71
Outflow direction	Horizontal

4.4.2.2. Inland Shipping

Table 4.7: Mode-specific modeling parameters inland shipping

Parameter	**Value**
Vessel type	Pressure vessel
Shipment capacity [kg]	225,000
Number of tanks in ship	6
Elevation [m]	1.0
Tank head [m]	5.0
Pipe length [m]	5.0
Specified condition	Temperature/bubble point
Bund height [m]	1.0
Bund area [m^2]	Urban: 4.9×10^3; Rural: 2.5×10^6
Bund failure modeling	Bund cannot fail (liquid overfill not possible)
Type of surface	Deep river or channel
Day/Night transport ratio	0.44 / 0.56
Outflow direction	Horizontal

4.4.2.3. Pipeline Transport

Table 4.8: Mode-specific modeling parameters pipeline transport

Parameter	Value
Flow rate [kg/s]	199
Pipeline diameter [mm]	400
Pipeline depth [m]	1.5
Elevation [m]	0.01
Pressure [bar]	60
Type of surface	Urban: Concrete; Rural: Wet soil
Day/Night transport ratio	1
Outflow direction	Vertical
Accident type (buried sections)	Puncture at the top

4.4.3. Scenario-Specific Parameters

In addition to mode-specific parameters, each scenario must also be defined by a set of scenario-specific values to accurately simulate the risks in Safeti-NL. These values vary depending on the transport modality, the surrounding terrain (urban or rural), and the severity of the incident. Differences between urban and rural values in the tables primarily stem from classification-based distinctions such as track complexity (Type A vs C) or navigability class (Class IV vs VI), which directly influence consequence probabilities and dispersion behaviour. Scenario frequencies (Fs) for rail transport and inland shipping were calculated according to the standard RIVM method (see Section 4.1.1.1). The failure frequency for pipeline transport is given in Module V (RIVM, 2025c). However, it should be adjusted based on a correction factor for the depth location of the pipeline, as the probability of failure depends on the depth location. An overview of the calculation process for the scenario-specific parameters for each modality is provided in Appendix B. The tables below provide an overview of the scenario-specific values used for each modality.

4.4.3.1. Rail Transport

Table 4.9: Scenario specific parameters for rail transport

Parameter	Scenario 1: Leak	Scenario 2: Rupture
Model scenario fraction	0.92	0.08
Consequence probability	Urban: 7.4×10^{-10} Rural: 6.2×10^{-11}	
Annual intensity [tank wagons]	1.25×10^{5}	
Scenario frequency [1/km·year]	Urban: 8.54×10^{-5} Rural: 7.15×10^{-6}	Urban: 7.42×10^{-6} Rural: 6.22×10^{-7}

4.4.3.2. Inland Shipping

Table 4.10: Scenario specific parameters for inland shipping

Parameter	Scenario 1: Small leak	Scenario 2: Big leak
Basic accident frequency [1/ship·km]	Urban: 8.67×10^{-8} Rural: 4.14×10^{-7}	
Consequence probability	Urban: 5.5×10^{-3} Rural: 1.25×10^{-2}	Urban: 2.64×10^{-5} Rural: 6.0×10^{-5}
Annual intensity [ships]	4.64×10^{3}	
Scenario frequency [1/km·year]	Urban: 2.21×10^{-6} Rural: 2.40×10^{-5}	Urban: 1.06×10^{-8} Rural: 1.15×10^{-7}

4.4.3.3. Pipeline Transport

Table 4.11: Scenario specific parameters for pipeline transport

Parameter	Scenario 1: Leak	Scenario 2: Breach
Correction factor	2.05×10^{-2}	
Event probability	1	
Failure frequency [1/km·year]	9.91×10^{-5}	2.38×10^{-5}

4.5. Running the Model: Simulation Process

This section outlines the computational steps followed in Safeti-NL to model the transport of ammonia for the selected scenarios, ensuring transparency and replicability of the simulation process. The modeling process followed a combination of standard procedures and additional steps tailored to the needs of this research. The core steps for running a QRA are largely based on the methodologies outlined in Module III and Module V of the RIVM guidelines (RIVM, 2025b; RIVM, 2025c). These include processes such as where to use what parameters as input, how scenario frequencies should be calculated, performing consequence modeling, and how to calculate risk indicators like individual and group risk. As these steps are well-documented in the RIVM guidelines, they are not further elaborated on here.

However, several steps required additional customization and setup specific to this research project. These include the preparation and import of georeferenced transport routes and the population datasets for the selected locations in these scenarios. These supplementary steps, which were necessary to adapt the model to the specific context of this study, are explained in more detail in the following sections. Figure 4.2 shows an overview of the steps.

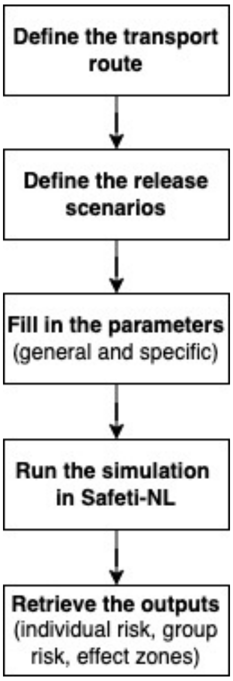


Figure 4.2: Flow diagram of computational steps in Safeti-NL

4.5.1. Setting up Transport Routes

First, transport routes for both the rural and urban locations were defined. To accurately project these routes onto real-world geography, maps of Breda and Moerdijk and their surroundings were exported from QGIS as images. These maps were then uploaded into Safeti-NL and georeferenced according to the Rijksdriehoek coordinate system, ensuring that the routes and background images correctly reflected the actual locations.

For the rail transport routes, the Basisnet rail network was used as a reference to draw the railway paths on the georeferenced maps (Atlas Leefomgeving, n.d.). For inland shipping, the Navigability Classes map was consulted to determine which waterways were accessible through the Moerdijk and Breda areas, after which the inland shipping route was drawn accordingly (Rijkswaterstaat, n.d.). In the case of pipeline transport, an existing map of the national gas pipeline infrastructure was imported into QGIS, adjusted where necessary, and used as a basis to guide the placement of the pipeline routes through the selected locations in Safeti-NL.

Once all routes were drawn in Safeti-NL, an overview of the different transport routes per modality was created in QGIS. This was achieved by extracting the coordinates of the drawn routes from the geometry tab in Safeti-NL, transferring them into Excel, and exporting them as CSV files. These CSV files were then uploaded into QGIS as Delimited Text layers and overlaid on the corresponding maps of Breda and Moerdijk.

This approach resulted in a clear visualisation of the three transport routes for each location, which are presented in Figures 4.3a and 4.3b. Inland shipping is presented as the orange lines, railway transport as the blue lines, and pipeline transport as the pink lines. A complete overview of all defined routes for both the urban and rural settings can be found in Appendix C.

(a) Transport modalities in Breda **(b)** Transport modalities in Moerdijk

Figure 4.3: The three transport modality routes through Breda and Moerdijk

4.5.2. Setting up Scenarios

Following the creation of the transport routes, the scenario setup was carried out for each modality. As outlined earlier, two scenarios were defined per transport mode—rail, inland shipping, and pipelines—representing a most probable case and a worst-case release. These scenarios varied by rupture or leak size and their event probability or failure frequency. Relevant physical and operational parameters were entered into Safeti-NL based on the assumptions and values detailed in Sections 4.3 and 4.4. After entering the scenario-specific parameters, the simulation settings were tailored for each location. This included selecting the appropriate weather data for the urban and rural environments and adjusting model options for terrain and land use where relevant.

To allow a realistic assessment of exposure, custom population datasets were also incorporated. For each transport mode and location, a population polygon was drawn manually over the relevant area in Safeti-NL, as shown in Figure 4.4a and Figure 4.4b (inland shipping example). Within these polygons, the total number of residents was entered. This spatially defined population data is essential for calculating group risk, as it allows the software to simulate the extent of exposure and generate FN-curves, which represent the relationship between incident frequency and the number of potential fatalities. After entering all the relevant parameters into Safeti-NL, the simulation was run and the output could be retrieved. These results will be presented in Chapter 5.

(a) Population polygon in Breda **(b)** Population polygon in Moerdijk

Figure 4.4: The population polygons in Breda and Moerdijk for inland shipping

5

Consequences of Ammonia Transport Accidents

This chapter presents and interprets the simulation outcomes of the scenario-based risk and effect modelling performed in Chapter 4. It answers sub-question 3, which focuses on identifying the quantified risks and consequences of ammonia transport via railways, inland shipping, and pipelines, and on understanding how these differ between modalities. The chapter aims to translate the configured scenarios, assumptions, and parameter inputs into meaningful risk and effect insights for each transport modality under both urban and rural conditions. First, it explains how the QRA results are integrated with the program QGIS to visualise the PR-contours and effect zones. Second, the risk results including the individual risk contours and group risk, visualized by the FN-curves, are presented. Then, an overview of the effect zone contours and calculated effect distances is shown, including those of the attention zone.

5.1. Integrating QRA Results with QGIS

The use of QGIS in assessing risk exposure offers detailed route-specific information. This is especially useful when the risk model presented is used to evaluate micro-level risk by analyzing specific segments along a route, which is the case in this research (Saat et al., 2014). The process of integrating individual risk contours (PR contours) from Safeti-NL into QGIS involved a series of export and styling steps. After running the QRA model while in the *Study* tab, the PR contours were accessed by navigating to the *Risk* section and selecting *Multilevel*. All desired PR contour levels were selected and exported as a GeoJSON file using the *Contours Only* export option. This GeoJSON file was then imported into QGIS as a vector layer.

To distinguish between contour levels visually, the symbology of the imported layer was modified. In the *Layer Properties* dialog, the *Symbology* tab was used to change the default *Single Symbol* style to *Categorized*. The *Value* field was set to $\mathrm{risklevel}$, and clicking *Classify* generated a list of unique PR levels. These were then manually assigned the following colours to allow for clear visual differentiation:

- 10^{-6} per year – red
- 10^{-7} per year – yellow
- 10^{-8} per year – green

Lastly, the map for each modality and corresponding PR-contour was exported as an image. To ensure visual comparability between all maps, a fixed scale of 1:91,506 was applied throughout the QGIS environment during figure generation.

The same procedure was followed to visualise effect zones, with a slight variation in the initial step. After running the model, the *Risk* tab was used again, this time selecting *Effect Zones*. The desired thresholds were selected prior to export. In this study, the following effect thresholds were visualised: the LBW, AGW and VRW outdoor zones, and the attention zone. As these contours were more extensive than the PR-contours, a fixed scale of 1:128,759 was applied to ensure exact comparison. The contours were assigned different colours in a similar way as the PR-contours, but the value field was set to label. They were manually assigned the following colors:

- Attention zone – dark blue
- LBW outdoor – light blue
- AGW outdoor – light green
- VRW outdoor – dark green

The interpretation of both the PR- and effect contours are further discussed in Sections 5.2 and 5.3.

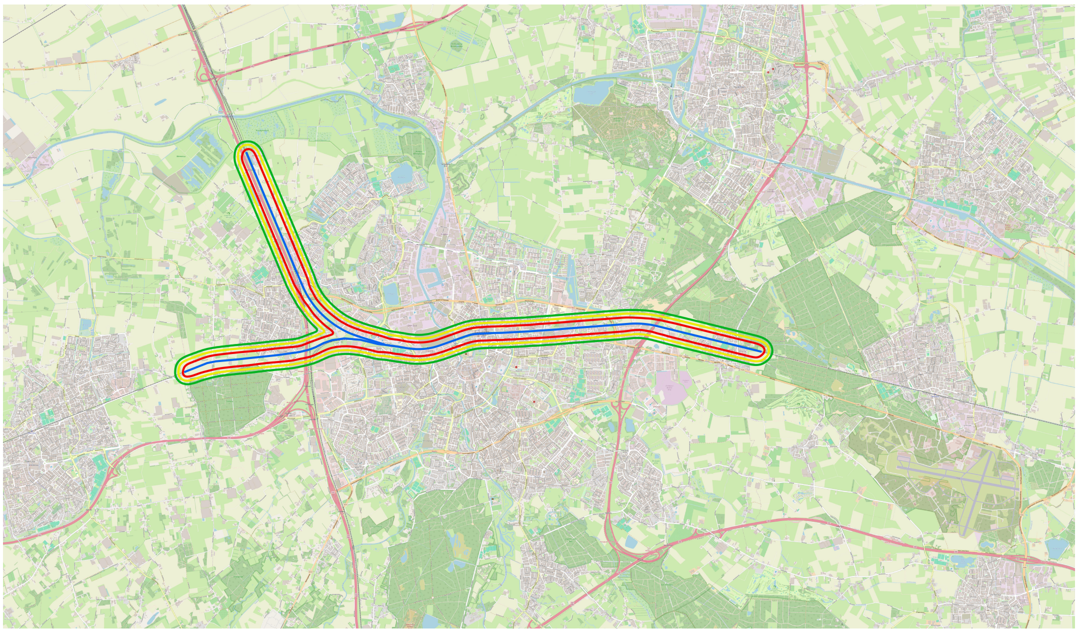
5.2. Individual Risk (PR-Contours)

This section presents the modelled individual risk contours (PR-contours) for rail transport, inland shipping, and pipeline transport across both Breda and Moerdijk. For each modality, the spatial characteristics of the resulting risk contours are discussed, as well as the factors that influenced them. Their implications for human health are evaluated based on whether the legal threshold of 10^{-6} annual fatality probability is exceeded in populated areas.

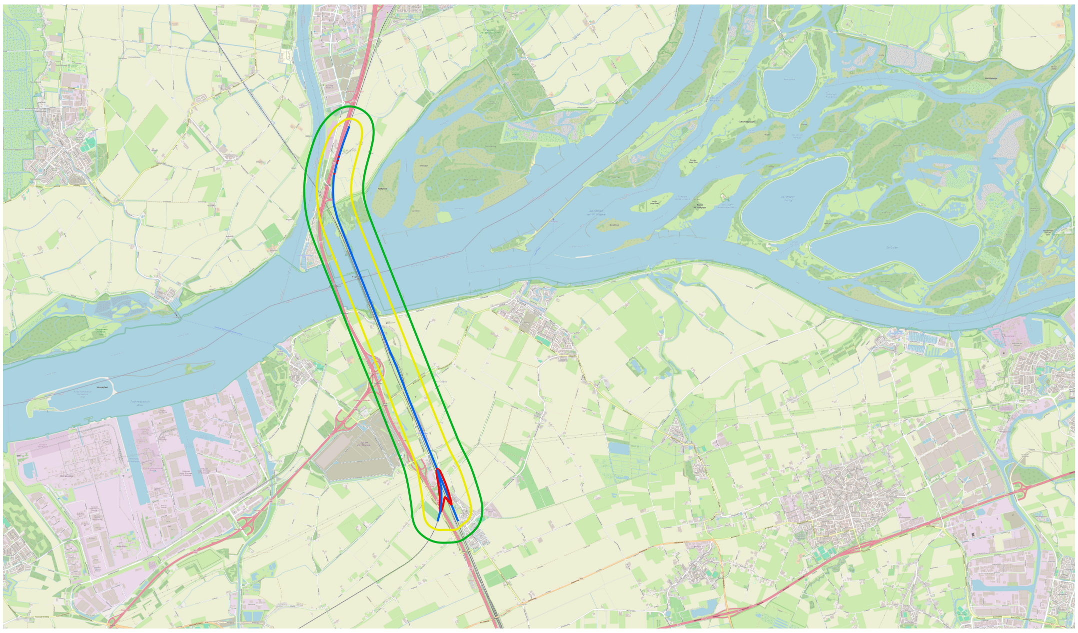
5.2.1. Rail Transport

In Breda, the contour is narrow but follows a long stretch of track through densely populated areas. This is primarily due to the relatively high accident frequency associated with the complex track layout in urban Breda (Type C), which includes switches and wide track bundles. In Moerdijk, the railway is classified as Type A, with a simpler track layout and thus a lower accident frequency. Nevertheless, a short section of the track splits briefly into two lines, locally increasing complexity and risk. This leads to a small but notable 10^{-6} exceedance zone.

Since individual risk is determined by both the scenario frequency and the total amount of ammonia released, the contours for rail transport are relatively compact compared to the other modalities that have larger release volumes. In Moerdijk, the spacing is slightly broader, which can be attributed to the lower surface roughness length, which causes the released ammonia to spread more freely. For both locations, the PR 10^{-6} contour lies very close to the track, indicating that people living directly adjacent to the railway line are exposed to annual death probabilities that exceed the regulatory threshold. This exceedance calls for potential mitigation strategies near the track.



(a) PR contours of rail transport in Breda



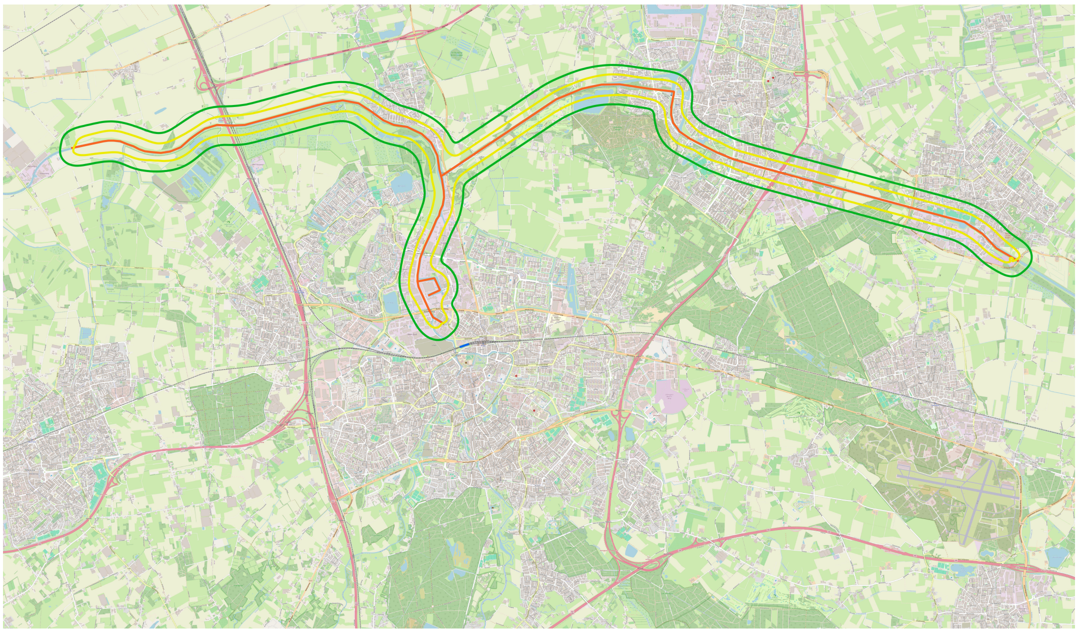
(b) PR contours of rail transport in Moerdijk

Figure 5.1: PR contours of rail transport in a) Breda and b) Moerdijk

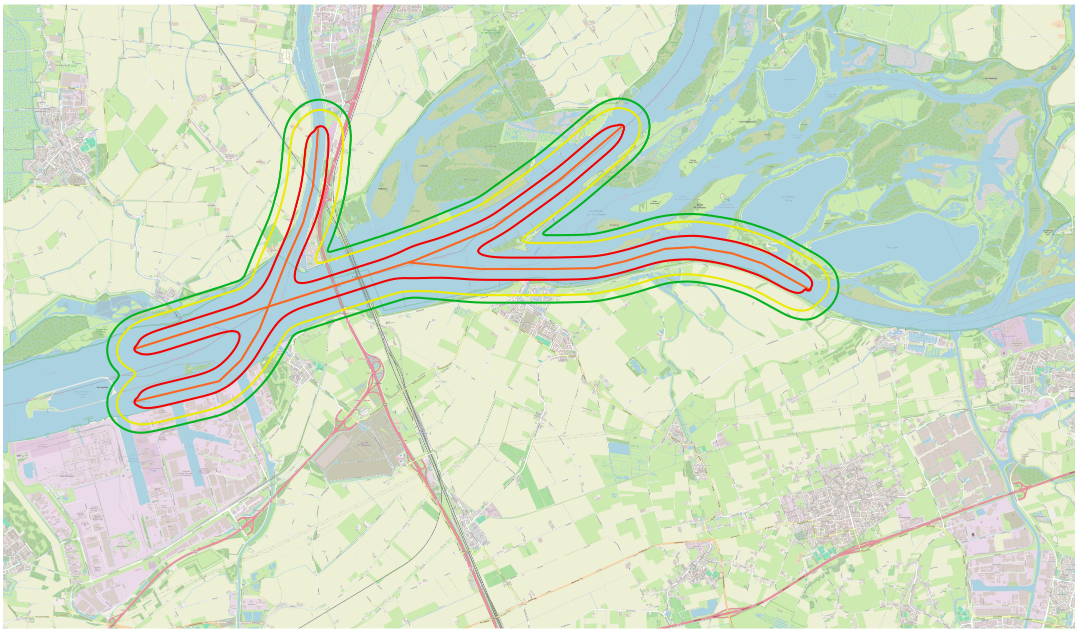
5.2.2. Inland Shipping

Inland shipping stands out in the comparative analysis because it does not generate a 10^{-6} individual risk contour in the urban scenario. This absence is particularly notable when compared to rail and pipeline transport, both of which do clearly exceed this legal threshold in Breda. The lack of a 10^{-6} contour most likely results from less frequent transport movements compared to rail and pipeline transport, and a lower consequence probability related with the Navigability Class in Breda compared to Moerdijk, which leads to a lower scenario frequency. In Moerdijk, a 10^{-6} contour is present. As mentioned previously, this is primarily the result of a higher scenario frequency, driven by the presence of a larger navigability class (Class VI). As inland shipping releases a bigger amount of ammonia than rail transport, the contours are more broad. Again, the spacing in Moerdijk is slightly broader, which can be attributed to the lower surface roughness length.

Although the modelled 10^{-6} contour appears in Moerdijk, it falls almost completely within the bounds of the waterway. Because waterways are not typically places of continuous human presence, the likelihood that someone would spend substantial time, unprotected, at the centre of a navigation channel is minimal. In practical terms, this means that even though the formal risk threshold is exceeded in Moerdijk, the real-world health impact remains minimal for inland shipping in both locations.



(a) PR contours of inland shipping in Breda



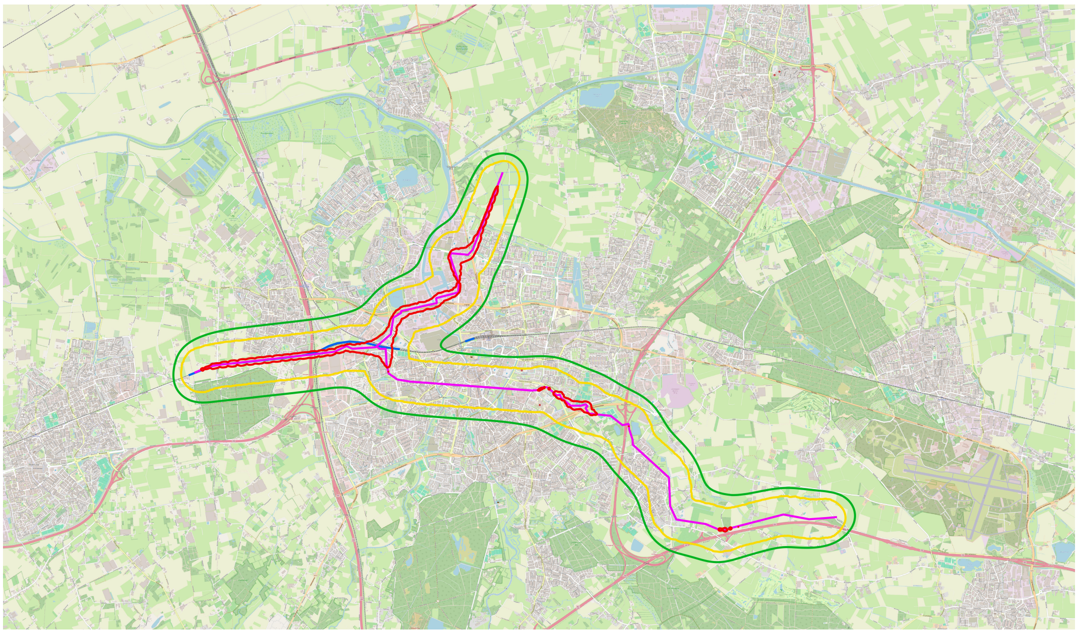
(b) PR contours of inland shipping in Moerdijk

Figure 5.2: PR contours of inland shipping in a) Breda and b) Moerdijk

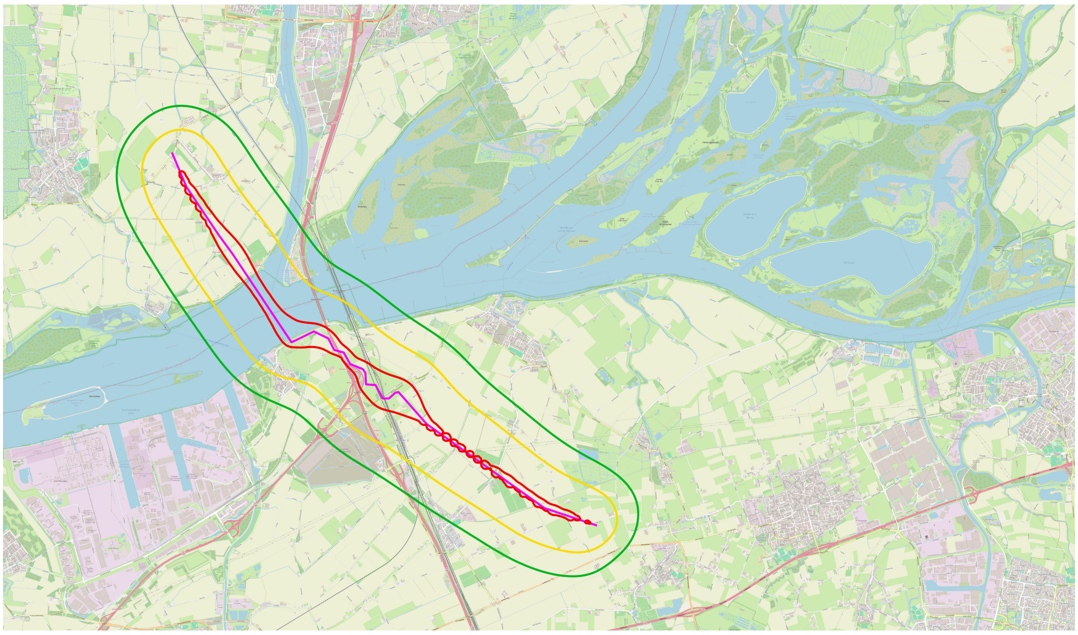
5.2.3. Pipeline Transport

Pipeline transport represents the most severe overall individual risk of all three modalities when considering both Breda and Moerdijk. In Breda, the PR contours for pipeline transport are more extensive than for inland shipping, and relatively similar to rail transport. In Moerdijk, its PR-contours are smaller than for inland shipping, but larger than those of rail transport. This means that pipeline transport consistently ranks among the two highest risk modalities in both locations. In contrast, rail and inland shipping each score lowest in at least one location. Therefore, pipelines can be considered the highest overall contributor to individual risk.

Additionally, since pipeline transport releases the highest amount of ammonia compared to the other two modalities, the contours are the broadest. As expected, the spacing in Moerdijk is again broader, which results from the lower surface roughness length. Due to the width of the PR-contours, large sections of both Breda and Moerdijk fall within zones where the annual probability of death exceeds 1 in 10^{-7} and 10^{-8}. The 10^{-6} contours are much more concentrated along the pipeline routes, indicating that strict mitigating measures should be implemented around these areas.



(a) PR contours of pipeline transport in Breda



(b) PR contours of pipeline transport in Moerdijk

Figure 5.3: PR contours of pipeline transport in a) Breda and b) Moerdijk

5.3. Group Risk (FN-Curves)

As described in Section 4.1.2.2 group risk refers to the annual probability that ten or more people may die as a direct result of an unusual incident occurring within an attention zone (Informatiepunt Leefomgeving, n.d.). This is visualized by FN-curves, which reflect the collective probability of rare but high-impact incidents. Each point on the curve represents the annual frequency (F) of events with N or more fatalities, making the curve cumulative. They are assessed against a predefined orientation value, which begins at a frequency of 10^{-5} and a number of 10 fatalities. This follows the idea of the individual risk limit, which equals 1 fatality with a frequency of 10^{-6}. For events with fewer than 10 deaths, the FN-curve has no formal comparison value as this is not considered a group risk and is thus acceptable.

To support analysis, Safeti-NL visualises FN output as a smoothed curve. This graph shows the overall group risk along the entire modelled transport route. If the curve lies above the orientation value, the population may be collectively exposed to an unacceptable level of risk. The steeper and higher the curve lies above the orientation line, the greater the concern. The FN-curves of the three modalities – rail transport, inland shipping and pipeline transport – are presented in the following sections.

5.3.1. Rail Transport

The FN-curve for rail transport in Breda shows that the calculated group risk exceeds the Dutch orientation value between approximately 10 and 17 fatalities or more. This implies that while large-scale incidents are rare, the likelihood of medium-sized fatal events is possible.

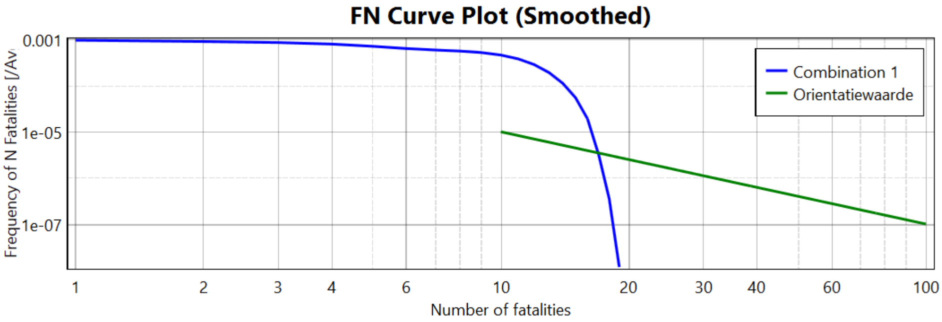
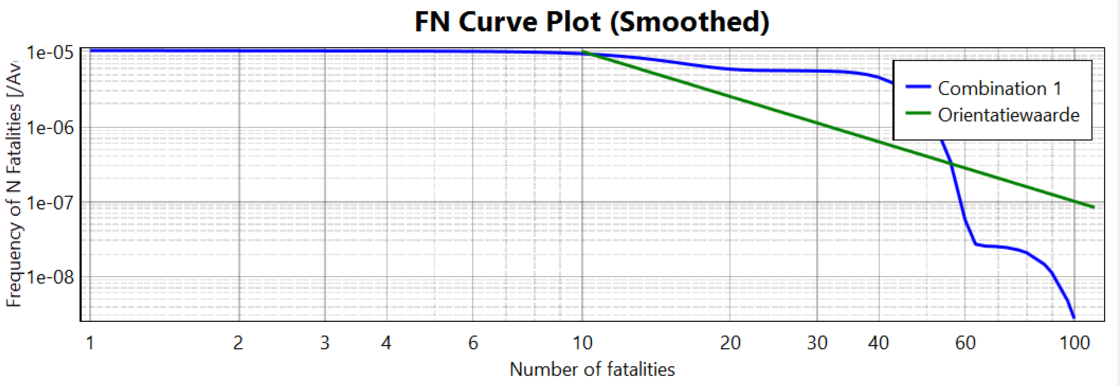


Figure 5.4: FN-curve for rail transport in Breda

For rail transport in Moerdijk, no FN-curves were generated by Safeti-NL. This is because the model did not identify any events in which multiple fatalities could occur within populated areas. As all the risk contours fall outside the town of Moerdijk, no individuals are exposed to lethal concentrations within the population cluster. As FN-curves are only produced when group risk is present, the absence of populated risk exposure explains why no FN data is available for this modality in this location.

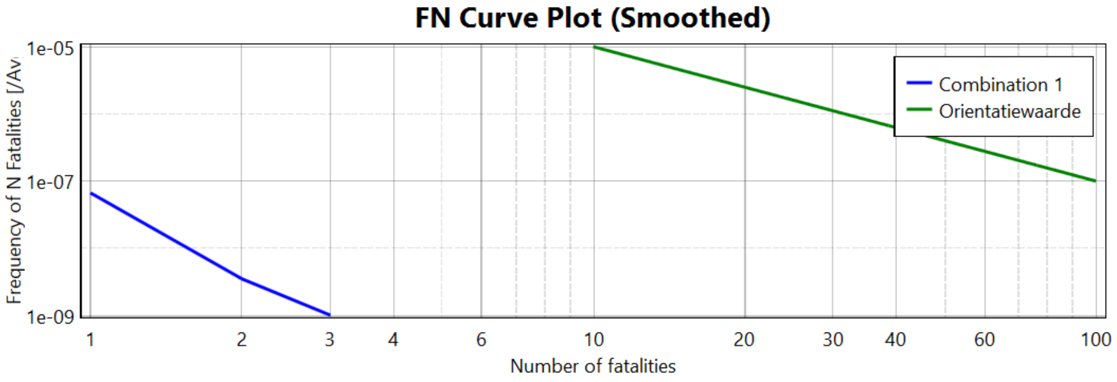
5.3.2. Inland Shipping

The FN analysis for inland shipping in Breda indicates that the group risk exceeds the Dutch orientation value for events involving between at least 10 and 56 fatalities. This means that a major release of ammonia could lead to an unacceptable high-consequence public health event. This also shows that just because the individual risk for inland shipping in Breda does not exceed the legal threshold of 10^{-6}, it does not mean group risk can be neglected.



(a) FN-curve for inland shipping in Breda

The FN-curve for inland shipping in Moerdijk indicates an extremely low societal risk. The calculated FN-values remain well below the Dutch orientation value across the entire fatality spectrum and stop entirely at around at least 3 fatalities. This means that even under worst-case scenarios, a release of ammonia via inland shipping is not expected to result in significant group casualties. Therefore, the group risk associated with inland shipping in Moerdijk is negligible and does not warrant additional risk-reducing measures.

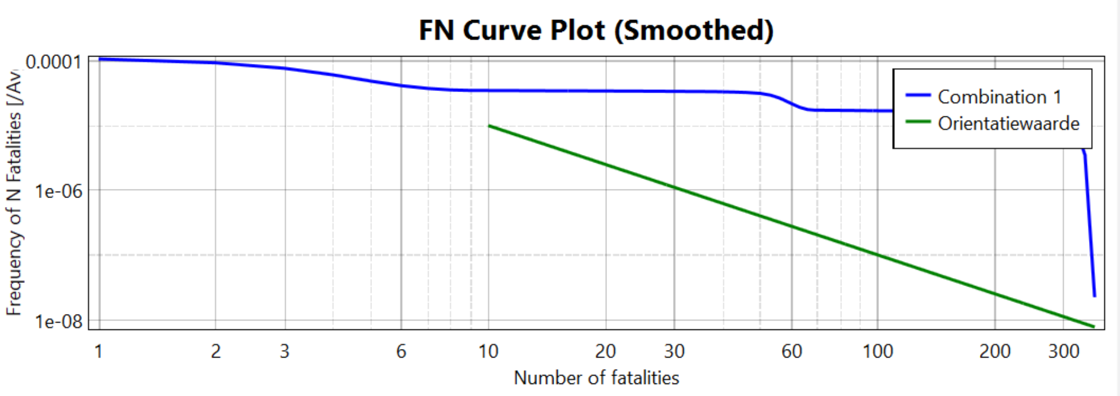


(b) FN-curve for inland shipping in Moerdijk

Figure 5.5: FN-curves for inland shipping in (a) Breda and (b) Moerdijk

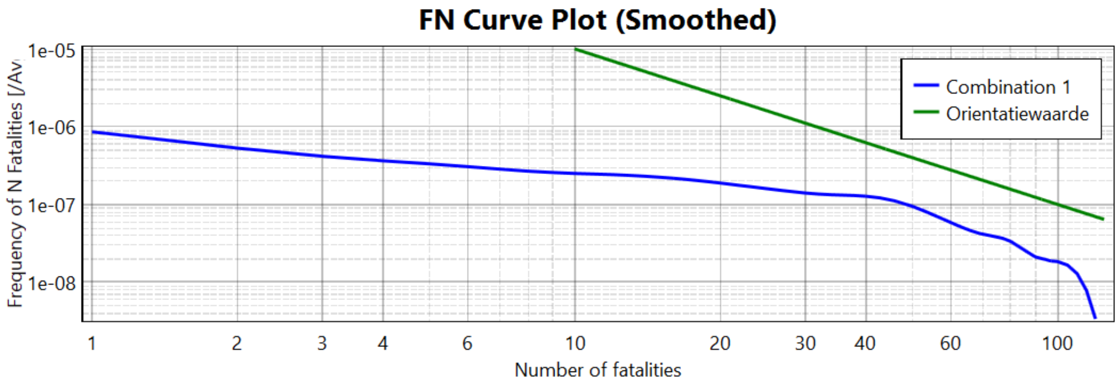
5.3.3. Pipeline Transport

The FN-curve for pipeline transport in Breda shows a substantial exceedance of the Dutch orientation value for events involving between 10 and over 300 or more fatalities. This suggests that a rupture of the high-pressure ammonia pipeline could result in mass casualty scenarios with a severity well beyond accepted societal thresholds. This makes pipeline transport the most severe modality in terms of collective risk, warranting urgent attention in risk mitigation.



(a) FN-curve for pipeline transport in Breda

The FN-curve for pipeline transport in Moerdijk does not indicate an exceedance of group risk. Though the curve decreases relatively stable from 0 to 40 fatalities, it decreases much faster between at least 40 and 110 fatalities. Despite the low probability, a major release of ammonia could lead to a high-consequence public health event. However, as the curve stays under the orientation value, it is not considered relevant.



(b) FN-curve for pipeline transport in Moerdijk

Figure 5.6: FN-curves for pipeline transport in (a) Breda and (b) Moerdijk

5.4. Effect Zones

This section presents and interprets the toxic effect zones that result from the ammonia release scenarios modelled in Safeti-NL. The effect zones are based on specific concentration thresholds (VRW, AGW, LBW). In addition to these threshold-based zones, the attention zone is also included in the analysis. The following sections first briefly explain the intervention thresholds and their health implications, then the maximum effect distances for each transport modality and scenario are presented, and finally the effect zones are spatially visualized using GIS outputs for both urban and rural environments.

5.4.1. Intervention Thresholds

In the Netherlands, intervention values are used by emergency response planning and risk evaluations to assess the severity of toxic exposure scenarios (RIVM, 2025a). The three levels of intervention values are defined as follows (Mahieu et al., 2025):

- **VRW (Public Information Value)**: The air concentration that is very likely to be perceived as disturbing by the exposed population, or above which mild health effects may occur.
- **AGW (Alarm Threshold Value)**: The air concentration above which irreversible or other serious

health effects may occur, or where exposure to the substance may impair a person's ability to bring themselves to safety.

- **LBW (Life-Threatening Value)**: The air concentration above which death or life-threatening conditions may occur.

The intervention values presented in Table 5.1 represent the concentration thresholds of ammonia (in mg/m^3) above which certain health effects are expected to occur, depending on the exposure duration (Mahieu et al., 2025). These thresholds form the foundation for calculating the toxic effect zones visualised in the spatial analysis.

Table 5.1: Intervention values for ammonia exposure (in mg/m^3)

Threshold	10 min	30 min	1 hr	2 hrs	4 hrs	8 hrs	End point
VRW	21	21	21	21	21	21	Faint / no irritation
AGW	200	200	140	99	99	99	Irritation eyes, nose, throat
LBW	1900	1100	780	550	390	280	Lethality

5.4.2. Effect Zone Distances

In Safeti-NL, each effect zone on the map represents the outer boundary of all locations where the relevant threshold has been exceeded during the simulation. However, this is not time-based; it simply reflects the concentration the model detects at a point in time during the simulation. This section presents the maximum distances from the release source to the toxic threshold values for the three transport modalities in both Breda and Moerdijk. These distances can be retrieved from SMEZ reports in Safeti-NL. The distances are presented for two scenarios, the most probable and worst-case scenario. These include the distances to Outdoor VRW, AGW, and LBW, and to the attention zone.

Although both weather types D5, the average weather type during the day in the Netherlands, and F1.5, the average weather type during the night in the Netherlands, were simulated, the F1.5 condition generally resulted in the largest effect distances across most scenarios and modalities (RIVM, 2009). This is because in these stable, low wind conditions, less dilution of the substance occurs than in unstable, high-wind conditions, allowing the ammonia cloud to travel further (RIVM, 2009). As only the largest distances are presented, most of these distances correlate with wind condition F1.5. However, an exception was found for the rupture scenario in rail transport, where the D5 condition produced the largest effect distances to the Outdoor LBW threshold for both urban and rural contexts. This may be attributed to the high initial release of ammonia during the rupture scenario, which under D5 conditions can be carried further downwind before significant dilution occurs. For this modality, these distances correlating with wind condition D5 were included, instead of the lower distances correlating with F1.5. To ensure transparency, the tables in which both weather conditions are shown can be found in Appendix C.

5.4.2.1. Rail Transport

The effect distance table shows that for the leak scenario, toxic ammonia clouds from rail transport can affect large areas. Catastrophic ruptures involve a shorter, high-intensity burst of ammonia that disperses more quickly, leading to high concentrations near the source, but less extensive spatial reach. Continuous leaks, on the other hand, release the same total mass over a longer time, leading to less instant dilution and therefore resulting in greater distances to toxic thresholds.

As expected, the distances to the Outdoor LBW threshold and the attention zone are shorter in Breda than in Moerdijk. Surprisingly however, the distances to Outdoor VRW and AGW are larger in Moerdijk than in Breda. Furthermore, the largest distance to the VRW threshold is higher for rupture than for leak in both Breda and Moerdijk. This can be attributed to the larger instant volume and release pressure of a rupture. Although the ammonia cloud dilutes quicker, the larger initial cloud can be carried over longer distances. In contrast, a leak emits the same total amount more slowly, resulting in a smaller total cloud failing to reach the VRW threshold as far downwind.

Rail shows the smallest distances to the intervention thresholds and the attention zones compared to the other two modalities. However, the distances are still significant. More than a kilometer from the track, life threatening exposure can take place, while 16 kilometers from the incident on the track, mild health consequences can still be experienced. This means that in case of an ammonia incident in rail transport, the health effects will be far-reaching.

Table 5.2: Largest distances to effect zones for rail transport

Location	Scenario	VRW [m]	AGW [m]	LBW [m]	Attention zone [m]
Breda	Leak	12806	3588	1092	711
	Rupture	16043	1695	583	265
Moerdijk	Leak	8985	2315	1552	1156
	Rupture	13758	1785	953	601

5.4.2.2. Inland Shipping

Across both Breda and Moerdijk, the 150 mm leak scenarios consistently result in larger effect distances than the 75 mm leaks. This is expected, given the higher release volumes which leads to greater ammonia dispersion and a broader reach of hazardous concentrations. The distances to the Outdoor LBW and attention zone are much larger in Moerdijk than in Breda. However, similar to rail transport, the distances to the outdoor VRW and AGW are larger in Breda than in Moerdijk.

The distances to the Outdoor LBW threshold and the attention zone for inland shipping are larger than those for rail transport, but almost half of those for pipeline transport. In both Breda and Moerdijk, these distances are fairly similar, reaching approximately 1.5 kilometres and 2 kilometres, respectively. Given these distances for the attention zone, this indicates that even people located indoors within these distances are at risk of life-threatening ammonia exposure.

The relatively small difference between the Outdoor LBW and attention zone distances can be explained by the large release volume and the leak scenario in inland shipping accidents. The slow but large amount of ammonia release results in a concentrated ammonia cloud that remains present for an extended period, keeping outdoor concentrations high. At the same time, ammonia slowly infiltrates buildings and accumulates indoors. Since the outdoor air remains highly contaminated, it cannot dilute the indoor concentration, allowing the indoor levels to rise to nearly the same critical threshold as outdoors.

