Hosting Military Transits

An Agent-Based Model (ABM) to simulate the effect of simultaneous infrastructure use by civilian and military vehicles, as well as different intervention strategies

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TU Delft

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by

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Cover: American military vehicles arriving in The Netherlands per ship (Herman Zonderland & Ministerie van Defensie, 2023)
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TU Delft

Preface

I proudly present the thesis report in front of you on simultaneous infrastructure use by military and civilian vehicles. When I started researching this topic one year ago, it took quite some time to grasp the essence of the problem and make it explainable to others. During the last months, the urgency of the problem has grown due to persistently high levels of geopolitical tensions and military threats to the Netherlands and Europe. The media attention for a resilient society, military capacities, and host nation support operations exemplifies this observation. On one side, this increased attention and urgency for my research topic is positive because it motivated me to fill the knowledge gaps as soon as possible. On the other side, the increased urgency also comes with additional challenges, such as increased confidentiality of required information.

In addition to subject matter challenges, I also experienced process challenges that come with a master's thesis. For example, touching different research fields - military logistics, the transportation system, agent-based modelling, and simulation - requires great efforts to bring everything together and explain the complete concept to experts in only one of the fields. The struggle to find the right way of explaining the model logic, for example, and using the right illustrations for it, is one of its consequences.

Something else that stood out is the iterative approach that is required to deliver a master's thesis. Where thesis projects are often pictured as linear, with consecutive research phases, the truth is that such projects require the researcher to keep iterating previous steps to come to a desired quality of work. This might sometimes feel like a step back, whereas they are steps towards a higher quality level.

Throughout this journey, I have often relied on the support from family and friends, my supervisors, and my team at the Dutch Ministry of Defence, which granted me a unique insight into the ins and outs of the Netherlands Armed Forces Defence Staff. I am grateful to everyone who took the time to be involved in my project, helped me with struggles, and provided new perspectives and ideas.

I also thank you for reading this thesis and preface, and I hope you find it as interesting as I do.

Jonathan van Loo
Delft, May 2025

Summary

The Netherlands has positioned itself as a transit nation within the context of military mobility on the European continent. By making its dense and well-developed infrastructure system available, the country facilitates rapid deployment from its seaports to destinations in neighbouring countries. However, using civilian infrastructure for military transits could potentially cause serious disruptions to the travel time of civilians due to capacity limitations. Recognising this tension, the Dutch Ministry of Defence (DMoD) is responsible for balancing the simultaneous use of transportation infrastructure by civil and military vehicles and seeks interventions in the system that can aid them.

The study follows a three-phase methodology:

1. The system analysis examines the transportation system with influences of military mobility by combining insights on the Dutch infrastructure's characteristics, military movements, and possible intervention strategies for the DMoD.
2. The model development results in a mesoscopic agent-based model (ABM) in NetLogo that simulates simultaneous infrastructure use by civil and military vehicles on synthetic Dutch-like infrastructure networks.
3. The experimentation tests different intervention strategies by simulating their effects on military transit time and travel time loss in the transportation system.

The simulation experiments show that using trains and barge ships is very effective in minimising travel time loss for civilian vehicles, but results in a longer duration of the military transit operation. Combining the road, rail and inland waterway modalities, applying short intervals between vehicles and using long road convoys, are effective in minimising that duration, but cause more travel time loss. The combination of these latter interventions with the avoidance of rush hours and/or daytime balances the trade-off between travel time loss and transit time. Additionally, operating short road convoys should be avoided as they serve neither of the two goals and reserving roads for military vehicles only does not significantly change either of the two goals. This differentiation stresses the importance of setting out the intent of operations - minimising travel time loss or the transit time - before planning them.

The sensitivities and limitations of the research, however, should be kept in mind when interpreting these conclusions. Especially the assumption that the speed flow of highways is capped at 80 km/h on two-lane roads when there are military convoys, strongly affects model outcomes. Other limitations are that the research neglected traffic congestion caused by accidents and road works, and the availability of transport vehicles. Microscopic research on the interaction between civil vehicles and road convoys is suggested to gain insights into these parts of the system.

In addition to partly filling the knowledge gap of simultaneous infrastructure use by military and civilian vehicles, this research also contributes to the scientific fields of managing multi-modal transport and traffic and modelling of transportation systems. Regarding multi-modality, four different management categories were studied, of which three are concluded to be effective: traffic demand management, congestion avoidance, and integrating multiple transport modalities. Prioritisation of roads for military vehicles, however, did not result in significant system-wide benefits in this context.

In the field of transportation modelling, this research confirms the applicability of Agent-Based Modelling (ABM) to this field and introduces a network generation algorithm used before the transportation simulation. The benefits of this algorithm are that it requires less data about the network, which was useful due to the sensitive character of this research topic, as well as a broader applicability of the model, because adjustments in the network generator allow simulation in a different context.

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Introduction

1.1. Research background

Escalating geopolitical tensions around the world underscore the importance of armed forces that can provide both deterrence and defence (NATO, 2024). In the European context, this involves the possibility of rapidly deploying non-European NATO troops to eastern countries. In response, the Dutch Ministry of Defence (DMoD) positions the Netherlands as ”transit nation” (Ministerie van Defensie, 2021), using its strategic location and advanced infrastructure to facilitate the swift and secure movement of military personnel and equipment from seaports to neighbouring countries (Ministerie van Defensie, 2024a). The Ministry argues that the Netherlands is well-equipped to do this, given its dense and efficient existing transport network, that military logistics will make use of.

However, the use of civilian infrastructure for military purposes introduces challenges, particularly due to its limited capacity. Daily traffic jams indicate that the capacity is already used intensively (ANWB, n.d.). According to transport research, high traffic volume is the most common reason for the occurrence of traffic jams (SWOV, 2022). Thus, a significant increase in military transport could cause serious disruptions to civil mobility. Due to the lack of dedicated infrastructure, additional prioritisation of military traffic comes at the expense of less capacity for civilian traffic, leading to even more disruptions for society.

The Dutch government is responsible for balancing the trade-off between the urgency of military mobility and the need to minimise disruption to everyday life in which the Dutch Ministry of Defence (DMoD) takes the lead. This balance is context-dependent and influenced by levels of military threats. As the Minister of Defence recently stated, the Netherlands finds itself in a “grey zone” - not at war, but not at peace either (Ministerie van Defensie, 2024b). If this situation shifts more to a state of war, it asks for a higher readiness of military troops and thus -among others- for more military use of infrastructure, indicating that the tension between military and civil mobility will increase along with military threats.

Inconveniently, existing literature on military mobility does not address simultaneous infrastructure use by civilian and military vehicles. Table 1.1 provides an overview of relevant literature on military mobility published after 2014. The literature has been reviewed using the three factors that potentially limit military mobility according to the EU: infrastructure capacity (especially bridges and tunnels), legislation around cross-border military movement, and the dependency on civilian infrastructure in the absence of dedicated military alternatives (European Union, 2024). Two key conclusions can be drawn based on this review: first, almost all of the papers confirm the dependency of military logistics on civil infrastructure, and second, there is a lack of research examining the simultaneous use of transport infrastructure by military and civilian traffic and strategies to balance those. The few studies that do touch on dual use only consider civilian applications of military resources (e.g. hydrogen infrastructure) or conceptually explore blurred boundaries between military and civilian infrastructure, stating that they are more intertwined than people realise.

Table 1.1: Synthesis of relevant literature

Paper	Scope	Capacity analysis	Border crossing	Dependence on civil infra	Dual use of infra
Håkansson, 2023	Governance behind Military Mobility project in the EU		X	X	Transport infrastructure is intertwined
Jančo and Kompan, 2023	Usability of road bridges for military mobility in Slovakia	X	X	X	Shared green energy infrastructure
Kompan and Hrnčiar, 2024	Challenges for enhanced military mobility in Eastern Europe			X	
Majchút and Brezina, 2023	Usability of infrastructure for military mobility in Slovakia		X	X	
Meidutė-Kavaliauskienė et al., 2024	Compliance of railways to NATO standards in Lithuania	X		X	
Merriman et al., 2017	Intertwineness of civil and military mobility in the USA			X	
Mori et al., 2023	Civilian-military shared energy hub in Slovenia			X	
Perot, 2024	Involvement of the EU in collective defense			X	

The absence of scientific literature on concurrent use could be explained by the unprecedented nature of the current context: in the last decades of growing infrastructure density (Koren & Molnár-in 't Veld, 2020), the level of military threat was at a minimal level compared to the current level, in which challenges of military infrastructure use are emerging for the first time.

To study the interaction between civil and military mobility, this research applies a systems perspective on the transportation system and its subcomponents. According to Van Nes (2002), the transportation system consists of two interrelated markets: the transport market, which matches travel activities to transport services, and the traffic market, which links these transport services to infrastructure use. In this framework, which is schematically displayed in figure 1.1, buses and private cars are considered different modalities of transport services and roads, railways, and inland waterways (IWW) are different modalities of traffic supply or infrastructure. Both markets are relevant to this study: the modal choice for military logistics is reflected in the transport market and military and civilian vehicles sharing the same infrastructure affects the traffic market.

Distinguishing between the transport and traffic markets is crucial for this research, because it reflects the different levels at which military mobility decisions are made. At the transport market level, strategic choices are made regarding the modality of transport, such as whether to move military goods by road, rail, or inland waterways. At the traffic market level, operational choices are made concerning the organization of movement over infrastructure, such as convoy length, departure times, and route selection. By structuring the analysis according to these two decision levels, the research can better explore how different types of choices independently and jointly influence the interaction between military and civilian mobility.

The transportation system and its two markets can be viewed as a complex adaptive system (CAS): a socio-technical system characterised by adaptivity, self-organisation, non-linear behaviour and emergent behaviour (Van Dam et al., 2012). These characteristics apply due to the human-infrastructure interaction which makes the system complex. For example, traffic jams emerge from the behaviour of drivers when the road intensity exceeds a certain intensity and consequently, the drivers adapts to these jams by avoiding the crowded road sections. The CAS-perspective enables researchers of different backgrounds, which are all relevant for researching infrastructures, to communicate efficiently and effectively (Lei et al., 2010). Research on a CAS can very well be conducted by students of the master's program Complex Systems Engineering and Management (CoSEM). These students are skilled in analysing the system through the technical, institutional and process-related perspectives and come up with integrated answers (TU Delft, n.d.).