Table 5.3: Largest distances to effect zones for inland shipping

Location	Scenario	VRW [m]	AGW [m]	LBW [m]	Attention zone [m]
Urban	Small leak	14344	3112	771	787
	Big leak	22102	4458	1510	1437
Rural	Small leak	12556	2029	1020	984
	Big leak	18672	3428	2122	1966

5.4.2.3. Pipeline Transport

The effect distances for pipeline transport in Breda and Moerdijk are the most extensive and severe of all three transport modalities. Contrary to rail transport, breach scenarios produce significantly larger effect distances than continuous leaks. This can be attributed to the fact that the ammonia volume in rail transport is totally released in both scenarios, only over different time periods. For pipeline transport however, there is no set volume for ammonia released, so a much larger volume of ammonia keeps flowing out of the ruptured pipeline compared to the pipeline that only has a 20 mm leak. For the distances to the AGW and LBW thresholds and the attention zones, the catastrophic rupture leads to distances that are more than five times larger than in the leak scenario.

The attention zone distance is crucial, and reaches 3.3 km in Breda and nearly 4.8 km in Moerdijk in the most severe scenario. These distances imply that people inside buildings could be exposed to lethal ammonia doses several kilometres away from the pipeline. What is notable for this modality is that the distance to the attention zone is higher than that to the LBW threshold. Similar to the minor difference between the two distances in inland shipping, this can be explained by the large release volume. Again, the huge amount of ammonia release results in a very concentrated ammonia cloud that remains present for an extended period. Therefore, the outdoor concentration becomes very high and ammonia slowly infiltrates buildings and quickly accumulates indoors. The outdoor air remains highly polluted with ammonia and the indoor concentration cannot be diluted by letting in fresh outside air. Now, the outside concentrations have to decrease first, before the contaminated air inside can mix with the cleaner air outside.

Table 5.4: Largest distances to effect zones for pipeline transport

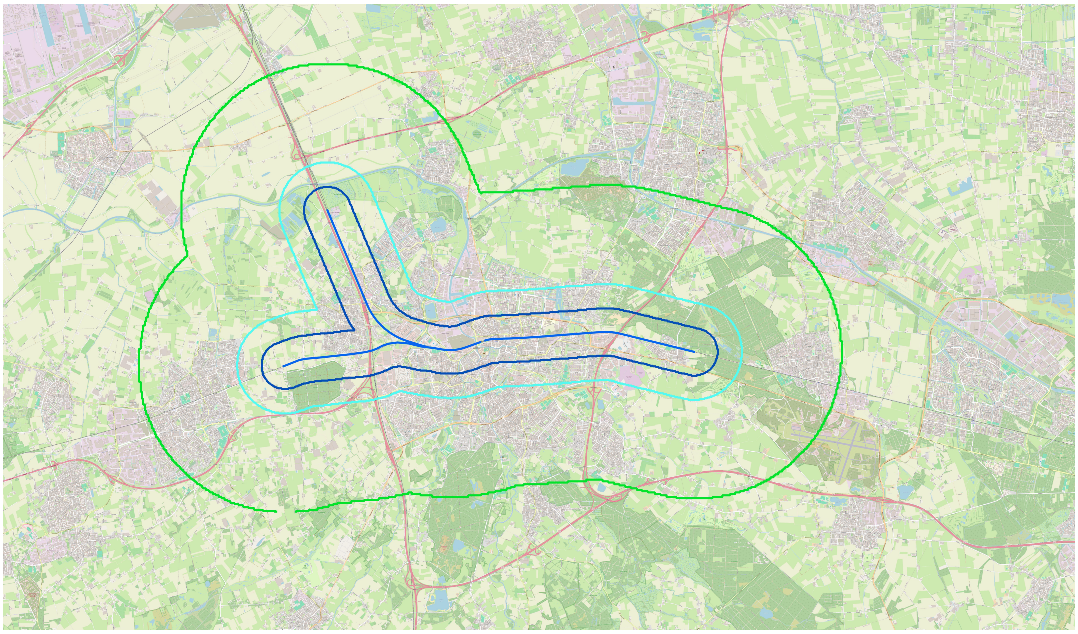
Location	Scenario	VRW [m]	AGW [m]	LBW [m]	Attention zone [m]
Urban	Leak	11893	2453	426	499
	Breach	45801	10990	2522	3263
Rural	Leak	11387	1971	800	783
	Breach	48833	13188	4031	4747

5.4.3. Effect Zone Contours

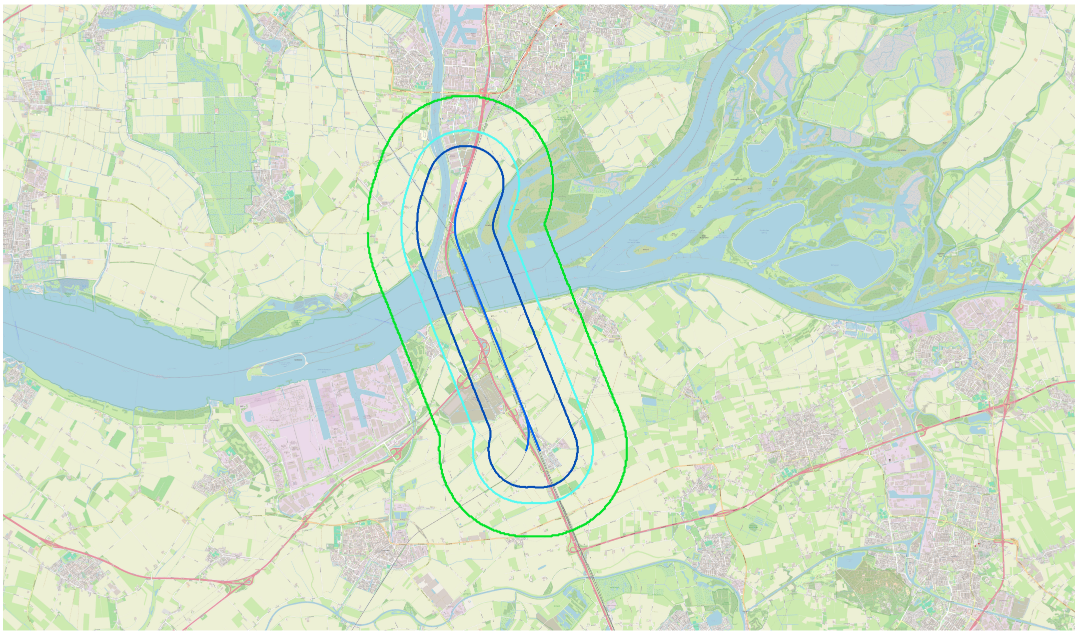
To support the interpretation of the intervention thresholds, in this section the effect distances are visualized in effect zone maps for both Breda and Moerdijk. The circles represent the effect zones accounting any possible wind direction. Only the largest effect distance of the two scenarios are visualized in the figures. The corresponding distances can be found marked red in Section 5.4.2. The VRW outdoor zone is considered less relevant for human safety implications and is difficult to visualise meaningfully at the appropriate scale, as it extends well beyond the immediate surroundings of Breda and Moerdijk. Therefore, it is not included in the presented figures. Nevertheless, the maps including the VRW zones are provided in Appendix C.

5.4.3.1. Rail Transport

The effect zones for rail transport are relatively compact compared to the other two modalities. As found in Table 5.2, the leak scenario provides the largest effect distances for the AGW, LBW and attention zones, which are visualized here. The attention zone lies relatively close to the track in both Breda and Moerdijk, followed by the LBW outdoor contour. The latter covers roughly half of Breda and only a very small portion of Moerdijk. As in Breda the attention zone and LBW contours intersect a large populated area, individuals in these zones may face life-threatening exposure. The AGW outdoor contour covers most of the city, indicating widespread potential for non-lethal but severe health effects. What sets rail transport apart, however, is that in Moerdijk, the attention zone and LBW contour barely intersect the town at all. While the AGW zone does cover the entire area, suggesting possible respiratory effects, the risk of fatal exposure in the population is minimal. This contrasts with the other two modalities, both of which place Moerdijk well within the LBW zones.



(a) Effect contours of rail transport in Breda



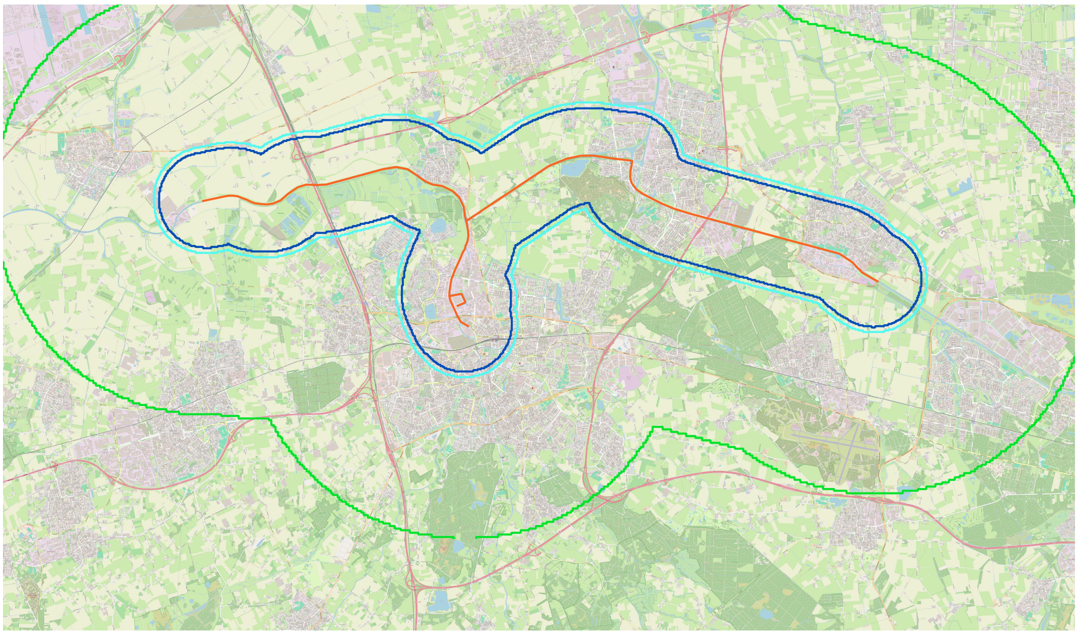
(b) Effect contours of rail transport in Moerdijk

Figure 5.7: Effect contours of rail transport in a) Breda and b) Moerdijk

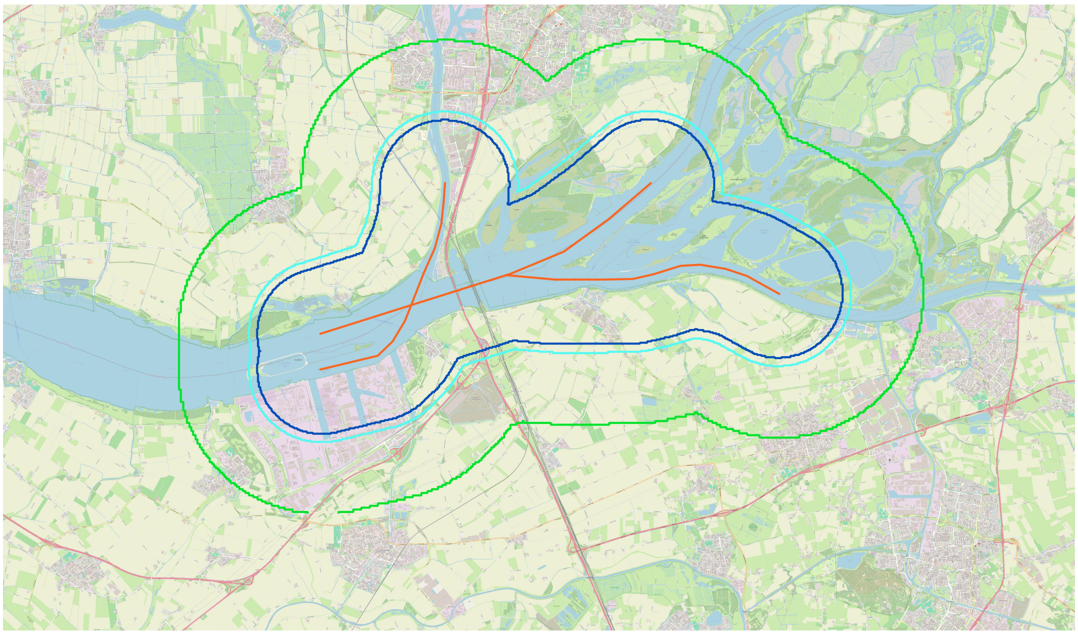
5.4.3.2. Inland Shipping

Inland shipping, by contrast to rail transport, involves much larger release volumes. Therefore, the inland shipping effect zones display a different spatial pattern. The attention zone contour lies at a noticeably greater distance from the route compared to rail, closely followed by the outdoor LBW contour, as expected from the distances found in Table 5.3.

In Breda only a relatively small part of the city is covered by the LBW and attention zone contour, but surrounding municipalities are also partly affected by these zones. Further out, the Outdoor AGW contours extend far beyond the city limits, affecting entire cities nearby. Similar to the PR-contours, a large portion of the effect contours in Moerdijk lies directly above the waterway, where human presence for a longer period of time is rare, minimizing the practical health dangers in this area. However, in Moerdijk the LBW and attention zone contour still fully overlap the town, with the AGW contour also covering parts of neighbouring towns. Like for rail transport, the Outdoor AGW contour appears somewhat shorter in spatial reach in Moerdijk than in Breda.



(a) Effect contours of inland shipping in Breda



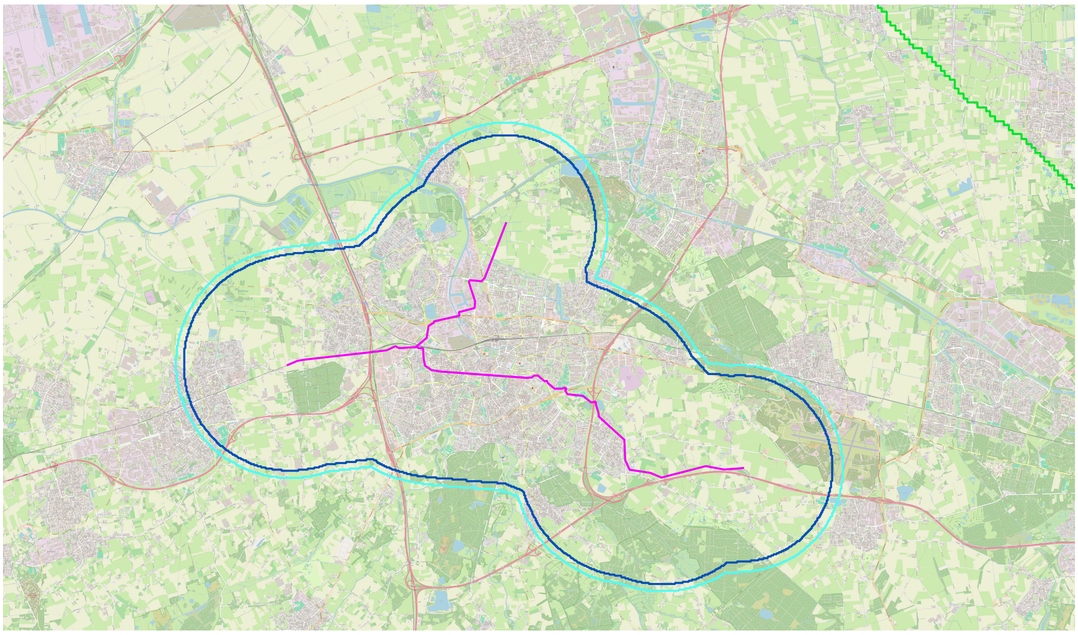
(b) Effect contours of inland shipping in Moerdijk

Figure 5.8: Effect contours of inland shipping in a) Breda and b) Moerdijk

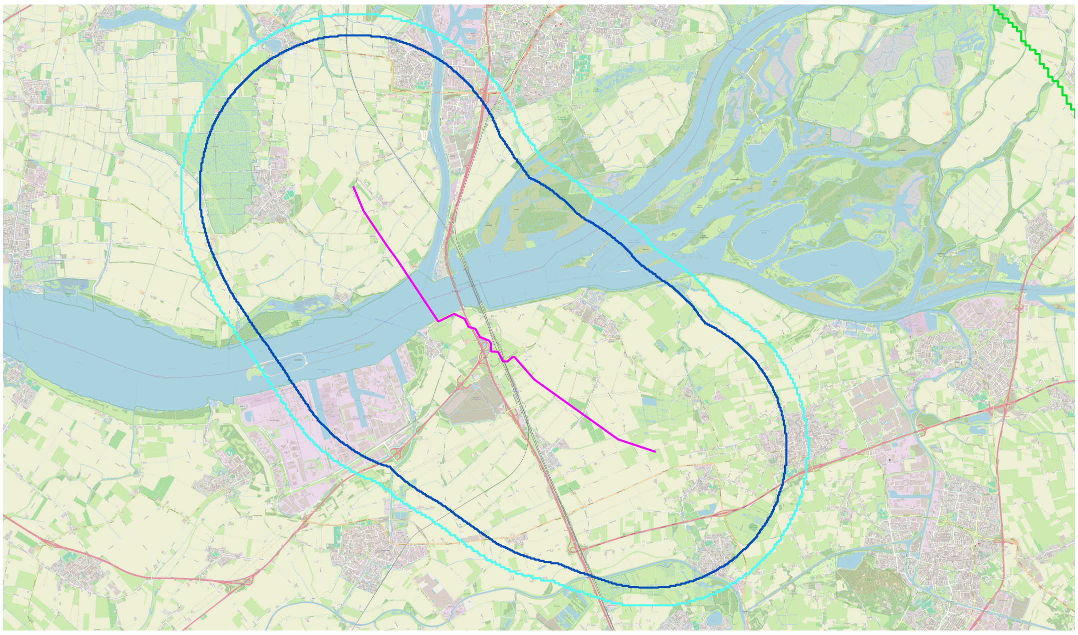
5.4.3.3. Pipeline Transport

Pipeline transport clearly exhibits the most extensive effect zones in both Breda and Moerdijk, with the contours lying much further away from the modeled route than for the other modalities. This can be attributed to the much larger release volume in pipeline accidents than for rail and shipping accidents. Again, the Outdoor LBW and attention zone contours are found close to each other, suggesting that the intensity of the release causes indoor and outdoor concentrations to be very similar.

In both Breda and Moerdijk, the Outdoor LBW and attention zone contours fully overlap the area. That means the people in both areas are exposed to life-threatening ammonia concentrations, whether located indoors or outdoors. Unlike the Outdoor AGW zone in rail transport and inland shipping, the AGW zone for pipeline transport extends far beyond the analyzed areas. Therefore, even people very far away from Breda and Moerdijk can still experience respiratory distress or other health issues. This makes the extent of pipeline incidents with ammonia the most extreme.



(a) Effect contours of pipeline transport in Breda



(b) Effect contours of pipeline transport in Moerdijk

Figure 5.9: Effect contours of pipeline transport in a) Breda and b) Moerdijk

5.5. Main Insights from Scenario Modeling

The quantitative scenario modelling provides a comparative insight into the human safety risks posed by the three transport modalities. These risks are evaluated through individual risk contours, group risk, and toxic effect zones. While all modalities are connected to safety concerns, the scale and actual impact of potential accidents vary significantly.

In Breda, only inland shipping avoids exceeding the legal 10^{-6} individual risk threshold. Rail transport shows the most significant PR-10^{-6} contour, and pipeline transport als shows a substantial exceedance. In Moerdijk, the pattern is reversed: rail transport exhibits the smallest 10^{-6} contour, and inland shipping the largest. Again, pipeline transport shows a consistent 10^{-6} contour in this location. The differences in contour shape and spacing are primarily linked to release volumes: pipelines release the largest volume and thus produce widely spaced contours, followed by inland shipping and then rail.

In terms of group risk, pipeline transport results in the highest group risk in Breda, followed by inland shipping, and rail showing the lowest. In Moerdijk, no FN-curve was recorded for rail, and both inland shipping and pipeline remain well below the orientation value, indicating that group risk in this rural context is negligible across all modalities.

Lastly, effect and attention zones reveal that there are also differences in consequences per modality. For rail transport, the most extensive zones were caused by the leak scenario — a surprising outcome that underscores that the theoretical worst-case scenario does not necessarily have to lead to the worst effects. Inland shipping and pipeline transport, as expected, generated their largest effect zones under the big leak and breach scenarios. When comparing absolute effect distances, rail transport leads to the smallest, followed by inland shipping, with pipeline transport showing the widest reach. Analyzing the visualized effect contours results in a similar outcome: although both rail and inland shipping overlap quite a big part of Breda, the LBW and attention zone contours for pipeline transport cover Breda completely. In Moerdijk, the LBW and attention zone contours of rail transport do not cover Moerdijk at all, while inland shipping and pipeline transport do cover the entire town.

6

Modeling and Evaluating Risk Mitigation Strategies

The modelling results presented in Chapter 5 show that ammonia transport by rail, inland shipping, and pipeline, is associated with significant risks and potential consequences for human health. These findings demonstrate the urgent need for mitigation measures to reduce the probability and impact of ammonia transport incidents. This chapter addresses sub-question 4 by introducing specific risk and consequence mitigation strategies into the modelling framework and assessing their expected individual and combined impact.

First, a selection of mitigation strategies relevant to each transport modality is introduced. These can then be translated into adjusted input parameters after which the models are re-run with these altered values. Finally, the modeling results of the mitigating measures are presented, the net impacts of the combined mitigation measures are shown per modality, and the comparison between the three modalities is made. By quantitatively evaluating the effectiveness of technical and organisational interventions, this chapter aims to provide information on how risks identified in earlier chapters can be meaningfully reduced.

6.1. Mitigation Strategies

Before presenting the possible mitigation strategies, it is important to distinguish between two different types of interventions: those that aim to reduce the probability of an incident — and are therefore focused solely on risk reduction — and those that aim to reduce the consequences of an incident. Preferably, both aspects can be addressed. Consequences can affect both the effects and the risks of an incident, meaning some consequence-mitigating measures may influence both the risk and effect outputs. This section first explains how the mitigation strategies were chosen, and then presents four mitigating measures for each transport modality.

6.1.1. Selection of Mitigation Strategies

The selection of mitigation measures in this chapter is based on a combination of literature insights, technical feasibility in Safeti-NL, and predefined options included in Module III and V (RIVM, 2025b; RIVM, 2025c). First, the range of adjustable parameters in Safeti-NL was explored to identify which types of interventions could be realistically modelled, such as the placement of shut-off valves, reducing the pipeline diameter, or the use of smaller tanks. These initial options were identified through the author's independent exploration of Safeti-NL's adjustable modelling parameters. Next, academic and policy literature was reviewed to identify possible risk reduction strategies for ammonia transport, such as slower speeds, variation in transport temperature, implementing better navigational tools, or release below the waterline. Only measures for which parameter values could be specified and effects modelled in Safeti-NL were included. Lastly, the implementation of the European Train Control System, the crash buffers and anti-climbing protection, the warning tape and the strict supervision of work activities were drawn from Module III and V, which provide correction factors for the scenario and failure frequencies.

To ensure a balanced and fair comparison across modalities, four mitigation measures were selected for each transport type. Rail transport exhibits relatively high individual risks compared to its effect distances, especially when set side by side with the other two modalities. Additionally, rail transport offers a broader set of available interventions targeting incident frequency. Therefore, the focus for rail transport was primarily on risk-reducing measures. For inland shipping, the emphasis was placed on consequence-reducing measures, since the risk level in Breda already remained below the 10^{-6} threshold in the base case, and a big part of the 10^{-6} contour in Moerdijk fell on top of the waterway. Pipeline transport exhibited both the highest risk and the largest effect distances compared to the other two modalities. This led to a balanced selection of measures targeting both risk and consequence reduction equally.

All selected measures were subsequently discussed with professionals in the field to assess their technical and practical feasibility. These consultations provided valuable insight into the realism and acceptability of each measure. While some interventions were confirmed to be feasible under current or near-future conditions, others were considered less likely to be implemented in practice due to economic, environmental or societal constraints. This will be further discussed in Section 7.1.6. However, it was confirmed that all measures could theoretically be implemented and modelled.

6.1.2. Rail Transport

For the transport of ammonia by rail, multiple risk management strategies can be implemented. Three that specifically address the likelihood of an incident occurring, and one to reduce the severity of their consequences. Given the presence of a 10^{-6} PR-contour in both rail contexts and the size of the toxic effect zones, especially in Breda, effective intervention is critical.

6.1.2.1. Risk Mitigating Measures

European Train Control System (ETCS)
The European Train Control System (ETCS) is a modern safety system that significantly reduces the risk of rail incidents by continuously supervising train speed and enforcing braking limits (European Commission, 2024). The ETCS has different levels in which it operates. In Level 1, the train's onboard computer calculates a safe braking curve and ensures compliance with the authorised movement limit, using information received from the trackside (European Commission, 2024). Compared to older signalling systems, ETCS offers more consistent control and faster responses to potential hazards.

Crash buffers and anti-climbing protection
To reduce the likelihood of tank damage leading to ammonia release during rail collisions, wagons can be equipped with crash buffers and anti-climbing protection, which are often combined (Onderzoeksraad voor Veiligheid, 2015). Crash buffers are designed to absorb part of the kinetic energy during a collision (RIVM, 2025b). This way, they reduce the deformation of the underframe of a tank wagon, thereby lowering the risk of structural failure or tank rupture (Onderzoeksraad voor Veiligheid, 2015). Anti-climbing protection prevents wagons from riding over one another in the event of a rear-end collision or sudden deceleration (RIVM, 2025b). Anti-climbing devices physically block this upward movement and protect the tank shell from mechanical damage (Antea Group, 2018).

Lower train speeds
Train operating speed is one of the factors affecting the likelihood of a release in railroad accidents involving tank cars transporting hazardous materials (Kawprasert and Barkan, 2010; NIPV, 2023; Uijt de Haag, 2019). With a higher speed of derailment, there is a higher probability that a derailed car will suffer a release (Kawprasert and Barkan, 2010). Based on the study by NIPV (2023), it can be observed that train speed has a significant impact on the scenario frequency in case of an incident.

6.1.2.2. Consequence Mitigating Measures

Smaller tank wagons
An intervention aimed at reducing the severity of rail-based ammonia incidents is the use of smaller tank wagons. In this case, in the event of a rupture or major leak, the released quantity per wagon is lower, most likely resulting in smaller consequences like toxic clouds and effect distances. However, this approach introduces a trade-off: to transport the same annual volume of ammonia, more tank wagons are required. This leads to an increase in transport intensity, which directly affects the scenario frequency component of the risk calculation. On the other hand, the decrease in release volume and therefore the extent of the consequences, could also lead to smaller risk contours decreasing the overall risk. This effect could minimize the trade-off.

6.1.3. Inland Shipping

Inland shipping has shown a variable risk profile, with no significant individual risk contour in Breda but a clear exceedance in Moerdijk. However, both locations show extensive effect distances. This suggests that risk mitigation efforts, but especially effect mitigating measures should be implemented to reduce these risks and effects.

6.1.3.1. Risk Mitigating Measures

Inland Automatic Identification System (AIS)
The leading cause of transport accidents in inland shipping is human failure, caused by factors such as lack of communication, misjudgment of navigational conditions or insufficient awareness of the surroundings. (Bačkalov et al., 2023). Therefore, improving navigation and communications systems could have a positive impact on reducing inland shipping risks. A promising tool is the inland Automatic Identification System (AIS), which is a system that automatically identifies vessels, mainly used for improving navigational safety, ship-to-ship communication, and ship reporting (Emmens et al., 2021). It enhances the situational awareness of ship operators by providing real-time data on the location, movement, and status of nearby vessels (Rijksoverheid, n.d.-a). It also provides up-to-date information about navigational conditions such as currents, water levels, and obstructions (CESNI, 2019).

The primary function of an AIS is to prevent vessel collisions (Emmens et al., 2021). Therefore, in this study, AIS is expected to reduce the failure frequency primarily in Moerdijk, not in Breda. This is because Moerdijk lies along a Navigability Class VI waterway, which is characterized by dense traffic and larger vessels, conditions under which the risk of ship-to-ship collisions is highest. In contrast, Breda is connected to a Class IV waterway, where such collisions are far less likely. Therefore, the implementation of AIS is only expected to have a significant impact on risk reduction in Moerdijk, where the baseline scenario currently exceeds the 10^{-6} PR threshold.

6.1.3.2. Consequence Mitigating Measures

Tank placement under waterline
One of the most promising interventions to reduce the human health consequences of ammonia release is the underwater placement of ammonia tanks within the vessel hull. This is because the severity of a leak is determined by the location of the rupture relative to the waterline (Riemersma, 2024). Releases occurring above the waterline result in the formation of toxic vapor clouds, whereas underwater breaches lead to far less airborne toxicity (De Looij and Wieme, 2011; Riemersma, 2024).

For the base case used in Chapter 4 and 5 it was assumed all ammonia leaks occurred above the waterline. However, by placing the tanks below the waterline, the surrounding water acts as both a physical barrier and a chemical sink (De Looij and Wieme, 2011). Firstly, the pressure of the surrounding water decreases the ammonia outflow in case of a leak. However, more importantly, when the ammonia flows out into the water, a significant portion dissolves into the surrounding water before it can reach the atmosphere. This could dramatically reduce the consequences in case of an ammonia release. Due to the lower volume that reaches the surface, this also influences the risk contours.

Smaller shipping tanks
Another measure to reduce effects is the use of smaller individual tanks on board. Rather than transporting relatively large volumes per tank, the ammonia can be distributed across smaller tanks, each with a lower maximum capacity. This reduces the released volume per tank in the event of an incident, thereby limiting toxic exposure. However, if this strategy requires the use of additional ships, the increased number of shipments may cancel out the safety benefits by increasing the overall scenario frequency. To address this, a more effective configuration is to equip a single vessel with more smaller tanks instead of the conventional six larger tanks, while keeping the total volume per ship constant. This approach reduces the effect severity without increasing the transport frequency or the exposure of the route. Again, due to the lower release volume this measure also influences the risk contours.

Semi-cooled ammonia transport
Ammonia is currently transported in pressurized form, except for sea going vessels which transport cooled ammonia (Riemersma, 2024). However, as 10°C is far above its boiling point, ammonia undergoes flashing upon its release which increases human exposure risks (Hassan et al., 2009; Bubbico et al., 2016). When transported in a semi-cooled state, flashing can be reduced which could have significant benefits for external safety (Ministerie van Klimaat en Groene Groei, 2024a). In both cases, the substance remains in liquid form due to pressurisation, but semi-cooled transport reduces the vapour pressure of the liquid. In the event of a release, the lower temperature results in slower evaporation, which can reduce the initial formation and dispersion speed of the ammonia gas cloud. Although the effect is moderate, it may provide a slight reduction in peak concentrations and effect distances.

6.1.4. Pipeline Transport

As found in Chapter 5, both the risk and effect profiles of pipeline transport are very high. Therefore, a balanced mitigation strategy that includes two risk- and two consequence-mitigating strategies is proposed. As mentioned in Section 3.2.3, the main cause of pipeline failure is third-party activity (Bubbico et al., 2016; RIVM, 2025c). Therefore, the risk mitigation measures are specifically aimed at reducing the probability of third-party activity. In addition, two consequence mitigating measures are discussed.

6.1.4.1. Risk Mitigating Measures

Warning tape
Placing warning tape as a physical marker above the pipeline in the soil during installation can reduce the likelihood of third-party activity accidentally damaging the pipeline, specifically during excavation (Singhal Industries, 2025). If during excavation the tape shows, it serves as a visual and physical warning before reaching the pipe itself (RIVM, 2025c). This simple measure provides an early alert to prevent unintentional damage and gives operators a chance to stop work before hitting critical infrastructure.

Strict supervision of work activities
Another measure aimed at reducing accidental third-party damages involves actively supervising any third-party work taking place near the pipeline. A pipeline operator or safety officer should be present on site to guide activities, enforce safety protocols, and immediately intervene in case of unsafe behaviour (RIVM, 2025c).

6.1.4.2. Consequence Mitigating Measures

Emergency shut-off valves
This intervention involves the placement of automated emergency shut-off valves along the pipeline. In the base scenario, no valves were present, meaning that any rupture would continue to release ammonia until the entire upstream volume had been emptied. As a mitigation measure, valves can be placed along the pipelines. Implementing valves allows for rapid isolation of the rupture site, limiting the total release volume and reducing the spatial extent of toxic effect zones (Brown, 2022). Due to the lower total volume that is released, this measure also influences the risk contours.

Pipeline diameter reduction
This intervention involves reducing the pipeline diameter by half. This reduces the mass flow rate and the total release volume per second, which thereby lowers the extent of effect zones. This reduction also introduces trade-offs. To compensate for the reduced transport capacity, the scenario assumes the construction of a duplicate pipeline, allowing the same overall volume of ammonia to be transported on an annual basis.

This modification leads to a doubling of the number of pipeline segments, which in turn increases the overall probability of failure. Even though the failure frequency per kilometre remains unchanged, the additional pipeline creates a higher likelihood that at least one pipeline will fail over time. Therefore, this measure reduces the consequences of individual accidents, but may increase the frequency of incidents and thus the risk.

6.2. Modelling Approach for Mitigation Scenarios

To assess the effectiveness of the proposed mitigation measures, the strategies described in Section 6.1 are translated into adjusted input parameters for Safeti-NL. This modelling step involves the re-configuration of relevant variables such as failure frequencies and release volumes. The adjusted parameters were calculated in Excel. The table overviews with these new calculated values, together with explanations on newly introduced or altered parameters, are presented in Appendix D.

6.2.1. Adjusted Rail Transport Parameters

European Train Control System (ETCS)
In quantitative terms, the implementation of ETCS Level 1 corresponds to a 14% reduction in scenario frequency (RIVM, 2025b). The new scenario frequencies for a decrease of 14% are shown in Table 6.1.

Table 6.1: Adjusted parameters for implementation of ETCS

Parameter	Scenario 1: Leak	Scenario 2: Rupture
Scenario frequency [1/km·year]	Urban: 7.34×10^{-5} Rural: 6.15×10^{-6}	Urban: 6.38×10^{-6} Rural: 5.35×10^{-7}

Crash buffers and anti-climbing protection
When both crash buffers and anti-climbing protection are present, a reduction of 8% may be applied to the scenario frequency. However, this only goes for open track sections such as track type A (RIVM, 2025b). The new scenario frequencies for a decrease of 8% can be found in Table 6.2.

Table 6.2: Adjusted parameters for crash buffers and anti-climbing protection

Parameter	Scenario 1: Leak	Scenario 2: Rupture
Scenario frequency [1/km·year]	Urban: 7.85×10^{-5} Rural: 6.58×10^{-6}	Urban: 6.83×10^{-6} Rural: 5.72×10^{-7}

Lower train speeds
Lower operating speeds significantly reduce the consequence probability in the event of an incident. Specifically, if a derailment occurs at a speed below 40 km/h rather than above, the probability that a tank car releases ammonia is approximately 86% lower for track type A and 78% lower for track type C (NIPV, 2023). This supports the view that reducing train speed is an effective risk mitigation measure. The updated scenario frequencies and consequence probabilities are shown in Table 6.3.

Table 6.3: Adjusted parameters for lower train speeds

Parameter	**Scenario 1: Leak**	**Scenario 2: Rupture**
Consequence probability	Urban: 1.63×10^{-10} Rural: 8.68×10^{-12}	
Scenario frequency [1/km·year]	Urban: 1.88×10^{-5} Rural: 1.00×10^{-6}	Urban: 1.63×10^{-6} Rural: 8.71×10^{-8}

Smaller tank wagons

Instead of transporting 50,000 kgs of ammonia in a single, high-capacity pressurised tank, the same total quantity can be distributed across smaller tanks, each carrying 40,000 kgs. However, this also leads to a slight increase in the annual intensity of tank wagons, which in turn increases the scenario frequency. The parameters that are influenced by the decrease from 50,000 kgs to 40,000 kgs are shown in Table 6.4.

Table 6.4: Adjusted parameters for smaller tank wagons

Parameter	**Scenario 1: Leak**	**Scenario 2: Rupture**
Tank capacity [kg]	40,000	
Annual intensity [tanks/year]	1.57×10^{5}	
Scenario frequency [1/km·year]	Urban: 1.07×10^{-4} Rural: 8.94×10^{-6}	Urban: 9.28×10^{-6} Rural: 7.77×10^{-7}

All rail transport measures combined

The total change in scenario frequency for the rail transport scenarios if all measures are implemented can be found in Table 6.5, along with the adjusted tank capacity and the increased annual intensity.

Table 6.5: Adjusted parameters for all rail transport measures combined

Parameter	**Scenario 1: Leak**	**Scenario 2: Rupture**
Tank capacity [kg]	40,000	
Annual intensity [tanks/year]	1.57×10^{5}	
Scenario frequency [1/km·year]	Urban: 6.94×10^{-5} Rural: 5.67×10^{-6}	Urban: 6.03×10^{-6} Rural: 4.93×10^{-7}

6.2.2. Adjusted Inland Shipping Parameters

Implementing advanced navigation and communication systems

On Class VI waterways, where the volume and size of traffic is substantially higher than on lower-class routes, this level of oversight is critical. The increased visibility and communication between vessels help to reduce the likelihood of collisions, which in turn reduces the baseline accident frequency. In contrast, on lower-intensity routes such as navigation class IV, where waterways are less congested, the added value of these systems is limited. For this reason, by implementing these systems, only the basic accident frequency in Class VI reduces from $4.14 \cdot 10^{-7}$ to $8.0 \cdot 10^{-8}$, which is a reduction of 80%. The reduction in basic accident frequency in Navigability Class VI and its influence on the scenario frequency can be found in Table 6.6.

Table 6.6: Adjusted parameters for implementation of navigation and communication systems

Parameter	**Scenario 1: Small leak**	**Scenario 2: Big leak**
Basic accident frequency [1/vehicle·km]	Urban: 8.67×10^{-8} Rural: 8.0×10^{-8}	
Scenario frequency [1/km·year]	Urban: 2.21×10^{-6} Rural: 4.64×10^{-6}	Urban: 1.06×10^{-8} Rural: 2.23×10^{-8}

Tank placement under waterline
According to De Looij and Wieme (2011), approximately 35% of the released ammonia dissolves before reaching the surface. The remaining ammonia accumulates on the water surface in the form of a liquid pool. From this pool, an additional 80% is expected to dissolve, resulting in only 13% of the total released ammonia becoming available for atmospheric dispersion.

As it is not possible to model anything in Safeti-NL that happens under water (in other words, Safeti only allows for modeling in air), it is not possible to fully simulate the process of counter pressure from the water, which reduces the release volume, and to include ammonia's solubility in water. That is why the parameter 'tank capacity' of an inland ship tank will simply be decreased to 13% of its original tank capacity. Furthermore, as the ammonia is dispersed from the surface of the water where it forms a pool, the elevation needs to be reduced to 0 meters (TNO, 2003). To simulate an increased counterpressure from the water, the tank head will be decreased to 1 meter (TNO, 2003). This is done as the higher this value is, the more pressure is assumed from above on the leaks, while in this case this pressure should be lowered. These changed values can be found in Table 6.7.

As Safeti-NL normally models the inland shipping model as if all released ammonia becomes available for atmospheric dispersion, this gives a very similar outcome as if it were modeled more exact with underwater interaction taken into account. However, a small overestimation may be possible in case that not the entire tank capacity flows out in the modeled time of 1800 s.

Table 6.7: Adjusted parameters for implementation of tank placement under waterline

Parameter	**Value**
Tank capacity [kg]	29,250
Elevation [m]	0
Tank head [m]	1

Smaller shipping tanks
For this measure eight tanks are introduced instead of six, which leads to a reduced tank capacity of 168,750 instead of 225,000. The new tank capacity and number of tanks modeled for this measure can be found in Table 6.8.

Table 6.8: Adjusted parameters for implementation of smaller shipping tanks

Parameter	**Value**
Tank capacity [kg]	168,750
Number of tanks	8

Semi-cooled ammonia transport
Semi-cooled ammonia is transported at a lower temperature of 5ºC instead of 9.8 and a pressure of 4.13 bars instead of 5.08. The adjusted values can be found in Table 6.9.

Table 6.9: Adjusted parameters for implementation of semi-cooled ammonia transport

Parameter	Value
Temperature [ºC]	5
Pressure [bar]	4.13

All inland shipping measures combined

The total change in scenario frequency for the inland shipping scenarios if all the risk mitigating and the effect mitigating measures are implemented, can be found in Table 6.10, along with the additional adjusted parameters. Note that for the combined measures, 13% of the tank capacity of 168,750 is taken, instead of 13% of the original tank capacity of 225,000. This leads to an even further reduced tank capacity in this scenario with all measures implemented simultaneously.

Table 6.10: Adjusted parameters for implementation of all inland shipping measures combined

Parameter	Scenario 1: Small leak	Scenario 2: Big leak
Scenario frequency [1/km·year]	Urban: 2.21×10^{-6} Rural: 4.64×10^{-6}	Urban: 1.06×10^{-8} Rural: 2.23×10^{-8}
Tank capacity [kg]	21,938	
Number of tanks	8	
Elevation [m]	0	
Tank head [m]	1	
Temperature [ºC]	5	
Pressure [bar]	4.13	

6.2.3. Adjusted Pipeline Transport Parameters

Warning tape

Implementing warning tape reduces the third-party failure frequency. The correction factor, corrected third-party failure frequency, and overall failure frequency can be found in Table 6.11.

Table 6.11: Adjusted parameters for implementation of warning tape

Parameter	Scenario 1: Leak	Scenario 2: Breach
Correction factor	1.67	
Corrected third-party failure frequency [1/km·year]	3.23×10^{-6}	2.17×10^{-6}
Corrected failure frequency [1/km·year]	9.69×10^{-5}	2.23×10^{-5}

Strict supervision of work activities

Implementing strict supervision during work activities also reduces the third-party failure frequency. The correction factor, corrected third-party failure frequency, and overall failure frequency can be found in Table 6.12.

Table 6.12: Adjusted parameters for implementation of strict supervision of work activities

Parameter	Scenario 1: Leak	Scenario 2: Breach
Correction factor	2.5	
Corrected third-party failure frequency [1/km·year]	1.80×10^{-6}	1.21×10^{-6}
Corrected failure frequency [1/km·year]	9.55×10^{-5}	2.13×10^{-5}

Emergency shut-off valves

The new parameters that are included and modeled in Safeti-NL for this measure are the number of valves, the valve distance from upstream of the pipeline, the valve closing time and the probability of valve failure. The values attributed to these parameters can be found in Table 6.13.

Table 6.13: Adjusted parameters for implementation of emergency shut-off valves

Parameter	Value
Number of valves	Urban: 4 Rural: 1
Detection time [s]	Urban: 10 (leak), 0 (rupture) Rural: 30 (leak), 0 (rupture)
Detection probability	Urban: 1 (leak), 1 (rupture) Rural: 0.9 (leak), 1 (rupture)
Valve distance upstream [m]	Urban: 500, 8500, 4500, 12500 Rural: 500
Valve closing time [s]	60
Probability of valve failure	0.01

Pipeline diameter reduction

This measure reduces the diameter from 400 to 200 millimeters, which leads to a halvation of the flow speed, but a doubling in the amount of pipelines required. Instead of modeling two identical pipelines with a 200 mm diameter in the same location, which could cause unwanted cascading effects, this can also be simulated by doubling the failure frequencies. The adjusted and new parameter for this measure can be found in Table 6.14.

Table 6.14: Adjusted parameters for implementation of pipeline diameter reduction

Parameter	Scenario 1: Leak	Scenario 2: Breach
Pipeline diameter [mm]	200	
Flow speed [kg/s]	99	
Failure frequency [1/km·year]	$1.98 \text{ x}10^{-4}$	$4.76 \text{ x}10^{-5}$

All pipeline transport measures combined

The total change in scenario frequency for the pipeline transport scenarios if all the risk mitigating and the effect mitigating measures are implemented, can be found in Table 6.15, along with the additional adjusted parameters.