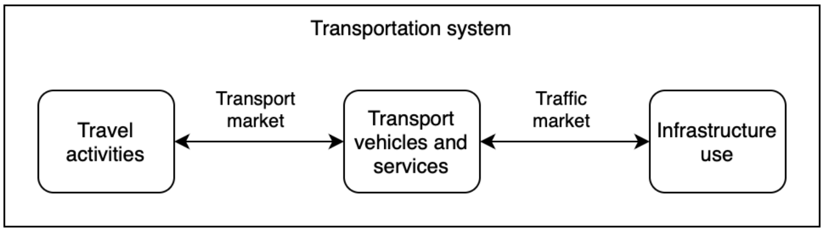

Figure 1.1: Transportation system (based on Van Nes, 2002)

1.2. Research questions

The previously stated problem and perspective lead to the following research question:

> ***How can the Dutch Ministry of Defence facilitate simultaneous use of infrastructure by civilian and military traffic with attention to the interests of both?***

This main research question will be supported by answering these five sub-questions:

1. How can military mobility influence the Dutch civil transportation system?
2. What are the different scenarios for military mobility demand in the Netherlands?
3. In what way can the Dutch Ministry of Defence influence military transportation?
4. How can the transportation system be modelled to experiment with the influence of the Dutch Ministry of Defence?
5. What is the effect of the Ministry's influence on civil travel time loss and the military transit time?

The purpose of the research questions is to provide an overview of the effects of different transit strategies for military traffic through the Netherlands that can be used in decision-making around these operations. The DMoD emphasises that the importance of basing operations on the right information is growing, especially to ensure fast and good decision making (Ministerie van Defensie, 2023b), to which this research can contribute.

1.3. Research approach and methodology

To contribute to the mentioned scientific and societal knowledge gap, study followed a three-phase research design to systematically examine the impact of military mobility on civilian traffic. The approach consists of: a system analysis, the development of a system simulation, and simulation-based experimentation. Each phase builds upon the previous one to gradually deepen understanding and provide evidence-based answers to the research questions. The phases are outlined in separate chapters: the system analysis in Chapter 2, the simulation model in Chapter 3, and the experimentation in Chapter 4.

The first phase aims to develop a clear understanding of the current civilian transport system and how it interacts with military mobility (RQ1). This is achieved through a literature review of the civilian transport infrastructure, its subsystems, and publicly available information on military logistics and troop deployment strategies. In addition, this phase addresses RQ2 by differentiating different possible scenarios in terms of military mobility intensity transiting the Netherlands.

To explore RQ3, which concerns the management of simultaneous infrastructure use, this analysis also examines literature on multimodal transportation. Due to the lack of research directly focused on military-civilian infrastructure sharing, the study draws on comparable cases, such as the co-use of roads by buses, trucks, and private vehicles, and logistics operations involving both trains and trucks. These insights help identify management strategies that could be adapted to the military context, particularly concerning the role of the DMoD.

The second phase focuses on modelling the system to allow for detailed analysis (RQ4). Literature on transportation modelling is reviewed to establish the appropriate framework, which leads to the selection of agent-based modelling (ABM) as the most suitable method for simulating interactions between agents in a complex, dynamic transport environment. The model is developed using established ABM guidelines by Van Dam et al. (2012), with verification and validation processes incorporated to ensure reliability. This simulation forms the technical basis for the experimental phase that follows.

In the final phase, the simulation model is used to run a series of experiments that answer RQ5. These experiments simulate different alternatives for simultaneous infrastructure use, applying the interventions that have been identified in answer to RQ4. The results are compared by their resulting travel time loss and the time it takes military equipment to its destination.

1.4. Outline

This report continues in line with the phase differentiation explained in section 1.3. **Chapter 2** presents the system analysis, followed by the model development in **chapter 3**. The experimentation and results analsysis are discussed in **chapter 4**. The report ends with a conclusion and discussion in **chapter 5**.

2

System analysis

To analyse the transportation system systematically, its subsystems are distinguished and described, with figure 1.1 as starting point. As can be seen in that figure, the transportation system consists of three elements: travel activities, transport vehicles and services, and infrastructure use. Travel activities refer to the movements that people or goods desire or need. These activities generate demand for transport services and vehicles, such as a private car or public transport. These vehicles and services in turn require the use of infrastructure, such as roads, railways and inland waterways (IWW). The two pairs of demand and supply are balanced by two markets: the transport market and traffic market, which are both influenced not only by direct interaction between users and services but also by (government) regulations.

Special attention goes to traffic management, which is an aspect of the traffic market. Where the traffic market involves the choice and use of infrastructure by transport vehicles and services, the traffic management only concerns handling traffic volume on a certain part of the infrastructure, which can happen in a decentralised or coordinated way. Decentralised traffic management can be observed on highways, where speed reductions emerge as traffic intensity increases. Coordinated traffic management is more common in systems like railways, where central authorities control scheduling and infrastructure access. This differentiation is important because it shapes the influence military mobility can have on transportation on different infrastructure modes.

This chapter first addresses the military influence on the Dutch transportation system in **section 2.1**, followed by an analysis of Dutch infrastructure and its civilian use in **section 2.2**. This is followed by a review of literature that introduces different ministerial interventions on military mobility in section **section 2.3**. The chapter concludes with a system conceptualisation based on the analysis of the other sections in section **section 2.4**.

2.1. Military influence on the Dutch transportation system

This section explores the expected military traffic demand on the Dutch transportation system, specifically the movement of non-European NATO troops towards Eastern Europe. As the Netherlands plays a strategic role as a transit nation, understanding how military logistics interact with national infrastructure is critical. However, publicly available literature on military logistics is limited due to operational security concerns. One of the available sources is the American field manual on unit movement operations (Shinseky, 2002), which is relevant to this study for three reasons: American doctrines were the foundation of NATO's doctrine (Katsos, 2021), 40% of NATO troops are American (Wikipedia-contributors, 2025), and American troops are already frequently transiting the Netherlands (Omroep Zeeland, 2024; Ministerie van Defensie, 2023a).

The manual distinguishes between movements within the Continental United States (CONUS) and those outside (OCONUS), of which the latter applies to the Netherlands. For OCONUS movements, the air and sea modalities are used for the 'strategic lift' into the foreign continent ("theatre") and the onward movement ("intratheater") relies on a combination of air, highways, rail, and inland waterways.

Importantly, the manual introduces the concept of Host Nation Support (HNS), which is the reliance on foreign infrastructure and services to facilitate military movement, in this case the Dutch transportation system.

Figure 2.1 shows the conceptual chain for OCONUS movements and the terminology in this figure is explained in table 2.1. The network includes key nodes such as ports of debarkation (PODs), marshalling areas, staging areas, and tactical assembly areas (TAAs), where equipment and personnel are disassembled and reassembled as needed.

While the manual does not quantify traffic volumes, it offers insight into the scale and pace of movement. Repeated references to brigade- and battalion-level responsibilities suggest that deployments are typically organized around these unit sizes. General Shinseki's vision of deploying a brigade anywhere in the world within 96 hours, a division within 120 hours, and five divisions within 30 days (Shinseky, 2002, p. 6) further illustrates the ambitious speed and scope of U.S. deployment doctrine. Public sources reveal that the size of a unit's equipment is around 2.000 pieces (Omroep Zeeland, 2024), matching the size of a battalion or small brigade. Table 2.2 provides an overview of standard unit sizes, from battalion up to corps level, to contextualize the scale of potential movements.

Table 2.1: Definitions around military unit movement from Shinseky, 2002

Term	Abbreviation	Definition
Area of responsibility	AOR	This is either the area of current operations or the area of the home base or origin.
Theatre		The entire area that is involved in war operations.
Port of Embarkation	POE	This is the location at sea or airport where equipment and/or personnel embarks ships or planes.
Port of Debarkation	POD	This is the location at sea or airport at the edge of the theatre where equipment and/or personnel debarks ships or planes.
	RSO&I	The reception, staging, onward movement and integration process that happens at PODs.
Marshalling area	MA	A location close to a terminal where personnel and equipment can be reassembled and provided with support.
Staging area	SA	A location where personnel and equipment are joined if necessary and are prepared for entering the theatre.
Tactical assembly area	TAA	An area where units make final preparations inside the theatre before entering combat.

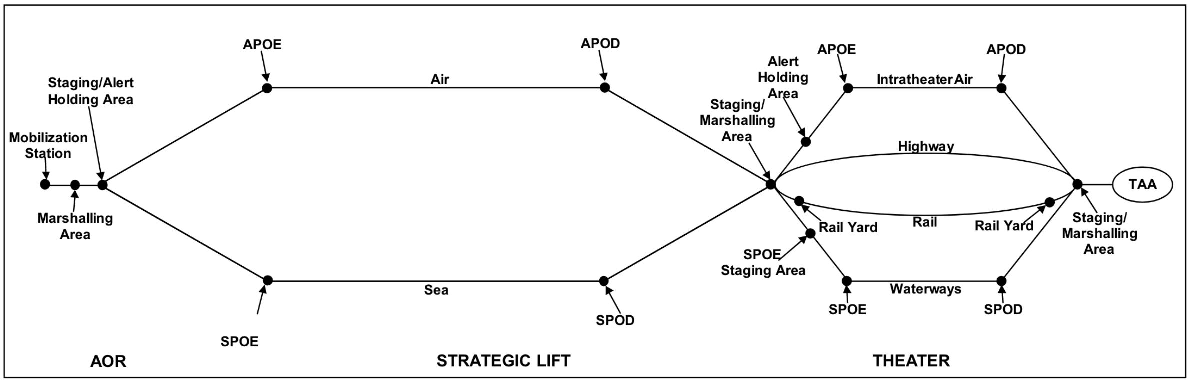

Figure 2.1: Unit movement into theatre (Shinseky, 2002)

Table 2.2: Army unit sizes (U.S. Department of Defense, n.d.)

Unit	Sub-units	Number of soldiers
Squad		10
Platoon	2-3 squads	up to 36
Company	3-4 platoons	up to 200
Battalion	4-6 companies	up to 1000
Brigade	2-3 battalions	3000 to 5000
Division	3-4 brigades	10.000 to 15.000
Corps	2-5 divisions	20.000 to 45.000

The different targets reinforce the concept that the magnitude of troop deployment depends on the level of military threats, as carried out in chapter 1. This varies from one or two ships in three days, to eight ships in five days or 40 ships in 30 days, under the assumption that all units within such a target would travel via the Netherlands.

A notable operational feature of intratheatre highway use is the deployment of convoys. These ensure that units remain cohesive and logistical support can be effectively allocated at marshalling and staging areas. However, these convoys operate with a speed of 65 km/h, which is slower than civilian cars and trucks, which could interfere with the traffic flow. Additionally, the vehicles maintain longer distances from each other than civil traffic, using more road capacity.

In summary, the field manual outlines the strategic and logistical framework in which military deployments operate. Four key transport modalities are all potential conduits for intratheatre military movement across the Netherlands: air, highway, rail, and inland waterway. The size and pace of these movements, often involving battalion or brigade units, suggest that military deployments could place significant additional pressure on the Dutch transportation network. This insight forms the basis for the analysis in the following sections, which assess the Dutch water, road, and railway networks in this context.

The air modality will not be examined further, as there are no reports of Dutch airports being used for military movements, and the transfer from strategic to intratheatre air transport would not interact with the Dutch transportation system but within individual airports only. Additionally, the doctrine does not mention any transshipment between transport modalities during intratheatre movements, which is why potential transshipment points are not analysed either.

2.2. Dutch infrastructure and its civilian use

This section will address water, road, and railway infrastructure in the Netherlands in its subsections. The networks of water, road and railway infrastructure are shown in figure 2.2. Before diving into the different networks, it is good to have a clear definition of the elements within traffic infrastructure. In general, four different elements form the basis of every network (Baggen and Van Ham, 2019, p. 405):

- Access points, where passengers, freight and/or vehicles can enter and exit the network;
- Edges, that primarily connect the access points;
- Junctions, where three or more edges of the same network meet; and
- Buffer and parking facilities, where vehicles can be stored for short or long periods without use.

The general use of infrastructure is distributed over transport modalities as follows: Dutch inhabitants use **cars** for 70% of their travelled kilometres, either as driver of the car or as passenger. Additionally they travel by **public transport** for 13% of the kilometres, by **bike** for 10%, **walking** for 4% and using other means for the last 4%. For cargo, 43% of the tonkm (an aggregation of weight and distance in kilometres) is transported via the **road**, 31% via **inland waterways**, 20% through **tubes** and 5% via **rail** infrastructure. (Kennisinstituut voor Mobiliteitsbeleid, 2024)

(a) Dutch inland waterways (Centraal Bureau voor de Statistiek, 2009)

(b) Dutch national roads (Rijkswaterstaat, n.d.-c)

(c) Dutch railways (Dennistw, 2020)

Figure 2.2: Maps of Dutch infrastructure networks

2.2.1. Water infrastructure and its use

Water infrastructure in the Netherlands includes both seaports and inland waterways. The country hosts several seaports, aggregated into four main port areas: Groningen, Amsterdam, Rotterdam, and Vlissingen/Terneuzen. These ports are spread along the coastline from the northeast to the southwest and vary significantly in terms of capacity. For instance the largest of the four (Rotterdam), handles 47 times more goods annually than the smallest (Groningen) (Centraal Bureau voor de Statistiek, n.d.-b).

In addition to the seaports, the inland waterways (IWW) are also part of the water infrastructure and are used for transporting goods and passengers. As depicted in Figure 2.2a and explained by Eichhorn (2021), the Dutch inland waterway network includes main transport axes with a total length of 552 km, that connect the three largest port areas to each other and to international borders: two crossings with Belgium and one with Germany. An additional 897 km of main waterways branch out from these axes, linking the smallest port area and various inland ports to both domestic and international destinations, including a border crossing with Belgium and Germany. Although Figure 2.2a shows a denser concentration of fairways in the northwestern part of the country, the network of main transport axes (dark blue) and main waterways (turquoise) together form a network that is spread evenly over the country.

Traffic management on inland waterways is a hybrid of decentralised and coordinated mechanisms. Vessels navigate autonomously, but locks and movable bridges require central coordination. In most cases, access is regulated by a first-come, first-served principle, which is legally mandated in the Netherlands (De Kloet, 2016). The system generally operates efficiently: in 80% of passages, waiting times remain under 30 minutes (Compendium voor de Leefomgeving, 2018). Moreover, a case study for a selection of locks and bridges shows that there is capacity left in most of them, because a 15% increase in vessel throughput would not significantly impact average waiting times (De Kloet, 2016). For the purposes of this study, it is therefore assumed that military barge transport would not interfere with regular civilian traffic on inland waterways.

To summarize, the structure and management of the water infrastructure support reliable and largely uncongested freight movement towards and through the Netherlands. Empirical data further shows that current usage levels do not fully exhaust available capacity, indicating room for additional traffic. As such, military transport by barge can be integrated without significantly affecting civilian operations, making waterborne transport a resilient and flexible modality within the broader infrastructure system.

2.2.2. Road infrastructure and its use

Figure 2.2b shows a map of national highways and motorways within the Netherlands. The roads on the map are all managed by Rijkswaterstaat, the executive agency of the Dutch Ministry of Infrastructure and Water Management (I&W), which oversees national road and water infrastructure (Rijkswaterstaat, n.d.-b). Regional and local roads managed by other authorities managers, do not typically serve international transit routes, for which this study focusses only on the national road network.

Snelder et al. (2007) compared the Dutch road network to an optimal road network generated by algorithmic design, providing an analysis of the road network's actual form. The findings suggest that the Dutch national road network generally follows a triangular form with important horizontal (west-east) and diagonal (west-north and northwest-southeast) highways. Such a triangular shape is one of the network forms as identified by Van Nes, 2002 (p.36). In addition, several large cities are surrounded by ring roads and have radial highways connecting them to other cities. Although the idealized triangles between junctions are more in the form of polygons in reality, the overall triangular form can clearly be identified in figure 2.2b. This figure also displays seven highway border crossings with Germany and six with Belgium. Based on the same figure, 96 junctions connect two or sometimes three national roads. On average, this results in a junction roughly every 16 km, although this metric is distorted by the high number of shorter roads (Rijkswaterstaat CIV, 2015).

For this study, entrance and exit ramps to and from the highways are excluded. While they are relevant to civil traffic, which originates and ends locally, they are less relevant to the international transit routes that start and end at seaports and border crossings. This simplification requires the assumption that traffic between two junctions is uniformly distributed over the road length.

Besides this assumption, however, the study still acknowledges differentiation between roads and time. Weekdays see higher volumes than weekends, with clear rush hour peaks in the morning and evening. During peak periods in the morning, there is 35% more traffic than at 11 am, leading to congestion and travel time loss. Evening rush hours are typically longer and result in even more travel time loss than morning rush hours. Conversely, between 11 p.m. and 5 a.m., traffic volumes are minimal. (Kennisinstituut voor Mobiliteitsbeleid, 2024)

The understanding of decentralised traffic management on highways and corresponding congestion originates from the work of Greenshields et al. (1935), who assumed a linear relationship between traffic intensity and speed flow. Immers et al. (2010) explains the corresponding fundamental relationship, which is shown in equation 2.1. In this equation, q represents traffic intensity (vehicles per hour), k denotes density (vehicles per kilometer), and u stands for average speed (kilometer per hour). Considering that drivers maintain a minimum time gap from the preceding vehicle, the density has an upper limit. This constraint removes k from the equation and leads to the assumption of linearity between intensity and speed.

$$q = k * u \tag{2.1}$$

An alternative is a triangular approach, which assumes that speeds remain constant up to a certain density threshold, after which speed declines linearly. More recent empirical studies, however, indicate that the relationship between intensity and speed is in fact exponential, particularly beyond the capacity threshold (Transportation Research Board, 2000). This exponential drop in speed forms the basis for understanding infrastructural scarcity in this research: when military traffic is added to already saturated roads, the system's performance declines sharply.

Importantly, reduced speeds act as both a consequence and an adaptation mechanism. They manage traffic flow locally and encourage drivers to choose alternate routes. This can both be planned, as regular traffic jams based on time and location cover 70 to 87% of the total traffic jams (Kok et al., 2012), as well as real-time by using available information through displays or navigation apps.

In summary, the road network, while highly developed and systematically structured, operates near or at capacity during peak periods. Civilian traffic shows strong temporal variation, with predictable rush hours and substantial travel time losses on weekdays. The non-linear, often exponential relationship between road traffic intensity and speed highlights the system's sensitivity to added pressure. The inclusion of military transport on these routes could quickly result in congestion, which makes the road modality a complex modality when assessing the impact of military mobility on civilian infrastructure.

2.2.3. Railway infrastructure and its use

Figure 2.2c shows that the rail network covers the country in a manner comparable to the road network, although there are some exceptions. The north-eastern part of the country is served by only a single link and the south-western part only has one railway. However, the connections from the port areas to the neighbouring countries do not seem to be limited by these exceptions, including 6 border crossings with Germany and 3 active ones with Belgium.