Table 6.15: Adjusted parameters for implementation of all pipeline transport measures combined

Parameter	**Scenario 1: Leak**	**Scenario 2: Breach**
Correction factor tape	1.67	
Correction factor supervision	2.5	
Corrected failure frequency [1/km·year]	1.90 x10^{-4}	4.20 x10^{-5}
Number of valves	Urban: 4 Rural: 1	
Detection time [s]	Urban: 10 (leak), 0 (rupture) Rural: 30 (leak), 0 (rupture)	
Detection probability	Urban: 1 (leak), 1 (rupture) Rural: 0.9 (leak), 1 (rupture)	
Valve distance upstream [m]	Urban: 500, 8500, 4500, 12500 Rural: 500	
Valve closing time [s]	60	
Probability of valve failure	0.01	
Pipeline diameter [mm]	200	
Flow speed [kg/s]	99	

6.3. Results and Comparison

In this section, the modified scenarios are simulated and presented to evaluate the impact of the mitigation measures on both the risk and the spatial extent of toxic effect zones. In doing so, the results can be directly compared to the unmitigated base cases presented in Chapters 4 and 5. For the comparison between the risks after the implementation of the individual measures, the distances to the PR-contours are presented. Similarly, for the comparison of the consequences per modality after implemented mitigation measures, only the effect distances are presented.

6.3.1. Individual Risk Results

The PR-contours are used as the primary comparison metric to evaluate the mitigating measures. While FN-curves could provide insight into broader societal risk profiles, they are not legally binding and are not suitable for comparing the spatial effects of the interventions (Boot, 2013). The PR-contours on the other hand are legally binding (Atlas Leefomgeving, 2024b). Only the distances from the route to the PR-contours are presented as a direct visual comparison mostly reveals limited and hard-to-identify differences in contour shape. Therefore, this section analyses the quantitative distance between the route and the PR-contours to evaluate the impact of each risk- and consequence-reducing measure more precisely. All PR-contour visualizations for the mitigated scenarios are included in Appendix D for reference.

6.3.1.1. Rail Transport

The distances to the PR-contours for rail transport show that the most effective single measure in reducing individual risk is lowering train speeds. This intervention drastically reduces the distances to all PR-contours, with the 10^{-6} contour in the rural area disappearing entirely. Both ETCS and the combination of crash buffers and anti-climbing protection show similar, moderate improvements in risk reduction. Interestingly, the use of smaller tank wagons still results in slightly lower PR distances than in the base case. While this may seem counterintuitive given the increased transport intensity, the reduced release volumes per wagon likely contribute to reducing the size of the PR-contour, thereby lowering the probability of fatal exposure.

Table 6.16: Effect of mitigation measures on distance to PR contours for rail transport.

Measure	**Location**	**PR 10^{-6} (m)**	**PR 10^{-7} (m)**	**PR 10^{-8} (m)**
Base case	Urban	165	241	326
	Rural	48	434	674
ETCS	Urban	153	237	319
	Rural	29	421	660
Buffers & anti-climbing	Urban	154	241	322
	Rural	37	430	668
Lower speeds	Urban	52	190	271
	Rural	-	133	477
Smaller tanks	Urban	156	231	290
	Rural	61	404	593

6.3.1.2. Inland Shipping

Among the measures applied to inland shipping, the underwater placement of ammonia tanks clearly has the most positive impact on the PR-contours. In Breda, this measure eliminates the 10^{-6} and 10^{-7} contours entirely, leaving only a compact 10^{-8} contour. In Moerdijk, it leads to denser 10^{-7} and 10^{-8} contours. The other measures, such as the use of smaller tanks and semi-cooled ammonia, show little to no change in PR distances compared to the base case. The implementation of advanced navigation systems only affects the rural location, removing the 10^{-6} contour, while the urban contour remains unchanged.

Table 6.17: Effect of mitigation measures on distance to PR contours for inland shipping.

Measure	**Location**	**PR 10^{-6} (m)**	**PR 10^{-7} (m)**	**PR 10^{-8} (m)**
Base case	Urban	-	221	422
	Rural	227	531	694
Navigation & communicat-	Urban	-	221	422
	Rural	-	334	586
Tank under waterline	Urban	-	-	38
	Rural	6	46	150
Smaller tanks	Urban	-	218	417
	Rural	224	526	687
Semi-cooled ammonia	Urban	-	206	405
	Rural	213	504	660

6.3.1.3. Pipeline Transport

For pipelines, the introduction of emergency shut-off valves shows the strongest impact on the PR-contour distances, removing the 10^{-6} contour in both Breda and Moerdijk entirely. The reduction in pipeline diameter, while theoretically increasing the number of segments and thus the failure probability, results in only a modest increase in the 10^{-6} PR-contour distances. However, the distances to the 10^{-7} and 10^{-8} contours are notably smaller than in the base case. This is likely due to the fact that the smaller amount of ammonia released and the lower ammonia release rate per second have a bigger impact on the observed PR-distances further away from the accident source, while the increased failure frequency has a bigger influence on the extent of the PR-distance closer to the source. Measures aimed at reducing third-party interference—such as warning tape and strict supervision—provide small improvements, slightly reducing the PR-distances.

Table 6.18: Effect of mitigation measures on distance to PR contours for pipeline transport.

Measure	Location	PR 10^{-6} (m)	PR 10^{-7} (m)	PR 10^{-8} (m)
Base case	Urban	65	488	760
	Rural	200	969	1581
Warning tape	Urban	50	480	754
	Rural	156	954	1543
Strict supervision	Urban	35	472	740
	Rural	122	930	1553
Shut-off valves	Urban	-	355	524
	Rural	-	629	1227
Smaller diameter	Urban	94	314	543
	Rural	232	565	979

6.3.2. Effect Distances Results

The effect distances are used to evaluate the impact of the mitigating measures on the consequences. Similar to the PR-contours, the effect contours show no to little visual differences after running the adjusted models with mitigating measures. Therefore, to evaluate the impact of each consequence-reducing measure on the effect zones more precisely, only the distances are presented. As explained in Section 4.1.2.3, effect and attention zones are based on scenario consequences, not on probabilities. Therefore, only consequence-mitigating measures lead to changes in their size.

6.3.2.1. Rail Transport

For rail transport, the only mitigation strategy that influences effect distances is the use of smaller tank wagons. As expected, the reduction in release volume leads to a slight decrease in toxic effect zones. However, the overall impact remains limited, with only minimal reductions observed in both the LBW and attention zone distances. This modest effect suggests that while smaller tanks reduce the severity of a single release, the change is not substantial enough to significantly shrink the overall effect areas.

Table 6.19: Effect of mitigation measures on distance to effect contours for rail transport.

Measure	Location	Outdoor LBW (m)	Attention zone (m)
Base case	Urban	1092	711
	Rural	1552	1156
Smaller tanks	Urban	997	581
	Rural	1515	1047

6.3.2.2. Inland Shipping

In the inland shipping scenarios, the underwater placement of tanks clearly has the most significant impact on reducing effect distances. This design measure leads to a roughly 300% reduction in the distance to the LBW outdoor threshold and even a 500 to 600% reduction in the attention zone distances. Interestingly, the measures semi-cooled ammonia and smaller tanks show differentiated mitigating results depending on the indicator. Semi-cooled ammonia transport results in shorter distances to the LBW outdoor, whereas smaller tanks lead to bigger reductions in the attention zone distance.

Semi-cooled ammonia disperses more slowly due to the lower vapour pressure, which results in shorter distances to the Outdoor LBW threshold. However, because the ammonia cloud remains present for longer, indoor concentrations have more time to accumulate, leading to larger attention zone distances. In contrast, scenarios with smaller tank volumes involve less ammonia being released overall. While this limits how much can accumulate indoors, the plume may still reach relatively far downwind before dispersing, especially under stable weather conditions. As a result, these cases may show longer Outdoor LBW distances but shorter attention zone distances than semi-cooled scenarios.

Table 6.20: Effect of mitigation measures on distance to effect contours for inland shipping.

Measure	Location	Outdoor LBW (m)	Attention zone (m)
Base case	Urban	1510	1437
	Rural	2122	1966
Tank under waterline	Urban	537	275
	Rural	614	357
Smaller tanks	Urban	1499	1338
	Rural	2107	1823
Semi-cooled ammonia	Urban	1454	1396
	Rural	1998	1867

6.3.2.3. Pipeline Transport

For pipeline transport, the most impactful mitigation strategy in terms of effect distances is reducing the pipeline diameter. This results in a reduction of approximately 33% in both LBW and attention zone distances. The decreased diameter limits the release rate, leading to lower peak concentrations and smaller toxic clouds.

A notable and somewhat counterintuitive outcome is observed for the implementation of emergency shut-off valves. Although this measure significantly reduced the individual risk by limiting the total release volume over time, the effect distances do not change compared to the base case. As the effect distances are primarily driven by the initial concentration and dispersion of ammonia, which remains extremely high in rupture scenarios, they remain identical to the base case. This highlights that valves do not influence immediate physical dispersion but rather reduce the risk by limiting the cumulative release volume

Table 6.21: Effect of mitigation measures on distance to effect contours for pipeline transport.

Measure	Location	Outdoor LBW (m)	Attention zone (m)
Base case	Urban	2522	3263
	Rural	4031	4747
Shut-off valves	Urban	2522	3263
	Rural	4031	4747
Diameter redcution	Urban	1628	2002
	Rural	2660	3003

6.3.3. Net Impact of Combined Measures

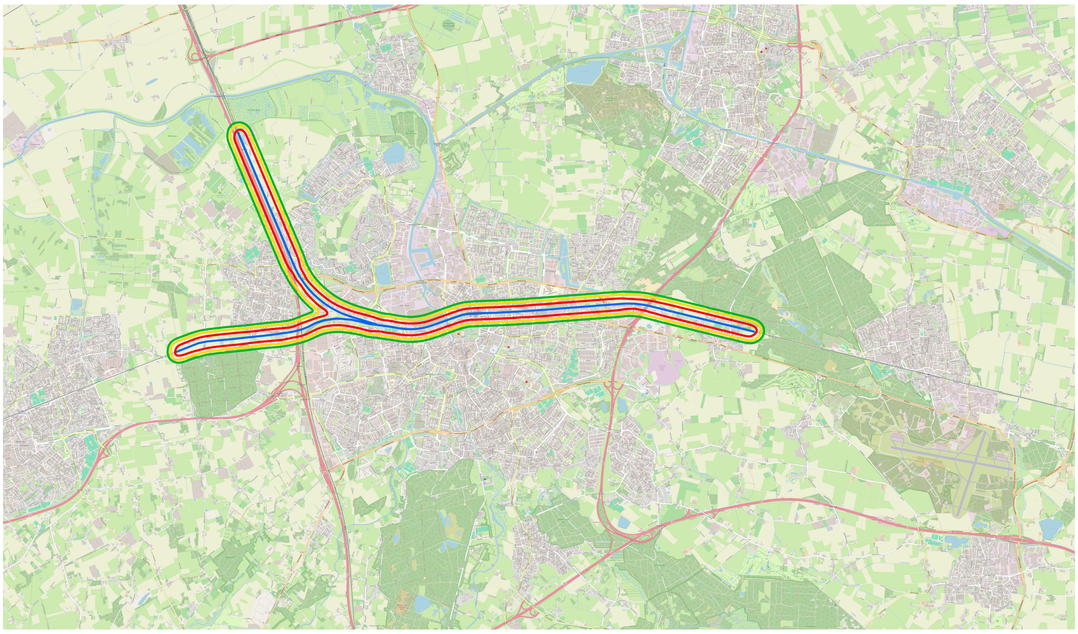
This section presents the combined impact of all risk- and consequence-reducing measures per transport modality. While previous subsections focused on the effect of individual interventions, the results here reflect fully mitigated scenarios — where all selected safety measures are simultaneously in place.

To enable a complete comparison with the base case, this section includes not only distance-based metrics, such as PR-contour reach and effect zone distances, but also full visualisations of the updated individual risk contours (PR), group risk profiles (FN-curves), and toxic effect contours. Including these spatial outputs allows for a more direct and visual comparison.

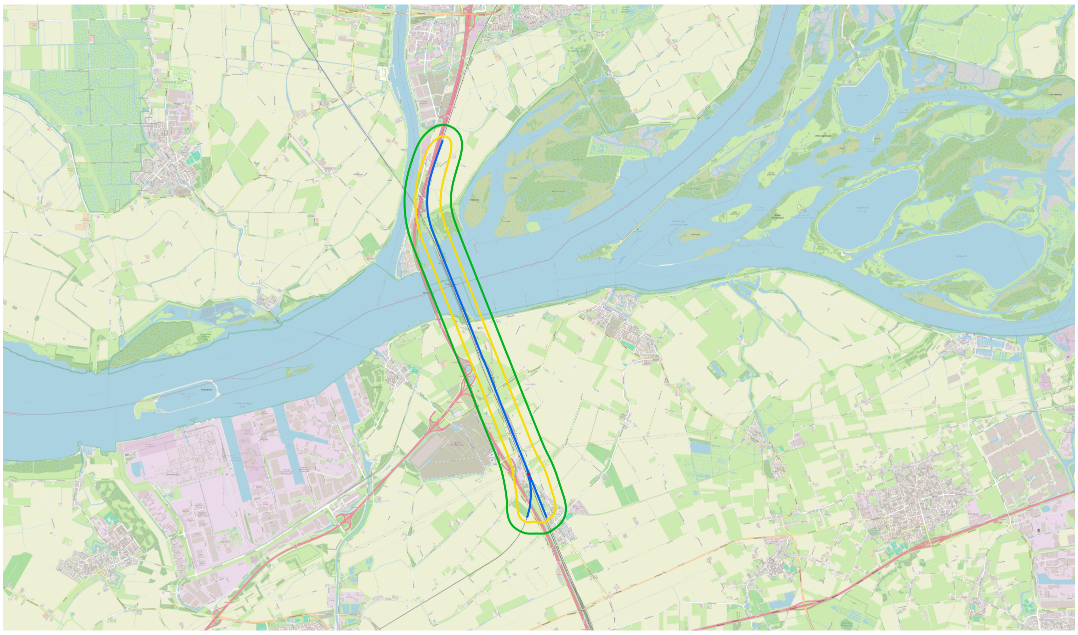
6.3.3.1. Individual Risk (PR-Contours)

The implementation of all risk and consequence mitigating measures has led to a substantial reduction in individual risk across all modalities. Most notably, both inland shipping and pipeline transport no longer exhibit any 10^{-6} probability contours in either Breda or Moerdijk. This indicates that, under the mitigated scenarios, the probability of fatality for an unprotected individual at any location surrounding the transport route has fallen below one in a million per year – the generally accepted threshold for individual risk.

Rail transport still shows exceedance of the 10^{-6} individual risk threshold in Breda. This suggests that the risk over this modality and location is still too high. Nevertheless, the extent of the PR-contours has decreased significantly compared to the baseline, indicating an improvement in overall risk.



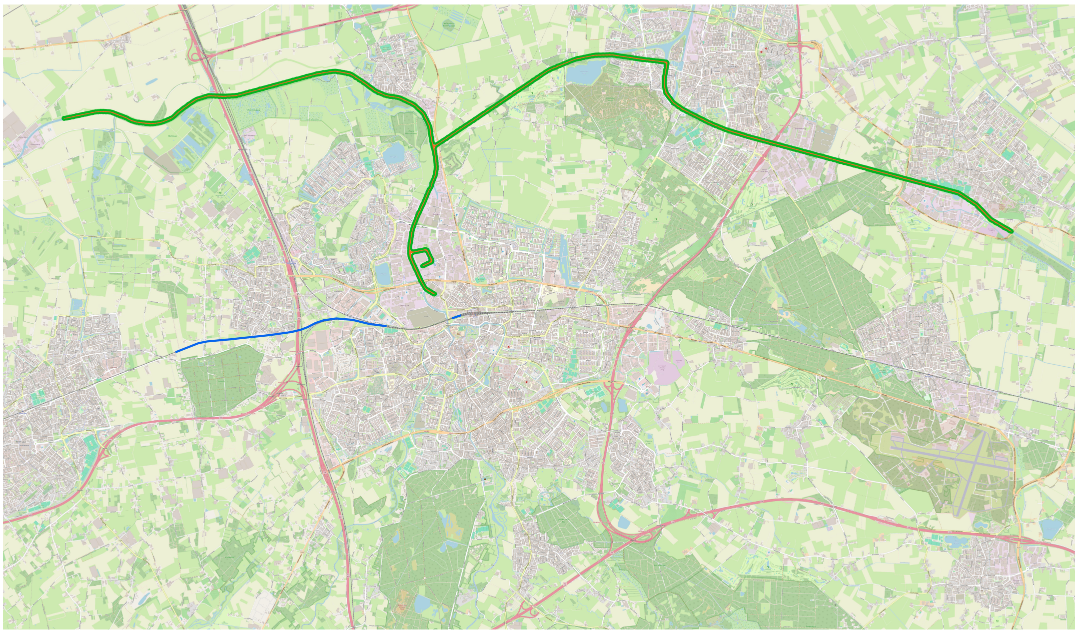
(a) PR contours of rail transport after implementation of all mitigation measures in Breda



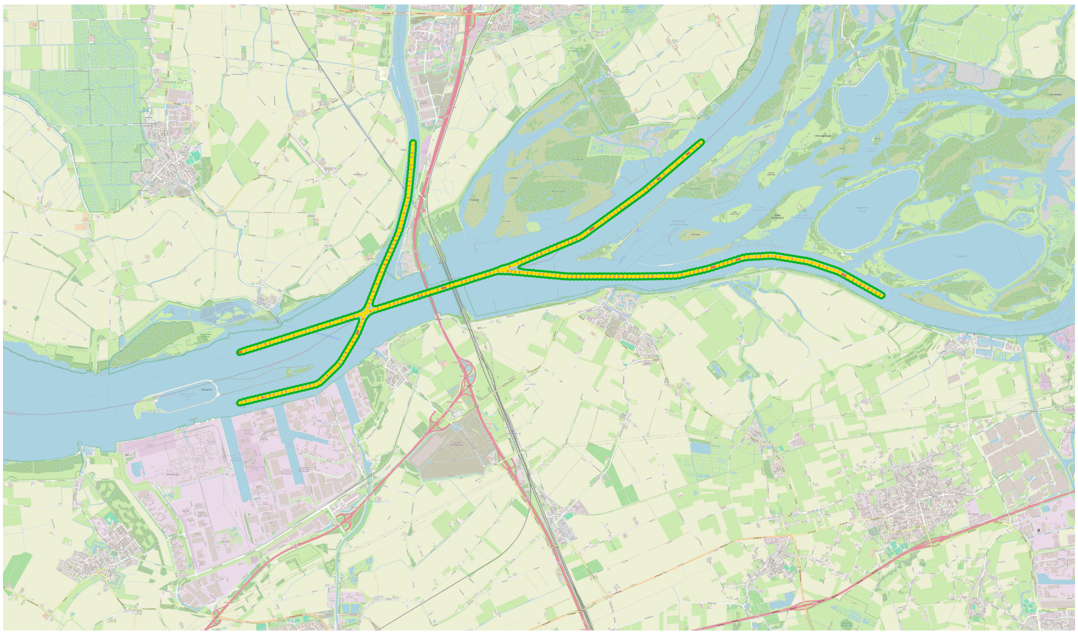
(b) PR contours of rail transport after implementation of all mitigation measures in Moerdijk

Figure 6.1: Mitigated PR contours of rail transport in Breda and Moerdijk

Inland shipping shows a strong improvement. In Breda, the 10^{-6} and 10^{-7} contours have disappeared entirely, with only a small and dense 10^{-8} contour remaining. In Moerdijk, while 10^{-7} and 10^{-8} contours are still present, their spatial extent is far more limited than in the base case. This indicates that the combined effect of the mitigating measures significantly lowers the probability of fatal exposure in the event of an incident.



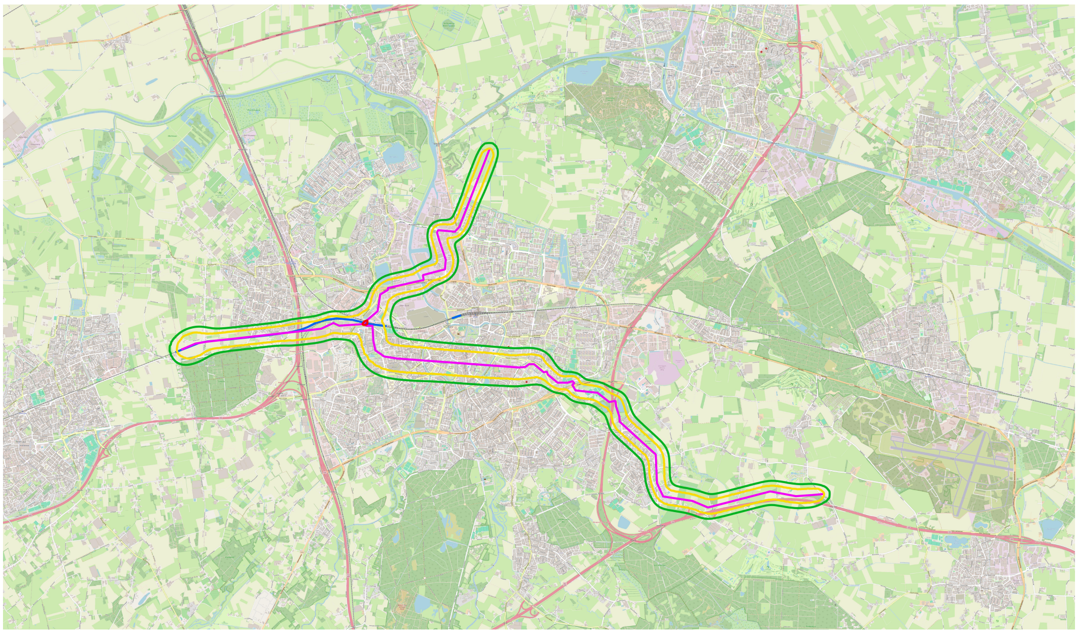
(a) PR contours of inland shipping after implementation of all mitigation measures in Breda



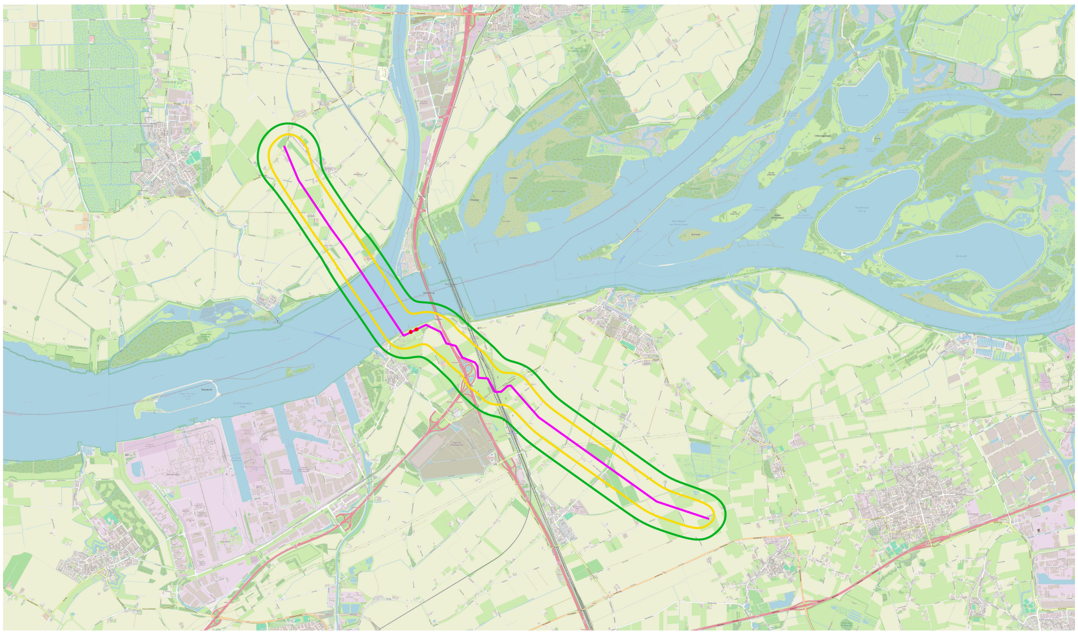
(b) PR contours of inland shipping after implementation of all mitigation measures in Moerdijk

Figure 6.2: Mitigated PR contours of inland shipping in Breda and Moerdijk

Pipeline transport also exhibits much more favorable results compared to the base case. In both Breda and Moerdijk, the 10^{-6} contours have been fully eliminated, with only 10^{-7} and 10^{-8} contours remaining. These contours are notably small and more dense than in the base case. The reduction is primarily due to the implementation of emergency shut-off valves and a smaller pipeline diameter, which together minimise the release volume and peak concentrations following a rupture.



(a) PR contours of pipeline transport after implementation of all mitigation measures in Breda



(b) PR contours of pipeline transport after implementation of all mitigation measures in Moerdijk

Figure 6.3: Mitigated PR contours of pipeline transport in Breda and Moerdijk

While all modalities benefit from risk mitigation, pipeline and inland shipping achieve individual risk levels well below the 10^{-6} threshold under the improved scenarios, with inland shipping showing the most compact risk profile across both locations. Since the visual comparison of the 10^{-6} to 10^{-8} contours in both Breda and Moerdijk already reveals a clear distinction between the transport modalities under the mitigated scenarios, no additional table with absolute PR-contour distances is included here.

6.3.3.2. Group Risk (FN-curves)

The FN-curves for the combined mitigation scenarios reveal clear differences in the group risk profiles between the three transport modalities. Notably, in Moerdijk, none of the modalities show any remaining group risk curves, indicating that the probability of incidents with ten or more fatalities has been reduced below the detection threshold across all modalities. In Breda, the differences become more clear.

For rail transport, the FN-curve still exceeds the orientation value. However, it declines steeply after reaching 10 or more deaths, intersecting the group risk orientation value at the value of around 12 fatalities or more. This indicates that, although rail transport technically remains a risk for the population, the curve has improved compared to the base case, and is likely to be acceptable.

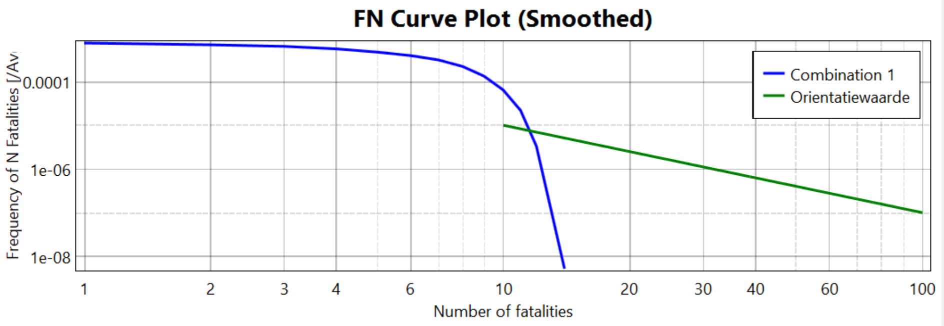


Figure 6.4: Mitigated FN-curve for rail transport in Breda

For inland shipping, the FN-curve remains well below the orientation value for its entire range, indicating a very small probability of multiple-fatality incidents. Therefore, the group risk level is now negligible. This reflects the overall effectiveness of the combined mitigation measures in reducing group risk for inland shipping.

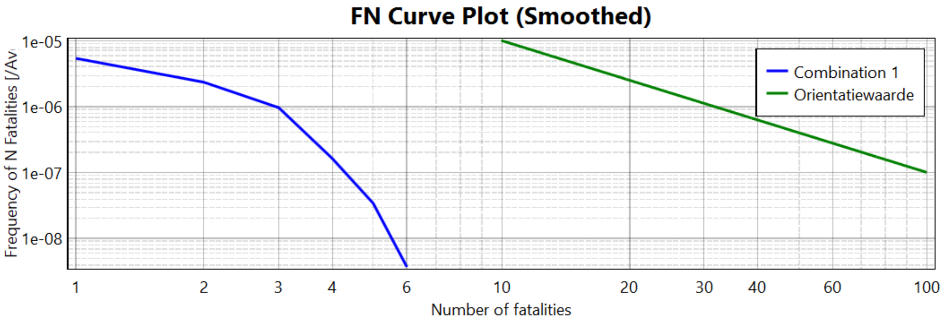


Figure 6.5: Mitigated FN-curve for inland shipping in Breda

In contrast, the FN-curve for pipeline transport still presents a significant concern in Breda. It remains above the orientation value for a wide range of potential fatalities. The curve only crosses the orientation threshold after 100 or more fatalities. Despite the effectiveness of shut-off valves and other technical interventions in reducing PR-contours, the group risk for pipeline transport still remains unacceptably high.

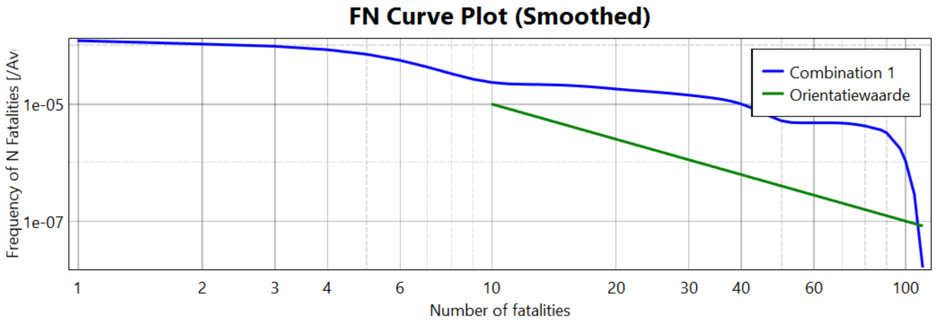


Figure 6.6: Mitigated FN-curve for pipeline transport in Breda

6.3.3.3. Effect Distances

For increased clarity of results, only the largest distances to the outdoor LBW and attention zone are shown in Table 6.22. Similar to section 5.4.2, only the largest distances corresponding to either weather type D5 or F1.5, are shown. While the largest distances were typically established under F1.5 conditions in the baseline scenarios (see Chapter 5), except for the rupture scenario in rail transport, the implemented mitigation measures altered this dynamic for inland shipping. For this modality, the largest distances to the Outdoor LBW contour and the attention zone are now detected for wind condition D5. This can be explained due to the fact that the ammonia now disperses from waterline level. For lower wind speeds, the ammonia stays relatively close to the water surface, which could lead to an even higher level of ammonia that dissolves. Higher wind speeds, which is the case under condition D5, quickly move the ammonia away from the water surface, leading to a higher level of ammonia being dispersed. For pipeline transport, the values remain highest under weather conditions F1.5.

From Table 6.22, it becomes clear that inland shipping consistently results in the lowest effect distances across all scenarios and locations. A distinct pattern emerges when comparing rail and pipeline transport. For the most probable scenarios, rail transport shows significantly larger effect distances than pipeline transport, whereas for the worst-case scenarios, the effect distances are considerably greater for pipelines than for rail. This can be explained by the differing characteristics of the two transport modes. In rail transport, the most probable scenarios involve moderate release volumes from leaks that disperse relatively widely due to the elevated position of tank wagons. In contrast, pipeline leaks occur at ground level, leading to lower dispersion. However, in worst-case scenarios the situation reverses. Pipelines can release large continuous volumes of ammonia under high pressure. This leads to significantly larger toxic clouds compared to rail ruptures, which are constrained by the limited volume per tank wagon and the lack of constant upstream pressure.

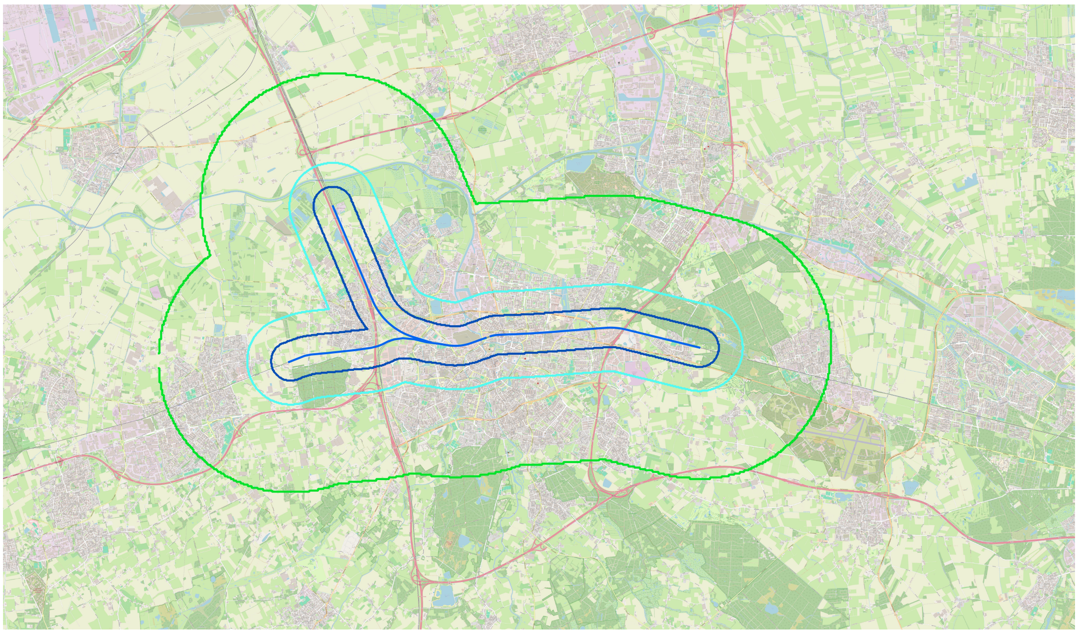
Table 6.22: Mitigated distances to the Outdoor LBW and attention zone for each modality.

Modality	Location	Scenario	Outdoor LBW (m)	Attention zone (m)
Rail transport	Urban	Most probable	997	581
		Worst-case	552	246
	Rural	Most probable	1515	1047
		Worst-case	907	569
Inland shipping	Urban	Most probable	232	193
		Worst-case	510	235
	Rural	Most probable	328	256
		Worst-case	585	302
Pipeline transport	Urban	Most probable	139	157
		Worst-case	1634	2008
	Rural	Most probable	321	336
		Worst-case	2660	3003

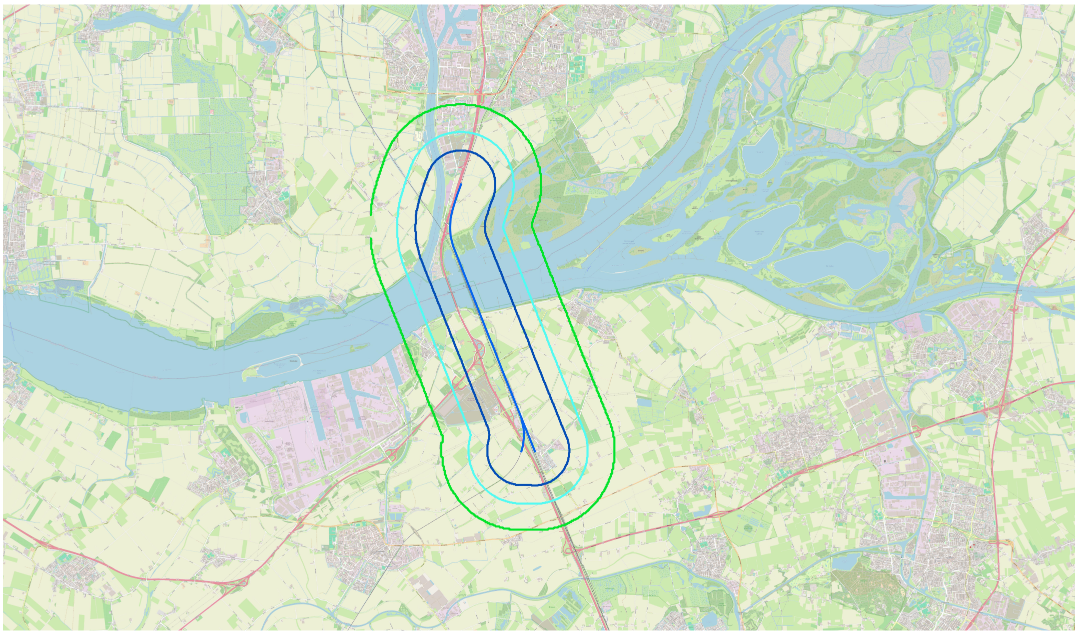
6.3.3.4. Effect Contours

Similar to the visualization of the effect contour results in Chapter 5, a fixed scale of 1:128759 was applied to ensure exact comparison. The effect zones under the combined mitigation scenarios reveal notable differences across the three transport modalities.

For rail transport, both the outdoor LBW contour and the attention zone remain close to the track. The AGW contour extends slightly further, but still remains relatively limited in reach. The VRW contour however, cannot be visualized in the image as its spatial extent is still too big. Compared to the base case, no major visual difference is observed — Moerdijk remains outside the outdoor LBW and attention zone but within the AGW contour, while Breda is partially covered by the LBW and attention zone and fully encompassed by the AGW. Overall, the impact of the implemented mitigation measures on effect distances is minimal for rail transport.



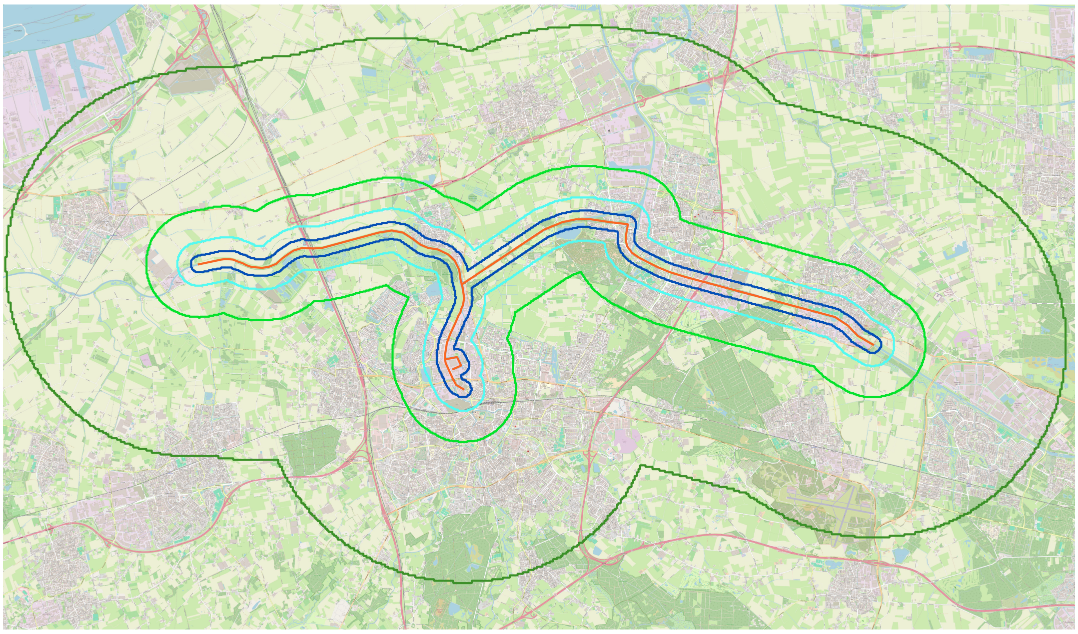
(a) Effect contours of rail transport after implementation of all mitigation measures in Breda



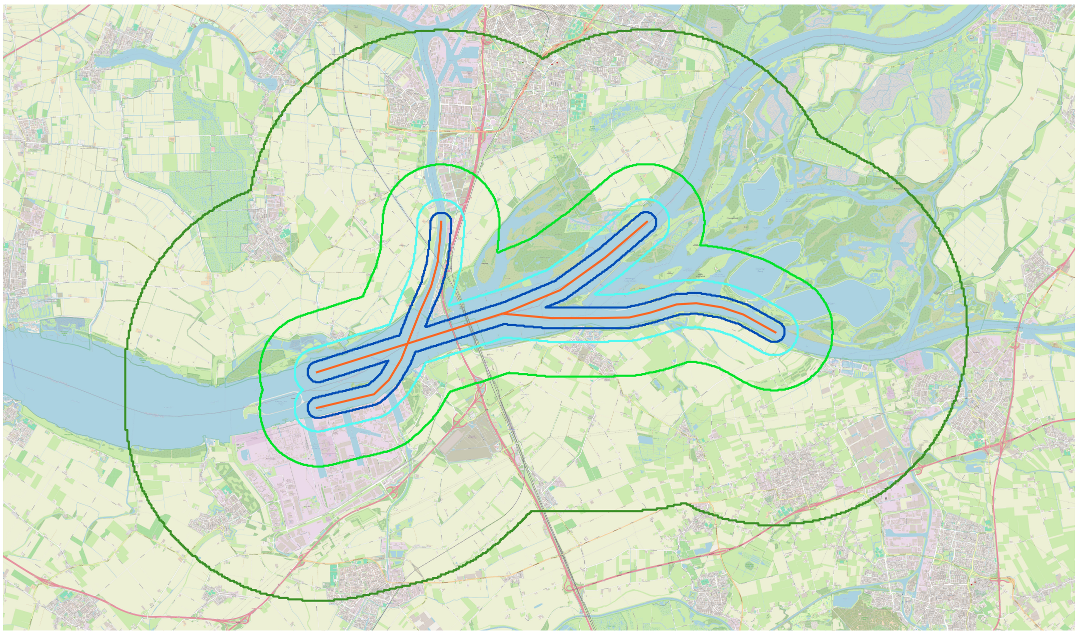
(b) Effect contours of rail transport after implementation of all mitigation measures in Moerdijk

Figure 6.7: Mitigated Effect contours of rail transport in Breda and Moerdijk

In contrast, inland shipping shows a substantial improvement compared to the base scenario. The attention zone and outdoor LBW contours now lie tightly around the shipping route. Just beyond them lies the AGW contour, and even the VRW contour is visible on the map. In Breda, only small portions are covered by the LBW and attention zone, while the AGW covers a modest area and the VRW extends across most of the city. In Moerdijk, only a small area is affected by the LBW, and the entire city falls within the AGW. However, all these contours have significantly shrunk compared to the base case. Notably, inland shipping is the only modality for which the VRW contour is visible in the mitigated scenario maps, underscoring that it has the smallest effect zones by far.



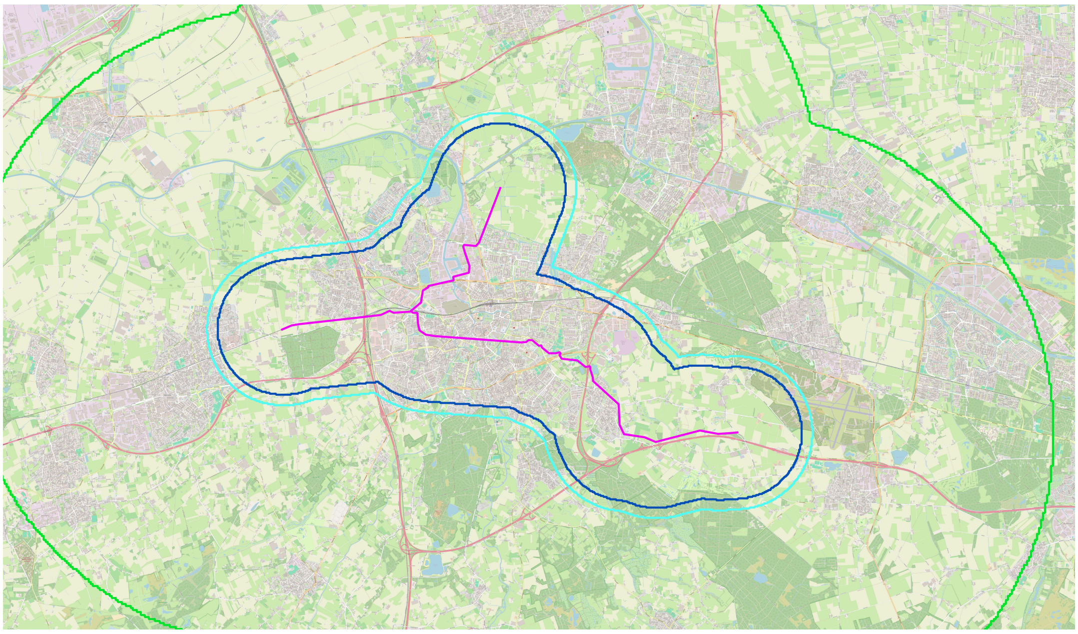
(a) Effect contours of inland shipping after implementation of all mitigation measures in Breda



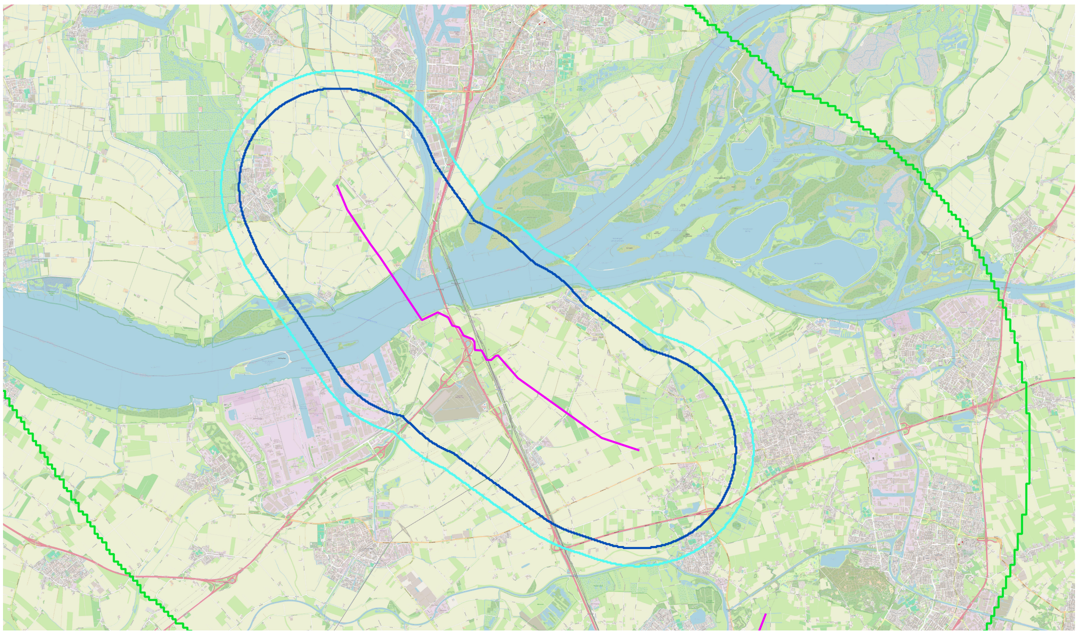
(b) Effect contours of inland shipping after implementation of all mitigation measures in Moerdijk

Figure 6.8: Mitigated Effect contours of inland shipping in Breda and Moerdijk

For pipeline transport, the attention zone and outdoor LBW contours have clearly decreased in spatial extent, and a significantly larger portion of the AGW contour is now visible. Nevertheless, the reductions are not sufficient to shift the overall picture: in Breda, the attention zone still covers nearly the entire city, and in Moerdijk it continues to cover the full area. Among all modalities, pipeline transport still exhibits the largest effect distances, even after implementation of mitigation measures.



(a) Effect contours of pipeline transport after implementation of all mitigation measures in Breda



(b) Effect contours of pipeline transport after implementation of all mitigation measures in Moerdijk

Figure 6.9: Mitigated Effect contours of pipeline transport in Breda and Moerdijk

6.4. Main Insight in Mitigation Potential of the Modalities

To assess how risk and consequence mitigation strategies affect ammonia transport safety, four different mitigation measures were selected and implemented per transport modality. The selection of the type of measures were chosen to reflect the dominant safety challenges of each mode. Relevant parameters were adjusted or added in Safeti-NL to quantify the new risks and effects.

The effectiveness of individual measures varies notably per modality. For rail transport, the reduction in train speed has the largest positive impact in lowering individual risk. The implementation of smaller tank volumes show only minor improvements in effect distances. For inland shipping, the placement of tanks under the waterline contributes the most to improved outcomes in both risks and consequences. For pipeline transport, only the installation of emergency shut-off valves leads to a strong reduction in risk. Other measures, such as reducing the pipeline diameter, reduce the size of effect zones quite significantly, but have a negative influence on the risk profile. These insights underline the importance of tailoring mitigation strategies to the specific risk dynamics of each transport modality.

For rail transport, a clear 10^{-6} contour remains in Breda, even after mitigation. Rail is therefore the only modality that still exceeds the legal individual risk threshold. In Moerdijk, this contour disappears, but the overall risk levels of rail transport remain higher compared to the other modalities. Inland shipping shows the strongest improvement. No 10^{-6} contours are present after mitigation in either Breda or Moerdijk, and in Breda even the 10^{-7} contour disappears. The contours are also extremely compact as most of the ammonia released during a shipping incident dissolves, and the fraction that becomes airborne is minimal. Lastly, for pipeline transport the 10^{-6} contours also disappear entirely after implementing the mitigation measures. However, wider 10^{-7} and 10^{-8} contours remain due to the relatively large volume still being released during a breach. While pipelines now meet the legal threshold, their remaining contours are more expansive than for inland shipping, reflecting their higher residual risk.

The group risk in Moerdijk disappears for all the modalities after the measures are implemented. In Breda, however, rail transport still shows a short exceedance of the group risk orientation value between 10 and 12 or more fatalities. Though this is an improvement over the base case, it still temporarily exceeds the orientation value. Inland shipping performs best on group risk. Its FN-curve in Breda remains well below the orientation line at all points, indicating a negligible group risk. Finally, for pipeline transport, the curve improves but remains the most concerning. In Breda, the FN-curve lies above the orientation value over a wide fatality range and only drops below it at around 100 or more fatalities. Despite the implementation of the mitigation measures, the likelihood of medium-scale incidents remains higher than for the other modalities.

Lastly, the effect zones for rail transport remain largely similar compared to the base case. In Breda, the AGW contour still fully covers the city, and about half of it lies within the life-threatening zone. In Moerdijk, the life-threatening contours stay clear of the populated area, but the AGW zone covers it completely. Inland shipping benefits considerably from the mitigating measures as the effect distances shrink visibly. Contrary to inland shipping's base case and even to the other two modalities in the mitigated context, the VRW contour fits on the visualisation maps. In Breda, only small parts of the city fall within any life-threatening contour, with a slightly bigger, but still small area falling within the AGW zone. In Moerdijk, a very small part of the area lies inside the Outside LBW zone, which is a substantial improvement over the baseline. Pipeline transport still produces the largest effect zones, even after mitigation. While the toxic effect distances have clearly decreased, Breda remains almost fully covered by the life-threatening zones, and Moerdijk falls entirely within it. Compared to the other two modalities, the residual area affected by a pipeline incident remains the most severe.

7

Multi-Criteria Evaluation of Transport Modalities

In this chapter, the fully mitigated versions of all three transport modalities are compared using a multi-criteria assessment (MCA) framework. This reflects the assumption that future decisions will be based on improved and optimised configurations, rather than unmitigated baseline scenarios. It answers sub-question 5, which investigates which ammonia transport modality performs best overall in the Dutch context based on a structured comparison of multiple evaluation criteria. MCA's offer an appropriate way to weigh heterogeneous criteria that are not easily expressed in a single unit (Stratelligence, 2024). In this study, the MCA brings together several criteria of ammonia transport across three modalities: rail, inland shipping, and pipelines.

Importantly, this MCA is not intended to produce definitive or empirical conclusions. Instead, it serves as a demonstrative example of how such a method can support holistic comparison and structured decision-making. The scores and weights used in this analysis are assigned by the researcher based on model outcomes, expert insights and interpretative judgement. As such, the results should be interpreted as illustrative rather than authoritative. This approach shows how an MCA can be used to integrate diverse evaluation criteria and to obtain a more comprehensive understanding of the relative strengths and weaknesses of different transport strategies.

A multi-criteria analysis typically consists of the five steps (Zijlstra and Rooij, 2024):

1. Defining the criteria,
2. Scoring the alternatives,
3. Normalising the scores for each criterion,
4. Weighting the criteria,
5. Ranking the alternatives

This chapter adopts a structured approach to conduct the multi-criteria assessment. First, the relevant evaluation criteria are defined. Next, each transport alternative is scored against all criteria based on the modelling outcomes and supporting analyses. Since all criteria are assessed using a uniform qualitative scale, the resulting scores are already considered normalised. Subsequently, weights are assigned to reflect the relative importance of each criterion. Finally, the transport modalities are ranked according to their aggregated, weighted scores.

7.1. Defining the Criteria

This section presents the evaluation criteria used in the MCA. First, the rationale behind the selection of criteria is explained. Then, the findings on each identified criterion is discussed. The criteria are introduced in the following order: Human safety is the primary focus of this study and is assessed quantitatively through modelling results. Security, environmental, and economic aspects are included due to their critical relevance to infrastructure decision-making. Finally, feasibility, adaptability, sustainability, and reliability are incorporated based on expert judgement and broader policy relevance.

7.1.1. Criteria Selection

The selection of evaluation criteria for the MCA was informed by a combination of desk research and exploratory expert consultation with RIVM employees. The aim was to identify a set of dimensions that together reflect the broad spectrum of factors influencing decision-making on ammonia transport infrastructure.

First, a review of academic studies on hydrogen carriers and infrastructure evaluation, including the multi-criteria study by Stratelligence (2024), provided initial inspiration for relevant criteria. This helped establish a base set of commonly used categories such as environmental impact, security, affordability, and feasibility. These were then refined and expanded based on their relevance to the Dutch context and the specific risks associated with ammonia.

Again, particular emphasis was placed on human safety, in line with the primary research focus. This criterion was further broken down into measurable indicators: individual risk, group risk, and toxic effect distances. Similarly, sub-indicators were included for other complex criteria such as security (impact of terrorism and cybersecurity), environmental harm (impact on soil and groundwater, and surface water), and affordability (investment, operational, and mitigation costs).

The decision to include sub-indicators was driven by the observation that the transport modalities perform very differently across the underlying aspects of each criterion. Without disaggregating these into separate components, meaningful comparison would be difficult and potentially misleading. This structured breakdown allows for a more transparent and balanced assessment, ensuring that both quantitative and qualitative dimensions are adequately captured and that the MCA framework remains aligned with the practical complexities of ammonia transport in the energy transition.

7.1.2. Human Safety

Human health risks represent the most critical criterion in this assessment. This section evaluates the impact of each transport modality on public safety under mitigated conditions using three indicators: individual risk, group risk, and toxic effect zones. The findings for these indicators are summarized in this section.

7.1.2.1. Individual Risk

For rail transport, the 10^{-6} probability contour remains present in Breda. In Moerdijk, only the 10^{-7} and 10^{-8} contours are present, but they are wider than in Breda. Inland shipping shows no 10^{-6} contours anymore. In Breda, the 10^{-6} and 10^{-7} contours have been completely eliminated, and only a very small 10^{-8} contour remains. In Moerdijk, there is still a 10^{-7} contour, however they are still very limited in spatial extent. For pipeline transport the 10^{-6} contour has disappeared entirely in both Breda and Moerdijk. However, the remaining 10^{-7} and 10^{-8} contours are relatively extensive compared to the other two modalities. Overall, both inland shipping and pipeline transport now meet acceptable individual risk thresholds, but inland shipping shows the most compact risk profile.

7.1.2.2. Group Risk

No FN-curves were found for all three modalities in the context of Moerdijk. The rail transport FN-curve for Breda remains significant, with the line shortly exceeding the orientation value. However, this exceedance is only between 10 and 12 or more fatalities. In the case of inland shipping, the FN-curve in Breda remains well below the group risk orientation line throughout, demonstrating a negligible group risk. Pipeline transport poses the largest concerns regarding group risk. The FN-curve remains well above the orientation value for a long portion of its range and only intersects it at approximately 100 or more fatalities. This indicates that medium-sized group casualty scenarios remain relatively likely and the group risk remains comparatively high.

7.1.2.3. Effect Distances and Contours

For rail transport the effect zones remain relatively large. Though the effect contours such as the outdoor LBW and the attention zone remain close to the track, the AGW fully covers Breda and Moerdijk, and the VRW is too extensive to be visualised. However, the overall distances to the LBW and attention zone contours are much shorter than for pipeline transport. Inland shipping displays the smallest effect zones among all modalities. Effect distances are short, and the contours lie tightly along the shipping route. In Breda, only limited areas fall within the LBW, AGW and attention zones, while the VRW extends somewhat further, but is small enough to be visualized. Moerdijk is similarly affected, though it does fall completely within the AGW zone. Pipeline transport presents the widest toxic effect zones. In Breda, the attention zone encompasses nearly the entire city, while in Moerdijk, it continues to cover the full area. The AGW zone cannot be visualized fully, while the VRW zone is not even visible. This shows that the spatial health impact of a pipeline incident is the largest among the three modalities.

7.1.3. Security

This section evaluates the impact of both terrorism and cybersecurity on the security of each transport modality. As mentioned in Section 3.4, security risks lack empirical data, are very unpredictable and cannot be quantified in a similar manner as safety risks. Therefore, they were not included in the quantitative modelling in this research. However, as ammonia transport volumes are expected to increase and the infrastructure becomes more digitally integrated, deliberate threats must be addressed in decision-making and are included in this multi-criteria analysis.

7.1.3.1. Terrorism

The likelihood and potential impact of a terrorist attack are strongly influenced by the physical accessibility and spatial context of the transport modality. Among the three modalities, rail transport is considered the most vulnerable to terrorism due to its accessibility and its routes through densely populated areas (Ovidi et al., 2020). Inland vessels are also accessible, but as they typically avoid urban centres, the direct societal impact of a targeted attack would likely be smaller. Pipelines, on the other hand, are generally buried more than one metre underground and are thus far less accessible (RIVM, 2025c). This physical inaccessibility reduces the likelihood of successful sabotage but does not eliminate the risk altogether.

7.1.3.2. Cybersecurity

The vulnerability of each transport modality to cybersecurity threats largely depends on the extent of digitalisation, system integration, and operational automation. While rail and inland shipping also depend on digital infrastructure, their level of automation is lower than that of pipeline systems. The cybersecurity threats they face—such as losing operational control or communication—could lead to service disruptions, but are less likely to result in major ammonia releases (Koninklijke Binnenvaart Nederland, n.d. ProRail, 2023). However, as the use of ECTS increases in rail transport, making operations more centralized, it has a higher chance of being a target for cybersecurity than inland shipping. Although the use of AIS also increases risks, inland vessels remain more autonomous and dependent on human navigation, making them less vulnerable.

Cybersecurity risks are particularly relevant for hazardous materials pipeline systems, which increasingly depend on digital control infrastructure to monitor and regulate flows (Cybersecurity & Infrastructure Security Agency (CISA), n.d.). A successful cyberattack on these systems could result in spills with severe health and environmental implications (Cybersecurity & Infrastructure Security Agency (CISA), n.d.).

7.1.4. Environmental Harm

In addition to human health, ammonia releases can also have widespread and long-lasting environmental consequences, particularly when dispersing into soil, groundwater, and surface water (Guo and Luo, 2022). In both soil and water, ammonia acts as a strong base and can alter natural pH balances, making the environment unsuitable for many species (Crolius et al., 2021). Therefore, this section presents the potential environmental harm that can be caused after ammonia spills in both soil and groundwater, and in surface water.

7.1.4.1. Soil and Groundwater

The risk of environmental harm on soil and groundwater emerges when ammonia is released into the environment during incidents on lands such as spills or leakages. The severity of contamination depends on various factors, including spill location, volume of release, and soil type (Anand and Barkan, 2006). When ammonia is released onto land, it can infiltrate the soil and as a result also contaminate groundwater (Saat et al., 2014). The risk is especially high in sandy or porous soils, which allow for rapid permeation, and in areas with shallow groundwater. In clay or compact soils, infiltration is slower, but ammonia can become trapped, causing long-term soil toxicity (Anand and Barkan, 2006).

Rail transport poses moderate risks for soil and groundwater intoxication. Though it takes place on land and can directly spill ammonia into soil or groundwater, the tank wagons typically carry smaller ammonia volumes compared to pipelines. Additionally, railway tracks often run through industrial and urban zones, where a harder or concrete underground may reduce infiltration. Among the three modalities, pipeline transport poses the highest soil and groundwater related risk (Ramírez-Camacho et al., 2017). A pipeline rupture would likely release large volumes of ammonia directly into the ground. Pipelines are expected to be constructed in both sandy and clay soils (RIVM, 2025c), where ammonia can either rapidly seep into shallow groundwater or persist in soil layers with long-term toxicity (Anand and Barkan, 2006). This high release volume and the type of soil surrounding pipelines amplifies the environmental risks. In contrast, inland shipping poses minimal risk to soil and groundwater, as ammonia releases from vessels would typically occur above or into water, and not on land.

These impacts can be ecologically and economically devastating. Soil contamination with ammonia disrupts nutrient balances, increases pH levels, and impairs photosynthesis, potentially leading to species imbalance and permanently altered ecosystems (Pearson and Stewart, 1993; Van der Eerden, 1982). In groundwater, ammonia contamination can persist for long periods, threatening drinking water quality and agricultural irrigation, and requiring costly clean-up efforts (Saat et al., 2014). These consequences underscore the importance of incorporating soil and groundwater vulnerability into the MCA.

7.1.4.2. Surface Water

Ammonia is extremely toxic to aquatic ecosystems, even in small concentrations (Kubas et al., 2022). It affects gill, liver, and kidney function in fish and invertebrates, leading to impaired growth, reduced reproductive success, and mortality (Crolius et al., 2021; Kubas et al., 2022; Oram, n.d. Riemersma, 2024; Zhang et al., 2023). It also disrupts ecological balance by favouring tolerant species and triggering oxygen depletion through algal blooms, suffocating aquatic organisms and leading to mass die-offs (Crolius et al., 2021; Kubas et al., 2022; Zhang et al., 2023).

Of all modalities, rail transport carries the lowest risk to surface water. Tracks typically do not run directly above water bodies, so ammonia is more likely to evaporate or spill on land than to enter nearby aquatic environments. However, risks still exist where railways cross bridges or dikes. Inland shipping poses by far the greatest risk to surface water. In the event of an accident, ammonia can leak directly into rivers or canals, especially when spills occur below the waterline. These leaks are highly persistent in aquatic systems due to ammonia's water solubility and toxicity. As such, inland shipping incidents could cause immediate and widespread ecological damage (Riemersma, 2024). Pipeline transport may also impact surface water, depending on routing. If a rupture occurs near water bodies, ammonia can flow into nearby water systems. However, because pipelines are usually buried and equipped with shut-off valves, this risk is more limited and situational.

7.1.5. Affordability

This section focuses on comparing the affordability of the three transport modalities using three indicators: upfront infrastructure investment, recurring operational expenditure, and the cost of implementing the proposed mitigation measures. Since exact cost figures are often unavailable or highly context-dependent, this evaluation is performed using mostly qualitative indicators. In some cases, monetary values are given when available.

7.1.5.1. Investment Costs

Ammonia's transport infrastructure plays an important role in its overall affordability (Negro et al., 2023). The investment costs include the upfront investments in actual infrastructure and the investments in transport vessels. Investment costs vary significantly between the three transport modalities due to differences in the existing infrastructure, its required expansions, and the additional amount of transport units needed.

Rail transport benefits from an already extensive national rail network, including designated routes for hazardous materials transport under the Basisnet system. However, ProRail (2025) admits that the Dutch rail freight transport is currently under pressure and urges the government to increase investments in infrastructure and its digitization. Especially if ammonia transport is to significantly increase in the coming decade, this expansion of the infrastructure is highly necessary. Moreover, transporting ammonia by rail would require substantial investment in new tank wagons. Currently only 2% of hazardous materials is transported by rail, which is equal to around 50,000 tank wagons transporting hazardous material per year (ProRail, 2024b; Robbe, 2024). Since the annual intensity of tank wagon transports will increase to 125,000, the current number of available wagons is likely insufficient. A significant scale-up would either require a large number of new tank wagons or a shift of other freight types to alternative modes of transport.

Inland shipping, by contrast, can largely rely on existing navigable waterways and port infrastructure. The Netherlands already has a modern and extensive inland shipping fleet of approximately 8000 ships, and 88% of hazardous materials in the country is already transported by water (Wereld van de Binnenvaart, n.d.; ProRail, 2024b). With an annual intensity of only 4640 shippings needed to transport all the required ammonia, this suggests that only limited investment in new vessels would be required to accommodate ammonia transport. In scenarios where other hazardous cargo could be shifted to different modalities, existing tankers could be repurposed without the need for additional ships being built. Additionally, the Dutch government is already actively investing in expansion of inland waterway infrastructure to keep locks, bridges, and dredged routes operational for larger vessels, and to increase capacity where future freight growth is expected (Rijksoverheid, n.d.-a). Additional infrastructure investments are therefore limited.

Pipeline transport would require the construction of entirely new infrastructure, as ammonia is not yet transported via pipelines in the Netherlands. These investment costs are very high and makes it the most capital-intensive modality in terms of infrastructure investment (Rijksoverheid, 2012). However, pipelines have the unique advantage of combining infrastructure and carrier function in one: once constructed, no separate wagons or vessels are needed. This reduces necessary investments in carrier vessels.

7.1.5.2. Operational Costs

Operational costs for transporting ammonia differ significantly across rail, inland shipping, and pipeline modalities. Operational costs depend on the fixed, variable, staff, mode-specific, general operating and (un-)loading costs (Panteia, 2024).

The labour costs per tonne-kilometre for rail transport are relatively low compared to inland shipping due to high capacity and efficiency. The overall fixed and variable costs per tonne kilometer are lower for rail transport than for inland shipping as well (Panteia, 2024). However, the mode-specific and general operating costs for rail transport are slightly more expensive than for inland shipping (Panteia, 2024). Additionally, the (un-)loading costs and infrastructure costs per tonne-kilometre for rail are very high compared to inland shipping (Visser, 2020). Rail operators also pay infrastructure access charges, which vary depending on train weight, distance travelled, and track usage (ProRail, 2024a). These costs are expected to increase further if rail capacity must be expanded to accommodate larger volumes of ammonia in the future.

Inland shipping is generally regarded as a cost-efficient transport mode for long distances. However, its operational costs are heavily influenced by various factors, such as distance, ship rental cost, fuel cost, crew cost, port cost, loading cost, and ship capacity (Khaksar et al., 2024). In recent years, the operational costs have increased due to rising labour expenses, higher capital and insurance costs, and more expensive maintenance (Binnenvaart Krant, 2025). Therefore, the fixed, variable and labor costs are higher for inland shipping than for rail transport (Panteia, 2024). Especially the growing shortage of qualified crew has led to rising costs in the inland shipping sector, as labour costs weigh more heavily than fuel on shorter distances (Binnenvaart Krant, 2025).

Pipeline transport has very low operational costs (Hendriks, 2021). Once the infrastructure is in place, pipelines require minimal staffing and no fuel input. The operational costs of a pipeline consist of costs for the operator and maintenance (Schipper et al., 2022). Maintenance is generally limited to periodic inspections, leak detection, and pressure monitoring, which makes pipelines highly cost-effective for the continuous transport of large volumes of a single substance (Schipper et al., 2022). The absence of vehicles or vessels further reduces logistical complexity and labour requirements. Therefore, transporting ammonia in large volumes for long distances by pipelines is more economically beneficial than by shipping and rail transport (Khaksar et al., 2024).

7.1.5.3. Mitigation Measures Costs

The implementation of the mitigation measures across the three transport modalities can also include high costs. The costs differ largely based on the complexity of the interventions and the required new infrastructure.

Implementing the ETCS entails substantial investment, with onboard equipment for new locomotives costing approximately €100,000, and retrofitting existing ones ranging between €200,000 and €300,000 (European Commission, 2005). Trackside installation costs can vary widely, influenced by factors such as traffic density and infrastructure requirements (European Commission, 2005). Retrofitting wagons with crash buffers and anti-climbing protection adds about €5,000 per wagon, while equipping new wagons costs approximately €3,500 per unit (Antea Group, 2018). Measures like reducing train speeds involve minimal direct costs but can highly impact operational efficiency and thus costs. Utilizing smaller tank wagons could increase the number of wagons required, affecting operational costs and logistical complexity.

Equipping 8000 inland shipping vessels with AIS systems requires estimated costs of 18 million euros (Stuurman, 2008). The costs for the installation program of onshore equipment for the entire area of the Netherlands are estimated at 30 million euros (Stuurman, 2008). However several investments in equipping ships with AIS systems have already been done by the government (Rijksoverheid, n.d.-a). Positioning tanks below the waterline requires vessel design modifications, which can be costly and technically complex. If no additional ships are built to transport ammonia, all existing ships would need to be adapted specifically for ammonia transport. Dividing ammonia into smaller tanks necessitates an increase in the number of tanks and adapted shipping layouts, which again could be costly and technically complex. Finally, transporting ammonia in a semi-cooled state involves additional equipment and energy costs for cooling systems. However, it is expected to be more energy-efficient than pressurized transport, which could offset this increase in costs (Ministerie van Klimaat en Groene Groei, 2024a).

Installing warning tapes during pipeline construction is a low-cost preventive measure. Supervising third-party activities near pipelines incurs labor costs but also remains relatively inexpensive. The installation of a manual or automatic emergency shut-off valve can vary dramatically, from as low as €30,000 to as high as €250,000, with the automatic valve costing the most (National Academies of Sciences, Engineering, and Medicine, 2024). The costs depend on factors such as pipeline diameter, operating pressure, and site-specific conditions (National Academies of Sciences, Engineering, and Medicine, 2024). Reducing the pipeline diameter necessitates constructing an additional pipeline to maintain the same capacity. This will double construction costs. However, smaller diameters, which lead to lower construction costs, may partially offset this increase.

7.1.6. Feasibility

Feasibility in this context refers to the practical realisation of the modalities and their mitigation strategies. This varies significantly depending on technical, economic, environmental and societal constraints. Expert consultations and policy references were used to evaluate the degree to which each measure and modality could realistically be adopted in the Dutch context.

For rail transport, the feasibility of accommodating the future ammonia flow is limited by infrastructure and tank wagon capacity. If all projected 2033 ammonia volumes were to be transported by rail, an estimated 125,000 tank wagons would be needed, which is 2.5 times the current 50,000 hazardous material wagons that are transported yearly in the Netherlands (Robbe, 2024). Even if only ammonia was to be transported in these tank wagons in 2033, such an increase would still require extensive and likely unfeasible investment. Of the mitigation measures considered, the implementation of the European Train Control System (ETCS) is deemed highly feasible, as it is already being rolled out across member states and is expected to become a future standard (European Commission, 2023). Likewise, crash buffers and anti-climbing protection are already applied to wagons transporting toxic gases and are considered technically standard and necessary for future deployment (Antea Group, 2018). In contrast, reducing train speeds was assessed as unfeasible by experts due to the disruptive impact on other freight and passenger services, unless separate low-speed tracks were constructed, which is considered impractical and very expensive. The use of smaller tank wagons is theoretically possible but deemed unlikely, as industry trends point towards increasing tank size rather than reducing it.

For inland shipping, the feasibility of large-scale ammonia transport itself is relatively high. The Netherlands has a modern inland shipping fleet of around 8,000 vessels, and already transports 88% of its hazardous materials via inland waterways (Wereld van de Binnenvaart, n.d.; ProRail, 2024b). Therefore, the annual intensity required for projected ammonia volumes could be accommodated without fleet expansion. However, inland shipping is restricted to navigable waterways and cannot serve all end destinations directly. In the specific case of transport between Rotterdam and Chemelot, where a port is available, it is logistically feasible. Inland AIS systems are already recognised by the Dutch government and actively invested in and used, making implementation feasible (Inspectie Leefomgeving en Transport, n.d. Rijksoverheid, n.d.-a). Semi-cooled ammonia transport is technically possible and already applied in seagoing vessels. Although still rare in inland shipping, it is seen as a promising future option (RIVM, 2025b; Ministerie van Klimaat en Groene Groei, 2024a). Conversely, modifying ships to position tanks below the waterline is technically complex and not likely to be socially accepted due to expected environmental objections. The use of smaller tanks onboard would also require extensive vessel redesign and is, as with rail, considered unlikely.

The pipeline transport modality is technically feasible in the long term, although ammonia transport has been excluded from the planned Delta Rhine Corridor for now (Ministerie van Klimaat en Groene Groei, 2024b). However, spatial reservations for a future ammonia pipeline have been made, indicating continued policy interest in its future implementation (Ministerie van Klimaat en Groene Groei, 2024b). Regulatory frameworks such as the Besluit activiteiten leefomgeving (Bal) require pipeline operators to implement prevention policies and a safety management system (Rijksoverheid, 2025). Measures such as warning tape and strict work supervision are considered feasible and standard as prevention policies. The installation of shut-off valves is also realistic to include in a safety management system, particularly given that the pipeline is yet to be constructed, allowing integration from the design phase. Finally, the use of smaller pipeline diameters is technically feasible and still under consideration. According to experts and correspondence with GasUnie, the optimal pipeline diameter has not yet been determined, meaning that a smaller-diameter configuration remains a viable option.

7.1.7. Adaptability

Adaptability in this context refers to the ability of a transport modality to accommodate future changes in demand, routing, or substance type without requiring major redesign or reinvestment. This is a crucial criterion in the evaluation of ammonia transport options, especially in light of ongoing uncertainties surrounding the use of ammonia in the energy transition. These uncertainties expose market actors to significant investment risks. To reduce these risks, operational flexibility and the potential for repurposing infrastructure or vehicles for other uses is important. The three transport modalities vary significantly in this regard.

Rail transport offers a moderate level of adaptability. The current rail system is not very flexible: the Dutch railway network is highly congested, and timetables are planned well in advance (Tavasszy, n.d.). Additionally, wagons used for ammonia transport must comply with strict safety specifications and are typically designed for pressure-resistant, corrosive, and toxic materials (Riemersma, 2024). This limits their versatility, as conversion for other substances may require retrofitting. Moreover, the projected increase in ammonia transport volumes would require a substantial expansion in the number of tank wagons or even rail infrastructure itself. Given the strict specifications of these wagons, it is unlikely that — if ammonia demand were to decrease in the future — a sufficient volume of alternative hazardous substances would emerge to make full use of this expanded fleet. This limits the long-term adaptability of such investments. On the positive side, if demand decreases only moderately, these wagons could potentially be used by other hazardous materials transport, provided compatibility and regulatory conditions are met.

Inland shipping is generally considered the most adaptable of the three modalities. Ships can carry a wide variety of cargo types, and tankers used for ammonia can, in principle, be reassigned to other chemicals with fewer logistical constraints than rail wagons (Ministerie van Infrastructuur en Waterstaat, 2023). Vessel routing is also flexible, allowing adjustments to shifting demand without the need for permanent infrastructure expansion. However, the adaptability of inland shipping is not without limitations. Ammonia may not be transported in tanks that previously carried certain substances unless those tanks have been thoroughly cleaned (Ministerie van Infrastructuur en Waterstaat, 2023). Moreover, special attention is required when transporting other substances in tanks where ammonia was first transported in tanks that are not made of stainless steel (Ministerie van Infrastructuur en Waterstaat, 2023). These strict cleaning and material requirements restrict the practical reusability of vessels for other chemicals in between ammonia shipments, thus reducing operational flexibility and overall adaptability.

Pipeline transport is the least adaptable modality. Pipelines are typically dedicated to the continuous transport of a single substance over a long period (Dombor, 2024). They lack operational flexibility, as capacity cannot be easily scaled up or down in response to demand fluctuations, and they cannot be reallocated to alternative substances without redesigns or safety approval (Schipper et al., 2023). While suitable for large-scale, stable flows, pipelines are not well-suited to applications where transport needs vary significantly over time or across substances. Once built, their function and routing are effectively fixed, making them a rigid option in a dynamic and uncertain energy landscape.

7.1.8. Sustainability

Sustainability evaluates the environmental performance of each transport modality beyond the direct effects of incidents, focusing on their emissions and energy use. As ammonia plays a central role in future hydrogen and energy systems, the environmental footprint of its transport becomes increasingly important. The three modalities differ significantly in their sustainability profiles.

Rail transport is generally regarded as a relatively sustainable option, primarily due to the high electrification rate of the Dutch railway network. As of 2022, approximately 75% of the Dutch rail system was electrified, significantly reducing CO_2 emissions (CBS, 2023). Ongoing sustainability efforts by the Ministerie van Infrastructuur en Waterstaat, ProRail and Rijkswaterstaat include using sulphur concrete and more circular material , as well as exploring more sustainable ways of rail steel production (Ministerie van Infrastructuur en Waterstaat, 2020). These developments contribute to the sector's transition toward more climate-neutral infrastructure and operations.

Inland shipping is typically energy-efficient and emits relatively low CO_2 emissions per tonne-kilometre (Lanjouw, 2018). However, the sector faces challenges in adopting cleaner fuels and reducing its overall environmental impact. Currently, diesel fuel is predominantly used in inland shipping (CCBS, 2025). A promising innovation is the use of green ammonia as a shipping fuel, which does not emit CO_2 and could therefore reduce emissions significantly (Maks, 2024). A project that involves creating a Green Shipping Corridor between Sweden and Belgium, is already exploring the integration of ammonia-powered vessels with electric logistics and shore power systems (North Sea Port, 2024). These developments demonstrate that inland shipping can play a sustainable role in ammonia transport, especially if zero-emission fuels are adopted more broadly. However, this will require setting up a completely new logistics infrastructure to make that possible, which will be very expensive (Maks, 2024).

Pipeline transport is considered the most sustainable modality in terms of operational emissions. Once operational, pipelines produce virtually no CO_2 or nitrogen emissions and are highly energy-efficient over long distances (Hendriks, 2021). Their long lifespan and low ongoing energy demand make them particularly well suited for the large-scale, climate-neutral transport of ammonia (Dombor, 2024). Although initial construction can be carbon-intensive, the long-term environmental benefits make pipelines a valuable asset in sustainable transportation.

7.1.9. Reliability

Reliability refers to the extent to which a transport modality can consistently deliver cargo on time and without disruptions, under both normal and exceptional conditions. This reliability is critical in the future for supply chain continuity.

Rail transport is largely unreliable, as it is subject to several structural constraints (Benjamin, 2025). The current Dutch rail network is heavily utilised and lacks flexibility, with limited room for additional freight services. Timetables are typically planned far in advance, leaving little capacity to adapt to sudden changes in supply or demand (Tavasszy, n.d.). Moreover, rail freight often shares infrastructure with passenger transport, which can lead to delays and prioritisation issues (Benjamin, 2025). Although ProRail is urging for investments to improve digitalisation and capacity in order to anticipate a strong growth in freight transport (ProRail, 2023), the rail's current congestion poses a challenge to dependable transport.

Inland shipping faces its own reliability risks, particularly due to changing climate conditions. The sector is especially vulnerable to fluctuations in water levels, which can increase the risk of grounding accidents and affect navigability and loading capacity (Bačkalov et al., 2021). For instance, during the extreme drought of 2018, inland vessels on the Rhine could only operate at half capacity due to low water levels, which severely disrupted supply chains for industrial clusters (Hendriks, 2021). In addition, inland shipping is sensitive to weather-related delays, lock failures, and port congestion. While the system is generally reliable under normal conditions, its performance is less predictable under climate stress. However, the Dutch government is actively investing in the maintenance and expansion of inland waterway infrastructure. Efforts focus on keeping locks, bridges, and dredged routes operational for larger vessels, and on increasing capacity where future freight growth is expected (Rijksoverheid, n.d.-a). These measures are intended to safeguard the long-term reliability of inland shipping, even under changing environmental conditions.

Pipeline transport is considered the most reliable of the three modalities (Rijksoverheid, n.d.-b). Once constructed, pipelines can operate continuously, independent of weather, traffic congestion, or workforce availability. They are not affected by surface disruptions and can deliver a constant flow of ammonia night and day (Dombor, 2024). This makes them particularly suited for high-volume transport over long distances (Rijksoverheid, n.d.-b). Moreover, because they are mostly automated and monitored remotely, human error and scheduling conflicts are minimised. Their underground construction also makes them more resilient to external shocks, such as storms or drought.

7.2. Scoring the Alternatives

The scores of the alternatives are based on the information presented in Section 7.1. Due to a lack of quantitative findings in the literature, none of the criteria can be completely quantified. Therefore the criteria are evaluated through literature and expert judgement. As a qualitative scoring is used, the criteria are simultaneously normalised. A linear min-max normalisation method is applied, which is the most commonly used approach (Bandaru, 2022). Either local or global normalisation are methods that can be used for this purpose (Stratelligence, 2024).

In this research local normalisation is used, where the best-performing modality receives a score of 1, and the worst receives a 0. For example, the cheapest modality (best on Affordability) gets a 1, and the most expensive gets a 0. The modality with intermediate scores falls proportionally in between. For global normalisation a theoretical minimum and maximum value for each criterion is used to place all modality scores on a consistent scale (Stratelligence, 2024). This approach is not preferred for this research as it is difficult to define the best and worst theoretical scores for qualitative criteria.

The table below presents the scores assigned to each transport modality for every evaluation criterion. Again, it is important to note that the scores assigned to the criteria were determined by the researcher, based on the modelling results, expert judgment, and the qualitative analysis as described in Section 7.1. As such, these scores should not be interpreted as an empirical scoring, but rather as an illustrative example of how weights can be assigned.

Table 7.1: Normalised MCA scores per criterion and indicator for each transport modality.

Criteria	Indicator	Rail	Shipping	Pipeline
Human Safety	Individual risk	0	1	0.85
	Group risk	0.80	1	0
	Effect zone	0.70	1	0
Security	Terrorism	0	0.50	1
	Cybersecurity	0.60	1	0
Environmental Harm	Soil and groundwater	0.40	1	0
	Surface water	1	0	0.90
Affordability	Investment costs	0.50	1	0
	Operational costs	0.25	0	1
	Mitigation measures costs	0.50	0	1
Feasibility		0	0.20	1
Adaptibility		0.20	1	0
Sustainability		0.70	0	1
Reliability		0	0.75	1

For human safety, rail transport performs the poorest on individual risk, as it is the only modality for which the 10^{-6} contour remains present in Breda. Inland shipping scores highest, showing no 10^{-6} contours at all, while pipeline transport shows acceptable but spatially larger 10^{-7} and 10^{-8} contours. For group risk, inland shipping again performs best due to its negligible FN-curve, while pipeline transport scores lowest due to its relatively high probability of medium-sized casualty scenarios. As rail transport exceeds the orientation value, even though only slightly, it still scores relatively high compared to inland shipping. Regarding toxic effect zones, inland shipping shows the most compact spatial impact and pipeline transport the widest. The LBW, AGW and attention zones for rail transport are also relatively spatially compact like inland shipping, but the VRW zone is very widespread, scoring it somewhat lower than inland shipping.

On security, pipelines score highest on terrorism as they are generally buried underground and not easily accessible, significantly reducing the likelihood of targeted attacks. Inland shipping receives an intermediate score, as vessels are physically accessible but typically avoid urban centres, limiting the potential impact of an attack. Rail transport scores lowest as its infrastructure is highly accessible and often runs through densely populated areas, making it a more attractive target for terrorism. In terms of cybersecurity, inland shipping scores highest due to its relatively low level of digitisation. Although technologies like AIS introduce some cyber risks, inland vessels remain largely autonomous, limiting potential consequences of cyber interference. Rail transport receives a medium score, as its increasing digitisation makes it more centralised and potentially vulnerable to targeted attacks. Pipeline transport scores lowest, as their automated control and monitoring systems make pipelines particularly vulnerable to cyberattacks which could result in severe and uncontrolled ammonia releases.

In terms of environmental harm, inland shipping scores best on soil and groundwater pollution due to limited land-based exposure, with almost all the ammonia spilling into surface water. Pipeline transport scores lowest due to large release volumes under ground and higher infiltration risks. Rail transport also faces infiltration risks but these are much lower than those for pipeline incidents. Conversely, for surface water, rail is the best-performing modality in terms of risk to surface water as train routes usually do not cross or go near surface water, while inland shipping scores worst due to its direct exposure to aquatic ecosystems. Pipeline transport scores a bit lower than rail transport as pipeline routes can be closer to waterways, which could result in small spills in surface water

Under affordability, inland shipping scores highest for investment costs, requiring only minor adaptation of existing infrastructure. Pipeline transport scores lowest due to the need for entirely new infrastructure. Rail transport scores exactly in between the other two modalities as it does not necessarily require totally new infrastructure, but it does require extensive investments in tank wagons. For operational costs, pipelines score highest due to their minimal staffing and energy needs, while inland shipping scores lowest due to rising labour and maintenance costs. Rail transport also scores relatively low as it still requires much more operational costs than pipeline transport. Mitigation measure costs follow a similar pattern as the operational costs. Pipelines generally require less expensive or more integrated measures, while shipping requires complex and extensive technical vessel modifications. Rail transport is scored in the middle, as it requires much less technical adjustments, but the decrease in speed could significantly increase investment and operational costs.

In terms of feasibility, rail transport scores lowest, mainly due to the required increase in tank wagons and impracticality of certain measures such as lower speeds. Though the use of inland shipping itself as ammonia transporter is highly feasible, its mitigation measures have limitations in terms of technical requirements and public acceptance. Therefore, it is also scored low, but slightly higher than rail transport. Pipeline transport scores highest, as all proposed measures are technically and operationally feasible, especially if integrated from the design stage. For adaptability, inland shipping stands out again. Its vessels can be reassigned, reconfigured, and rerouted relatively easily, while rail is limited by specialised wagon requirements and infrastructure constraints, making its score relatively low. Pipelines are even more inflexible and dedicated though, resulting in the lowest adaptability score.

Regarding sustainability, pipeline transport scores highest due to its very low operational emissions. Rail also performs well due to its high level of electrification and infrastructure sustainability efforts. Inland shipping currently relies heavily on diesel fuel, and while sustainable innovations exist, they are not yet widely adopted. Finally, for reliability, pipeline transport again performs best, offering continuous, weather-independent service. Inland shipping is also relatively reliable but susceptible to climate-induced disruptions, especially in summer. Rail transport scores lowest due to network congestion and limited scheduling flexibility. These results highlight clear trade-offs between the modalities and show how each performs under the distinct evaluation criteria of the MCA.

7.3. Weighting the Criteria

Since the highest score on Affordability is not necessarily of equal relative value as the highest score on Human Safety, weighting needs to be applied to combine scores into a final result. The outcome of the assessment is therefore highly sensitive to how much importance is attached to each criterion. Therefore weights are attributed to each criteria and its indicators. However, objective or scientific justification for these weights is difficult as different stakeholders may prioritise the criterion differently. In this research, the weights were determined by the researcher, with the preferences of the national government in mind. This was done as the government holds final responsibility for spatial planning, public safety, and infrastructure investments. The chosen weights thus reflect a public decision-making lens with the main focus on human safety. Similar to the assigned scores, these weights should not be interpreted as an empirical weighing, but rather as an illustrative example of how weights can be assigned.

Human safety received the highest total weight (0.30), as public safety is the main focus in this research and a non-negotiable value in any future infrastructure or public project. Within this criterion, individual risk was prioritised most heavily (0.60), because the exceedance of the 10^{-6} threshold is a legal threshold. Effect zones (0.25) were next, since they are a direct indicator that shows the extent of potential harmful consequences. However, it should be noted that these zones are based on concentration thresholds averaged over time, meaning that in many cases, there may still be time to evacuate before actual harm occurs. Group risk (0.15), although important, was assigned a lower weight as it is not legally binding.

Security was assigned a total weight of 0.15, acknowledging the growing relevance of deliberate threats in hazardous material transport. Its two sub-indicators, terrorism and cybersecurity, were considered equally important and were therefore assigned equal weights of 0.50 each. Environmental harm was also assigned a total weight of 0.15. The two sub-indicators, soil and groundwater as well as surface water, were weighted equally (0.50 each). This equal distribution acknowledges that both environmental aspects are of similar importance.

Affordability received a total weight of 0.10, consistent with the government's aim to ensure economically viable infrastructure decisions. Within this criterion, investment costs (0.50) were given the greatest emphasis. These costs represent a critical threshold for realising infrastructure projects, as the initial investment burden is often politically or financially prohibitive. This makes investment costs a major determining factor in whether a project can proceed at all. Operational costs (0.30) were considered slightly less important, as they are incurred over time and can, in principle, be optimised or offset through long-term planning and efficiency gains. Mitigation measure costs (0.20) were weighted lowest, as they also represent one-time costs that may even be eligible for subsidies.

Feasibility and sustainability were also both weighted at 0.10. In this context, the feasibility reflects the degree to which a modality can realistically be implemented under current technical conditions. Sustainability reflects longer-term alignment with climate and energy goals, and was considered equally important. Adaptability and reliability received lower weights (0.05 each), as they represent secondary but still meaningful concerns, especially under conditions of uncertainty and transition. An overview of these weights can be found in Table 7.2. The total weight of each subindicator is calculated as the product of the criterion weight and the sub-weight within that criterion.