The national rail network spans 3200 km, of which the large majority is electrified and has two or more tracks. The network has roughly 400 stations and serves both passenger and freight traffic. Some lines, however, are dedicated to one type of transport. The Betuweroute, for example, is a 160-kilometer freight-only line connecting the Port of Rotterdam to Germany. There is a 109-kilometer high-speed line (HSL) as well, exclusively transporting passengers between Amsterdam, Rotterdam, and Belgium. (Centraal Bureau voor de Statistiek, n.d.-a)

Similar to road use, the occupation of passenger trains depends greatly on the day and time. Passenger traffic peaks during the morning rush hours (lasting two hours), with 4 times more passengers than between 10 am and 4 pm. The evening rush hour lasts 3 hours and has a similar occupation. In contrast to road use, this passenger variation is not directly related to the number of trains in operation, since service is frequent throughout the day, with some exceptions to match demand. For example, trains are added during peak hours, after 8 pm train frequency decreases and around midnight, service is interrupted for around 5 hours, with the exception of two night trains. (Kennisinstituut voor Mobiliteitsbeleid, 2024)

Freight rail is primarily oriented toward international transport, in contrast to the daily commute of passengers, due to the relatively small size of the Netherlands and long-distance efficiency for transporting goods via rail. There are more than 45.000 trains per year and they mainly use two routes: the Betuwe route, which is a dedicated cargo track, and the Brabant route, where cargo trains share capacity with passenger trains. Both routes connect Rotterdam with the German border and handle over 20.000 trains per year. Additionally, eight other mixed-use corridors handle between 1250 and 7500 freight trains annually, supporting both east-west and north-south transportation. (Kennisinstituut voor Mobiliteitsbeleid et al., 2020)

Unlike road traffic, rail traffic is centrally managed, for which the fundamental relationship explained in section 2.2.2 does not apply. A national authority coordinates the allocation of infrastructure to vehicles guided by (inter-)national law and regulations. In case of congested tracks, this framework prioritizes passenger services over freight operations (Rijksoverheid, 2024).

In brief, the Dutch railway system is dense, electrified, and serves both freight and passengers. Although some regional limitations exist, there are multiple connections linking seaports to Germany. Centralized traffic management and legal prioritisation of passenger trains ensure orderly operation, but they also imply limited flexibility for sudden shifts in demand. While freight by rail is a viable military transport option, its dependence on shared infrastructure and international coordination may present operational constraints during the daily periods of well-occupied and frequent trains.

2.3. Ministerial interventions on military mobility

This section discusses literature related to the management of multi-modal traffic and transport, as approach to find the way the DMoD can influence military transportation. Multi-modality in the literature can refer to multiple modes of vehicles using the same infrastructure, like cars, buses and trucks or to the integration of various transport mains, like rail, road and IWW.

Focussing on multi-modal traffic first, several studies address the interrelationship between truck traffic and congestion, and what measures can be taken to manage this. For example, Ampountolas et al. (2017) research the effect of using perimeter and internal boundaries to prevent congestion in an urban network. This is a form of traffic demand management, indicating that limiting military or civil traffic could ease congestion. Specific to military traffic, this can be arranged by differentiation in the waiting interval between departures of military vehicles.

Lovrić et al. (2017) concluded that congestion causes roughly 23 % of the total delay time in road freight transport and noted a growing trend in night deliveries, a logistical adaptation to improve reliability. Similarly, Kok et al. (2012) mentions that road conditions tend to get better when a centrally controlled fleet avoids peak hour traffic congestion. Although congestion is largely caused by non-controlled road users, the avoidance of peak hours by a controlled fleet can cause a significant improvement to the speed flow for both the controlled and the uncontrolled fleet. These two examples are using the daily congestion pattern in advantage and suggest that shifting military movements outside peak periods or day time in general could result in mutual efficiency gains.

Other strategies in the literature focus on prioritisation and advanced vehicle coordination. Park et al. (2019), for example, compared freight signal priority with public transit signal systems, demonstrating that giving preference to a particular traffic mode —like trucks or buses—can enhance the flow of both that modality and the other modalities. In other words, prioritising military traffic could potentially arrange a better flow for those vehicles, which benefits civil traffic. This could for example involve the reservation of one highway lane or a complete highway to military vehicles.

Malik et al. (2024) introduced the concept of collaborative autonomous driving, where smaller time gaps between vehicles increase the maximum road capacity. This mirrors the convoy driving approach used in military logistics, offering insights into how convoy structure could optimize infrastructure use. At the same time, the doctrine mentioned in section 2.1 does not mention such collaboration technology, indicating it is not likely to be available to current operations. In contrast to this study, military vehicles actually maintain a longer distance to the vehicle in front.

There is not a lot of research around management of the multi-modal freight transport market in counterpart of the traffic market measures that have already been discussed. Jansen et al. (2004) explored an algorithm that assigns long-distance container transport to rail and short-distance to road. This kind of allocation could also be relevant for military logistics, particularly when considering cost-efficiency and capacity balancing between road and rail.

In conclusion, the literature reviewed in this section offers a toolbox of five traffic and transport management strategies that could inform the DMoD's actions within its decision space: traffic demand management, congestion avoidance, prioritisation of traffic modes, collaborative driving strategies, and integrating multiple transport modalities. While the applicability of these strategies to military contexts must be carefully assessed, they provide a solid conceptual foundation.

2.4. System conceptualisation

To provide a schematic overview of the insights in the previous sections, this section shows a causal relations diagram (CRD) of military involvement in the road and rail traffic system, respectively in figures 2.3 and 2.4. There is no diagram of the IWW traffic system because of the conclusion that military barge ships would not affect that system.

The diagrams are used to visualize the qualitative relationships between several factors, providing insight in how the dynamics of both traffic systems function and what the effects of military influences are. The arrows in the diagram represent the relationships and they are marked with either a plus or a minus sign. A plus indicates positive correlation and a minus indicates negative correlation. The colours of the factor indicate which part of the system they belong to, as detailed by the legend and besides the name, every factor contains unit in which it is measured between [ ].

2.4.1. Road traffic system

Figure 2.3 provides the causal relation diagram of (military) road traffic. The following insights stand out:

- The (civilian) vehicle intensity is higher during the day and especially during rush hours (section 2.2.2). This higher intensity eventually results in more travel time loss and a higher military transit time.
- The speed flow is limited by the maximum speed on the road: a higher maximum speed allows for a higher speed flow. When the speed flow is decreased due to high vehicle intensity, however, the maximum speed does not influence the speed flow.
- Another external factor is the infrastructure capacity. High capacity indicates the road provides room for more vehicles before the speed decreases. Therefore, higher capacity indicates a higher speed flow. Additionally, more capacity can indicate more roads. These roads can provide shorter routes, which decreases the travel time.

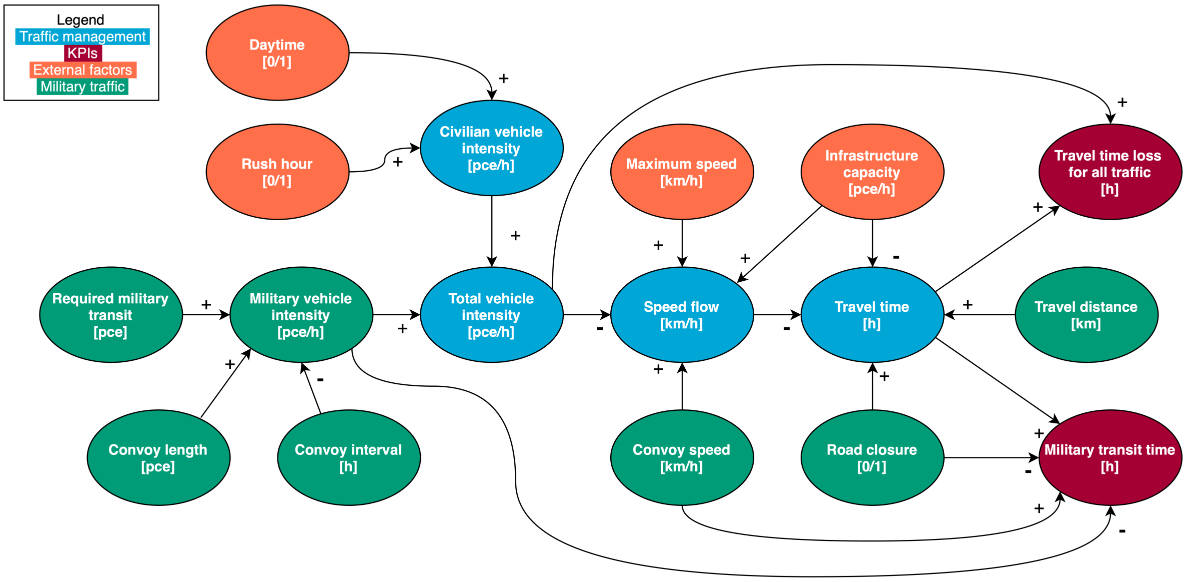

Figure 2.3: Causal relations diagram of (military) road traffic

- The convoy length is one of the factors within the influence of the DMoD. A longer convoy means more military vehicles on the road, so a higher military vehicle intensity. This increases the travel time loss and can also increase the military transit time. Another factor is the convoy interval, which is the time between two convoys . A higher interval means that less military vehicles are using the road at the same time. This lowers the travel time loss and can increase the military transit time.
- The convoy speed is also an important factor within military traffic. A lower convoy speed has a negative influence on the speed flow of civilian vehicles and consequently in more travel time loss. Alternatively, a higher speed results in a higher speed flow. The military transit time is also influenced by the convoy speed: a higher speed results in a shorter transit time.
- The decision to close roads for civilian users results in more travel time loss for civilians but not for military vehicles, which can drive their desired speed.

2.4.2. Rail traffic system

A similar diagram is drawn for (military) rail traffic, which is presented in figure 2.4. A key difference with the road traffic system is that this system is managed centrally. The mechanism of slower speeds caused by a higher intensity is replaced by a fixed capacity, in which a military train causes the cancellation of a civilian train. Another difference is that the length of trains is not included, because it does not affect traffic management.

Because it is to complex to calculate the travel time loss for freight trains due to their diverse destinations and purposes, it was decided to focus on travel time loss for passenger trains instead. Even though freight trains are more likely to be cancelled, this calculation still provides an indication of the impact that is well comparable with figures in the road system. The key insights of this diagram are:

- When the total intensity is more than the infrastructural capacity that is available, this indicates that passenger trains must be cancelled. When the travel distance for military trains is longer, more trains are cancelled, because each train takes up more capacity. The number of passengers this affects depends on the number of passengers per train.
- During daytime and especially during rush hours, the number of passengers per train is higher. During the nights, there are rarely any passenger trains, for which there are no cancelled trains or affected passengers.