Table 7.2: Weighting structure for each criterion and sub-indicator used in the MCA.

Criteria	Criteria-specific weight	Indicator	Indicator-specific weight	Total weight
Human Safety	0.30	Individual risk	0.60	0.18
		Group risk	0.15	0.045
		Effect zone	0.25	0.075
Security	0.15	Terrorism	0.50	0.075
		Cybersecurity	0.50	0.075
Environmental Harm	0.15	Soil and groundwater	0.50	0.075
		Surface water	0.50	0.075
Affordability	0.10	Investment costs	0.50	0.050
		Operational costs	0.30	0.030
		Mitigation measures costs	0.20	0.020
Feasibility	0.10			
Adaptability	0.05			
Sustainability	0.10			
Reliability	0.05			

7.4. Ranking the Alternatives

To rank the alternatives the multi-criteria analysis combines the normalised scores and their weights to produce a final score, which is called a utility score or ”Nuts-score” (Stratelligence, 2024). The scores for each criteria and their indicators can be found in Table 7.3, along with the total score for each modality. This score reflects the societal value for each alternative.

Table 7.3: Weighted MCA scores per indicator and total scores per transport modality.

Criteria	Indicator	Rail	Shipping	Pipeline
Human Safety	Individual risk	0	0.18	0.153
	Group risk	0.036	0.045	0
	Effect zone	0.0525	0.075	0
Security	Terrorism	0	0.0375	0.075
	Cybersecurity	0.045	0.075	0
Environmental Harm	Soil and groundwater	0.03	0.075	0
	Surface water	0.075	0	0.0675
Affordability	Investment costs	0.025	0.05	0
	Operational costs	0.0075	0	0.03
	Mitigation measures costs	0.01	0	0.02
Feasibility		0	0.02	0.1
Adaptibility		0.01	0.05	0
Sustainability		0.07	0	0.1
Reliability		0	0.0375	0.05
Total scores		0.361	0.645	0.5955

The resulting utility scores for the three transport modalities show that inland shipping scores 0.645, followed by pipeline transport with 0.5955. Rail transport ranks third with a significantly lower score of 0.361. Although inland shipping outperforms pipeline transport, the difference of approximately 0.05

remains modest, suggesting that both alternatives perform well across most criteria. Rail, by contrast, consistently underperforms and is not considered a competitive alternative in the current analysis. However, the relative closeness between inland shipping and pipeline transport implies that the final ranking is not entirely robust to changes in the assigned weights. Small shifts in priorities — such as increased emphasis on affordability or environmental performance — may alter the outcome. Section 7.5 further explores the robustness of these results through a sensitivity analysis.

7.5. Sensitivity Analysis

This section tests how sensitive the ranking of alternatives is to changes in the weightings of the evaluation criteria. Given the close results in utility scores for inland shipping and pipeline transport in Section 7.4, sensitivity analysis is essential to assess the robustness of the outcome.

To explore this, five alternative weighting scenarios were defined, each reflecting a modest shift in priorities. In each scenario, the weight of Human Safety, Security, Environmental Harm, Affordability, and finally of Feasibility and Sustainability was increased by 0.10 to reflect an increased emphasis on that objective. To keep the total weight equal to 1.0, the increase was compensated by reducing the weights of other criteria proportionally. The five resulting sensitivity scenarios are:

- **Scenario 1**: Increases the weight of *Human Safety* from 0.30 to 0.40, representing a safety-first approach focused on minimising risk to human life even more.
- **Scenario 2**: Increases the weight of *Security* from 0.15 to 0.25, showing a scenario in which security becomes even more important due to geopolitical instability.
- **Scenario 3**: Increases the weight of *Environmental Harm* from 0.15 to 0.25, reflecting stronger environmental ambitions and concern for ecological decay.
- **Scenario 4**: Increases the weight of *Affordability* from 0.10 to 0.20, simulating a more cost-adverse policy environment where cost-effectiveness is prioritised.
- **Scenario 5**: Increases the weight of *Feasibility* and *Sustainability* from 0.10 to 0.15 each, reflecting a long-term, implementation-oriented perspective that prioritises realistic and practical deployment and environmental durability.

Table 7.4 shows an overview of the new weights assigned to each criterion for every sensitivity scenario. In scenarios where a higher weight is assigned to human safety, the weight of security remains unchanged. This is because both criteria address risks to human life—human safety focuses on unintentional hazards such as accidents, while security covers intentional threats such as sabotage or terrorism—making them thematically linked and jointly relevant. Likewise, when environmental harm is prioritised, the weight assigned to sustainability is not reduced, as sustainability encompasses broader long-term environmental considerations that align with immediate ecological risks. The full set of adjusted total weights per criterion and indicator for each scenario is provided in Appendix F1, and the resulting weighted scores per criterion for each modality are presented in Appendix F2. This structured sensitivity analysis reveals how minor shifts in decision priorities may affect the final recommendation and provides transparency on the robustness of the MCA outcome under varying stakeholder preferences.

Table 7.4: Overview of new weights assigned to the criteria in each sensitivity scenario.

Criteria	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Human Safety	0.30	0.40	0.30	0.275	0.275	0.275
Security	0.15	0.15	0.25	0.125	0.125	0.125
Environmental Harm	0.15	0.125	0.125	0.25	0.125	0.125
Affordability	0.10	0.075	0.075	0.075	0.20	0.075
Feasibility	0.10	0.075	0.075	0.075	0.10	0.15
Adaptability	0.05	0.05	0.05	0.05	0.05	0.05
Sustainability	0.10	0.075	0.075	0.10	0.075	0.15
Reliability	0.05	0.05	0.05	0.05	0.05	0.05

The results in the table below show that inland shipping remains the preferred transport modality in the first four scenarios. In scenario 1, where human safety is given even more weight, inland shipping achieves its highest utility score of 0.715. In scenario 2 (Security), scenario 3 (Environmental Harm) and scenario 4 (Affordability), its score remains highest at 0.69, 0.63375, and 0.63875. However, scenario 5 shows a different outcome. When feasibility and sustainability are given more weight, pipeline transport becomes the preferred alternative with a utility score of 0.6465. This result indicates that if realistic long-term implementation and environmental performance are prioritized, pipeline transport becomes the most promising option. This is particularly because of its low operational emissions and the high feasibility of both the transport system and its associated mitigation measures. However, despite its high feasibility, due to the current lack of ammonia pipelines in the Netherlands this option would only be viable in the long-term. In all scenarios, rail transport remains the least favourable option, with significantly lower scores than the other two modalities.

These results indicate that the outcome of the MCA is moderately sensitive to the applied weighting scheme. While inland shipping is generally the most favourable option, it does not dominate in all sensitivity scenarios. In scenarios where contextual criteria are given priority over safety, security, environmental and economic risks, pipeline transport becomes more attractive. This underscores the importance of clearly defining priorities when using MCA results to guide decision-making.

Table 7.5: Overview of the total scores belonging to each modality.

Sensitivity scenario	Rail transport	Inland shipping	Pipeline transport
Base case	0.361	0.645	0.5955
Scenario 1	0.344875	0.715	0.57275
Scenario 2	0.345375	0.69	0.57175
Scenario 3	0.4055	0.63375	0.57775
Scenario 4	0.353625	0.63875	0.584
Scenario 5	0.353	0.58625	0.6465

7.6. Preferred Transport Modality and Justification

Based on the aggregated results of the multi-criteria analysis and supported by a sensitivity analysis, inland shipping emerges as the most suitable transport modality for future ammonia flows in the Netherlands.

The objective of this analysis was to identify the transport mode that offers the best balance between public safety, security, environmental protection, economic viability, and broader implementation considerations such as feasibility, adaptability, sustainability, and reliability. Human safety was assigned the highest priority, reflecting its status as a non-negotiable foundation for any hazardous material transport decision. Security and environmental considerations were the second highest focus of the analysis.

These main focus points are consistent with the leading role of the Dutch government in guaranteeing safety, security and protection of the environment.

The base-case utility scores reveal that inland shipping scores highest (0.645), followed by pipeline transport (0.5955), and rail transport in third place (0.361). Inland shipping's high score is primarily driven by its strong Human Safety scores compared to the other two modalities. The sensitivity analysis in Section 7.5 further supports this conclusion. In four out of five alternative weighting scenarios, inland shipping remains the best-performing modality, showing that the outcome is relatively robust to changes in criteria priorities.

Only in Scenario 5, where greater weight is given to feasibility and sustainability, does pipeline transport surpass inland shipping. This reflects the long-term environmental benefits and implementation potential of pipelines, especially under high and steady demand. However, as outlined in the 2024 parliament letter on hydrogen carriers (Ministerie van Klimaat en Groene Groei, 2024a), the Dutch government expects that the role of ammonia will decrease over time as alternative hydrogen carriers become more dominant. This reinforces the conclusion that inland shipping is the most suitable modality, especially in the short to medium term, when ammonia transport is expected to be at its peak. Inland shipping offers a flexible and comparatively safe transport option without requiring major infrastructure investments, making it a practical and future-proof option within the expected timeline. Rail transport consistently ranks lowest across all criteria and scenarios. Even under weighting adjustments, rail transport does not outperform the other modalities.

In conclusion, inland shipping offers the most promising combination of criteria. Although pipelines may become more attractive in the long term, inland shipping is the most realistic and effective solution for the short to medium term. Therefore, it is recommended that the Dutch government prioritize this modality in near-future ammonia transport strategies, while continuing to monitor the development of future ammonia needs and pipeline safety, which could serve as a possible long-term option.

8

Discussion

8.1. Reflection on Research Findings

In this section, the results of this research are reflected on by comparing and contrasting them with the literature found in the literature exploration in Section 1.2. It highlights where this research confirms earlier findings, addresses previously identified knowledge gaps, or diverges from common assumptions. Later in this section, the findings are also positioned within the Dutch policy context.

8.1.1. Comparison with Similar Studies

A central insight from the literature review was that most existing studies on hazardous materials transport adopt a modality-specific lens, focusing either on rail (Fang et al., 2017; Ovidi et al., 2020) or pipelines (Zhou and Chen, 2015), while inland shipping remains underexplored. This is because each mode presents unique risks and challenges, necessitating mode-specific risk assessment (Guo and Luo, 2022; Blišťanová et al., 2023). However, cross-modal comparisons of specific modalities remain absent in the literature, and only a few studies provide spatially explicit, substance-specific risk assessments (Kubas et al., 2022; Polorecka et al., 2021). These two studies found that the actual consequences of ammonia incidents differed greatly across different locations. This study confirms these findings by explicitly modelling ammonia effect zones and visualising their spatial extent in different settings. This study also addresses the knowledge gap on cross-modal comparison by modelling and comparing ammonia transport across all three modalities.

For rail transport, the findings of this study broadly support an earlier conclusion about its vulnerability in populated areas (Ovidi et al., 2020). This study shows that even after mitigation, rail remains the only modality with a 10^{-6} individual risk contour in the urban setting and still exceeds the group risk orientation value. Therefore, as stated by Blišťanová et al. (2023) and Vosooghi and Verma (2025), despite strict regulations, railway transport remains vulnerable to incidents, which continue to pose both significant environmental and health risks.

One of the most notable findings is the strong safety performance of inland shipping, which receives limited attention in the gathered scientific literature. While Blišťanová et al. (2023) and Schipper et al. (2023) mention inland shipping as a relevant mode for hazardous materials, this study is the first to empirically show its advantages for ammonia transport. The findings align with the general insights from Blišťanová et al. (2023) on the adaptability of the transport mode and its sensitivity to environmental changes, but broadly expand on the existing research by demonstrating its relative superiority in terms of safety.

This research also confirms earlier findings that pipelines are generally the most energy-efficient and reliable method for transporting hazardous materials (Zhou and Chen, 2015), though they have very limited adaptability (Schipper et al., 2023). However, it partially disagrees with the finding in Zhou and Chen (2015) that pipeline transport is the safest method for transporting hazmat material. Though the sensitivity analysis in the MCA shows that the results are somewhat perceptive to a change in weighing the criteria, and therefore to differing priorities in decision-making, the overall results show that inland shipping is a safer method of transportation. The findings of this research are consistent with concerns raised by Zhou and Chen (2015) on the potential consequences of ammonia releases. These concerns state that although pipeline transport has generally low accident rates, pipeline ruptures can lead to severe environmental and safety consequences. This nuance is often underrepresented in existing policy documents and adds important context to the assumption that pipelines are always the safest long-term option.

From a methodological standpoint, this research builds on the studies from Fang et al. (2017), Liu et al. (2021), Kubas et al. (2022), Ovidi et al. (2020), Vosooghi and Verma (2025), and Polorecka et al. (2021). These studies assessed risks based on incident probability (Liu et al., 2021), on population exposure (Liu et al., 2021; Kubas et al., 2022; Ovidi et al., 2020; Vosooghi and Verma, 2025) and on scenario modeling (Fang et al., 2017; Kubas et al., 2022; Ovidi et al., 2020; Polorecka et al., 2021). By combining these three risk assessment tools, this research provides a more integrated analysis than most earlier studies. However, it also mirrors a common limitation mentioned in the literature: the difficulty of incorporating reactive measures, such as emergency response time, into risk modelling (Liu et al., 2021; Guo and Luo, 2022). What was similarly found in this study, is that the effectiveness of post-incident response depends on many dynamic and context-specific factors, which are challenging to quantify. For this reason, this study focused exclusively on preventive measures, which is a limitation it shares with most existing models.

8.1.2. Placing the Findings in the Dutch Context

As noted in the literature exploration, despite growing policy interest in ammonia as a hydrogen carrier, academic studies on the specific safety implications of large-scale inland ammonia transport remain limited. To help place and validate this research within the Dutch context, the findings are therefore also compared to the most recent Letter to Parliament outlining the government's latest position on preferred transport modalities for ammonia (Ministerie van Klimaat en Groene Groei, 2024a).

In that letter, pipeline transport is presented as the overall preferred option, primarily due to its perceived external and transport safety, and its limited spatial footprint. However, the findings of this study challenge that preference. Based on scenario-based modelling, inland shipping scores better than pipeline transport on several safety indicators: it shows smaller effect zones, less extensive PR-contours, and negligible group risk—while pipeline transport, even after mitigation, still poses a potential for high-fatality incidents. Although the 10^{-6} contour disappears after mitigation, this study argues that the potential severity of consequences should weigh more heavily and be more extensively researched in future planning and safety assessments.

The letter also acknowledges uncertainty about the long-term role of ammonia and anticipates the development of safer and more cost-effective hydrogen carriers. This aligns with the position of this study: if ammonia transport is expected to peak temporarily, inland shipping offers a more flexible and lower-risk solution, even without mitigation measures, that avoids the risk of high sunk costs. Conversely, if long-term structural growth is expected, pipeline transport may become more viable—especially if combined with additional risk-reducing measures. This reinforces the importance of researching realistic time horizons and future developments in hydrogen carriers.

In this light, the findings of this study partially echo the government's stance—particularly in rejecting rail transport as a viable option—but also highlight important nuances. Where the government prioritises system-level optimisation, this research argues that flexibility and robustness in the short to medium term may be better served by inland shipping. However, this fully depends on the time line that is considered.

8.1.3. Placing the Findings in an International Context

While this research is explicitly grounded in the Dutch policy and risk context, its findings may offer valuable insights for international decision-making on ammonia transport. Large-scale ammonia imports via Dutch ports, such as Rotterdam, are expected to form part of a broader European hydrogen corridor, with final destinations including industrial clusters in Germany, Belgium and beyond (Ministerie van Klimaat en Groene Groei, 2024b). As such, the infrastructure choices made within the Netherlands will likely have cross-border implications.

Although risk perceptions and regulatory thresholds differ between European countries, the methodological approach adopted in this study, combining spatially explicit modelling, scenario-based safety assessment, and multi-criteria comparison, can serve as an illustrative framework for other countries. In particular, the structured comparison between modalities and locations may be used as a starting point for developing integrated corridor strategies that span multiple jurisdictions.

However, it is important to emphasize that the findings should not be directly extrapolated to other countries. For example, although rail transport within Europe is governed by the RID (Regulations concerning the International Transport of Dangerous Goods by Rail), the Netherlands uses additional dedicated infrastructure policies, such as the Basic Network (Ministerie van Infrastructuur en Waterstaat, n.d.). The Netherlands also applies some of the strictest safety standards in Europe, including highly conservative risk thresholds (e.g. the 10^{-6} contour for individual risk), which do not have direct equivalents in countries like Germany or Belgium (Rijksoverheid, 2024; Rijksoverheid, 2025). Moreover, Dutch spatial planning practices such as the attention zones, hazardous materials routing and population densities differ significantly from those in neighbouring countries (Informatiepunt Leefomgeving, n.d.). As a result, even if risk profiles are similar, they may lead to varying regulatory decisions in different countries.

Nonetheless, the underlying concern of ensuring safe, flexible and future-proof ammonia transport infrastructure is shared across borders. This study contributes to that conversation by demonstrating the importance of spatial and modal context in safety assessments, and by offering a transparent and transferable analytical structure that other countries may adapt to their own needs and thresholds. It is also important to note that evaluating criteria such as risks, security, and costs on an international rather than national scale may significantly influence which transport modality is considered most desirable. The preferred modality in a Dutch context might not align with that of a European corridor perspective, underscoring the need for alignment between national strategies and broader transnational objectives.

8.2. Reflection on Research Contributions

This section reflects on the contributions of this thesis to both academic knowledge and societal goals. It outlines how the findings advance the scientific understanding of ammonia transport and how they can support evidence-based policymaking and infrastructure planning in the context of the energy transition.

8.2.1. Reflection on Academic Contribution

The academic contribution of this research is twofold. First, it provides new empirical insights into the comparative safety and overall performance of ammonia transport across rail, inland shipping, and pipelines, a topic that remains largely underexplored in the existing literature. Second, it offers a multimodal risk comparison approach that future studies can adopt, refine, and extend to other substances, geographies within the Netherlands, or stakeholder contexts.

Most academic studies on hazardous materials transport assess generalised risks, often focusing on a single transport mode and rarely on ammonia specifically. This thesis addresses that gap by conducting a substance-specific, spatially explicit risk assessment for ammonia transport across three modalities under harmonised assumptions. By combining individual risk (PR-contours), group risk (FN-curves), and toxic effect zones within a broader multi-criteria assessment framework—including security, environmental, economic, and operational criteria—this study enables a balanced and integrated comparison.

The findings also challenge the common assumption in literature that pipelines are the safest transport option for hazardous substances. While pipeline transport scores well on individual risk thresholds, this study shows it performs worse on group risk and consequence severity. In contrast, inland shipping, on which limited academic research exists, emerges as a relatively balanced and robust alternative. These outcomes provide quantified, context-specific evidence that can inform and nuance future scientific and policy discussions on hazmat transport.

Lastly, this research demonstrates how scenario-based modelling can be used not just for isolated safety assessments, but as part of a broader decision-support approach. The integration of Safeti-NL risk modelling with a multi-criteria analysis offers a novel contribution to academic work on how to compare complex infrastructure and safety trade-offs. This approach can also be adapted to other substances, different locations in the Netherlands where the legal individual thresholds are often exceeded, and different stakeholder preferences that affect the MCA.

8.2.2. Reflection on Societal Contribution

This research directly addresses the social challenges posed by the expected increase in the role of ammonia in the energy transition. As countries prepare for the possibility of large-scale ammonia imports, understanding the social and environmental risks of its domestic transport becomes a matter of public interest and political urgency.

The findings of this study provide policymakers with concrete evidence of where safety risks concentrate, how they differ per transport modality, and what the possible mitigation options are as well as their theoretical effectiveness. This is particularly relevant for Dutch authorities that are currently shaping long-term hydrogen carrier infrastructure and evaluating the role of ammonia pipelines within the Delta Rhine Corridor. This research shows that inland shipping may offer a safer and more adaptable short-to-medium-term solution than pipelines, especially in the absence of robust post-incident control measures in the latter.

Beyond informing transport strategy, this research also contributes to public safety by highlighting how risks manifest differently in urban and rural settings, how populations are potentially affected, and what legal risk thresholds are at stake. It underscores the importance of making infrastructure decisions not only based on the likelihood of an accident happening, but also with attention to the actual spatial extent of the human health consequences and the risks they could experience.

Lastly, the study strengthens societal understanding by translating complex risk metrics into accessible visuals and structured trade-offs. It invites a more informed public discourse on ammonia as a hydrogen carrier, offering citizens and interest groups a clearer view of the risks and implications tied to infrastructure choices. In doing so, it helps close the gap between technical expertise and societal engagement which is an important requirement for a transparent and successful energy transition.

8.3. Limitations of the Approach

While this study offers valuable information on the relative safety and overall performance of ammonia transport modalities, several limitations must be considered in the interpretation of the findings and conclusions. These limitations concern both the theoretical framework of the research and the methodological choices made during the modelling and evaluation.

8.3.1. Theoretical Limitations

Several theoretical limitations should be acknowledged. The first theoretical limitation relates to the assumptions presented in Chapter 4. These assumptions were necessary to enable consistent modelling across modalities, but they often simplify or idealize real-world conditions. For example, assumptions about infrastructure availability, population presence, and operational parameters do not always reflect current or likely future practice. While these simplifications help delineate system boundaries, they may reduce the realism and external validity of the results and should be considered when interpreting the outcomes of the model.

Additionally, the estimation of future ammonia transport volumes was based on a synthesis of different secondary sources, many of which predate recent market developments. Although a more recent 2024 source was used to update the projections, these remain speculative and could differ substantially from actual future demand.

Another limitation is the lack of distinction between short- and long-term vision. The current study uses a 2033 demand forecast horizon, in which all transport modalities are expected to be at least feasible to operate. Although this provides a useful reference point, it does not fully account for the different technology readiness levels of the three transport modalities. Inland shipping and rail already transport small amounts of ammonia and have existing infrastructure and operational networks in place, making them more feasible in the short term. However, pipeline transport requires new, large-scale infrastructure investments that have not even been formally planned or initiated for ammonia yet. This means that it might very well not even be an option to transport ammonia in 2033 by pipelines.

Moreover, this research focused exclusively on preventive risk mitigation measures while excluding reactive emergency response measures, such as evacuation protocols or containment after release. This was due to the practical difficulty of quantifying response effectiveness and integrating it into the Safeti-NL software. Nonetheless, reactive risk management can play an important role in limiting the real-world consequences of hazmat incidents and should not be overlooked. Additionally, in this study, it was assumed that all proposed preventive measures could theoretically be implemented. This simplification was necessary to allow for a consistent comparative analysis across modalities. Although the ‘Feasibility’ criterion was included to account for the practical challenges associated with each measure, it is likely that implementation in the real world would be more constrained and determinative. If a measure is found to be technically unworkable or legally non-permissible under Dutch regulations, it would be rendered infeasible regardless of its theoretical effectiveness.

The analysis was also limited to the Dutch context, while future ammonia flows are expected to serve wider European energy needs. Many of the ammonia imports passing through Dutch ports will likely be destined for neighbouring countries such as Germany, meaning that cross-border infrastructure and coordination will be essential. Assessing risks in isolation neglects this broader geopolitical and infrastructural reality.

Furthermore, this study did not take into account public risk perception, even though such perceptions can strongly influence the acceptance and implementation of ammonia transport infrastructure. Perceived risks of hazardous materials transport can diverge significantly from technically calculated risks. For example, since pipelines are buried underground, the public is generally not aware that hazardous materials are being transported beneath their neighbourhoods, which may reduce perceived risk. In contrast, rail and inland shipping involve visible transport, which can increase perceived danger, even when quantitative risk assessments suggest otherwise. These mismatches between perceived and calculated risk can significantly influence public opposition, decision-making processes, and ultimately the implementation of specific transport options.

Finally, to allow for a structured and isolated comparison between the safety levels of the three transport modalities, it was assumed that each would independently carry the full projected ammonia volume. In reality, it is more likely that a multimodal distribution system will be adopted. However, the future allocation of flows across modalities remains highly uncertain and depends on many unknown factors, such as infrastructure development, political decision-making, and market demand. In the absence of reliable forecasts, a full division could not be modelled without many speculative assumptions. The adopted approach therefore enables a clearer comparison of relative risk profiles but should not be interpreted as a reflection of actual future deployment.

8.3.2. Methodological Limitations

Several methodological limitations are also present. Although terrorism and cybersecurity risks are widely recognized as potential threats to hazardous materials transport, they were not included in the modelling due to the lack of reliable data and quantifiable metrics. These risks are inherently low-frequency but high-impact and cannot be represented with standard probabilistic modelling tools like those used in this study. Therefore, this study did not include these security aspects. This limits the completeness of the quantitative analysis, particularly in long-term planning contexts where security concerns may increase. Security is, however, included in the MCA to decrease the severity of this limitation.

Another limitation is that this study only considered risks occurring during the actual transport phase. Critical process steps such as loading and unloading of ammonia were not included in the quantitative analysis. These phases, however, may carry substantially different risk profiles depending on the modality. For instance, rail and inland shipping typically require manual coupling and decoupling of tankers, opening and closing of valves, and the use of external handling infrastructure. These activities can increase the likelihood of human error or mechanical failure. In contrast, pipeline systems often use fully enclosed, automated systems for transfer operations, which may significantly reduce operational risk at loading and unloading points. The exclusion of these phases may therefore underestimate the relative risk of rail and shipping compared to pipelines, and limit the completeness of the risk assessment presented here.

To enable consistent comparison, each transport modality was simulated through the same urban (Breda) and rural (Moerdijk) settings. However, this introduces practical issues: for instance, it is unlikely that inland ships carrying ammonia would navigate through Breda's city centre. Similarly, pipelines often offer the flexibility to be routed around densely populated areas, but in this study an existing pipeline route (which is currently in use for natural gas) was used, which passes directly through Breda. This does not reflect a probable future situation.

Moreover, the general applicability of the findings to other areas is limited by local conditions. Although failure frequencies and event probabilities were based on national statistics, the dispersion and actual risk are heavily influenced by location-specific factors such as meteorological data, population exposure, and surface roughness. While Breda and Moerdijk were selected to represent typical Dutch settings, the results are not directly generalisable to all regions of the country.

The Safeti-NL software itself imposes constraints on the analysis. For example, simulations stop at 1800 seconds, even though the risks of large-scale incidents could persist well beyond this timeframe. Additionally, Safeti-NL is unable to model under-water releases, limiting the accuracy of scenarios involving inland shipping accidents below the waterline.

There are also uncertainties in scenario definition. The selected worst-case and most probable scenarios were determined through a combination of literature and expert judgement, but it cannot be guaranteed that specific parameters such as leak diameters reflect the actual most likely or worst-case outcomes.

Within the Multi-Criteria Analysis, several limitations arise from the scoring and weighting procedures. The MCA applied a single governmental perspective, which excludes other stakeholder views that might yield different preferences. Additionally, because many evaluation criteria are not quantifiable, scores and weights had to be assigned based on literature and expert judgement. This scoring and weighing was ultimately done by the researcher. This introduces subjectivity and reduces reproducibility. Likewise, while the assigned criterion weights were carefully argued, they remain normative and open to debate. However, since the MCA in this study is not intended as an empirical assessment but rather as an illustrative example of how multi-dimensional evaluation could support future policy design, these limitations are considered acceptable for the purposes of this research. Furthermore, while the selection of evaluation criteria was grounded in literature and expert judgement, it cannot be ruled out that other relevant aspects, such as social acceptance, have been overlooked. This limitation is inherent in all multi-criteria frameworks and underscores the need for further stakeholder-informed refinement of the MCA structure.

Lastly, the current MCA approach relies on local normalization, in which the best-performing alternative for each criterion receives a score of 1 and the worst a score of 0. While this enables relative comparison, it does not account for the absolute distance between a modality performance and an acceptable minimum or maximum threshold, like a maximum amount of potential people at risk or of investment costs. As a result, modalities that score significantly below what would be considered socially or technically acceptable for a given criterion may still appear favourable in the overall scoring if they outperform other options. This limitation is very relevant in issues that involve so many diverse criteria, where certain minimum standards must be met regardless of relative performance. Alternative methods such as VIKOR, which combines closeness-to-ideal with regret minimization, or TOPSIS, which evaluates distance to positive and negative ideal solutions, may offer a more robust basis for decision support in future analyses (Gul et al., 2016; Chakraborty, 2022).

9

Conclusion

This chapter presents the main conclusions of the study. It begins by answering the five sub-questions, followed by the overall answer to the main research question. Based on these insights, policy recommendations are formulated. Lastly, future research directions are provided.

9.1. Research Questions

The Netherlands is working toward a safe and sustainable energy transition, in which hydrogen is expected to play a major role. Due to challenges related to hydrogen transport and storage, ammonia is increasingly considered a viable energy carrier. However, its toxic and hazardous nature raises crucial questions about public safety and risk management. As the volume of ammonia transport is expected to increase, choosing an appropriate transport modality becomes more important. Pipelines, railways, and inland ships each have distinct risk profiles and spatial implications that must be carefully considered. To support responsible decision-making, this research investigates, first and foremost, how scenario-based risk modelling can be used to assess the safety risks and consequences of ammonia transport. In addition, a multi-criteria evaluation is conducted to compare the overall performance of the three transport options, taking into account safety as well as other relevant criteria. Five sub-questions were addressed to ultimately answer the main research question.

SQ 1. What are the most significant health risks associated with ammonia releases, under which conditions can these releases occur in railways, inland shipping, and pipelines, and which factors influence its dispersion?

Ammonia poses significant health risks when released, primarily through inhalation or dermal contact. Of these, inhalation is by far the worst, as it can lead to death. Releases can occur under various conditions depending on the transport modality. In railway transport, mechanical failure is the most common accident cause. In inland shipping, human error largely accounts for inland waterway incidents. Pipeline incidents are most frequently caused by third-party activity. In addition to unintentional failures, malicious causes such as cyberattacks or terrorism can also result in large-scale ammonia releases.

Once released, the dispersion of ammonia is influenced by various physical and environmental factors. These include the temperature and pressure at which the ammonia is transported, its release height, volume, and discharge rate, and the wind speed and the surrounding terrain at the time and location of the release. These factors collectively influence the extent of ammonia cloud formation and the degree of exposure risk and consequences for nearby populations.

SQ 2. How can scenario-based modelling with Safeti-NL be used to quantify and compare the dispersion behaviour and risk levels of ammonia releases across different transport modalities?

Before the dispersion behaviour and risk levels of ammonia transport incidents can be quantified using scenario-based modelling, it is important to define how risk is measured and how dispersion is visualized. Individual risk, expressed as PR-contours, and group risk, represented by FN-curves, can be used to quantify the potential risk level. Dispersion behaviour can be quantified through effect distances and visualized by effect contours that show the spatial reach of toxic ammonia concentrations. To ensure that the model outcomes are applicable to real-world situations, two representative locations are selected along an existing ammonia transport route, which reflect different environmental and demographic characteristics. Additionally, realistic and comparable scenarios are developed for each transport modality, by determining a most probable and a worst-case scenario.

Following this, relevant general, mode-specific, and scenario-specific parameters are gathered or calculated. These parameters, together with the selected routes, are implemented into Safeti-NL. Running the model with these defined inputs leads to the quantification of the three chosen indicators—PR-contours, FN-curves, and toxic effect zones. These concrete outputs make it possible to consistently compare the risk levels and dispersion behaviour of ammonia releases across pipelines, railways, and inland shipping.

SQ 3. What are the quantified risks and consequences of ammonia transport via railways, inland shipping, and pipelines, and how do these differ between modalities?

Individual risk, group risk and effect zones, including the attention zone, are a quantified representation of the risks and consequences of each modality. For individual risk, pipeline and rail transport both exceed the legal 10^{-6} threshold in Breda, with the rail contour covering a larger part of the city. In Moerdijk, the individual risk for rail is the lowest with only a very small 10^{-6} contour, while inland shipping shows the largest 10^{-6} contour, though this lies mostly over water. Pipeline transport displays a similar risk contour in width to Breda, covering the most extensive part of the land area. In terms of group risk, pipeline transport results in the highest risk in Breda, exceeding the orientation value from 10 to over 300 fatalities, followed by inland shipping which exceeds this value between 10 and 56 or more fatalities. Rail transport shows the lowest group risk, ranging from 10 to at least 17 deaths, likely due to smaller release volumes. In Moerdijk, group risk is negligible for all modalities.

Looking at the effect and attention zones, rail transport shows the shortest distances, followed by inland shipping which absolute distances are approximately twice as far, and concluded by pipeline transport, which again shows more than twice the distances compared to inland shipping. However, the spatial overlap with populated areas also plays a role in its actual concrete risks and consequences. In Breda, the life-threatening effect zone for rail overlaps a substantial part of the urban area, making it more critical than inland shipping, which zones cover a smaller part, despite its smaller absolute size. In Moerdijk, the opposite is true. The effect zone of inland shipping extends over the town, while rail remains relatively contained. Pipeline transport consistently covers the largest part of both locations compared to the other two modalities.

SQ 4. What risk and consequence mitigation strategies are possible for each transport modality and what is their expected individual and combined impact on the risks and consequences of ammonia transport incidents?

For rail transport, the European Train Control System (ETCS), crash buffers and anti-climbing protection, and smaller tank wagons each have a similar impact on risk and reduce the PR-contours by approximately 10 metres. Lowering train speeds has a much greater effect: it eliminates the 10^{-6} contour in Moerdijk and reduces it by over 100 metres in Breda. The only consequence-reducing measure is the use of smaller tank wagons, which shortens the life-threatening effect zones by 50 to 100 metres.

For inland shipping, the Inland Automatic Identification System (AIS) significantly lowers the PR-contours in Moerdijk as the 10^{-6} contour disappears, with the contours in Breda remaining the same. However, tank placement below the waterline has an even greater effect. In Moerdijk, the 10^{-6} contour shrinks to only 6 metres and no longer reaches land while in Breda even the 10^{-7} contour disappears entirely. Smaller shipping tanks and semi-cooled ammonia transport provide more modest reductions of 10 to 30 metres. Regarding consequences, tank placement below the waterline reduces the LBW outdoor threshold by approximately 300% and the attention zone by 500–600%. Semi-cooled ammonia also reduces these distance, but only by 60–125 metres, while smaller tanks achieve even smaller reductions of 10–100 metres.

For pipeline transport, warning tape and strict supervision of excavation activities reduce the 10^{-6} PR-contours by 15–50 metres and 30–80 metres, respectively. Emergency shut-off valves have the greatest effect and eliminate the 10^{-6} contours entirely. In contrast, reducing pipeline diameter slightly increases the 10^{-6} contour by around 30 metres in both locations, although it does decrease the 10^{-7} and 10^{-8} contours. As a consequence-reducing measure, smaller diameters significantly reduce effect zone distances by 1,000-2,000 metres.

The combined effect of all mitigation strategies differs per modality. For rail, the impact is limited: the 10^{-6} contour in Breda remains, the FN-curve still exceeds the orientation value, and the effect zones show only minor reductions of 50 to 100 metres. Inland shipping sees the most significant improvement: the PR-contours become extremely compact and the 10^{-6} contour disappears in Moerdijk, while both the 10^{-6} and 10^{-7} contours disappear in Breda, the FN-curves are negligible, and the life-threatening and attention zones are substantially reduced by 300 and 600% respectively. Pipeline transport shows a strong reduction in individual risk as both 10^{-6} contours disappear. However, the group risk in Breda still exceeds the orientation value up to 100 fatalities. Although effect zones are reduced by over 1,000–2,000 metres, they remain the most extensive and continue to cover nearly all of Breda and Moerdijk.

SQ 5. Based on a multi-criteria assessment, which ammonia transport modality performs best overall in the Dutch context?

A multi-criteria assessment is conducted to evaluate rail transport, inland shipping, and pipeline transport against a diverse set of criteria. The most important criterion is Human Safety, followed by Security and Environmental Harm. Affordability, Feasibility, Adaptability, Sustainability, and Reliability are also included. Based on the weighted scores across all criteria, inland shipping emerged as the best-performing modality overall. This outcome remained consistent in four out of five sensitivity scenarios. Only in one scenario did pipeline transport outperform inland shipping. Rail transport scored the lowest in both the base case and in all sensitivity scenarios.

Now that responses to all sub-questions have been formulated, the main research question can be addressed:

What do scenario-based modelling with Safeti-NL and multi-criteria evaluation reveal about the relative safety and overall performance of ammonia transport via railways, inland shipping, and pipelines in the Netherlands?

Scenario-based modelling with Safeti-NL and a multi-criteria evaluation reveal that the relative safety and overall performance of ammonia transport modalities in the Dutch context vary considerably. Scenario-based risk modelling shows that ammonia can pose serious health risks by quantifying individual and group risks and by generating spatial effect zones under realistic conditions.

The modelling outcomes demonstrate that pipeline transport generally results in the most extreme group risk and the largest effect zones, despite the potential for significant risk reduction through strong mitigation measures. Although in the base case pipeline transport also showed the largest individual risk contours, after mitigation the legal threshold of 10^{-6} in both locations is no longer exceeded. Rail transport exhibits concentrated but critical risks, especially in Breda, where even after the implementation of mitigation measures individual and group risk levels exceed the accepted values. Inland shipping performs most favourably in terms of risk containment. Even before the implementation of mitigation measures, transport in Breda does not exceed the 10^{-6} threshold and in Moerdijk large parts of this critical risk contour fall over water, reducing actual human exposure. After the implementation of the mitigation measures, no 10^{-6} contours remain, the group risk is completely eliminated, and compared to the other two modalities, the effect zones become very small.

The multi-criteria evaluation confirms these findings. In addition to being deemed the safest, inland shipping is still the best-performing modality when additional criteria are also taken into account. However, in one of the sensitivity scenarios in which feasibility and sustainability gain importance, pipeline transport emerges as the preferred option. This shows that differing priorities can have a big impact on the outcomes of the multi-criteria analysis. Rail transport consistently scores lowest across all criteria and is not recommended as a safe or overall preferred option for large-scale ammonia transport in the Netherlands.

In this research scenario-based modelling and multi-criteria assessment jointly reveal that inland shipping offers the most balanced combination of safety and overall performance, making it the preferred modality under current conditions. Pipeline transport may become more attractive in the long term if strategic mitigation investments are made. Rail transport, however, should be avoided wherever possible due to its comparatively poor safety performance and limited mitigation potential.

9.2. Recommendations

This final section provides recommendations based on the findings of this study. First, several policy recommendations are presented to support the safe and sustainable transport of ammonia. Second, suggestions for future research are outlined to address current limitations and to further develop and strengthen the theory and methodology used in this thesis.

9.2.1. Policy Recommendations

A key consideration for policy and planning is whether the anticipated increase in ammonia transport will be temporary—due to the current lack of alternatives—or whether it represents a structural, long-term development. As the energy transition progresses, other hydrogen carriers may become more competitive, for example by offering lower costs, easier handling, or reduced safety risks. If the role of ammonia is indeed limited to the short- to medium-term phase of the transition, inland shipping stands out as the most robust and suitable modality. Even without additional mitigation measures—should these prove infeasible or too costly—shipping remains the relatively best overall performing option. In Moerdijk, for instance, although a 10^{-6} individual risk contour was present, it fell almost entirely over water. This suggests that in other locations with wide inland waterways, the actual exposure risk will remain low, reinforcing inland shipping as a pragmatic and resilient choice.

If, however, ammonia transport is expected to grow structurally over the long term, a more comprehensive, multi-perspective multi-criteria assessment should be conducted. In such a case, pipeline transport could offer a viable alternative, especially if further investments are made in risk-reducing or consequence-mitigating measures, both preventive and reactive, that further improve human safety. The fact that pipelines performed well in one of the sensitivity scenarios highlights their potential as a long-term solution—provided the necessary safety systems are in place.

Regardless of the time horizon considered, rail transport should be avoided where possible. It consistently performed worst across all evaluated criteria and poses particularly high risks in densely populated areas. Policy efforts should therefore aim to discourage ammonia transport by rail and prioritise investment in safer, more scalable alternatives such as inland shipping or pipelines.

9.2.2. Future Research Recommendations

Several directions for future research emerge from the limitations identified in this study. Additional research in these fields could strengthen the robustness and applicability of the ammonia transport evaluation. One promising research avenue lies in the integration of terrorism and cybersecurity threats into hazardous materials transport risk models. Traditional probabilistic risk assessments are not well-suited for intentional, low-frequency events. Future research could explore the use of game theory or cost-benefit analyses to assess how such threats might influence risk profiles and mitigation priorities. This would allow for a more comprehensive understanding of system vulnerabilities and resilience, particularly as digitalisation and geopolitical tensions increase.

Future research could also extend the scope of risk assessment beyond the transport phase to include related operations such as loading, unloading, and temporary storage. These activities can present unique risk profiles that differ substantially between transport modalities. Including these operations in the risk modelling process would enable a more holistic and realistic comparison of total risk across transport options.

Another valuable topic for future investigation is to analyse the difference in relevance and feasibility of transport infrastructure across time horizons. Future research could explore the expected timeline of increases, stagnation, or decreases in ammonia volumes to enable a better understanding of the need for a short-, medium- or long-term focus in decision-making. This distinction is vital for avoiding technology lock-ins, high sunken investments and ensuring flexible infrastructure planning under rapidly evolving hydrogen market conditions.

In addition to technical risk modelling, research could focus on how public and political perceptions of ammonia influence infrastructure decisions. Understanding the social acceptability of different transport modalities under uncertain conditions could lead to more resilient, participatory, and broadly supported policy frameworks.

Where most studies focus on preventive mitigation, future work could investigate the role of reactive emergency measures in shaping ammonia transport safety. This includes response time, evacuation capacity, and inter-agency coordination. Such a study could result in the development of hybrid frameworks that merge preventive and responsive strategies for risk reduction.

Moreover, given that ammonia transport is expected to serve as part of an international energy corridor, it is vital to conduct research beyond the scope of the Netherlands. Future research could investigate how cross-border ammonia transport can be safely governed and regulated at the EU level. This includes exploring the feasibility of coordinated infrastructure corridors, harmonising emergency response standards, and aligning safety thresholds across countries. Furthermore, if such coordinated corridors prove feasible, future studies should also examine how the evaluation criteria used in this study's multi-criteria assessment would apply in a transnational context. This entails assessing whether different scoring or weighing may be required.

Another valuable direction for future research would be to expand the MCA framework developed in this study by incorporating input from multiple stakeholder groups—such as municipalities, citizens, logistics operators, and environmental NGOs. This would allow the MCA to move beyond an exploratory, researcher-led analysis and serve as a more empirical, stakeholder-informed tool for decision-making. To achieve this, both the weighting of criteria and the scoring of alternatives should be based on a sufficiently large and diverse sample of stakeholders, rather than being assigned by the researcher alone. Additionally, this research could use a more objective quantitative scoring method to enhance transparency and reproducibility. As there is a lack of quantitative academic data on the criteria, empirical data could be collected from stakeholders in the ammonia value chain, such as ProRail, Gasunie, port authorities, emergency services, and community organisations. These interviews could provide new quantitative insights supporting quantitative and objective decision-making.

Lastly, future research could consider applying alternative multi-criteria decision-making methods such as VIKOR or TOPSIS to assess hazardous materials transport options. Unlike the current MCA structure, which focuses on relative ranking based on aggregated scores, these methods also account for underperformance on individual criteria. This makes them particularly useful for identifying alternatives that may appear favourable overall but fail to meet minimum acceptability thresholds in specific risk domains. Incorporating such techniques could enhance both the analytical robustness and the practical relevance of future assessments in this field.