- The travel time loss depends on the number of affected passengers and the average waiting time of those passengers. This travel time loss is higher when the train interval is shorter, the travel distance gets longer and during daytime and rush hour.
- There is no travel time loss for military transits, as it is assumed that they have priority over civilian trains. The military transit time is therefore only longer when train intervals are longer, when the travel distance is lower or when the train speed is slower.

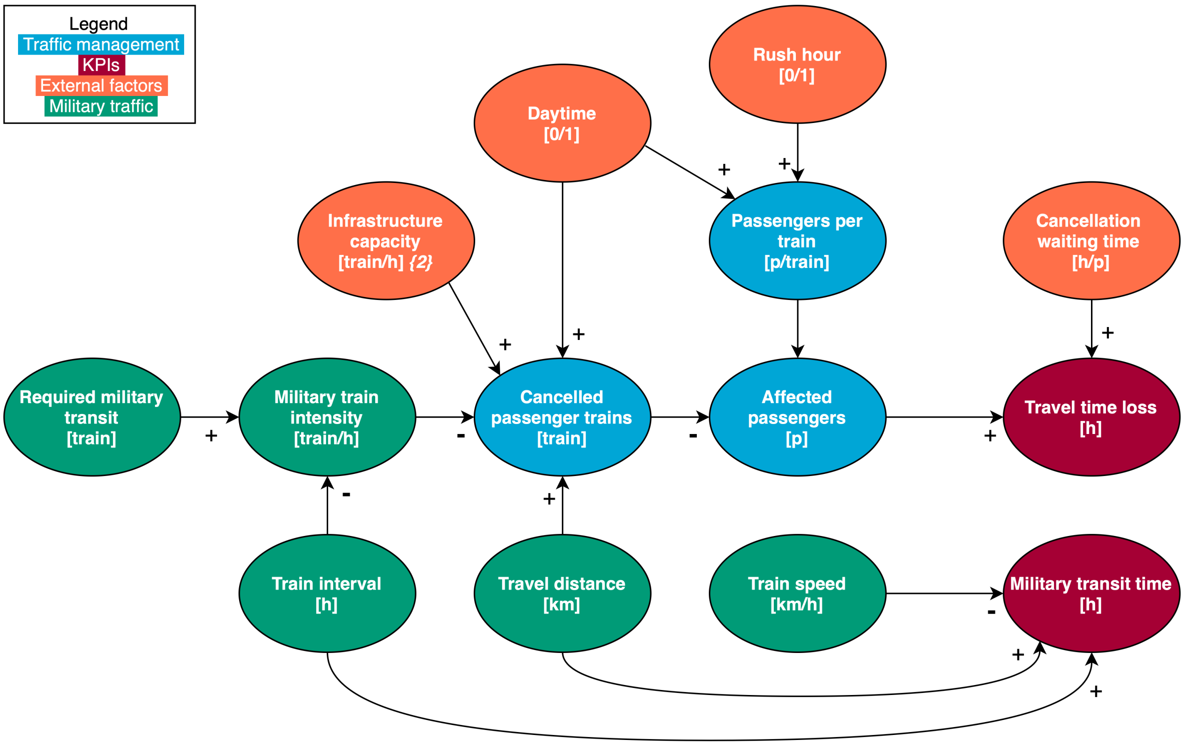

Figure 2.4: Causal relations diagram of (military) rail traffic

3

A simulation of military mobility in the Dutch transportation system

Where the previous chapter concluded qualitative relations in the transportation system of interest, this chapter describes the development of a simulation model to allow for quantitative experimentation with simultaneous infrastructure use by civil and military vehicles. A review of scientific works on modelling of transportation systems can be found in **section 3.1**, which concludes the development of a mesoscopic Agent-Based Model as appropriate for this system. **Section 3.2** outlines the objectives and assumptions for the development of such a model, followed by an explanation of the model logic in **section 3.3**. **Section 3.4** provides details of the performed verification tests that are required to ensure the model complies with the conceptualisation and the chapter ends with a similar description on the model validation in **section 3.5**.

3.1. Modelling of transportation systems

Related to RQ4 on developing a simulation model of the system of interest, this section reviews how transportation systems have been modelled in previous research. A key distinction lies in macroscopic, microscopic, and mesoscopic models (De Kloet, 2016). Macroscopic models study the traffic and transport markets at an aggregate level, while microscopic models simulate individual vehicle behaviour, such as lane changing or car-following (Cristiani & Sahu, 2016). Mesoscopic models are a hybrid, aggregating in some parts of the model and simulating individual behaviour in other parts (Burghout, 2004; Burghout et al., 2006). Because this research focuses on the system-wide effects of military mobility, a macroscopic approach is required. However, as military vehicles are not spread evenly over the network, a mesoscopic model is proposed: civilian traffic will be modelled macroscopically and the movement of military vehicles will be modelled individually.

The understanding of the fundamental relationship, as mentioned in section 2.2.2, also formed the basis for decades of transportation research and modelling. In the 1960s, four-stage models were introduced that used data from different areas in the network to calculate the demand for transportation, which is then attributed to the different roads in the network. Using the fundamental relationship, it is possible to convert these intensities into speed and travel times. This approach was further refined in the 1980s with the introduction of disaggregated models, which incorporated individual decision-making based on nested choice models and also included alternative modes of transport. (Gunn, 1994)

In the Netherlands, this led to the National Model System (NMS) that was later complemented by regional models that provide more spatial detail (Taale et al., 2005). The Dutch government also provides software to low-level governments with which they can forecast mobility performance across different modalities (Hofman, 2017), aiding them in a sustainable traffic management process (Stoelhorst & Middelham, 2006). Recent developments in these models cover the impact of socio-economic factors on traffic demand (Kennisinstituut voor Mobiliteitsbeleid et al., 2018) and better simulation techniques, also for modelling public transport (Smit et al., 2021). However, the NMS is not publicly accessible and can only be used by Rijkswaterstaat. Therefore, this research requires the development of a custom transportation model.

Additionally, to avoid revealing sensitive details of military mobility, the Dutch network will not be replicated directly; instead, a separate synthetic network generator is introduced besides the transportation model, based on the dynamics found in section 2.2. Although unconventional, this approach adapts to other regions easily by adjusting the identified parameters accordingly.

Although modelling techniques have evolved, travel time remains the standard output for assessing mobility (Taale et al., 2005; Lovrić et al., 2017). Even innovative studies like Pirra & Diana (2019), which use GPS data to calculate mobility performance, ultimately express this performance in travel time. Therefore, this research also uses (changes in) travel time for both civilian and military traffic as a measure to assess the transportation system.

The model must also account for multimodality, both in transport modality choice (transport) and shared infrastructure (traffic). Research shows that different modes, such as buses and trucks, interact differently with general traffic. Geroliminis et al. (2014) and Ampountolas et al. (2017) both showed that buses cannot be reduced to a simple car equivalent and therefore proposed models that take a variable traffic demand composition into account. Other researchers introduced similar approaches to differentiate between freight traffic and passenger cars (Lovrić et al., 2017; McKinnon et al., 2009). These findings suggest that the relationship expressed in section 2.4 (military intensity expressed in car-equivalent units is added to civil intensity) does not address the complexity of multi-modal traffic, especially the atypical behaviour of military convoys as found in section 2.1. Therefore, a further consideration of a convoy's impact should be included in the development of the transportation model.

To implement a mesoscopic transportation model that includes a network generation algorithm and addresses multi-modality, Agent-Based Modelling (ABM) is chosen. At its core, ABM is suitable for capturing disaggregated behaviours and emerging system-level effects (Van Dam et al., 2012; Bastarianto et al., 2023). Specific to transportation modelling, this enables the levels of the four-stage models to be calculated simultaneously instead of sequentially. In other words, ABM can account for the interconnection between the location of military vehicles and traffic performance, but calculate them independently.

Where data availability is sometimes challenging for transportation modelling, in the absence of nationwide travel diary data (Bastarianto et al., 2023), Ziemke et al. (2019) demonstrated that open data can be used to generate a synthetic population that can be used in an ABM model to simulate the transportation system. A similar approach is adopted in this research, using aggregated Dutch traffic demand data to simulate civilian flows macroscopically.

To ensure an appropriate development of the model, this research uses a 10-step framework by Van Dam et al. (2012). This framework addresses computing efficiency, unified verification and validation methods, and reproducibility, specific to the modelling of socio-technical systems like the transportation system. In this way, this research addresses the key concerns in ABM development as concluded by Bastarianto et al. (2023). For software, NetLogo (Wilensky, 1999) is selected for its user-friendly interface and appreciation by both literature sources. While less widely mastered than Python-based tools, NetLogo's interface enables the DMoD to visualise the complexity and urgency of the military mobility problem to other government bodies, which enhances the communicative value of the model and this research.

3.2. Model objectives and scope

Building on the previous section's review of transportation modelling techniques and their applicability to military mobility, this section continues by outlining the objectives and assumptions for an ABM of the system of interest. The **purpose** of the simulation model is to simulate the dynamics of the total transportation system and the way it is influenced by military traffic. The performance **output** of these simulations is the combination of travel time loss for civilians in the system and the travel time for military vehicles in the system. Additionally, the model must enable **experimentation** with different transit strategies of the DMoD and provide insights into their effects on the system, which can be used by decision makers to plan the military transit operations.

The model is formalised and implemented with the **model user** in mind. The primary model user is the researcher experimenting with parameters of the Dutch (military) traffic system and studying the effects on the travel times. This principle is met by providing the model user with the required parameters to perform the research. Other model users, such as decision makers or foreign researchers, are facilitated in their model use by thoroughly documenting the functioning of the model so these users are also able to use it or even to adjust the model when required for their use.

The model focuses on civilian traffic within the Netherlands, although the journeys of military vehicles extend to destinations far beyond the borders. To capture the influence of modal choices on international transit efficiency, the measure for military transit time is extended to destinations beyond the border with a user-defined distance from the Dutch border. The following simplifications and model boundaries ensure a clear comparison in experimentation and avoid unnecessary complexity:

- Loading and unloading times are not modelled due to a lack of consistent data. Instead, the arrival of a ship with military equipment is defined as the moment when the equipment is loaded off the ship and onto another vehicle, ready for onward transportation.
- Availability of vehicles for transportation of equipment is assumed infinite in the model, because the purpose of the model is to assess effects on traffic, not to allocate scarce transportation means.
- As stated in section 2.1, inland transhipment locations are not considered in the model, because they are not part of intratheatre military movements. To allow for this simplification, the destinations of the different modalities are assumed to be at the same location, where in reality this would not be the case.
- Bi-directional transportation is simplified to movement from seaports to destinations. While reverse logistics and redeployment are important as well, the magnitude and urgency of these transportations are generally lower than those of (rapid) deployments. The findings of this direction can also be applied to the reverse direction.
- Not only will the model include a network generation algorithm, as set out in section 3.1, but it will also apply a mesoscopic approach, in which civil traffic is aggregated to its intensity instead of every individual vehicle. This model seeks to address the interaction between military traffic and civilian traffic, not the mutual interaction of civil vehicles, and modelling them individually would therefore bring unnecessarily large amounts of computation. The military vehicles, however, will be modelled individually, because the effects of their presence depend on their location in the network.
- The scenarios that are briefly described in section 2.1 are included in the model by allowing the model user to set the number of ships with military equipment and the interval with which they do that.

These simplifications maintain model focus while aligning with ABM principles, where emergent behaviour often stems from simple rules rather than exhaustive detail (Wilensky & Rand, 2015).

The model operates in discrete time steps, with movement and system changes calculated at each step. Initially, a 1-minute tick is proposed to balance precision (e.g., differentiating between 4- and 8-minute drives) and performance. A coarser 6-minute step can reduce run time by over 80% if needed, while preserving overall insights. During the verification (section 3.4), it was found that the run time is acceptable when using a 1-minute tick, as the model can be run on a laptop multiple times within a minute. The 1-minute tick is used during the development of this model and is, therefore, not changed to a 6-minute step or else.

3.3. Model logic

Figure 3.1 shows an overview of the different elements in the model, which are categorised in three phases: the network generation algorithm, the transportation simulation and the end of a model run. Where the model network generation only takes place at the beginning of a model run to set up the simulation environment, the simulation is repeated until the run is ended. The diagram also shows what parameters influence which phase or elements and where the output is based on.

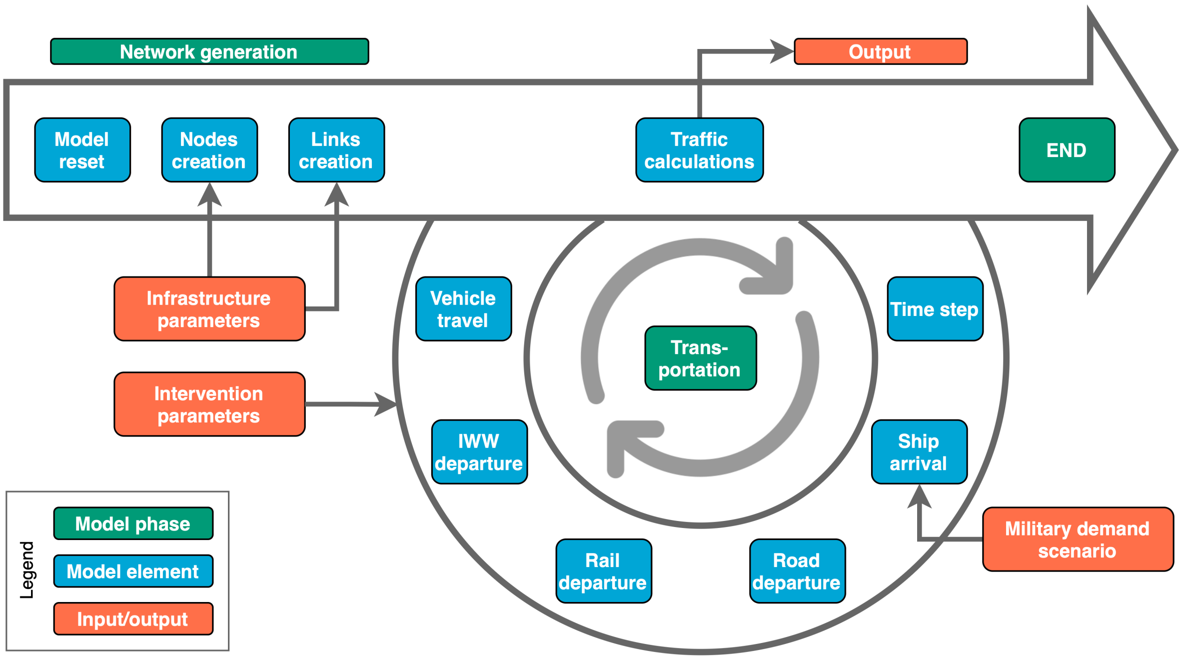

Figure 3.1: Schematic overview of the simulation model

This section continues with discussing the model entities and relations in **subsection 3.3.1**. After that, the logic of the network generation algorithm is discussed in **subsection 3.3.2** and the transportation simulation in **subsection 3.3.3**. The section concludes with a subsection on stochastic elements in the model in **subsection 3.3.4**.

3.3.1. Model entities and relations

Figure 3.2 provides an overview of the three different entity types in the model. These are infrastructure nodes, infrastructure links and military vehicles. The three different entity types have their own properties and are all connected to the same simulation environment. This environment contains the input and output parameters as its properties, which are: the time, input variables on infrastructure and military demand, and output travel time performance indicators. The interrelationships between the entity types are as follows: the infrastructure links connect the infrastructure nodes, and the vehicles drive between those nodes, using the links. These entity types, the environment and their properties form the basis of the model, and their creation and behaviour are discussed in the coming two sub-sections.

3.3.2. Network generation algorithm

The purpose of this algorithm is to prepare for running the transportation simulation. This is done by providing the model with a set of commands that reset the model, generate the nodes and links of the network, and perform traffic calculations. All those parts of the algorithm are discussed in this section.

First, all entities that might already be in the simulation environment due to previous simulation runs, are deleted and the environment is reset. The time steps are also reset to zero, and the time is set to the start time that the user has provided. Similarly, the counter since the last ship arrival is set to the provided ship arrival interval, so that a new ship will arrive immediately when executing the model.

Next, the network nodes are created in correspondence with the infrastructure parameters, which are seaports and per modality, the right number of junctions and border crossings. The nodes are given a coordinate within the simulation environment, as well as the right type, modality and corresponding shape and size, of which Table 3.1 provides an overview. All seaports and border crossings of the same type are spread evenly on the same vertical line, for which they have a fixed x-coordinate. The number of nodes that will be created per node type follow the corresponding infrastructure parameter as given by the model user.

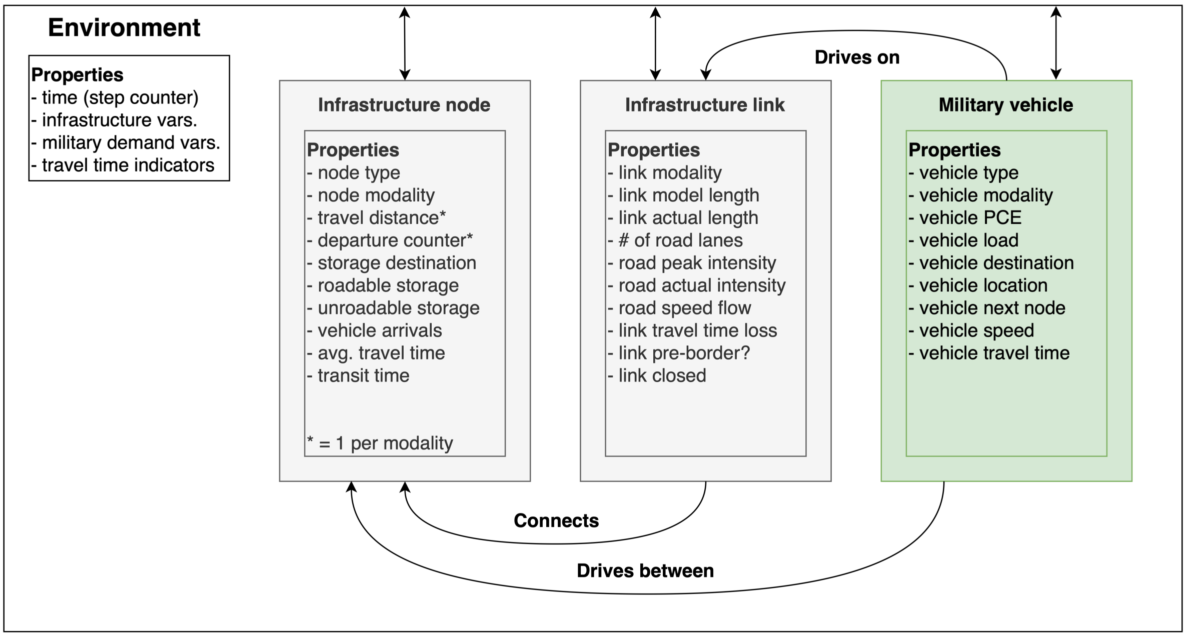

Figure 3.2: Schematic overview of model entities, their properties and their relations

Once the nodes are placed, the algorithm connects them with links. This is done in four rounds, each aimed at ensuring a well-connected network with a realistic structure that resembles the Dutch infrastructure network:

1. Initial connections: each seaport and border crossing is linked to the closest junction of every modality.
2. Forward connections (port to border): every node with fewer than three neighbours is connected to the nearest node with the same modality and fewer than four neighbours. This happens in order of increasing x-coordinate and nodes can only be connected to nodes that are further away from the ports (higher x-coordinate), which results in horizontal and diagonal roads that together with the links in the next step resemble the triangular form of the Dutch infrastructure network.
3. Backward connections (border to port): this step repeats the previous step, but the other way around. Nodes are now connected to other nodes in decreasing order of x-coordinates and to nodes that are closer to the ports (lower x-coordinates). Additionally, nodes are now only connected if the distance between them is smaller than 75 km to prevent unrealistic connections.
4. Nodes with less than 3 neighbours are sorted on their x-coordinates in **decreasing** order and every node is connected by an edge to the closest node that has a **lower** x-coordinate, has less than 4 neighbours, is not a neighbour of this node, has the same modality as this node and is not more than 75 kilometres away from this node;
5. Fallback connections: nodes that still have less than 3 neighbours are connected by an edge to the closest node that has less than 4 neighbours, is not a neighbour of this node, has the same modality as this node and is not more than 75 kilometres away from this node.