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A

Literature Review

A.1. Selection Methodology

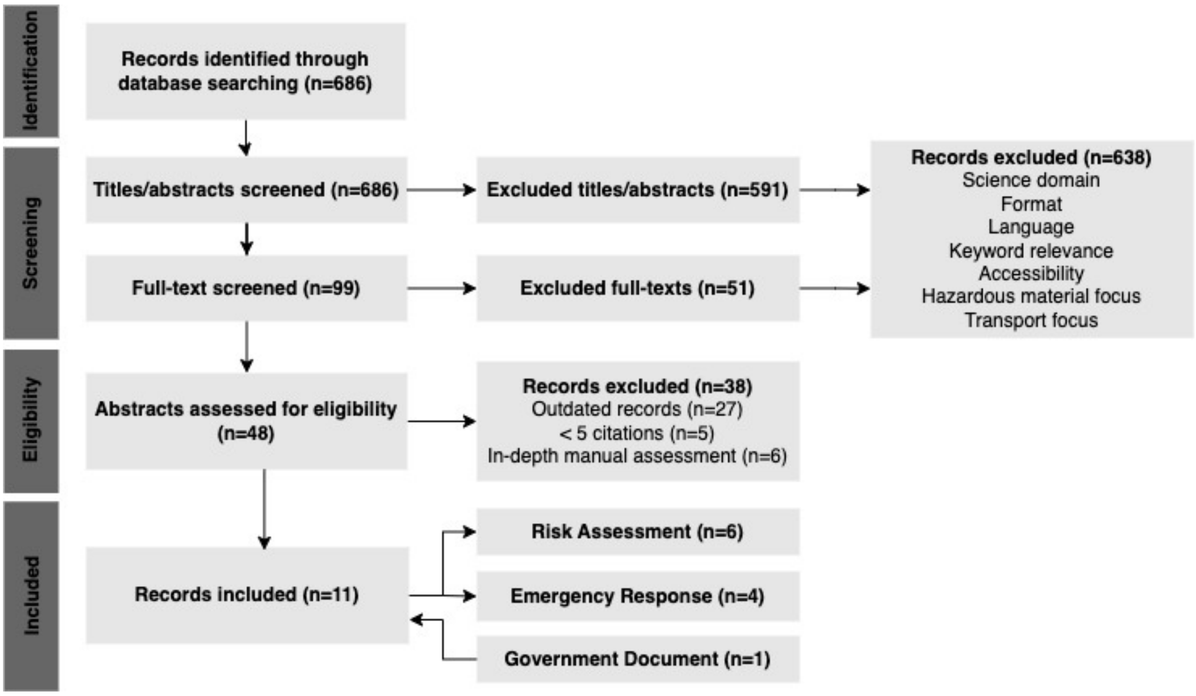

Figure A.1: PRISMA Flow Diagram

A.2. Selected Literature

Table A.1: Overview of selected literature.

Author	**Year**	**Title**
Blišťanová et al.	2023	A cross-comparative analysis of transportation safety research.
Fang et al.	2017	A routing and scheduling approach to rail transportation of hazardous materials with demand due dates.
Guo & Luo	2022	Risk assessment of hazardous materials transportation: A review of research progress in the last thirty years.
Kubas et al.	2022	Use of toxic substance release modelling as a tool for prevention planning in border areas.
Liu et al.	2021	Research on route optimization of hazardous materials transportation considering risk equity.
Mohri et al.	2022	Hazardous material transportation problems: A comprehensive overview of models and solution approaches.
Ovidi et al.	2020	HazMat transportation safety assessment: Analysis of a “Viareggio-like” incident in the Netherlands.
Polorecka et al.	2021	Use of software on modeling hazardous substance release as a support tool for crisis management.
Schipper et al.	2023	Evaluatie Basisnet.
Vosooghi & Verma	2025	A novel strategy to managing hazmat risk for rail shipments.
Zhou & Chen	2015	Challenges to risk management of underground transmission hazardous material pipelines in China.

A.3. Literature Overview

Table A.2: Overview of findings in the literature studies.

Article	Transport Mode Analyzed	Hazardous Material	Risk Assessment Methodology	Risk Management Strategy
Blišťanová et al. (2023)	Rail & inland shipping	Non-specific	N/A	Preventive & mitigating measures
Fang et al. (2017)	Rail	Non-specific	Scenario-based risk assessment	N/A
Guo & Luo (2022)	Non-specific	Non-specific	N/A	Preventive & mitigating measures
Kubas et al. (2022)	Non-specific	Ammonia	Population exposure & scenario-based risk assessment	Preventive & mitigating measures
Liu et al. (2021)	Rail	Non-specific	Incident probability & population exposure	Preventive & mitigating measures
Mohri et al. (2022)	Non-specific	Non-specific	N/A	Preventive & mitigating measures
Ovidi et al. (2020)	Rail	Non-specific	Population exposure & scenario-based risk assessment	Preventive & mitigating measures
Polorecka et al. (2021)	Non-specific	Ammonia	Scenario-based risk assessment	Preventive & mitigating measures
Schipper et al. (2023)	All	Non-specific	N/A	Preventive & mitigating measures
Vosooghi & Verma (2025)	Rail	Non-specific	Population exposure	Preventive measures
Zhou & Chen (2015)	Pipeline	Non-specific	N/A	Preventive measures
Thesis, Gerbens, L. (2025)	Rail, pipeline & inland shipping	Ammonia	Incident probability, population exposure & scenario-based risk assessment	Mitigating measures

B

Assumptions and Parameters Explained

B.1. General Assumptions and Parameters

Amount of ammonia
Since current volumes of ammonia transport in the Netherlands are still relatively limited, future projections were used to estimate the expected transport quantities per modality. The year 2033 was chosen as reference, based on available estimates for the ammonia demand associated with the energy transition in Kraan et al. (2024).

While this thesis focuses on inland shipping, rail, and pipeline transport, no consistent or directly comparable estimate is currently available for pipeline transport. For that reason, road transport was included in this calculation as a placeholder to ensure the total projected ammonia volume is accounted for in all single-modality scenarios. This approach allows each transport modality to be modelled as if it were responsible for transporting the entire projected ammonia demand, enabling a uniform comparison of associated risks and effects across modalities.

The following assumptions were made to estimate the total amount of ammonia transported in 2033 for each modality, based on available literature and scenario data. These values were used as input for modal risk calculations.

Rail Transport

- Total expected rail volume: 1.11×10^9 kg (Kraan et al., 2024)

Inland Shipping

- Number of expected shipments: 3,700 (Kraan et al., 2024)
- Volume per barge: six tanks of $\sim$225 tonnes each, total $\sim$1,350 tonnes (Riemersma, 2024)
- Total expected shipping volume: 3,700 shipments • 1,350,000 kg = 5.00×10^9 kg

Road Transport

- Number of expected shipments: 13,000 (Kraan et al., 2024)
- Volume per truck: assumed average of 13 tonnes (range: 6–20 tonnes; Riemersma, 2024)
- Total expected road volume: 13,000 • 13,000 kg = 1.69×10^8 kg

This amounts to a total of $5.00 \times 10^9 + 1.11 \times 10^9 + 1.69 \times 10^8 = 6.27 \times 10^9$ kgs of ammonia.

Transport temperature
From Module III and V RIVM (RIVM, 2025b; RIVM, 2025c).

Release duration

From Module III and V RIVM (RIVM, 2025b; RIVM, 2025c).

Meteorological conditions

In this study, two standard meteorological conditions were selected for dispersion modelling: D5 and F1.5. D5 represents average daytime weather conditions in the Netherlands, with a neutral atmospheric stability (class D) and a wind speed of 5 m/s at 10 metres height. This condition allows for moderate dispersion and is often used as a reference scenario in Dutch risk assessments (RIVM, 2009). F1.5 reflects very stable atmospheric conditions that typically occur at night, with low wind speed (1.5 m/s) and stability class F. Under this condition, vertical mixing is limited, resulting in reduced dilution of toxic clouds. This can lead to higher concentrations at greater distances from the source, making F1.5 a common choice for worst-case assessments (RIVM, 2009). These two weather classes were chosen to capture both average and conservative dispersion behaviour in the modelling of ammonia releases.

Release location

See section 4.2.1 for reasoning.

Population distribution

Retrieved from Brinkhoff (2024) and Brinkhoff (2025) for rural and urban location respectively.

Weather station

To ensure accurate dispersion modelling, representative meteorological data was selected from KNMI weather stations located closest to the two scenario locations (Diemen, 2012). For Breda, the Gilze-Rijen station was chosen, located approximately 15 km northeast of the city. This station is commonly used for regional meteorological assessments in Midden-Brabant and provides reliable data on temperature, wind speed, and atmospheric stability. For Moerdijk, the Rotterdam (Zestienhoven) station was selected due to its proximity and comparable meteorological conditions along the Hollands Diep waterway. An overview of the weather stations can be found in Figure B.1.

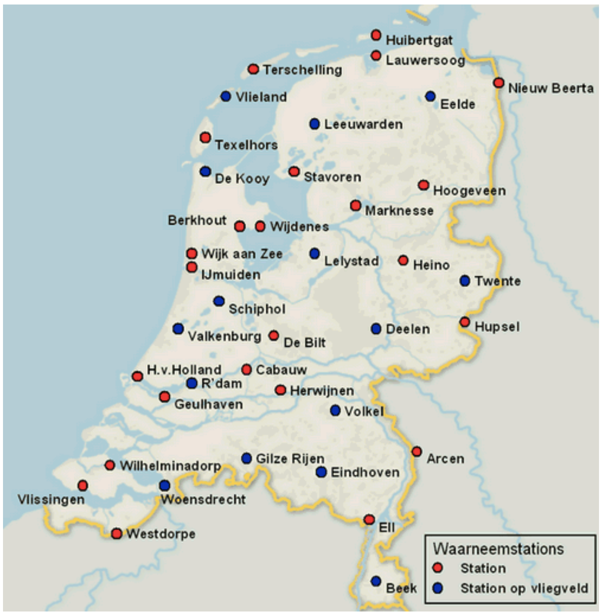

Figure B.1: Weather stations in the Netherlands

Surface roughness length

In the dispersion modelling, the surface roughness length was specified per location to account for differences in land use and terrain characteristics, which influence dispersion behaviour.

For Breda a surface roughness length of 3.0 m was used. This value corresponds to a city centre with a mix of high-rise and low-rise buildings, leading to significant surface drag and turbulent mixing. It reflects typical urban morphology as defined in standard roughness classifications used in atmospheric dispersion modelling.

For Moerdijk a surface roughness length of 0.1 m was chosen. This represents an open landscape with low vegetation like crops or grassland and occasional larger obstacles such as trees or buildings. This lower value allows for longer travel distances of gas clouds under stable atmospheric conditions.

B.2. Rail Transport

Vessel type
Derived from Module III (RIVM, 2025b).

Tank capacity
According to Riemersma (2024), the tank capacity of a tank wagon is 50,000 kg.

Tank head
Derived from Module III (RIVM, 2025b).

Specified condition
Derived from Module III (RIVM, 2025b).

Elevation
Derived from Module III (RIVM, 2025b).

Type of surface
Derived from Module III (RIVM, 2025b).

Day/Night transport ratio
Derived from Module III (RIVM, 2025b).

Outflow direction
Derived from Module III (RIVM, 2025b).

Model scenario fraction
Values derived from Module III (RIVM, 2025b).

Consequence probability
Both urban and rural values derived from Module III (RIVM, 2025b). For rail it is the product of Fb (basic accident frequency), Pu (probability of a relevant release) and Pv (probability of relevant consequence), which were not separately derived for this modality. In other words Frail was predetermined as Fb • Pu • Pv.

Annual intensity
The annual intensity is the total amount of ammonia tanks that are transported during a year. This number was derived from dividing the total amount of estimated ammonia by the amount of ammonia in a tank: $6.27 \times 10^9 / 5.00 \times 10^4 = 1.25 \times 10^5$ tanks

Scenario frequency
The scenario frequency (formula can be found in 4.1.1.1) for rail transport is the product of the model scenario fraction, consequence probability and the annual intensity. The model scenario fraction and consequence probability for Track type A and C were retrieved from module III (RIVM, 2025b). The annual intensity can be found in the calculation above. The product of these three values results in the following scenario frequencies:

Scenario 1

- Urban: $0.92 \cdot 7.4 \times 10^{-10} \cdot 1.25 \times 10^5 = 8.54 \times 10^{-5}$
- Rural: $0.92 \cdot 6.2 \times 10^{-11} \cdot 1.25 \times 10^5 = 7.15 \times 10^{-6}$

Scenario 2

- Urban: $0.08 \cdot 7.4 \times 10^{-10} \cdot 1.25 \times 10^{5} = 7.42 \times 10^{-6}$
- Rural: $0.08 \cdot 6.2 \times 10^{-11} \cdot 1.25 \times 10^{5} = 6.22 \times 10^{-7}$

B.3. Inland Shipping

Vessel type
Derived from Module III (RIVM, 2025b).

Shipment capacity and number of tanks on ship
According to Riemersma (2024) the tank capacity of an individual tank in an inland shipping vessel is 225 tonnes. There are six tanks on average in a vessel, each carrying the same type of material. This means a total 1,350 tonnes are transported on the entire ship.

Elevation
In accordance with an RIVM expert, the elevation was set to 1.0 m, representing the approximate height of the leak point above the waterline on a typical ammonia tanker. This value reflects a situation where the release occurs well above the water line. A higher elevation allows for more free-space dispersion and can affect the initial plume shape and direction. The assumption of 1.0 m provides a realistic basis for modelling above-water releases under standard tank configurations.

Tank head
In accordance with an RIVM expert„ the tank head was set to 5.0 m, indicating that there is a 5-metre vertical column of liquid ammonia above the leak point inside the tank. This value reflects a scenario where the tank is largely filled at the time of the incident. It governs the initial outflow rate of ammonia. A greater tank head results in a higher force behind the release. The 5.0 m assumption ensures a conservative yet plausible estimation of release dynamics for a fully or nearly full tank under transport conditions.

Specified condition
Derived from Module III (RIVM, 2025b).

Pipe length
Derived from Module III (RIVM, 2025b).

Type of surface
Derived from Module III (RIVM, 2025b).

Bund height
Derived from Module III (RIVM, 2025b).

Bund area
The represents the surface area into which a potential spill may be initially contained or spread. For inland waterway scenarios in this study, the bund area was estimated using the simplified assumption that it equals the square of the average waterway width:

Bund area = b^2

Here b is equal to the average width of the waterway. To determine the average width, spatial measurements were conducted in QGIS using topographic layers. For the urban location the width of the Mark river measured from ’t Spijk to Haagse Beemdenbos was approximately 70 metres. At the rural site, the width of the Hollands Diep waterway (between Oeverlanden and Zuid-Hollands Diep) was measured at 1,582 metres.

These values were squared to obtain the bund area input used in Safeti-NL for each inland shipping scenario:

- Urban: $70^2 = 4.9 \times 10^3$ m^2
- Rural: $1{,}582^2 = 2.5 \times 10^6$ m^2

Bund failure modeling
Derived from Module III (RIVM, 2025b).

Day/Night transport ratio
Derived from Module III (RIVM, 2025b).

Outflow direction
Derived from Module III (RIVM, 2025b).

Basic accident frequency
Values derived from Module III (RIVM, 2025b).

Consequence probability
Both urban and rural values derived from Module III (RIVM, 2025b). For inland shipping it is the product of Pu (probability of a relevant release), Pv (probability of relevant consequence), and fm (model scenario fraction) which were not separately derived for this modality. In other words Fship was predetermined as Pu • Pv • fm.

Annual intensity
The annual intensity is the total amount of inland shipping vessels that are transported during a year. This number was derived from dividing the total amount of estimated ammonia by the product of the amount of ammonia in a tank and the number of tanks: $6.27 \times 10^{9} / (2.25 \times 10^{5} \cdot 6) = 4.64 \times 10^{3}$ shipments

Scenario frequency The scenario frequency (formula can be found in 4.1.1.1) for inland shipping is the product of the basic accident frequency, consequence probability and the annual intensity. The basic accident frequency and consequence probability for Navigability Class IV and VI were retrieved from module III (RIVM, 2025b). The annual intensity can be found in the calculation above. The product of these three values results in the following scenario frequencies:

Scenario 1

- Urban: $8.67 \times 10^{-8} \cdot 5.5 \times 10^{-3} \cdot 4.64 \times 10^{3} = 2.21 \times 10^{-6}$
- Rural: $4.14 \times 10^{-7} \cdot 1.25 \times 10^{-2} \cdot 4.64 \times 10^{3} = 2.40 \times 10^{-5}$

Scenario 2

- Urban: $8.67 \times 10^{-8} \cdot 2.64 \times 10^{-5} \cdot 4.64 \times 10^{3} = 1.06 \times 10^{-8}$
- Rural: $4.14 \times 10^{-7} \cdot 6.0 \times 10^{-5} \cdot 4.64 \times 10^{3} = 1.15 \times 10^{-7}$

B.4. Pipeline Transport

Corrected failure frequency
The table below shows the failure frequency after correction for the 1.5 m pipeline burial depth. The burial depth is taken into account in the failure cause third-party interference. The corrected failure frequency is calculated as follows (RIVM, 2025c):

$$\text{Failure frequency}_{\text{third-party, corrected}} = \text{Failure frequency}_{\text{third-party}} \times \text{factor} \tag{B.1}$$

$$\text{factor} = e^{2.4\times(0.84-z)}, \tag{B.2}$$

where z = burial depth (in metres).

The original failure frequency for third-party interference can be found in RIVM (2025c), and is 2.63×10^{-5} in the most probable scenario and 1.77×10^{-5} in the worst-case scenario. The calculated value for the correction factor is 0.21. With this factor the new third-party failure frequency, and with that the new total failure frequency, is calculated.

This table shows the overview of the different failure causes and their failure frequencies:

Table B.1: Failure frequencies for different failure causes in pipeline transport.

Failure cause	**Leak** *Failure frequency*	**Breach** *Failure frequency*
Third-party (corrected for 1.5 m depth)	5.40×10^{-6}	3.63×10^{-6}
Mechanical	3.86×10^{-5}	7.96×10^{-6}
Corrosion	4.69×10^{-5}	5.66×10^{-6}
Natural causes	3.60×10^{-6}	4.25×10^{-6}
Operational	4.56×10^{-6}	2.26×10^{-6}
Total	$\mathbf{9.91 \times 10^{-5}}$	$\mathbf{2.38 \times 10^{-5}}$

Flow rate
The pumped inflow was set to 199 kg/s, representing the continuous mass flow required to transport the entire projected annual ammonia volume through a single pipeline over the course of one year. This value was calculated using the following formula:

Mass flow rate = Myear / tyear, where:

- Mass flow rate is in (kg/s)
- M_{year} = projected total annual transport volume (in kg)
- t_{year} = number of seconds in a year (31,536,000 s)

This resulted in: Flow rate = 6.27 $\times$ 10^9 kg / 31,536,000 s ≈ 199 kg/s

While this flow rate is relatively high, it serves an analytical purpose: to model each transport modality as if it were solely responsible for the full ammonia demand. This enables a uniform comparison of risks and consequences between inland shipping, rail, and pipeline scenarios.

Pipeline diameter
In consultation with an RIVM employer specialized in Pipeline transport in Safeti-NL, a pipeline internal diameter of 400 mm was assumed. This size is representative of high-capacity industrial pipelines designed for long-distance transport of pressurised liquefied ammonia. The diameter was chosen to correspond with the calculated pumped inflow of 199 kg/s. A 400 mm diameter provides sufficient area to accommodate such flow rates under typical operating pressures.

Furthermore, the pumped flow speed (m/s), should be between 1-10 m/s. This can be calculated using the formula:

Flow speed = Myear / (Apipe • tyear • ρ), where:

- M_{year}: total annual transport volume (kg/year)
- A_{pipe}: internal cross-sectional area of the pipeline (m²), where $A_{\text{pipe}} = \frac{\pi}{4} \cdot D^2$
- t_{year}: seconds per year (31,536,000 s)
- ρ: density of liquid ammonia (584 kg/m³)

Only for a diameter of 400 mm and higher, the flow speed is under 10 m/s. To be precise for a diameter of 400 mm the flow speed is:

Flow speed = 6.27 $\times$ 10^9 / (4π • 0.042 • 31,536,000 • 584) = 2.71 m/s

Pipeline depth
Value derived from Module V (RIVM, 2025c).

Elevation (release height)
Value derived from Module V (RIVM, 2025c).

Pressure
Value derived from Module V (RIVM, 2025c).

Type of surface
In consultation with an RIVM employer specialized in Pipeline transport in Safeti-NL it was determined that the type of surface would differ between the urban and rural location. Given the assumption that pipelines are always buried 1.5 metres underground, the characteristics of the overlying soil or surface layer influence how gas may escape and disperse in the event of a release.

For the urban location, the surface was set to concrete, reflecting the built-up nature of the environment and the likelihood that the pipeline passes beneath paved infrastructure such as roads. For the rural location near Moerdijk, which is close to open terrain and surface water, the surface type was set to wet soil. This reflects the higher groundwater levels and softer, less sealed terrain.

Day/Night transport ratio
Pipeline transportation is continuous transport. Therefore, the day/night transport ratio is 1.

Outflow direction
Derived from Module V (RIVM, 2025c).

Accident type for buried sections
For the accident type in buried pipeline sections, the option ”puncture at the top” was selected. This option was chosen, as in practice, one of the most frequent causes of pipeline damage is third-party activity, particularly excavation work. When a buried pipeline is accidentally struck by a digging machine or drill, the impact typically occurs from above, resulting in damage to the upper surface of the pipe. Therefore, choosing ”puncture at the top” reflects the most plausible leak option.

Event probability
Derived from Module V (RIVM, 2025c).

Failure frequency
Derived from Module V (RIVM, 2025c).

C

The Safeti-NL Model

C.1. Transport Routes

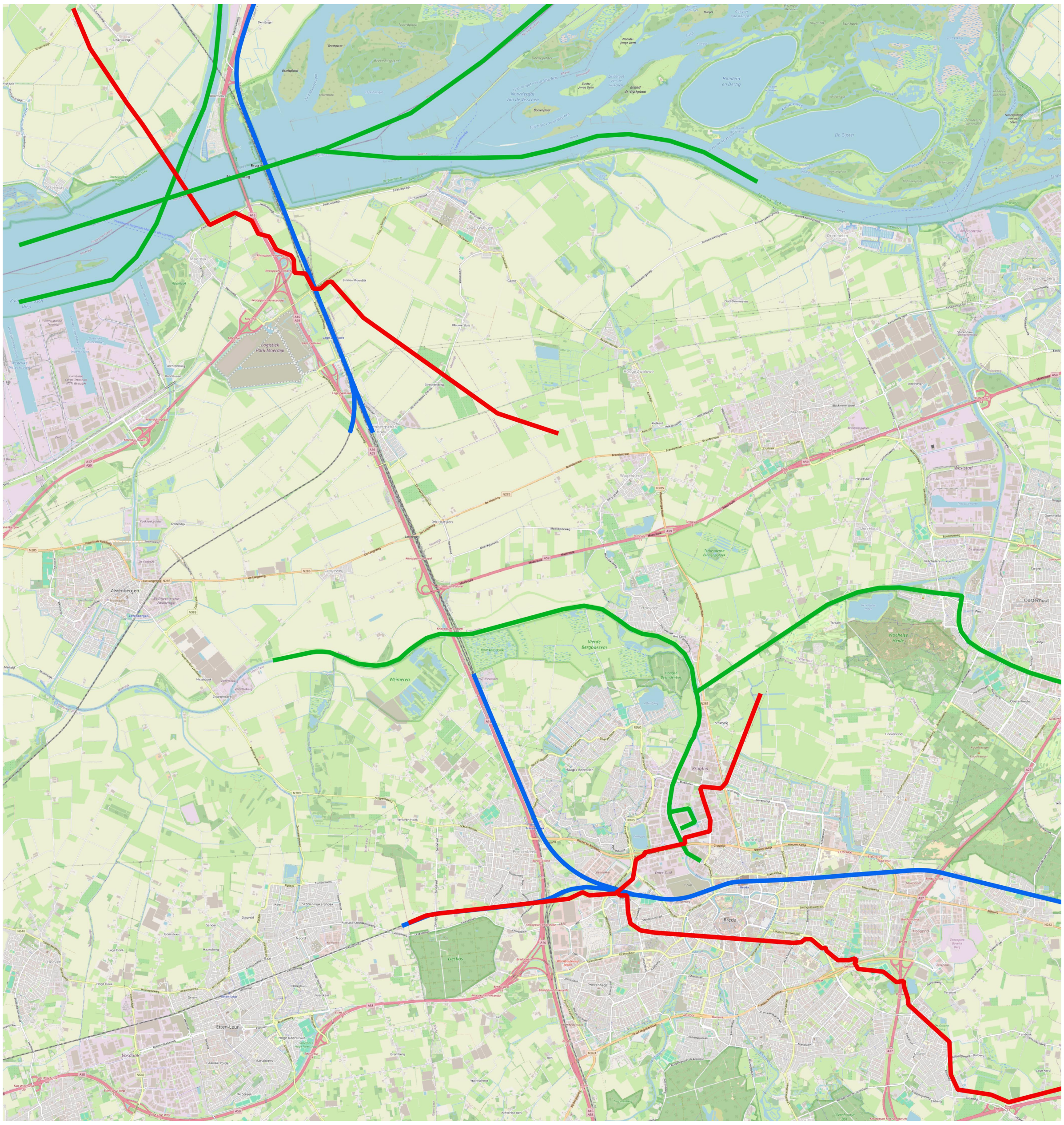

Figure C.1: An overview of all transport routes in Breda and Moerdijk

C.2. Complete Effect Distances

Scenario	Weather type	VRW [m]	AGW [m]	LBW [m]	Attention zone [m]
Leak	D5	4509	1131	375	247
	F1.5	12806	3588	1092	711
Catastrophic rupture	D5	5913	1497	583	121
	F1.5	16043	1695	579	265

Table C.1: Effect distances for rail transport in Breda

Table C.2: Effect distances for rail transport in Moerdijk

Scenario	Weather type	VRW [m]	AGW [m]	LBW [m]	Attention zone [m]
Leak	D5	8516	1915	857	696
	F1.5	8985	2315	1552	1156
Catastrophic rupture	D5	5933	1574	953	324
	F1.5	13758	1785	778	601

Table C.3: Effect distances for inland shipping in Moerdijk

Scenario	Weather type	VRW [m]	AGW [m]	LBW [m]	Attention zone [m]
Leak (75 mm)	D5	4232	1000	411	428
	F1.5	14344	3112	771	787
Leak (150 mm)	D5	9037	2077	807	790
	F1.5	22102	4458	1510	1437

Table C.4: Effect distances for inland shipping in Moerdijk

Scenario	Weather type	VRW [m]	AGW [m]	LBW [m]	Attention zone [m]
Leak (75 mm)	D5	4656	1128	524	536
	F1.5	12556	2029	1020	984
Leak (150 mm)	D5	11866	2516	1105	1102
	F1.5	18672	3428	2122	1966

Table C.5: Effect distances for pipeline transport in Breda

Scenario	Weather type	VRW [m]	AGW [m]	LBW [m]	Attention zone [m]
Leak	D5	2395	515	105	120
	F1.5	11893	2453	426	499
Breach	D5	13694	3257	1075	728
	F1.5	45801	10990	2522	3263

Table C.6: Effect distances for pipeline transport in Moerdijk

Scenario	Weather type	VRW [m]	AGW [m]	LBW [m]	Attention zone [m]
Leak	D5	3704	842	322	337
	F1.5	11387	1971	800	783
Breach	D5	23939	5393	2147	1576
	F1.5	48833	13188	4031	4747

C.3. Complete Effect Contours

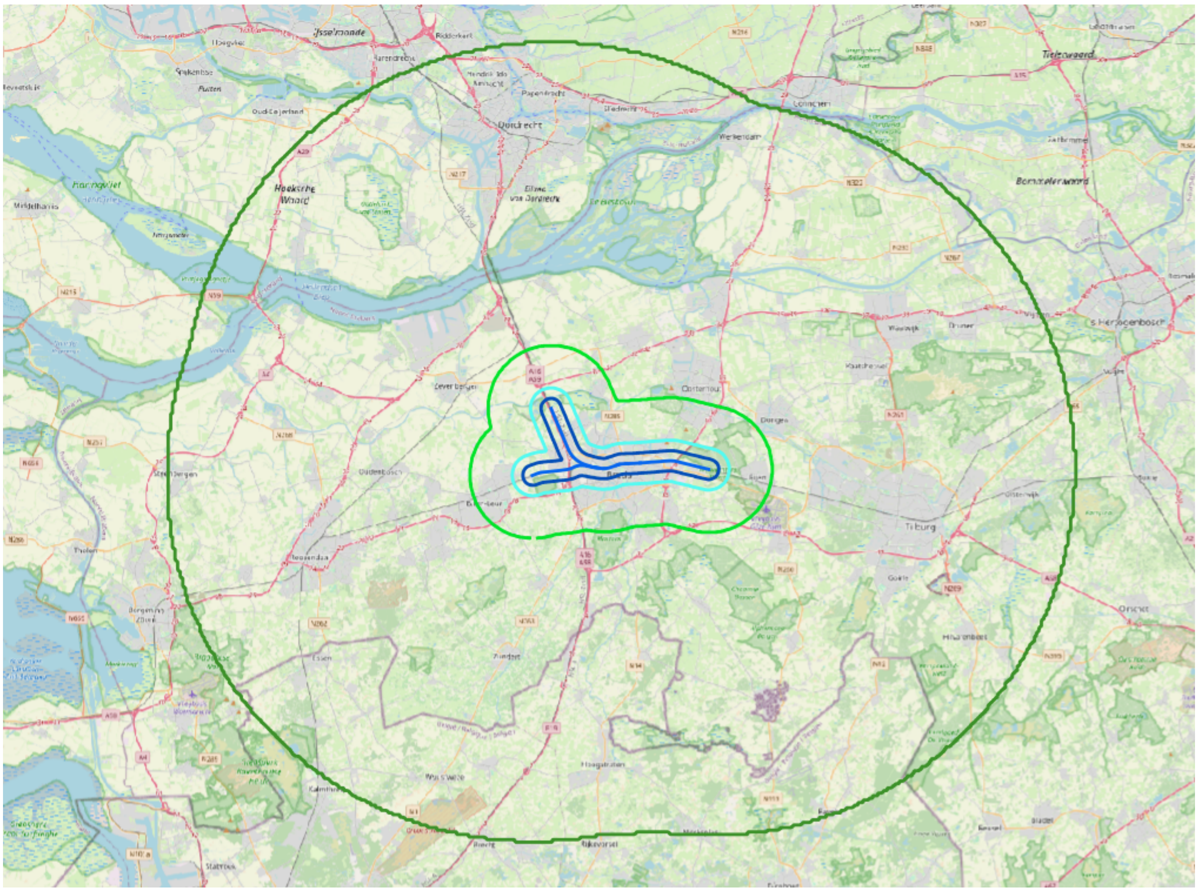

Figure C.2: All effect contours for rail transport in Breda

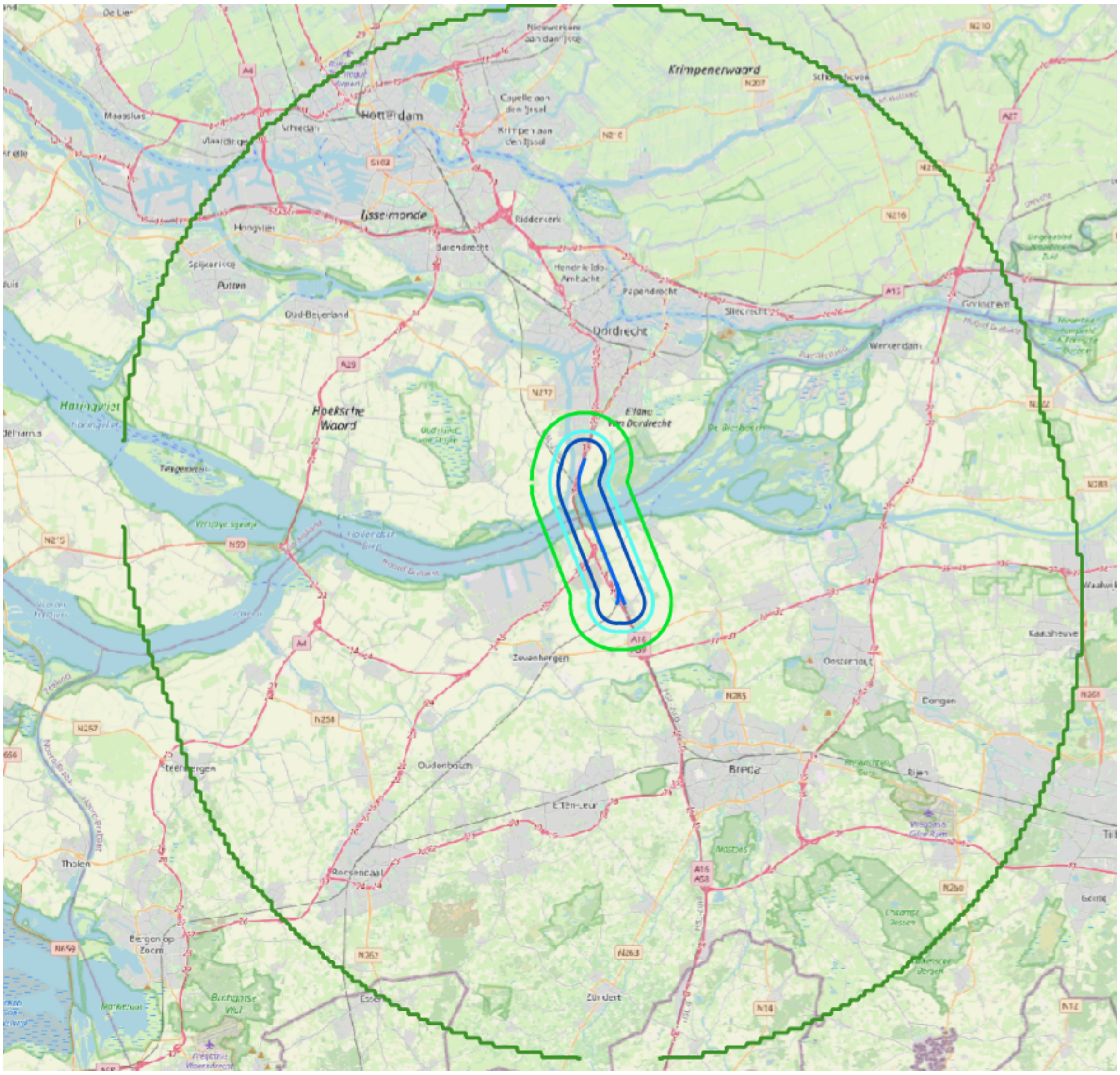

Figure C.3: All effect contours for rail transport in Moerdijk

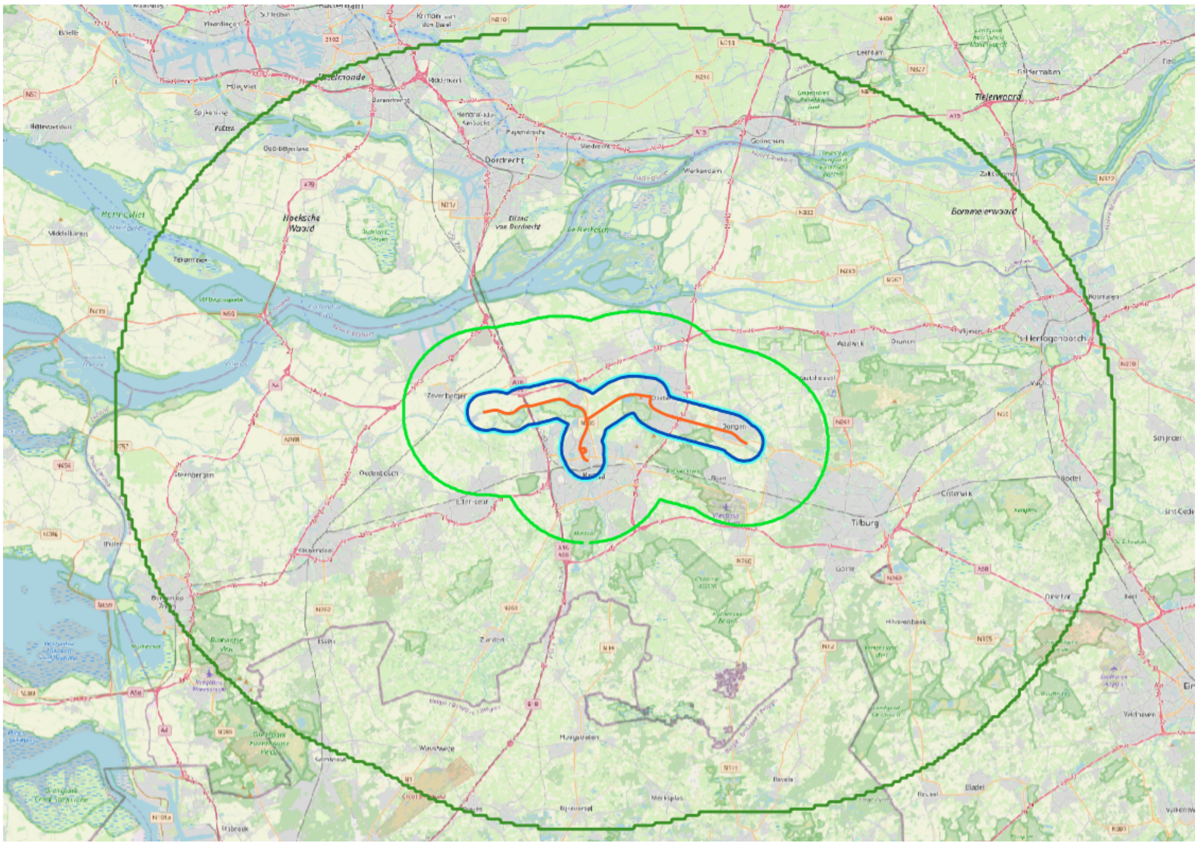

Figure C.4: All effect contours for inland shipping in Breda

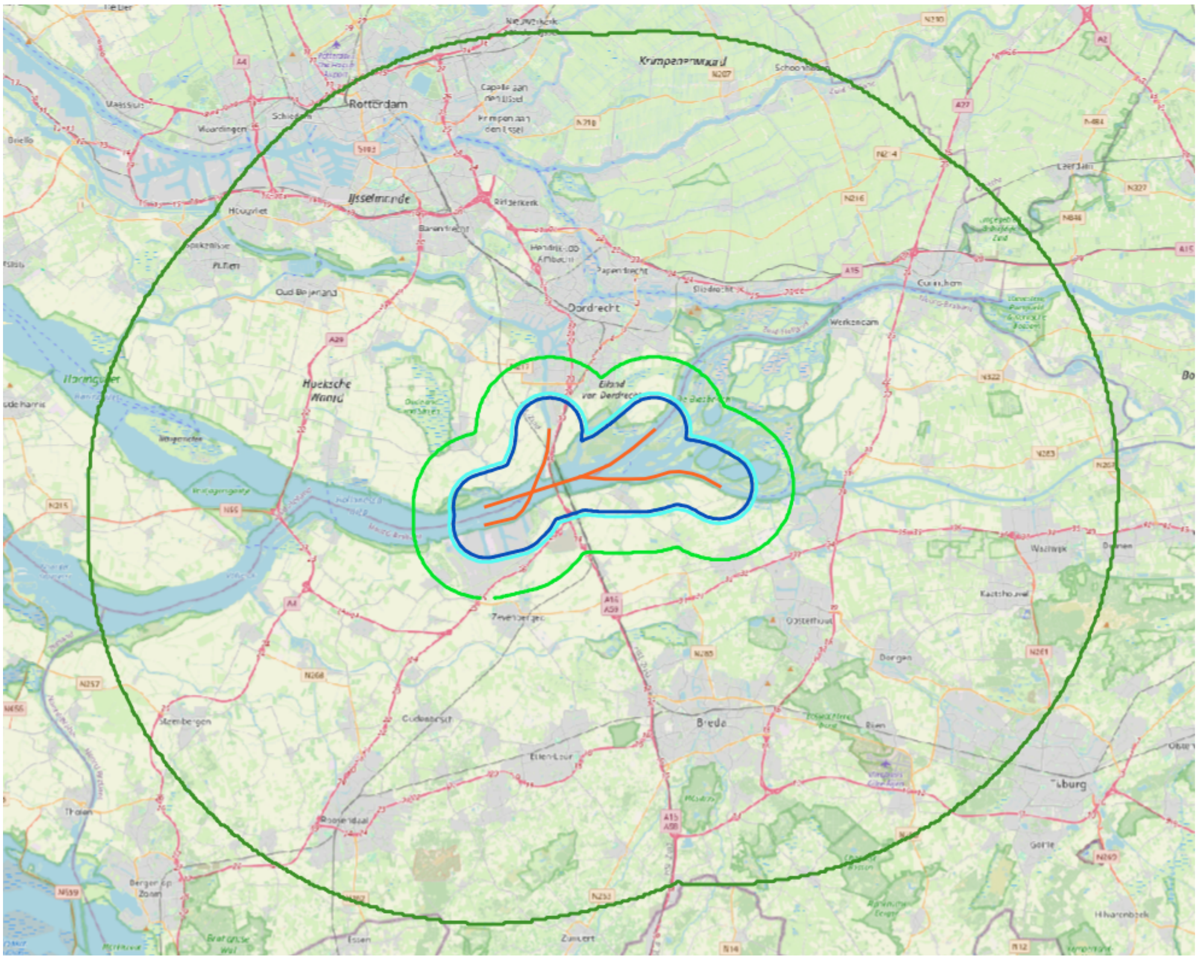

Figure C.5: All effect contours for inland shipping in Moerdijk

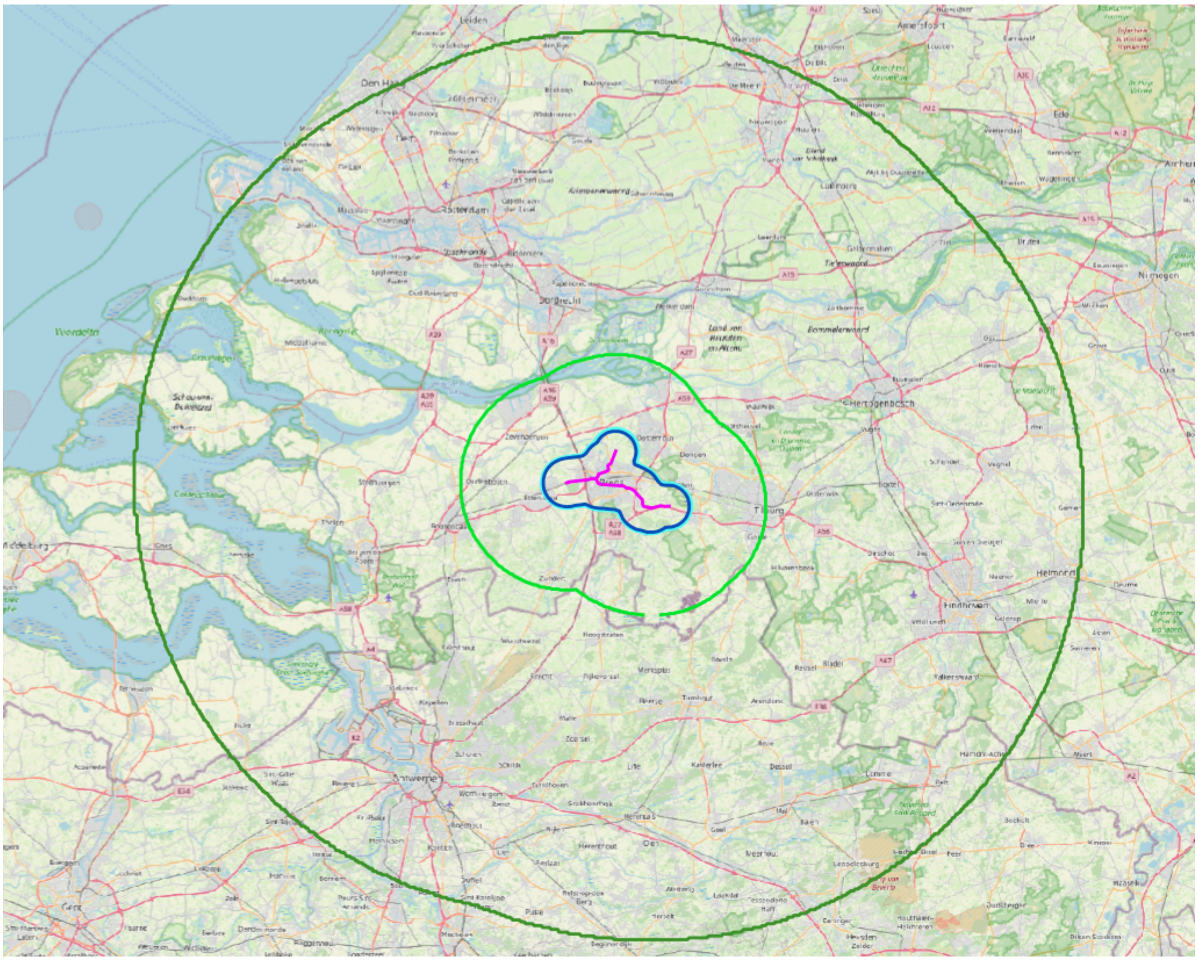

Figure C.6: All effect contours for pipeline transport in Breda

Figure C.7: All effect contours for pipeline transport in Moerdijk

D

Mitigation Measures

D.1. Adjusted Parameters

D.1.1. Rail Transport

This section shows the newly calculated scenario frequencies after implementing the mitigation measures for rail transport. Before the new frequencies for all measures can be calculated, it is shown how the new annual intensity for measure 4, smaller tanks, were calculated.