The lengths of the links are then scaled using two user-defined real-world distances: from seaport to border and from border to destination. The algorithm calculates scaling factors based on these inputs to ensure that the relative lengths in the model correspond to the desired real-world proportions, and also distinguishes the three modalities by giving them different colours.

The final part of the setup involves estimating peak traffic intensities for links of the road modalities, based on findings in Section 2.2.2 that shorter roads are typically more congested and may have more lanes. The peak intensity per road link Ip is calculated based on the link length L with formula 3.1. The data in this formula is based on data on the mean intensity per hour of national roads per region in the Netherlands, varying from 1031 to 4418 vehicles per hour (Centraal Bureau voor de Statistiek, 2020) and the idea that the 7 peak hours handle around 50% of all road traffic (Kennisinstituut voor Mobiliteitsbeleid, 2024).

$$Ip = \begin{cases} 1000 & \text{for } L \leq 50 \\ 1000 + 85 * (50 - L) & \text{for } 15 \leq L < 50 \\ 3200 + 85 * (50 - L) & \text{for } 5 \leq L < 15 \\ 7250 & \text{for } L < 5 \end{cases} \tag{3.1}$$

Table 3.1: Node variables based on parameters derived from chapter 2

Parameter	Type	Modality	Coordinates	Shape & size
# of seaports	Seaport	All	(8,xxx)	Container, 3
# of road junctions	Junction	Road	(10<x<195,xxx)	Circle, 1
# of road border crosings	Border	Road	(200,xxx)	Circle, 3
# of railway junctions	Junction	Rail	(10<x<195,xxx)	Circle, 1
# of railway border crosings	Border	Rail	(200,xxx)	Circle, 3
# of IWW junctions	Junction	IWW	(10<x<195,xxx)	Circle, 1
# of IWW border crosings	Border	IWW	(200,xxx)	Circle, 3

3.3.3. Transportation simulation algorithm

This subsection discusses the following elements that figure 3.1 shows to be part of the transportation simulation: time step, ship arrival, departure of road, rail, and IWW vehicles, vehicle travel, and traffic calculations.

As explained in section 3.2, the model runs in discrete time steps of one minute, and the simulation algorithm provides the commands executed in each of those steps. The time step model element adds one time step to the time counter, and this is translated to days, hours, and minutes to provide a clear time indication to the model user.

The ship arrival element starts by updating the counter that keeps track of the last ship arrival by adding one time step. The procedure for the arrival of a ship is executed when this counter exceeds the arrival interval set by the model user. The simulation always starts with the arrival of a ship, since the counter is set to the interval value in the previous algorithm. Such a ship arrival is modelled by increasing the equipment storage of one of the seaports by 2000 pieces, based on the findings of ship sizes in section 2.1. In addition, a node of the ”destination” type is created, and all equipment will have this node as its destination. In this process, new links are created between this destination and every border crossing and the lengths of these edges are multiplied by the factor that corresponds to the celestial distance between the border and destinations that the user has set.

The model continues with departure of road vehicles by increasing the counters since the last road departure at every seaport by one time step. If in one or more seaports, the user allows road vehicles, the counter since the last departure via road exceeds the given road departure interval, and the time of day does not interfere with rush hour or daytime avoidance, a road vehicle is created at those nodes, simulating the departure of a vehicle. Only one road vehicle entity is created in a time step, but this entity symbolises a convoy with a varying length of vehicles, set by the model user. If a vehicle is indeed created, the counter since the last road departure is set to zero again.

The model follows by increasing the seaports’ counters since the last rail departure. If a seaport meets the conditions of rail departure, which are the same as for road departure but translated to rail, a rail vehicle departs from that seaport. The same procedure also happens for IWW departure. In contrast to road and rail vehicles, these ships do not consider rush hours or daytime.

The model continues by moving every vehicle forward. When a vehicle is not driving on a link at the beginning of a time step but is on a node instead, it starts by determining the link it should drive on, based on the shortest route to its destination. After this or when the vehicle was already driving on a link, the vehicle moves forward on one of the links. When the distance to the end of the link can be driven within the time step of one minute, the vehicle moves to the node at that end of the link and will decide its new direction in the next time step. If the distance to the end of the link was longer, the vehicle simply moves in the direction of that end with a distance that corresponds to the lowest of its maximum speed on one side and the speed flow on the link on the other side. If the vehicle has reached the end of a link and this is also its destination, its arrival and travel time are administered, and the vehicle is deleted from the simulation.

After every vehicle has moved, this algorithm ends by calculating the travel time loss by sequentially applying formulas 3.2, 3.3, 3.4 for determining the travel time loss on the road and formulas 3.5 and 3.6 for the travel time loss on the road. They make use of the following variables and reasoning:

- T_h: time of day in hours.
- I_p: civil peak intensity in passenger car equivalents (pce) per hour, calculated in section 3.3.2.
- I_c: civil actual intensity in pce per hour, calculated using formula 3.2, which is based on a graph deplicting the distribution of traffic the national road network of the Netherlands throughout the day (Kennisinstituut voor Mobiliteitsbeleid, 2024).
- I_m: military intensity in pce per hour, a reflection of the military vehicles on a link as observed during model execution.
- l: number of lanes on a link, as set in section 3.3.2.
- S: speed flow in km per hour, calculated using formula 3.3. This formula is modified from the exponential relations displayed in EXHIBIT 13-2 of Transportation Research Board (2000). There are two exceptions to the standard calculations: speeds are capped at 100 km/h between 6:00 and 19:00, in line with Dutch speed regulations, and at 80 km/h when there are military vehicles on a road with 2 lanes, in answer to the literature on multi-modal traffic in section 3.1.
- Δ_{road}: Travel time loss on the road, calculated by subtracting the travel time including the effect of military vehicles minus the travel time without those vehicles in formula 3.4.
- P: Passengers in the network as function of the time and calculated in formula 3.5, based on a figure of pre-covid train use throughout the day (Kennisinstituut voor Mobiliteitsbeleid et al., 2020).
- $V_{rail,military}$: Number of military trains in the network.
- Δ_{rail}: Travel time loss in trains is calculated in formula 3.6, based on the passengers in the network and the military rail vehicles in the network. Assuming there are 400 trains in the Netherlands operating at the same time, the number of trains in the network is divided by 400 to determine the number of passengers per train. The average travel distance for a Dutch train passenger is around 50 km (Centraal Bureau voor de Statistiek, 2024) and the trains travel with an average speed of 90 km/h (Taekema, 2023), which indicates that the average trip of a train passenger takes 33 minutes. Additionally, the setup of the timetable is in such a way that trains in the same direction follow each other after either 10, 15 or 30 minutes (Ministerie van Infrastructuur en Waterstaat, 2023, p. 111), which is assumed to be 15 minutes on average. This can be summarized to stating that when a train does not operate for 33 minutes, one train full of passengers has a delay of 15 minutes. In conclusion, per minute that a military train drives instead of a passenger train, every passenger has 1/33 of 15 minutes delay.

$$I_c = \begin{cases} 0.15 * I_p & \text{for } T_h < 6 \\ 0.75 * I_p & \text{for } 6 \leq T_h < 7 \\ I_p & \text{for } 7 \leq T_h < 9 \\ 0.75 * I_p & \text{for } 9 \leq T_h < 16 \\ I_p & \text{for } 16 \leq T_h < 19 \\ 0.15 * I_p & \text{for } T_h \geq 19 \end{cases} \tag{3.2}$$

$$S(I) = \begin{cases} \begin{cases} 120 & \text{for } I < 1800 \\ 100 & \text{for } I < 1800 \\ 120 - 0.075 * (\frac{I}{l} - 1800) & \text{for } 180 \leq I < 2200 \\ 90 - 0.3 * (\frac{I}{l} - 2200) & \text{for } I > 2200 \end{cases} & \forall T_h, \forall L, \forall I_m \\ \leq 100 & \text{for } 6 \leq T_h < 19 \\ \leq 80 & \text{for } L = 2 \text{ and } I_m > 0 \end{cases} \tag{3.3}$$

$$\Delta_{road} = \sum_{i=1}^{R} (S(I_c + I_m) - S(I_c) \tag{3.4}$$

$$P = \begin{cases} 0 & \text{for } T_h < 6 \\ 45000 & \text{for } 6 \leq T_h < 7 \\ 120000 & \text{for } 7 \leq T_h < 9 \\ 45000 & \text{for } 9 \leq T_h < 16 \\ 100000 & \text{for } 16 \leq T_h < 19 \\ 45000 & \text{for } T_h > 19 \end{cases} \tag{3.5}$$

$$\Delta_{rail} = V_{rail,military} * P_n / 400 / 33 * 15 \tag{3.6}$$

3.3.4. Stochastic elements in the model

The model includes some stochastic elements in both the network generation algorithm and the transportation simulation algorithm. This causes every simulation run to be a little bit different - within the boundaries of the set parameters.

There are two categories of stochastic elements in the model: location-randomness and selection-randomness. Location-randomness occurs when nodes are created in one of the two algorithms and they are assigned with a random coordinate. In the network generation algorithm, this happens when the nodes in table 3.1 are created and in the transportation simulation algorithm this happens when destinations are created as part of the ship arrival element explained in subsection 3.3.3. Some of these nodes are assigned with a given x-coordinate and a random y-coordinate, other nodes with a random x- and y-coordinate, as explained in the respective sections.

Selection-randomness is used when an algorithm selects a subset of agents (nodes, links or vehicles) or when all of them are selected. Randomness is always used in the order of which they are selected, unless this uses a given order, for example during the second and third phase of the links creation element, as explained in section 3.3.2. When the algorithm selects a subset of agents, randomness is additionally used to determine which ones. An example is the selection of one of the seaports for the ship arrival element explained in section 3.3.2.