Annual intensity
The smaller tank volume was set to 40,000 kgs. The new annual intensity could then be calculated as follows:

$$\frac{6.27 \times 10^9}{40{,}000} = 1.57 \times 10^5 \tag{D.1}$$

New scenario frequencies
This is the overview of the newly calculated scenario frequencies for each rail transport mitigation measure. The formula that was used can be found in 4.1.1.1 (RIVM, 2025b).

Table D.1: Scenario parameters for Rail transport measure 1 (ETCS)

Rail type	Scenario type	Scenario frequency (Fs)	Model fraction (fm)	Annual intensity (Ns)	Consequence probability (Fb•Pu•Pv)
Rail Type C (urban)	Most probable	7.34×10^{-5}	0.92	1.25×10^5	7.4×10^{-10}
	Worst-case	6.38×10^{-6}	0.08	1.25×10^5	7.4×10^{-10}
Rail Type A (rural)	Most probable	6.15×10^{-6}	0.92	1.25×10^5	6.2×10^{-11}
	Worst-case	5.35×10^{-7}	0.08	1.25×10^5	6.2×10^{-11}

Table D.2: Scenario parameters for Rail transport measure 2 (crash buffer)

Rail type	Scenario type	Scenario frequency (Fs)	Model fraction (fm)	Annual intensity (Ns)	Consequence probability (Fb•Pu•Pv)
Rail Type C (urban)	Most probable	7.85×10^{-5}	0.92	1.25×10^{5}	7.4×10^{-10}
	Worst-case	6.83×10^{-6}	0.08	1.25×10^{5}	7.4×10^{-10}
Rail Type A (rural)	Most probable	6.58×10^{-6}	0.92	1.25×10^{5}	6.2×10^{-11}
	Worst-case	5.72×10^{-7}	0.08	1.25×10^{5}	6.2×10^{-11}

Table D.3: Scenario parameters for Rail transport measure 3 (lower speeds)

Rail type	Scenario type	Scenario frequency (Fs)	Model fraction (fm)	Annual intensity (Ns)	Consequence probability (Fb•Pu•Pv)
Rail Type C (urban)	Most probable	1.88×10^{-5}	0.92	1.25×10^{5}	1.63×10^{-10}
	Worst-case	1.63×10^{-6}	0.08	1.25×10^{5}	1.63×10^{-10}
Rail Type A (rural)	Most probable	1.00×10^{-6}	0.92	1.25×10^{5}	8.68×10^{-12}
	Worst-case	8.71×10^{-8}	0.08	1.25×10^{5}	8.68×10^{-12}

Table D.4: Scenario parameters for Rail transport measure 4 (smaller tank)

Rail type	Scenario type	Scenario frequency (Fs)	Model fraction (fm)	Annual intensity (Ns)	Consequence probability (Fb•Pu•Pv)
Rail Type C (urban)	Most probable	1.07×10^{-4}	0.92	1.57×10^{5}	7.4×10^{-10}
	Worst-case	9.28×10^{-6}	0.08	1.57×10^{5}	7.4×10^{-10}
Rail Type A (rural)	Most probable	8.94×10^{-6}	0.92	1.57×10^{5}	6.2×10^{-11}
	Worst-case	7.77×10^{-7}	0.08	1.57×10^{5}	6.2×10^{-11}

Table D.5: Scenario parameters for rail transport with all measures combined

Rail type	Scenario type	Scenario frequency (Fs)	Ammonia/tank (kg)
Rail Type C (urban)	Most probable	6.94×10^{-5}	4.00×10^{4}
	Worst-case	6.03×10^{-6}	4.00×10^{4}
Rail Type A (rural)	Most probable	5.67×10^{-6}	4.00×10^{4}
	Worst-case	4.93×10^{-7}	4.00×10^{4}

The scenario frequencies shown in Table D.5 represent the average expected frequencies when all four rail transport measures (ETCS, crash buffers, lower speeds, and smaller tank volume) are implemented simultaneously. To derive these values, the scenario frequencies from each individual measure were added together and divided by the number of measures (four). This approach provides an indicative frequency value under the assumption that each measure contributes equally and independently to the overall risk reduction.

D.1.2. Inland Shipping

This section further elaborates the adjusted parameters resulting from the mitigation measures

Adjusted basic accident frequency
Table D.6 shows the overview of the newly calculated scenario frequency for the first inland shipping

mitigation measure. This is the only measure that alters the scenario frequency. The formula that was applied can be found in Section 4.1.1.1 (RIVM, 2025b).

Table D.6: Scenario parameters for Inland shipping measure 1 (advanced navigation systems)

Shipping class	**Scenario type**	**Scenario frequency (Fs)**	**Consequence probabilities (Pu • Pv • fm)**	**Basic accident frequency (Fb)**	**Annual intensity (Ns)**
Navigability Class IV (urban)	Most probable	2.21×10^{-6}	5.50×10^{-3}	8.67×10^{-8}	4.64×10^{3}
	Worst-case	1.06×10^{-8}	2.64×10^{-5}	8.67×10^{-8}	4.64×10^{3}
Navigability Class VI (rural)	Most probable	4.64×10^{-6}	1.25×10^{-2}	8.00×10^{-8}	4.64×10^{3}
	Worst-case	2.23×10^{-8}	6.00×10^{-5}	8.00×10^{-8}	4.64×10^{3}

Tank outflow under waterline
The new input parameter for the tank capacity is represented by the following formula, as only 65% of the ammonia reaches the surface and then only 20% dissolves into the atmosphere:

$$225{,}000 \times 0.65 \times 0.20 = 29{,}250 \text{ kg} \tag{D.2}$$

Smaller shipping tanks
The new amount of ammonia the the inland shipping tanks when the number of tanks is increased from 6 to 8 tanks, is:

$$225{,}000 \times 6 \div 8 = 168{,}750 \text{ kg} \tag{D.3}$$

D.1.3. Pipeline Transport

This section further elaborates the adjusted parameters that were chosen for the mitigated scenarios of pipeline transport.

New failure frequencies
This section provides an overview of the newly calculated failure frequencies for the two pipeline transport risk mitigation measure. These values can be calculated by correcting the original failure frequencies by using the correction factors corresponding to each mitigation measure.

Table D.7: Failure frequencies for different failure causes in pipeline transport.

Failure cause	**Leak** *Failure frequency*	**Breach** *Failure frequency*
Third-party (corrected for 1.5 m depth)	5.40×10^{-6}	3.63×10^{-6}
Mechanical	3.86×10^{-5}	7.96×10^{-6}
Corrosion	4.69×10^{-5}	5.66×10^{-6}
Natural causes	3.60×10^{-6}	4.25×10^{-6}
Operational	4.56×10^{-6}	2.26×10^{-6}
Total	$\mathbf{9.91 \times 10^{-5}}$	$\mathbf{2.38 \times 10^{-5}}$

Table D.7 provides an overview of the original failure frequencies associated with different causes in pipeline transport, which was previously provided in Appendix B.4. It distinguishes between ”most probable” and ”worst-case” scenarios. The third-party failure rate has already been corrected for a pipeline burial depth of 1.5 metres in this overview. The totals per scenario represent the cumulative failure frequencies across all categories. Measure 1 (warning tape) and 2 (strict supervision) alter the total failure frequency as they reduce the total third-party interference. Table D.8 shows the correction factors for these measures, retrieved from RIVM (2025c), how these measures change the third-party failure frequency and how this also changes the total failure frequencies.

Table D.8: Failure frequencies for pipeline transport, adjusted for correction factors.

Measure	Scenario	Correction factor	Third-party failure frequency	Total failure frequency
Warning tape	Leak	1.67	3.23×10^{-6}	9.69×10^{-5}
	Breach		2.17×10^{-6}	2.23×10^{-5}
Strict supervision	Leak	3	1.80×10^{-6}	9.55×10^{-5}
	Breach		1.21×10^{-6}	2.13×10^{-5}
Combined	Leak	4.17	1.29×10^{-6}	1.90×10^{-4}
	Breach		8.71×10^{-7}	4.20×10^{-5}

When both these pipeline risk-reduction measures are implemented in combination, their collective effect on risk reduction is slightly less than the sum of their individual effects. This is because the measures partially address the same failure mechanisms and therefore overlap in impact. To account for this interaction, a correction factor of 4.17 is applied instead of the full cumulative factor of 4.67 (RIVM, 2025c). This adjusted factor more accurately reflects the diminished marginal contribution of one measure when the other is already in place.

Number of valves

Based on international pipeline safety standards such as ASME B31.4, the maximum recommended valve spacing in urban high-risk areas is 8 km, while rural areas may allow for 16 to 32 km spacing (American Society of Mechanical Engineers (ASME), 2022). To ensure conservative safety assumptions, this study applies an 8 km spacing for the 22.4 km of pipeline passing through the urban area of Breda, and a 16 km spacing for the 13.5 km through the rural surroundings of Moerdijk. In Breda, the pipelines were separated in two parts, with one being 9.8 km and the other 12.6 km. In both parts, two valves were placed. As a result, four valves were assumed for the Breda section and one for the Moerdijk section, totaling five emergency shut-off valves in the modelled pipeline network.

Valve distance from upstream end of the pipeline In Safeti-NL, a valve distance of 500 metres from the upstream end of the pipeline was assumed for both locations as rapid isolation is essential. As Breda has four valves, the two valves of the first pipeline are placed at 500 meters and the second at 8500, and the two valves of the second pipeline are placed at 4500 and 12500 meters, which reflects a total of 8000 m from each previous valve.

Valve closing time

The valve closing time was set to 60 seconds, reflecting typical performance of automatic shut-off valves in high-pressure ammonia pipelines, as advised by international standards such as the DNV-RP-F107 (DNV, 2019).

Probability of failure

The probability of valve failure was set to 0.01, reflecting a conservative estimate based on expert recommendations from an RIVM employee.

Detection probability

Detection probability refers to the likelihood that a release is noticed and acted upon. It depends on the visibility of the incident, monitoring infrastructure, and human response capacity (Tian et al., 2022). In consultation with an RIVM employee specialized in Pipeline transport in Safeti-NL the assumed detection probabilities per scenario type were set to:

Scenario 1 (leak)

- Urban: 1
- Rural: 0.9

Scenario 2 (rupture)

- Urban: 1
- Rural: 1

As it is assumed there will be extensive monitoring systems in the ammonia pipelines, it is expected that all ruptures will be detected, as well as all leaks in Breda. In Moerdijk a small chance that a leak cannot be detected is included, in case the automated shut down system doesn't work and visual confirmation should take over. As it is less populated a small chance is assumed that this will not be detected.

Detection time
Detection time reflects the expected time delay between the start of a release and the moment it is recognised and responded to. It is influenced by both technology like automated alarms and organisational processes like manual confirmation. The assumed detection times are:

Scenario 1 (leak)

- Urban: 10 s
- Rural: 30 s

Scenario 2 (rupture)

- Urban: 0 s
- Rural: 0 s

Ruptures cause immediate pressure drops, noise, and visible dispersion, leading to much faster detection compared to leaks. Therefore, it was assumed these were detected immediately and responded to automatically. Leaks may go unnoticed for a bit longer. In urban areas, alarm response and visual detection are typically faster due to proximity of people than in rural areas. Therefore, leaks in Moerdijk may persist unnoticed for slightly longer periods. However, the leaks are still detected within a minute as it is assumed strict monitoring will take place of the ammonia pipeline. These detection times were used as baseline inputs in the Safeti-NL model.

D.2. Mitigated PR-Contours

The following sections give an overview of all the PR-contours in the mitigated scenarios for each transport mode.

D.2.1. Rail Transport

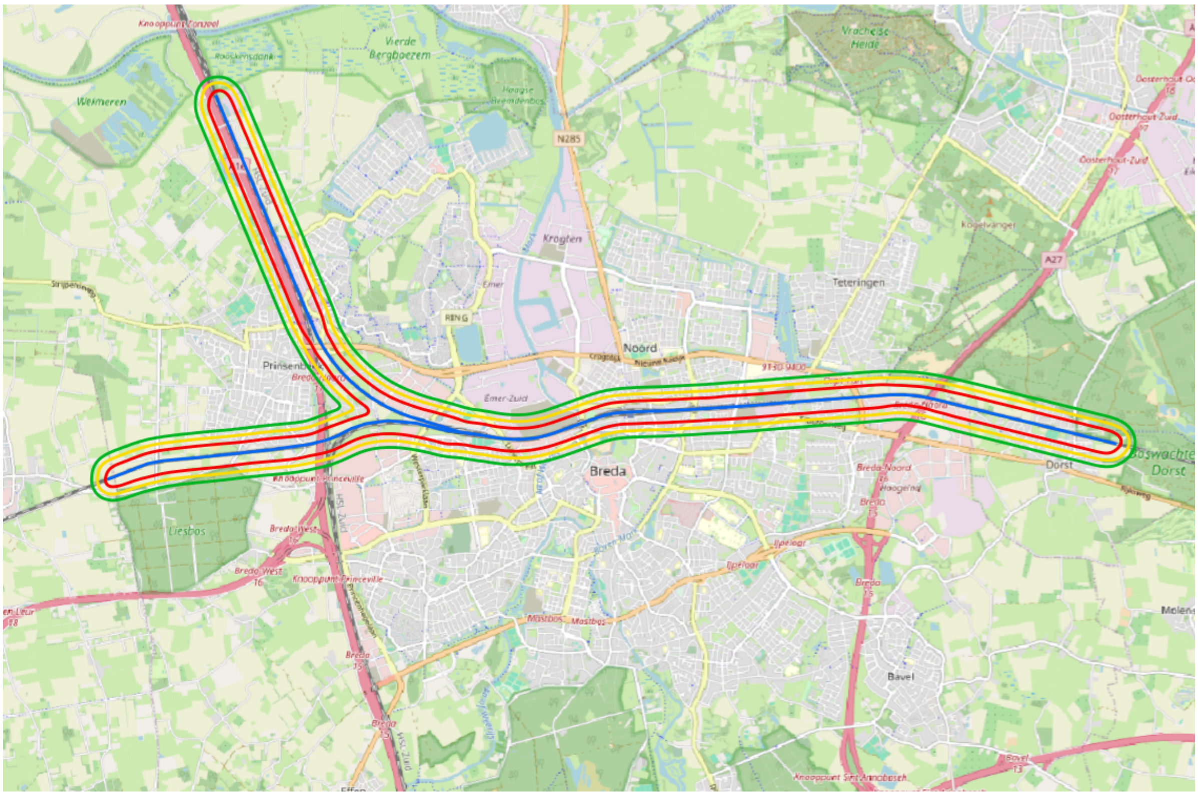

Figure D.1: Rail transport PR-contours after implementing mitigation measure 1 in Breda

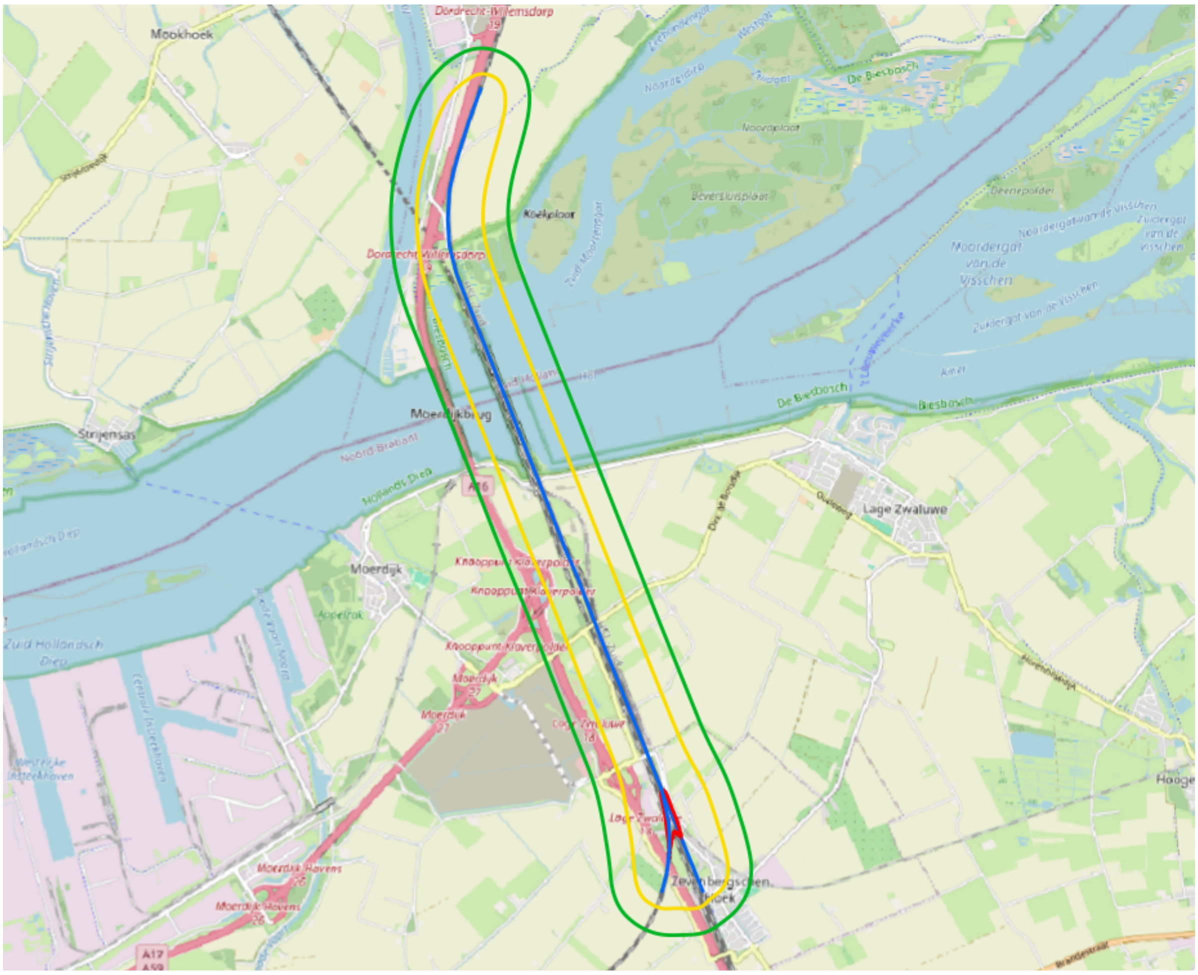

Figure D.2: Rail transport PR-contours after implementing mitigation measure 1 in Moerdijk

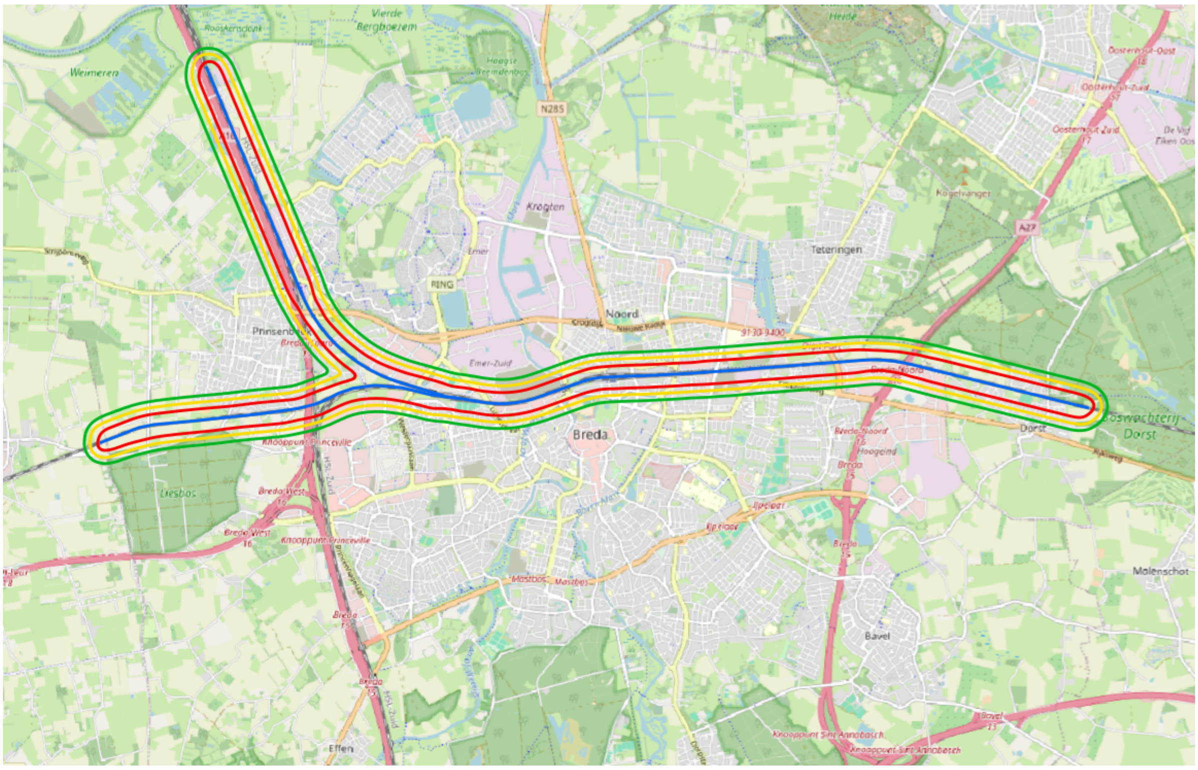

Figure D.3: Rail transport PR-contours after implementing mitigation measure 2 in Breda

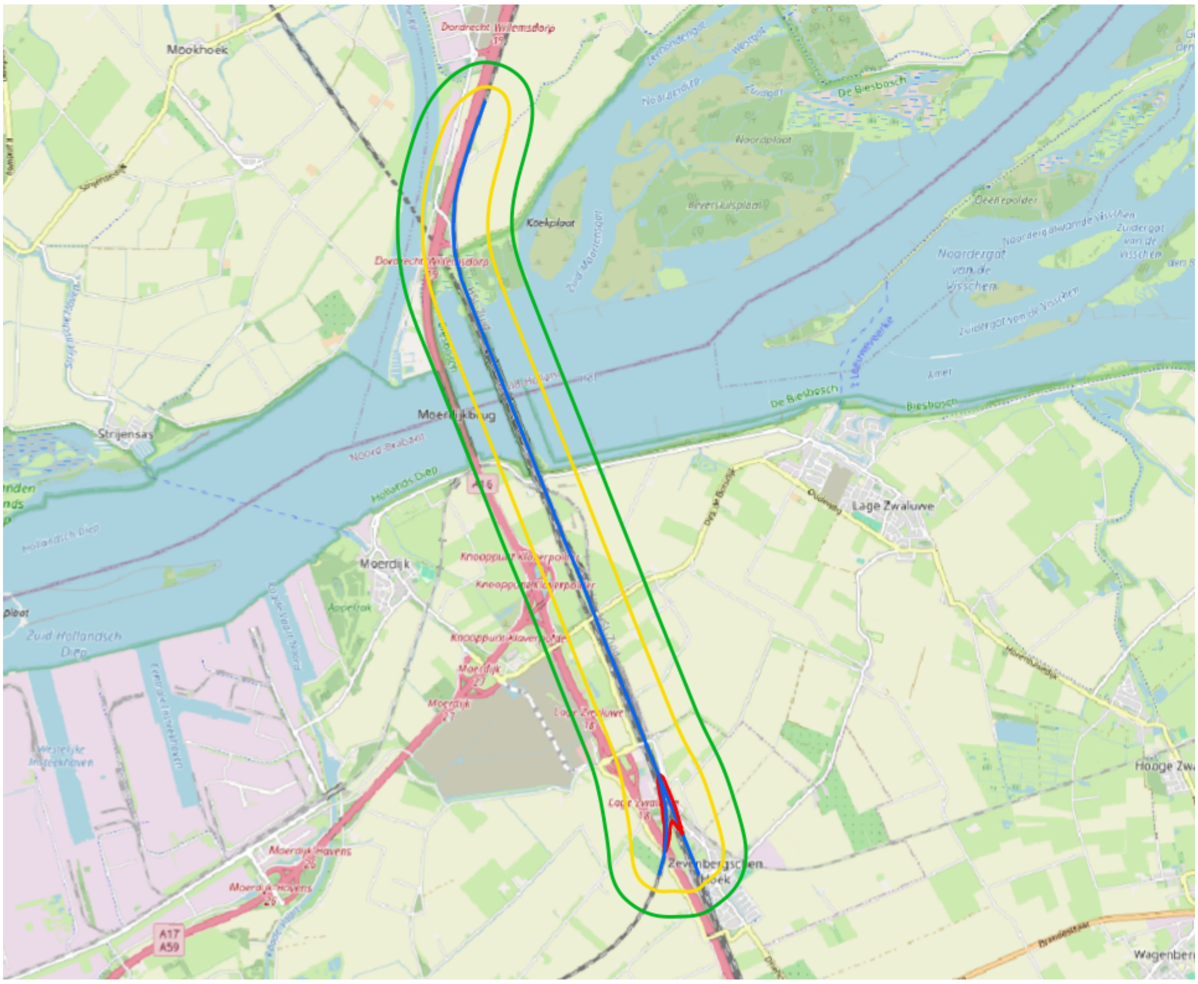

Figure D.4: Rail transport PR-contours after implementing mitigation measure 2 in Moerdijk

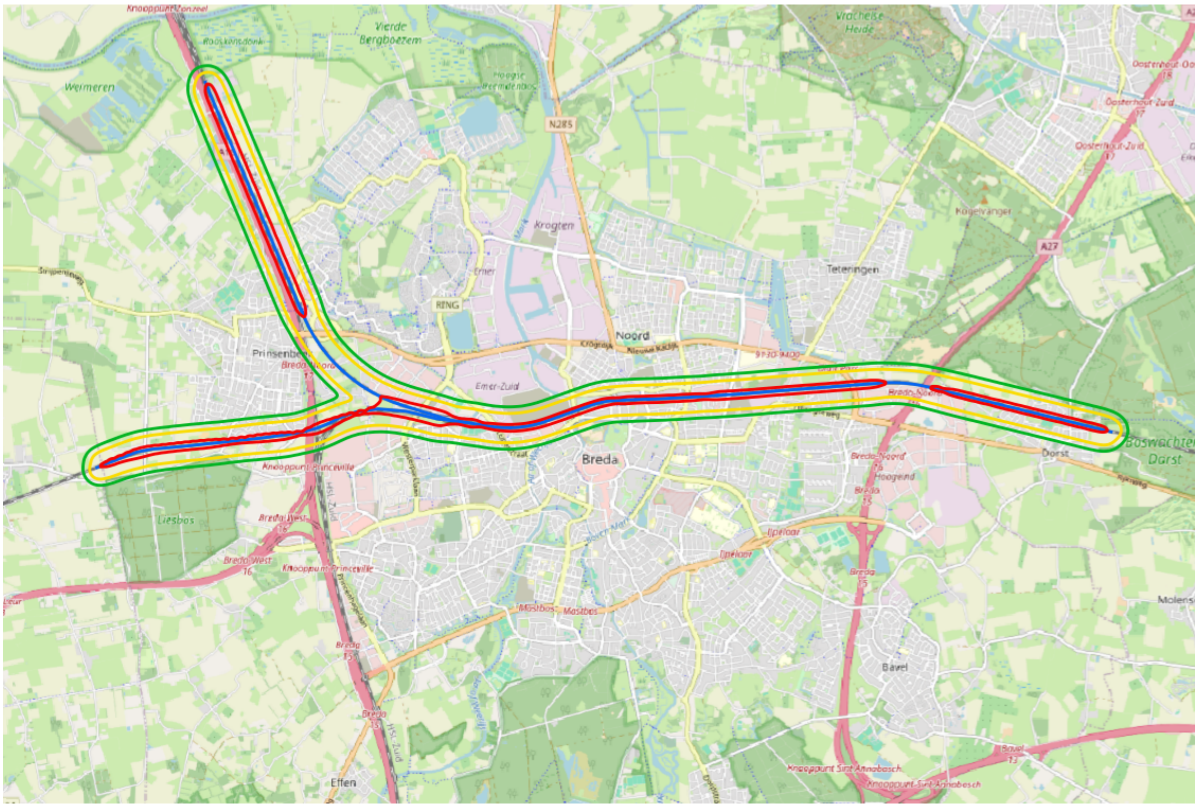

Figure D.5: Rail transport PR-contours after implementing mitigation measure 3 in Breda

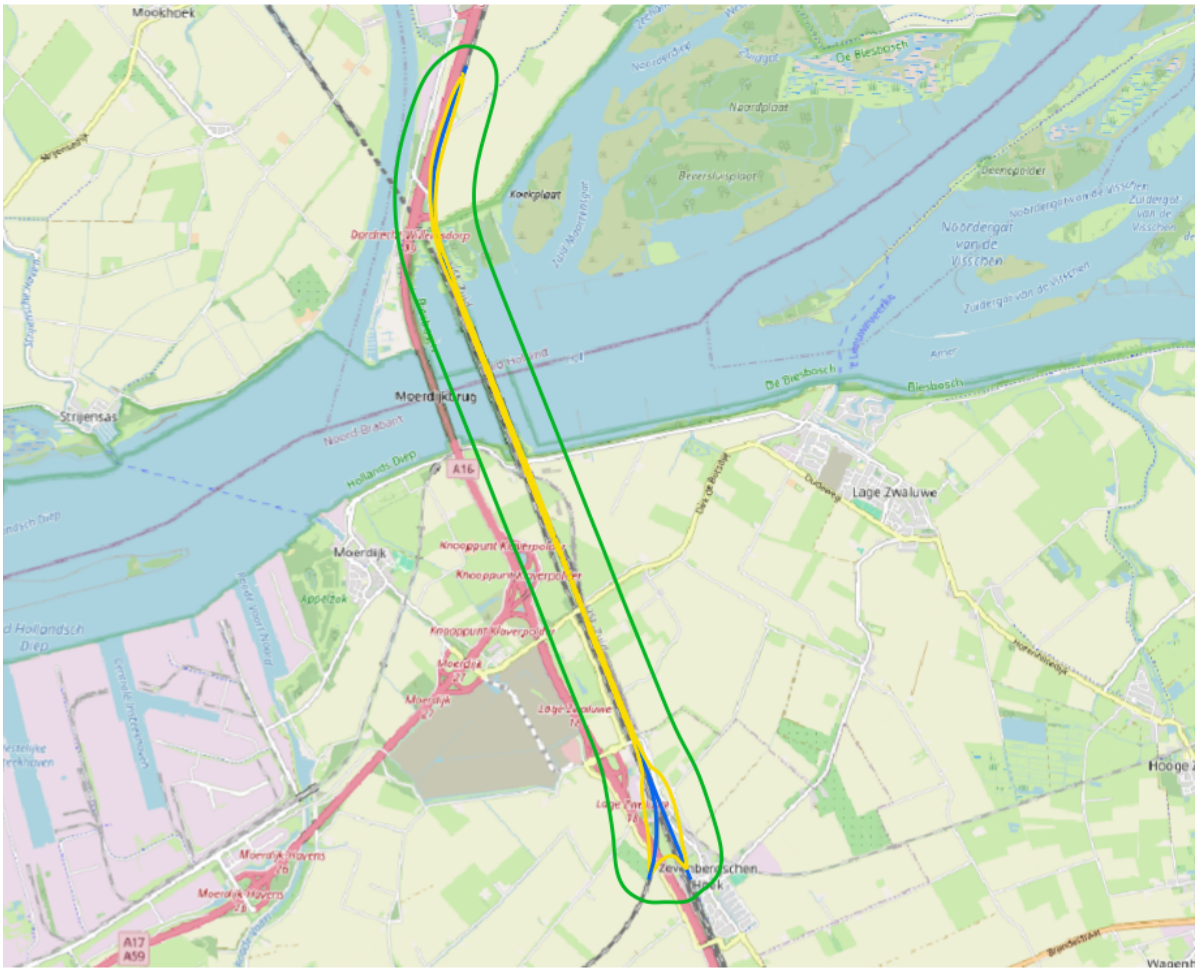

Figure D.6: Rail transport PR-contours after implementing mitigation measure 3 in Moerdijk

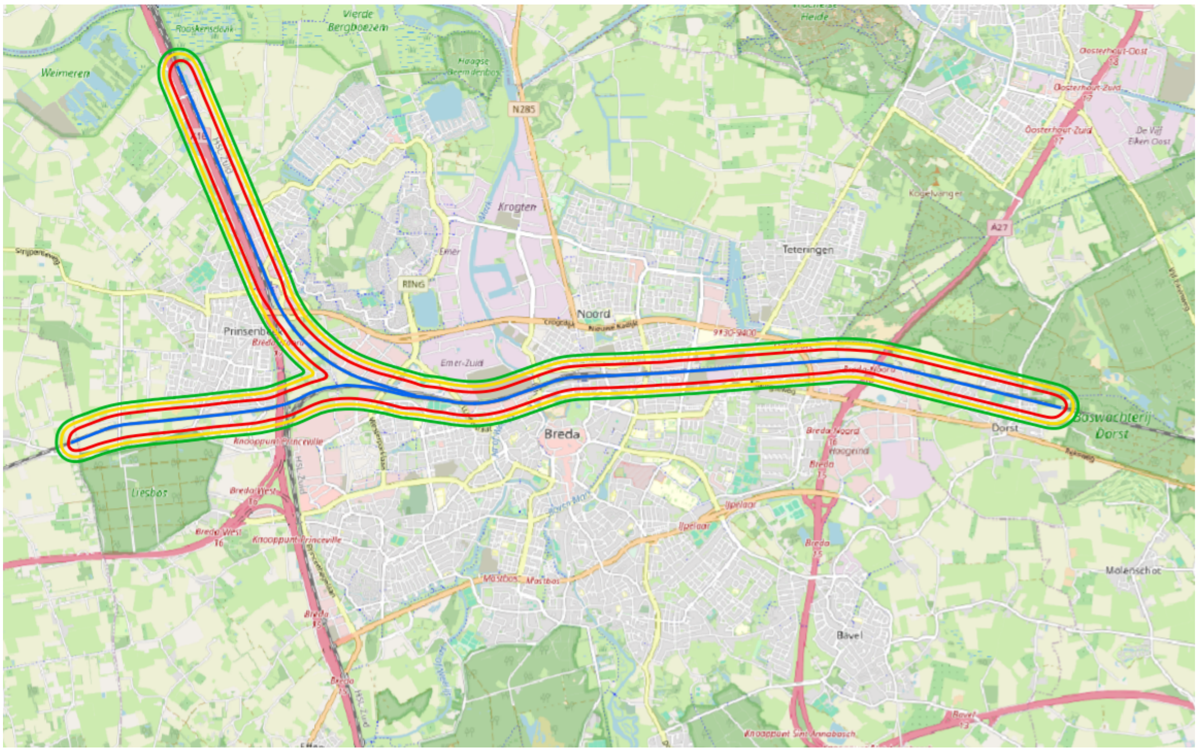

Figure D.7: Rail transport PR-contours after implementing mitigation measure 4 in Breda

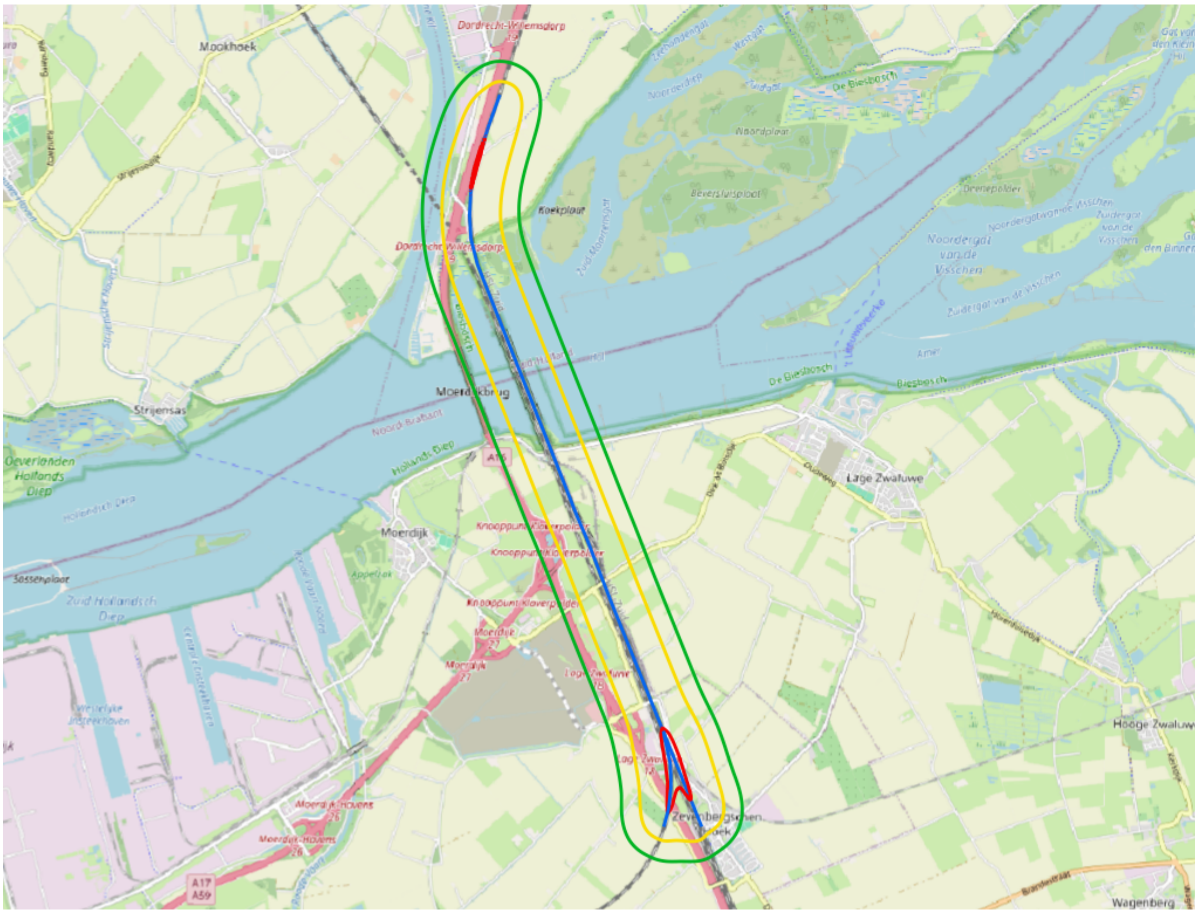

Figure D.8: Rail transport PR-contours after implementing mitigation measure 4 in Moerdijk

D.2.2. Inland Shipping

There is no adjusted PR-contour for measure 1 in Breda as the advanced navigation and communications system has a negligible influence here. This contour is equal to the PR-contour in the base case.

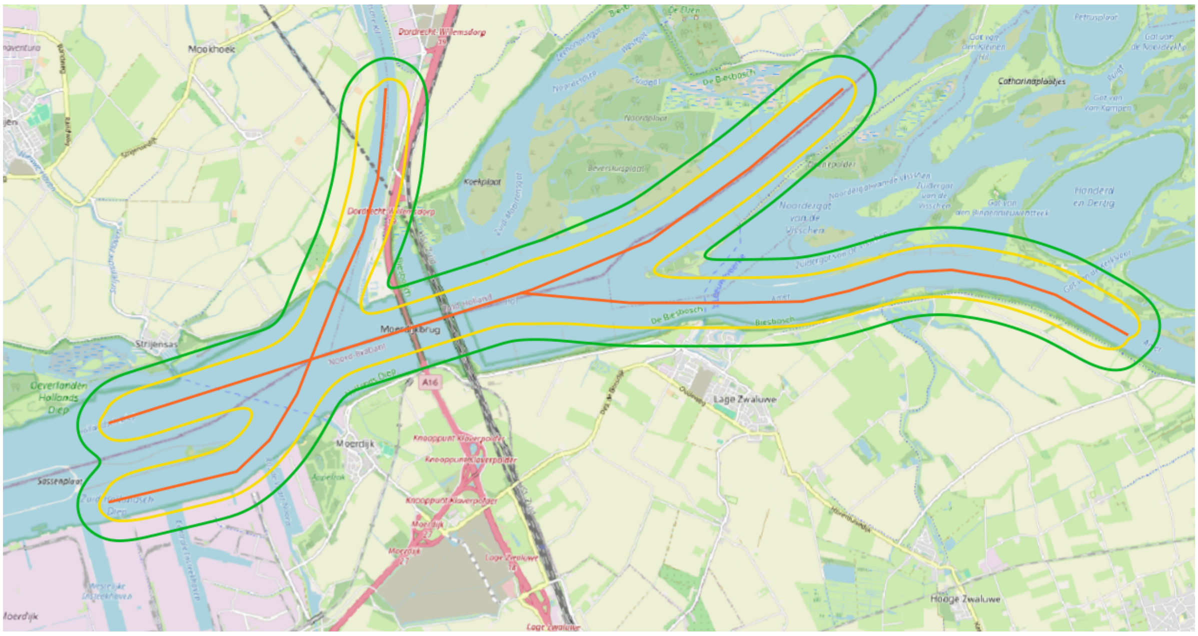

Figure D.9: Inland shipping PR-contours after implementing mitigation measure 1 in Moerdijk

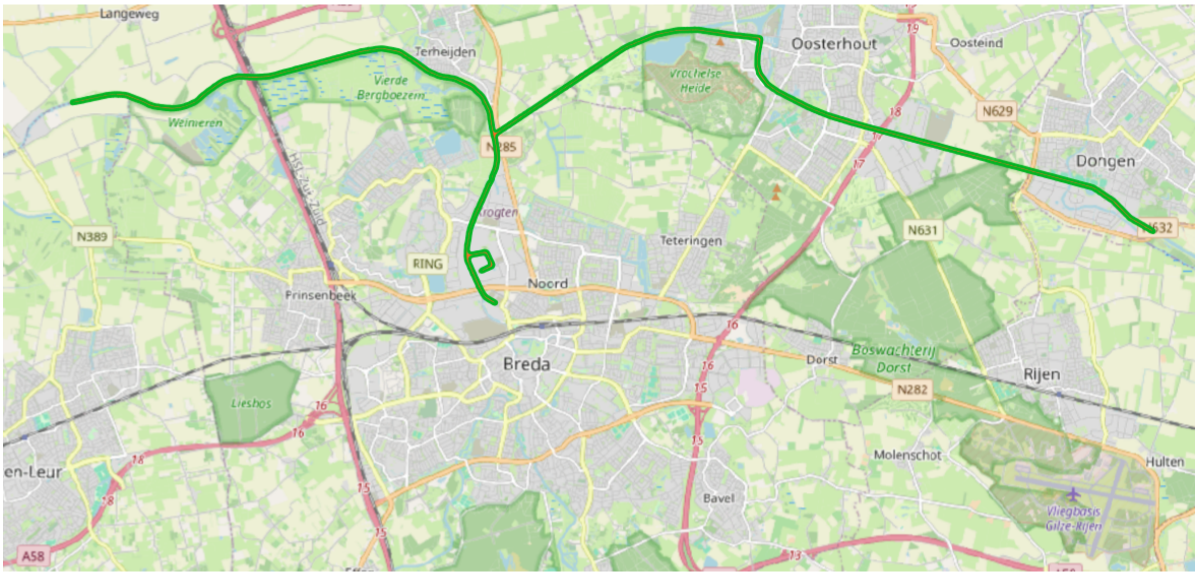

Figure D.10: Inland shipping PR-contours after implementing mitigation measure 2 in Breda

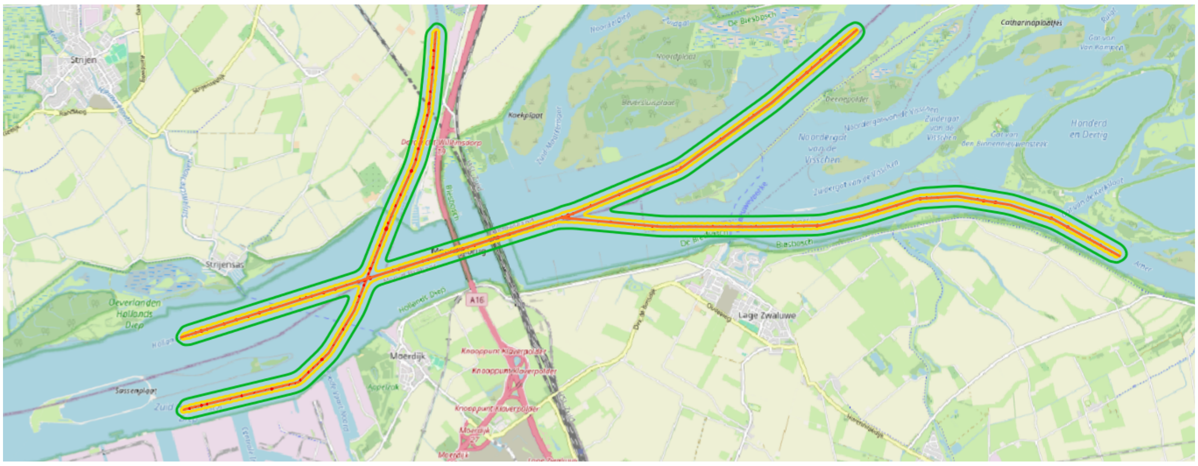

Figure D.11: Inland shipping PR-contours after implementing mitigation measure 2 in Moerdijk

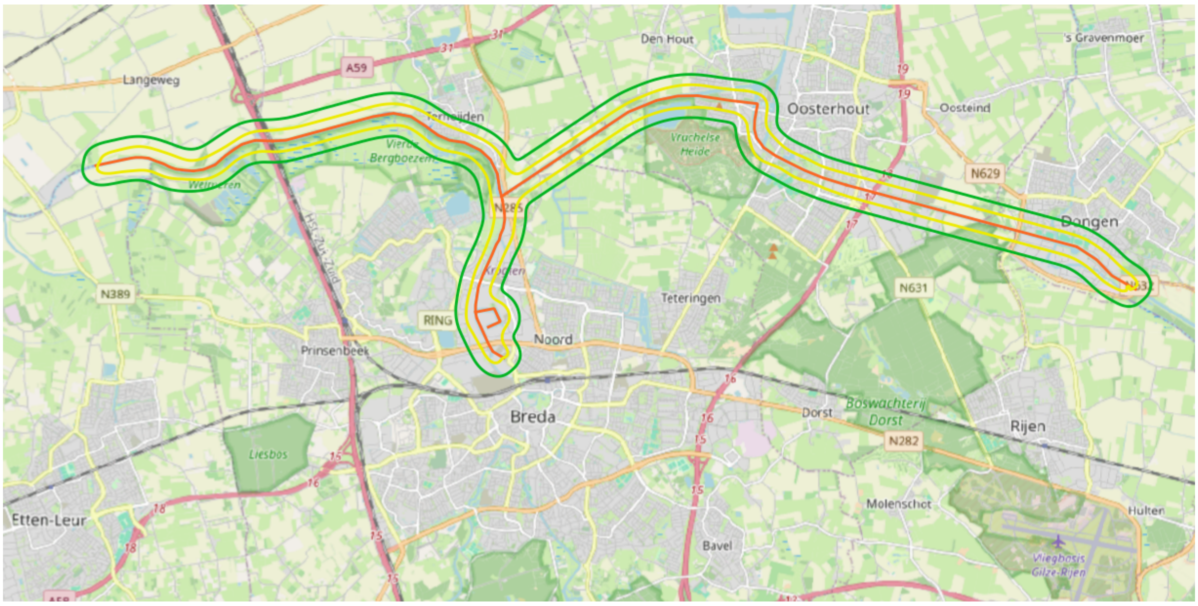

Figure D.12: Inland shipping PR-contours after implementing mitigation measure 3 in Breda

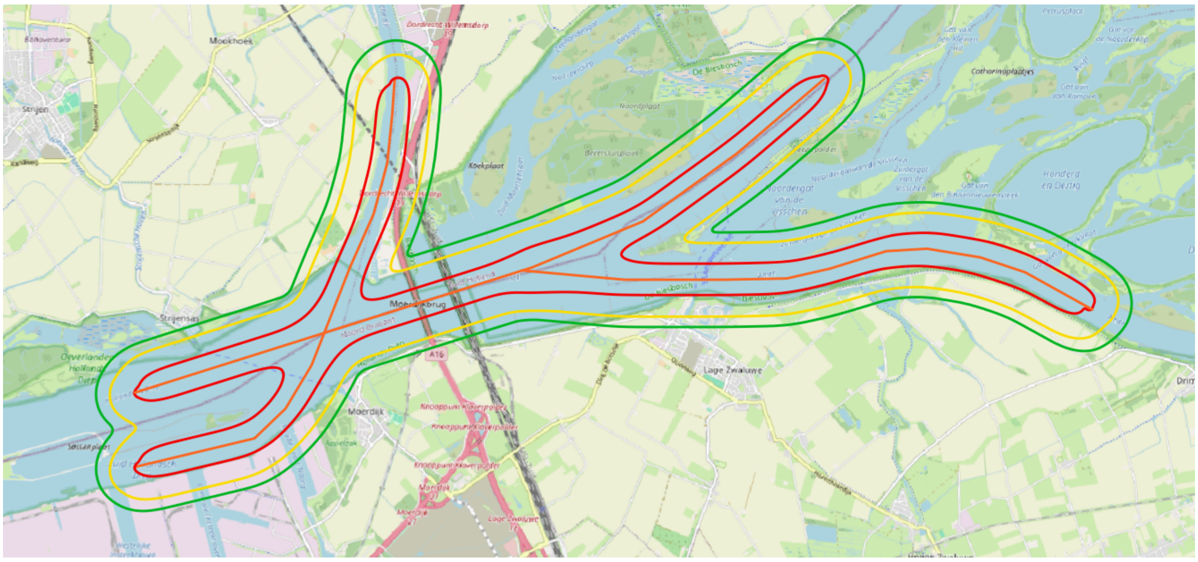

Figure D.13: Inland shipping PR-contours after implementing mitigation measure 3 in Moerdijk

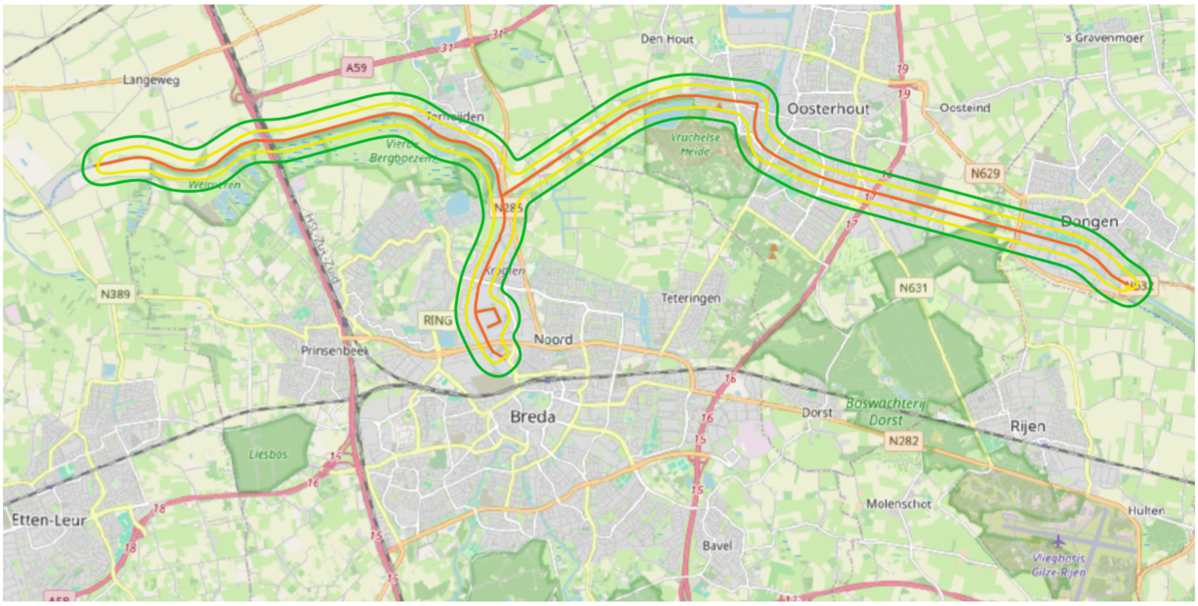

Figure D.14: Inland shipping PR-contours after implementing mitigation measure 4 in Breda

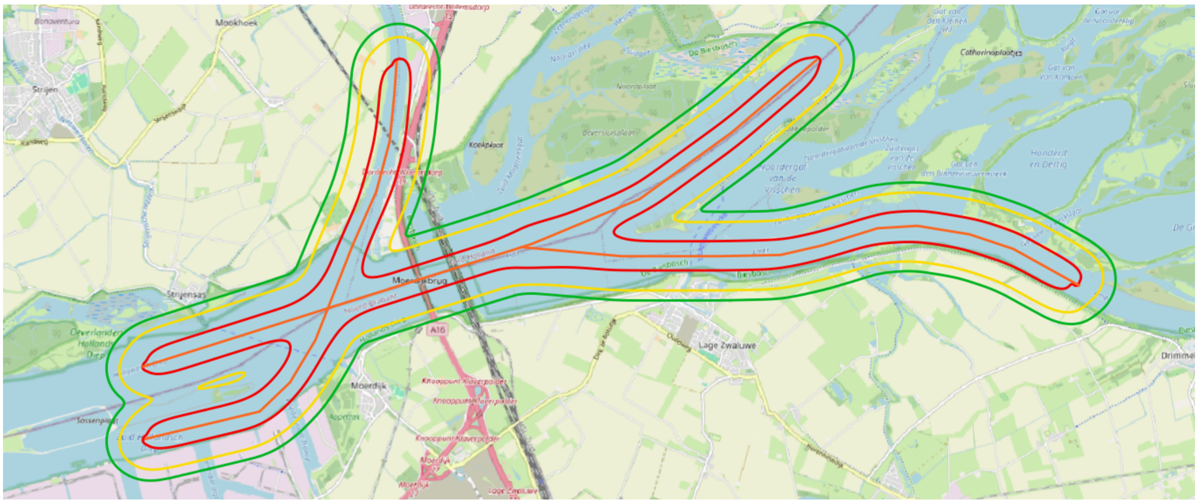

Figure D.15: Inland shipping PR-contours after implementing mitigation measure 4 in Moerdijk

D.2.3. Pipeline Transport

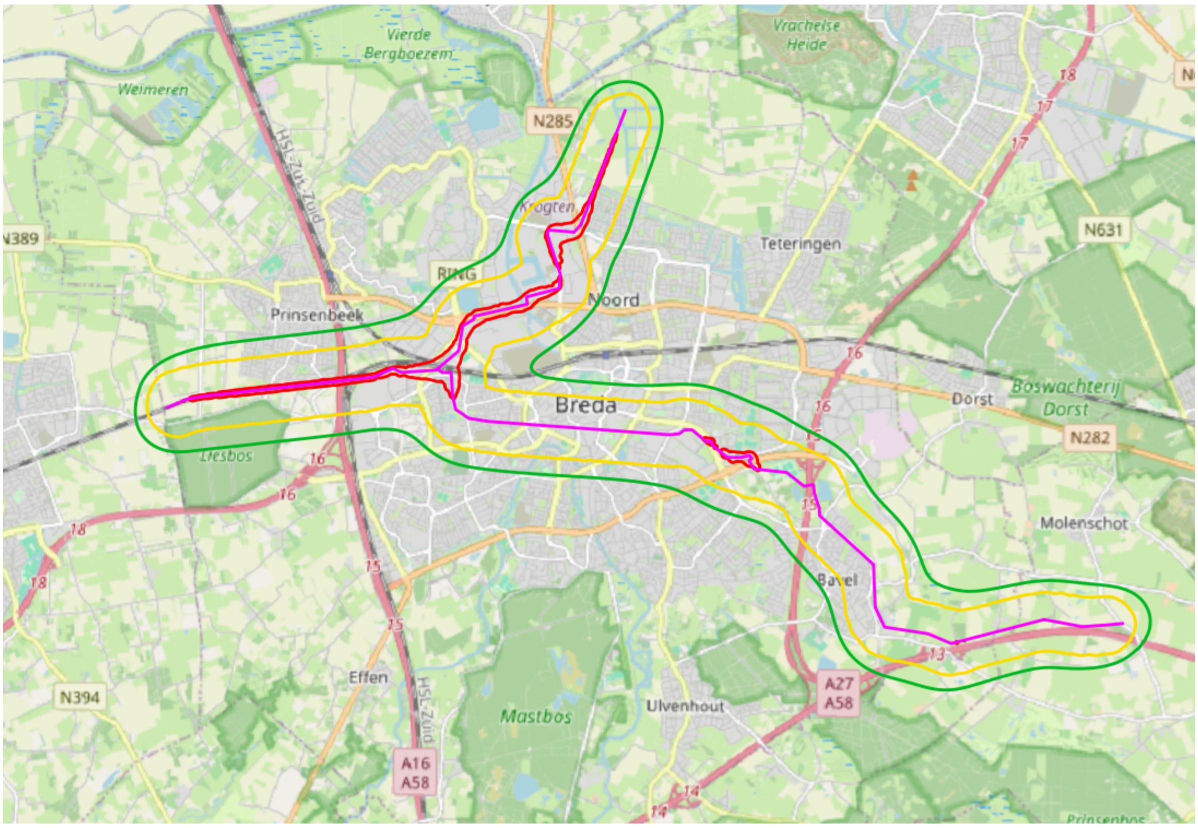

Figure D.16: Pipeline transport PR-contours after implementing mitigation measure 1 in Breda

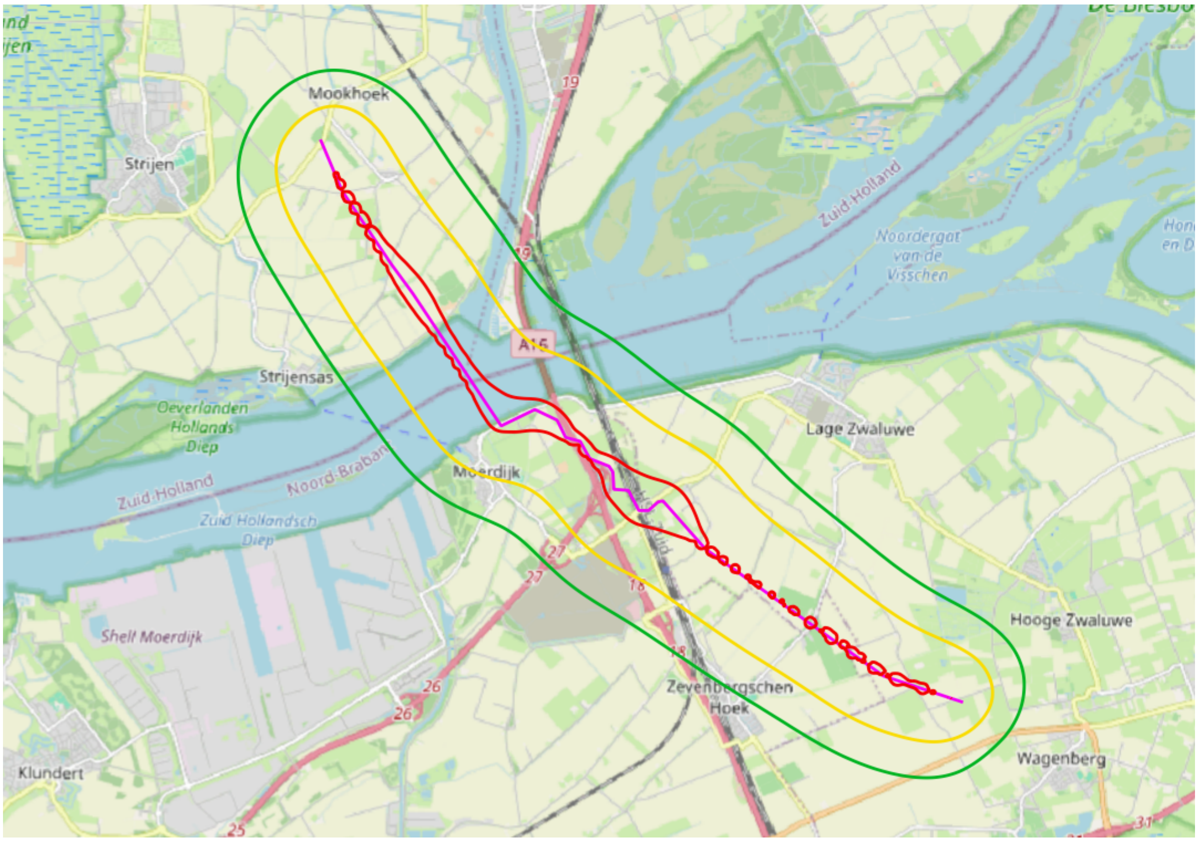

Figure D.17: Pipeline transport PR-contours after implementing mitigation measure 1 in Moerdijk

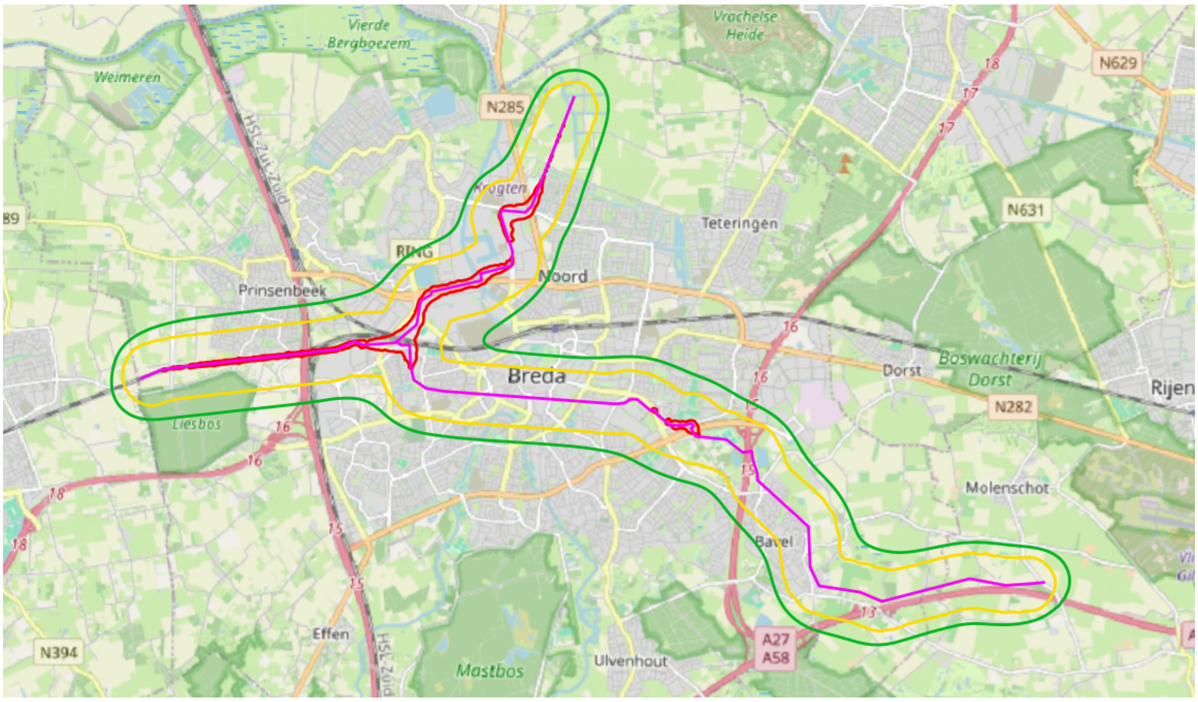

Figure D.18: Pipeline transport PR-contours after implementing mitigation measure 2 in Breda

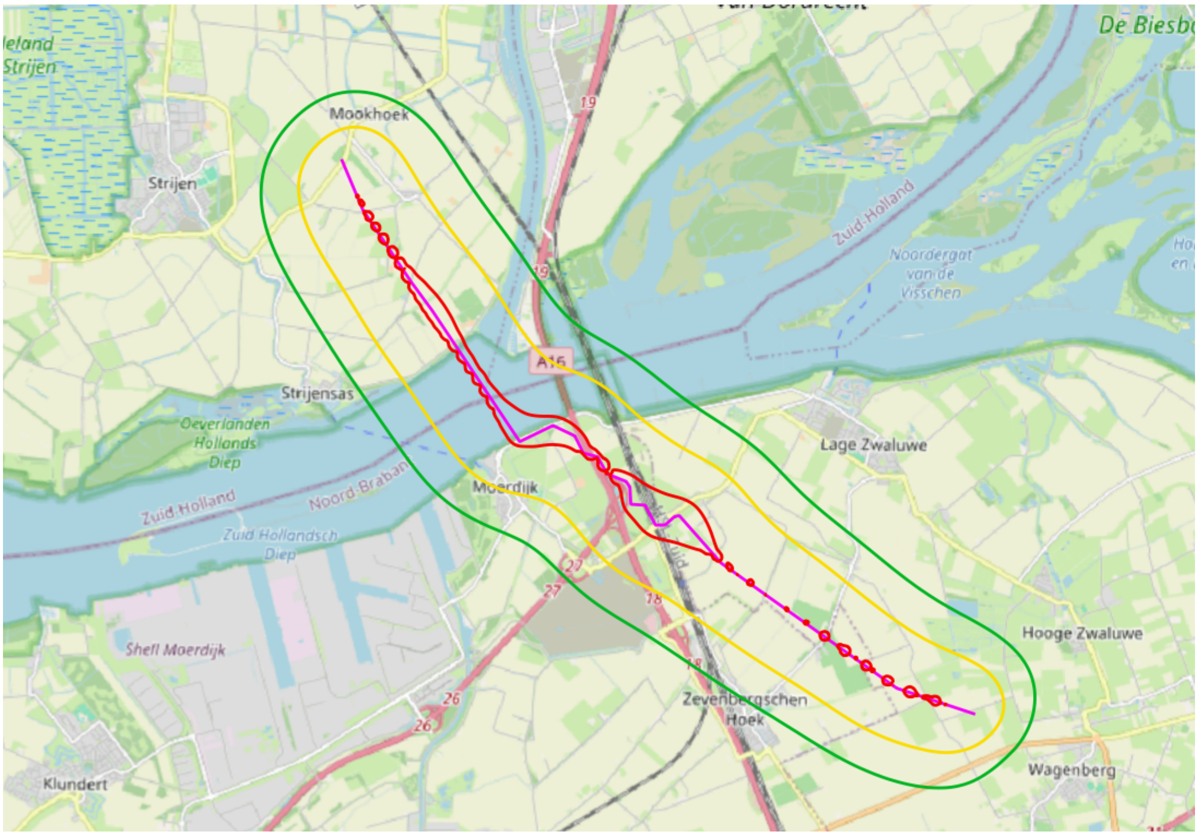

Figure D.19: Pipeline transport PR-contours after implementing mitigation measure 2 in Moerdijk

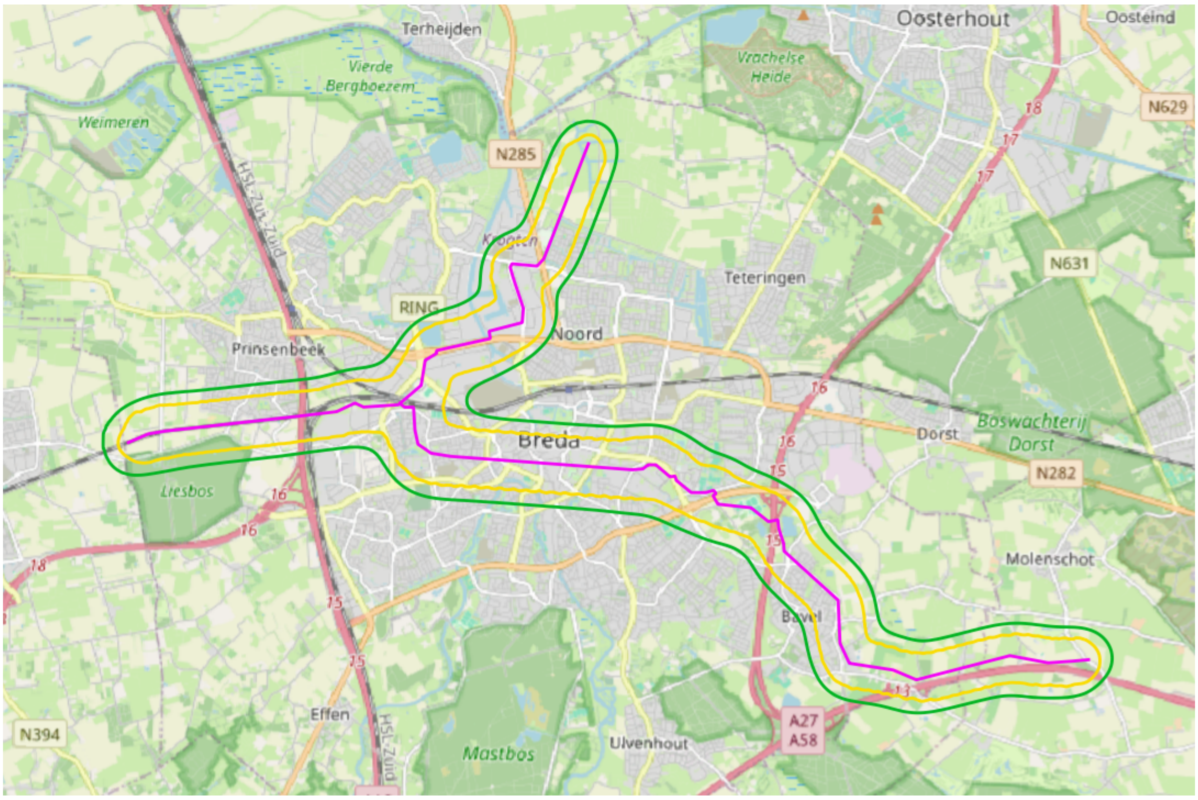

Figure D.20: Pipeline transport PR-contours after implementing mitigation measure 3 in Breda

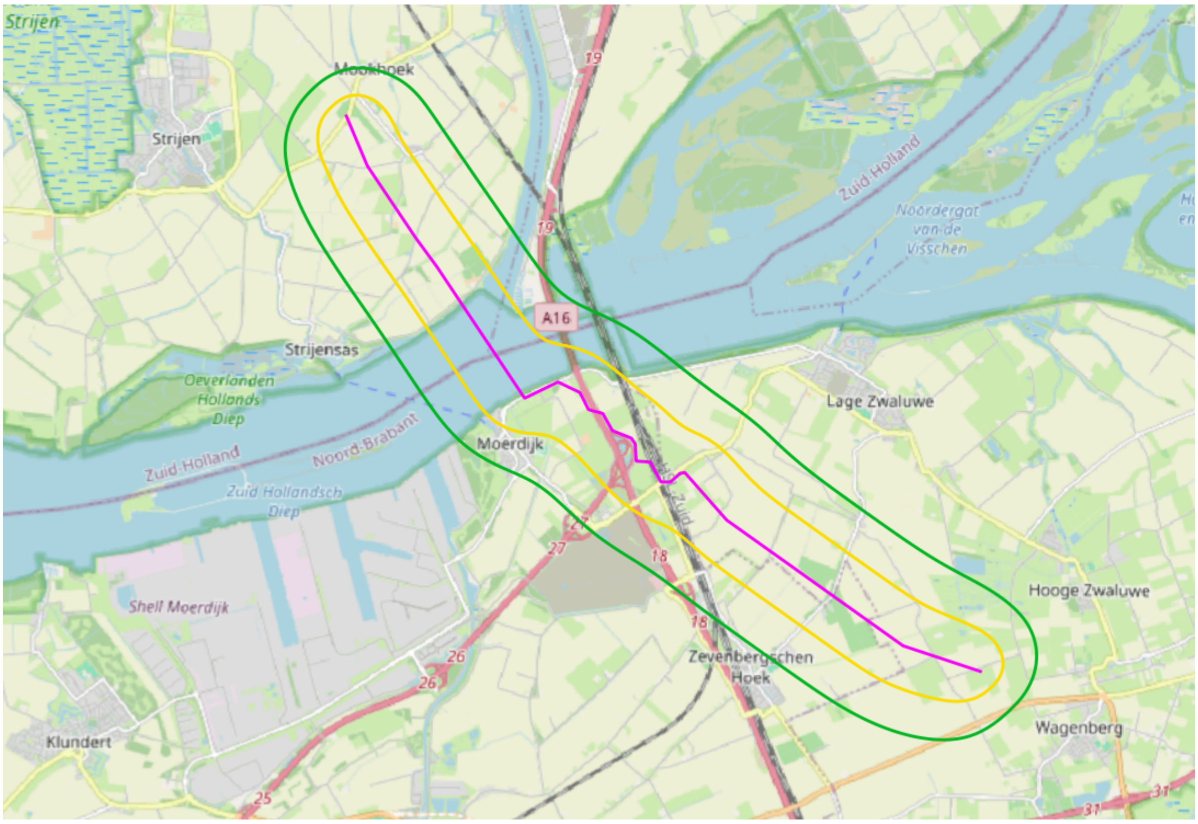

Figure D.21: Pipeline transport PR-contours after implementing mitigation measure 3 in Moerdijk

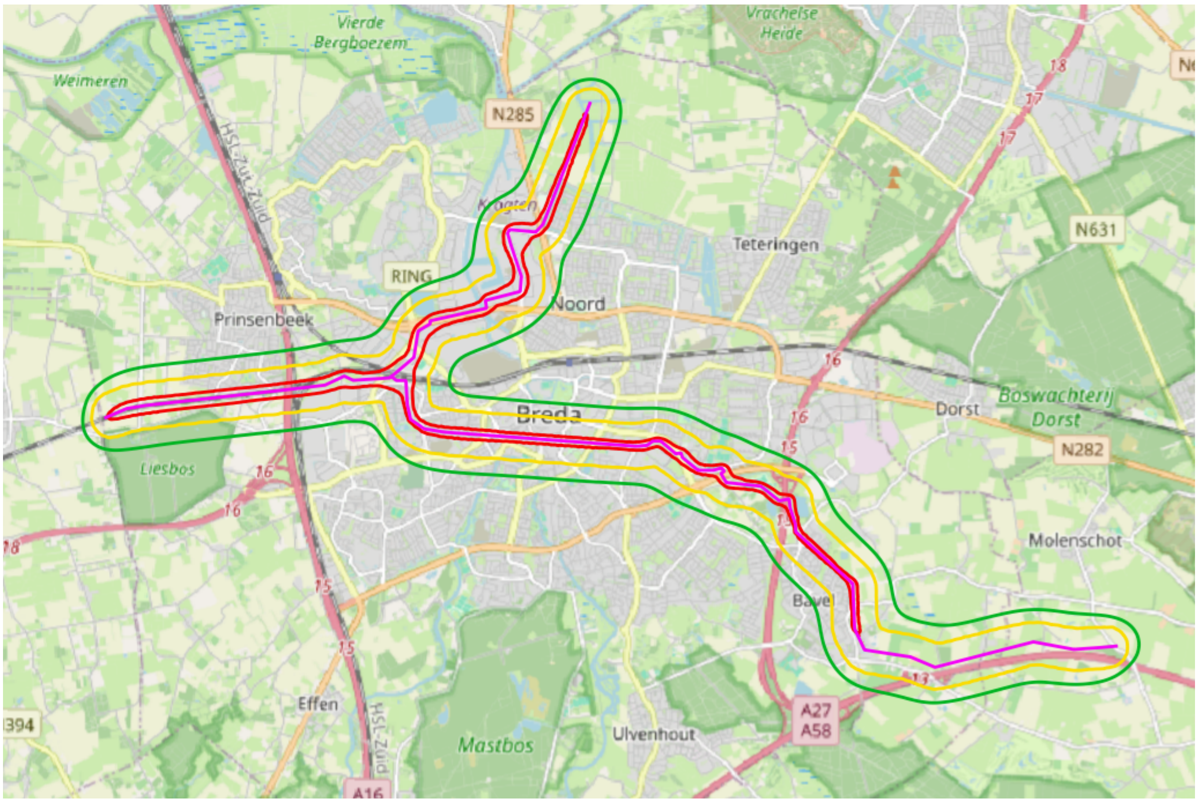

Figure D.22: Pipeline transport PR-contours after implementing mitigation measure 4 in Breda

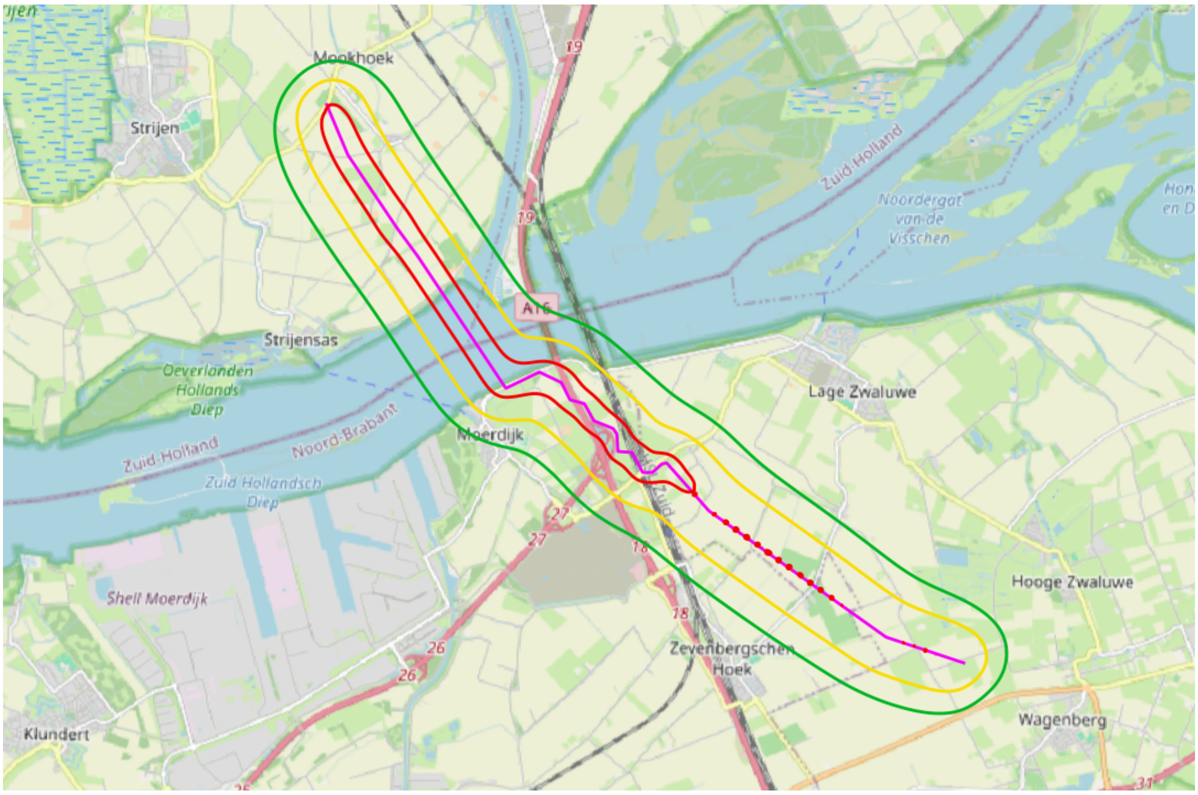

Figure D.23: Pipeline transport PR-contours after implementing mitigation measure 4 in Moerdijk

E

Multi-Criteria Analysis

E.1. Sensitivity Analysis - New Weights

Table E.1: Weighting structure used in sensitivity scenario 1 of the MCA.

Criteria	Criteria-specific weight	Indicator	Indicator-specific weight	Total weight
Human Safety	0.40	Individual risk	0.60	0.24
		Group risk	0.15	0.06
		Effect zone	0.25	0.10
Security	0.15	Terrorism	0.50	0.075
		Cybersecurity	0.50	0.075
Environmental Harm	0.125	Soil and groundwater	0.50	0.0625
		Surface water	0.50	0.0625
Affordability	0.075	Investment costs	0.50	0.0375
		Operational costs	0.30	0.0225
		Mitigation measures costs	0.20	0.015
Feasibility	0.075			
Adaptability	0.05			
Sustainability	0.075			
Reliability	0.05			

Table E.2: Weighting structure used in sensitivity scenario 2 of the MCA.

Criteria	Criteria-specific weight	Indicator	Indicator-specific weight	Total weight
Human Safety	0.30	Individual risk	0.60	0.18
		Group risk	0.15	0.045
		Effect zone	0.25	0.075
Security	0.25	Terrorism	0.50	0.125
		Cybersecurity	0.50	0.125
Environmental Harm	0.125	Soil and groundwater	0.50	0.0625
		Surface water	0.50	0.0625
Affordability	0.075	Investment costs	0.50	0.0375
		Operational costs	0.30	0.0225
		Mitigation measures costs	0.20	0.015
Feasibility	0.075			
Adaptability	0.05			
Sustainability	0.075			
Reliability	0.05			

Table E.3: Weighting structure used in sensitivity scenario 3 of the MCA.

Criteria	Criteria-specific weight	Indicator	Indicator-specific weight	Total weight
Human Safety	0.275	Individual risk	0.60	0.165
		Group risk	0.15	0.04125
		Effect zone	0.25	0.06875
Security	0.125	Terrorism	0.50	0.0625
		Cybersecurity	0.50	0.0625
Environmental Harm	0.25	Soil and groundwater	0.50	0.125
		Surface water	0.50	0.125
Affordability	0.075	Investment costs	0.50	0.0375
		Operational costs	0.30	0.0225
		Mitigation measures costs	0.20	0.015
Feasibility	0.075			
Adaptability	0.05			
Sustainability	0.10			
Reliability	0.05			

Table E.4: Weighting structure used in sensitivity scenario 4 of the MCA.

Criteria	**Criteria-specific weight**	**Indicator**	**Indicator-specific weight**	**Total weight**
Human Safety	0.275	Individual risk	0.60	0.165
		Group risk	0.15	0.04125
		Effect zone	0.25	0.06875
Security	0.125	Terrorism	0.50	0.625
		Cybersecurity	0.50	0.625
Environmental Harm	0.125	Soil and groundwater	0.50	0.625
		Surface water	0.50	0.625
Affordability	0.20	Investment costs	0.50	0.1
		Operational costs	0.30	0.06
		Mitigation measures costs	0.20	0.04
Feasibility	0.10			
Adaptability	0.05			
Sustainability	0.075			
Reliability	0.05			

Table E.5: Weighting structure used in sensitivity scenario 5 of the MCA.

Criteria	**Criteria-specific weight**	**Indicator**	**Indicator-specific weight**	**Total weight**
Human Safety	0.275	Individual risk	0.60	0.165
		Group risk	0.15	0.04125
		Effect zone	0.25	0.06875
Security	0.125	Terrorism	0.50	0.0625
		Cybersecurity	0.50	0.0625
Environmental Harm	0.125	Soil and groundwater	0.50	0.625
		Surface water	0.50	0.625
Affordability	0.075	Investment costs	0.50	0.0375
		Operational costs	0.30	0.0225
		Mitigation measures costs	0.20	0.015
Feasibility	0.15			
Adaptability	0.05			
Sustainability	0.15			
Reliability	0.05			

E.2. Sensitivity Analysis - New Scores

Table E.6: Weighted MCA scores per transport modality in sensitivity scenario 1.

Criteria	Indicator	Rail	Shipping	Pipeline
Human Safety	Individual risk	0	0.24	0.204
	Group risk	0.048	0.06	0
	Effect zone	0.07	0.10	0
Security	Terrorism	0	0.0375	0.075
	Cybersecurity	0.045	0.075	0
Environmental Harm	Soil and groundwater	0.025	0.0625	0
	Surface water	0.0625	0	0.05625
Affordability	Investment costs	0.01875	0.0375	0
	Operational costs	0.005625	0	0.0225
	Mitigation measures costs	0.0075	0	0.015
Feasibility		0	0.015	0.075
Adaptibility		0.01	0.05	0
Sustainability		0.0525	0	0.075
Reliability		0	0.0375	0.05
Total scores		**0.344875**	**0.715**	**0.57275**

Table E.7: Weighted MCA scores per transport modality in sensitivity scenario 2.

Criteria	Indicator	Rail	Shipping	Pipeline
Human Safety	Individual risk	0	0.18	0.153
	Group risk	0.036	0.045	0
	Effect zone	0.0525	0.075	0
Security	Terrorism	0	0.0625	0.125
	Cybersecurity	0.075	0.125	0
Environmental Harm	Soil and groundwater	0.025	0.0625	0
	Surface water	0.0625	0	0.05625
Affordability	Investment costs	0.01875	0.0375	0
	Operational costs	0.005625	0	0.0225
	Mitigation measures costs	0.0075	0	0.015
Feasibility		0	0.015	0.075
Adaptibility		0.01	0.05	0
Sustainability		0.0525	0	0.075
Reliability		0	0.0375	0.05
Total scores		**0.345375**	**0.69**	**0.57175**

Table E.8: Weighted MCA scores per transport modality in sensitivity scenario 3.

Criteria	Indicator	Rail	Shipping	Pipeline
Human Safety	Individual risk	0	0.165	0.14025
	Group risk	0.033	0.04125	0
	Effect zone	0.048125	0.06875	0
Security	Terrorism	0	0.03125	0.0625
	Cybersecurity	0.0375	0.0625	0
Environmental Harm	Soil and groundwater	0.05	0.125	0
	Surface water	0.125	0	0.1125
Affordability	Investment costs	0.01875	0.0375	0
	Operational costs	0.005625	0	0.0225
	Mitigation measures costs	0.0075	0	0.015
Feasibility		0	0.015	0.075
Adaptibility		0.01	0.05	0
Sustainability		0.07	0	0.1
Reliability		0	0.0375	0.05
Total scores		**0.4055**	**0.63375**	**0.57775**

Table E.9: Weighted MCA scores per transport modality in sensitivity scenario 4.

Criteria	Indicator	Rail	Shipping	Pipeline
Human Safety	Individual risk	0	0.165	0.14025
	Group risk	0.033	0.04125	0
	Effect zone	0.048125	0.06875	0
Security	Terrorism	0	0.03125	0.0625
	Cybersecurity	0.0375	0.0625	0
Environmental Harm	Soil and groundwater	0.025	0.0625	0
	Surface water	0.0625	0	0.05625
Affordability	Investment costs	0.05	0.1	0
	Operational costs	0.015	0	0.06
	Mitigation measures costs	0.02	0	0.04
Feasibility		0	0.02	0.1
Adaptibility		0.01	0.05	0
Sustainability		0.0525	0	0.075
Reliability		0	0.0375	0.05
Total scores		**0.353625**	**0.63875**	**0.584**

Table E.10: Weighted MCA scores per transport modality in sensitivity scenario 5.

Criteria	**Indicator**	**Rail**	**Shipping**	**Pipeline**
Human Safety	Individual risk	0	0.165	0.14025
	Group risk	0.033	0.04125	0
	Effect zone	0.048125	0.06875	0
Security	Terrorism	0	0.03125	0.0625
	Cybersecurity	0.0375	0.0625	0
Environmental Harm	Soil and groundwater	0.025	0.0625	0
	Surface water	0.0625	0	0.05625
Affordability	Investment costs	0.01875	0.0375	0
	Operational costs	0.005625	0	0.0225
	Mitigation measures costs	0.0075	0	0.015
Feasibility		0	0.03	0.15
Adaptibility		0.01	0.05	0
Sustainability		0.105	0	0.15
Reliability		0	0.0375	0.05
Total scores		**0.353**	**0.58625**	**0.6465**