For these two forms of randomness, the model makes use of the built-in randomness functions in NetLogo (Wilensky, n.d.). These numbers are pseudo-random, which is typical in computer programming, and are generated based on a seed. At the beginning of a run of the network generation and transportation simulation model, this seed is generated based on the exact time of running. This seed is used for the randomness in the model execution and is stored in the output data. If the model is run with the same parameters and the same seed, the model will give the same output, through which experiments can be repeated.

3.4. Model verification

To ensure the correctness of the implemented agent-based model and to verify that each component behaves as expected, a structured verification process was carried out. This process included four main types of testing: agent behaviour testing, single-agent testing, interaction testing, and multi-agent testing, as suggested by Van Dam et al. (2012).

Agent behaviour testing involved checking the logic, inputs, states, and outputs of individual agents. This was done by recording their internal processes and responses during model execution.

Single-agent testing focused on isolating individual agents and evaluating them under controlled conditions. This included subjecting agents to extreme input values to test for robustness, such as division-by-zero errors and unexpected outputs.

Interaction testing was performed using a minimal version of the model, involving only two agents (or one per kind). The goal was to verify that interactions occurred as intended and to evaluate both desired and undesired emergent behaviours from these interactions.

Multi-agent testing assessed the complete model with all agents active. The primary aim here was to validate whether the full system exhibited expected behaviour without being misled by unexpected but potentially acceptable outcomes. Two verification strategies were used:

- *Variability testing*, where the model was run between 100 and 1000 times. Output metrics such as standard deviation, variance, and outliers were analysed to ensure consistent behaviour.
- *Timeline scrutiny*, which involved tracing the behaviour of a single, normal model run to ensure the logic of the simulation unfolded as intended.

These verification steps were crucial in validating the technical implementation of the model and ensuring that its internal logic was reliable before conducting the experiments described in the following chapters. In addition to the general testing strategies, specific verification tests were conducted for each model component. These tests focused on validating the correct implementation of key procedures and ensuring that all relevant elements of the model logic functioned as intended.

- **Seaports**
    - *Ship arrival procedure:* Verify time-based triggering using the ship arrival interval; check that ships arrive at the correct simulation time and that arrival resets the counter appropriately.
    - *Vehicle creation procedure:* Confirm that vehicles are instantiated with the correct attributes (modality, destination, cargo) upon ship arrival.
    - *Vehicle departure procedure:* Ensure that vehicles depart in accordance with convoy size and interval constraints; check that modal departure logic is respected and linked nodes are used correctly.
- **Infrastructure Links**
    - *Link creation:* Validate that all link types (road, rail, IWW) are created according to the four-step linking algorithm, including correct neighbor counts and distance thresholds.
    - *Travel time calculations:* Confirm that the travel time reflects scaled edge lengths and peak intensity logic, including additional lanes and congestion adjustments for short links.
    - *Road closure procedure:* Check whether road closures dynamically affect link accessibility and whether vehicles are rerouted or paused correctly.
- **Destinations**
    - *Destination creation:* Ensure that destinations are correctly instantiated with appropriate location, type, and connection to infrastructure.
    - *Vehicle arrival procedure:* Validate that vehicles are received only when arrival conditions are met (i.e., correctly connected and accessible); track accurate arrival time and completion of the journey.
    - *Last arrival procedure:* Confirm that model termination or statistics logging is triggered upon the arrival of the final vehicle, and that it reflects accurate timing.
- **Vehicles**
    - *Departure procedure:* Check correct initialization of the journey, selection of links, and respect of departure conditions (convoy timing, vehicle readiness).

  - *Movement procedure:* Verify correct updating of position along links based on modality-specific travel times and network topology.
  - *Arrival procedure:* Ensure that arrival logic correctly triggers upon reaching the destination node, and that model statistics or events are updated accordingly.

One issue is that the network generation algorithm sometimes does not deliver a fully connected network for every modality, when the algorithm has a lot of seaports and border crossings and not enough junctions. The consequence is that military vehicles are then not able to reach the destination for that modality, where in reality every seaport is connected to every modality. This problem only occurs now and then when applying extreme values (high for seaports and borders, low for junctions). Therefore, this is not an issue for experimentation in this research, however, this could be a problem when applying the algorithm to other countries.

3.5. Model validation

To assess the validity of the developed model, its outputs were systematically compared with the insights derived from the system analysis in Chapter 2. This validation process focused on ensuring that both the quantitative outputs and the qualitative dynamics of the model align with real-world observations and theoretical expectations.

The most important output is the travel time loss on the road, because this number should resemble the real-world situation if the influence of military mobility is excluded from a simulation run. In the real-world, the total travel time loss on the Dutch national roads is around 101,3 million hours (Rijkswaterstaat, n.d.-a), which is 0,5 million hours per day if divided by 40 * 5 working days per year. The infrastructure parameters in the model are adjusted in such a way that the average of travel time loss of one simulation day per run is the same value. These values for these infrastructure parameters are presented in section 4.1.

Another validation step includes comparing the results of experimentation with interventions, with the expected effects as identified in the conceptual diagrams of section 2.4. This is done per experiment and reported in section 4.2.

4

Experimentation and results

Experimentation is used to address the last subquestion of this research, regarding the effects of different decisions by the DMoD on civilian and military transportation. Figure 3.1 in chapter 3 shows three input categories in the model: infrastructure parameters, intervention parameters, and military demand parameters. **Section 4.1** discusses their role in the experiment design. **Section 4.2** continues with describing the exact experiments and their results. The performed system analysis is described and analysed in **section 4.3**.

4.1. Experiment design

This section discusses the use of infrastructure parameters, intervention parameters, and military demand parameters in the experimentation with the model as presented in the previous chapter. The purpose of this experimentation is to measure the measure the effect of certain intervention parameters which the DMoD can influence, as concluded in section 2.3. The experiment design will therefore vary in intervention parameters, whereas the infrastructure and military demand parameters remain static, as shown in table 4.1. These values reflect the insights from section 2.2 for the infrastructure parameters. For the scenario, 1 ship is chosen to keep experimentation simple, and the start hour is an arbitrary value. These values are in principle not changed in the experiments, with an exception to the number of ships arriving that is adjusted for the last experiments. The other values are only adjusted as part of the sensitivity analysis in section 4.3.

Table 4.1: Scenario and infrastructure parameter values

Parameter	Value
Start hour of simulation	5 o'clock
Number of ships arriving	1 ship (with 2000 pieces of equipment)
Interval between ships arriving	-
Number of seaports	4 seaports
Port to border distance	200 km
Border to destination distance	400 km
Number of road junctions	88 junctions
Number of road border crossings	8 border crossings
Number of rail junctions	45 junctions
Number of rail border crossings	6 border crossings
Number of IWW junctions	21 junctions
Number of IWW border crossings	10 border crossings

Combinations of values for intervention parameters are referred to as alternatives. Not all parameters are always mentioned, for example, when in a road-only alternative, the departure interval for trains is irrelevant. The following parameters can be part of the alternatives:

- Avoid rush hours [active/inactive], which ensures military vehicles avoid rush hours when active
- Avoid daytime [active/inactive], which ensures military vehicles avoid daytime hours when active
- Road transport [active/inactive], which indicates whether military road vehicles are used
- Convoy length [# vehicles], which indicates the number of vehicles in a road convoy
- Convoy interval [minutes], which indicates the time between convoy departures
- Convoy speed [km/h], which indicates the maximum speed for convoys
- Slow convoy overtaking [active/inactive], which indicates whether civilian traffic is assumed to overtake military convoys with a maximum speed of 80 km/h, because the convoys drive slower than civilian trucks
- Empty roads [active/inactive], which indicates whether roads in use by military vehicles are cleared from other traffic
- Empty roads time factor [%], which prescribes the relative extra travel time for civilian vehicles caused by clearing roads
- Rail transport [active/inactive], which indicates whether military trains are used
- Train interval [minutes or hours], which indicates the time between train departures
- Train speed [km/h], which indicates the operational speed of trains
- IWW transport [active/inactive], which indicates whether military barge ships are used
- Iww interval [minutes or hours], which indicates the time between barge ship departures
- IWW speed [km/h], which indicates the operational speed of barge ships

Table 4.2: Experiment parameter values per modality

Parameter	1. Slow road transit	10. Slow rail transit	15. Slow IWW transit
Avoid rush hours	inactive	inactive	inactive
Avoid daytime	inactive	inactive	inactive
Road transport	active	inactive	inactive
Convoy length	10 veh.	-	-
Convoy interval	30 min	-	-
Convoy speed	65 km/h	-	-
Slow convoy overtaking	active	-	-
Empty roads	inactive	-	-
Empty roads time factor	-	-	-
Rail transport	inactive	active	inactive
Train interval	-	12h	-
Train speed	-	80 km/h	-
IWW transport	inactive	inactive	active
IWW interval	-	-	12h
IWW speed	-	-	20 km/h

As mentioned before, the experimentation in the next section concerns the interventions found in section 2.3. These interventions are applied by varying in certain modal parameters. Managing the military traffic demand is done by varying the interval between military vehicles per modality and by varying the convoy length. Congestion avoidance can be activated by the binary switches ”avoid rush hours” or ”avoid daytime”. Prioritisation of military traffic can be arranged with the ”empty roads” switch and the corresponding time factor is used to calculate the extra travel time for civil traffic. Individual transport modalities can be (de-)activated by the respective switches. Collaborative driving strategies have not been experimented with due to infeasibility in the real world.

Table 4.2 shows an overview of a base alternatives per modality. Table 4.3 presents road alternatives in which one or two of the parameters are changed compared to the road base alternative. Table 4.4 presents the same but then for the different rail and IWW alternatives. Additionally, some experiments will performed combining multiple modalities. Table 4.5 shows the two variants for this, respectively combining road and rail, and combining all modalities. Table 4.6 uses these for experimentation with alternative uses of these modalities and table 4.7 presents experimentation with 8 arriving ships in 4 days, referring to a possible increased volume as set out in section 2.1.

Table 4.3: Experiments with alternative road use

Alternative	Changed parameter	Base value	New value
2. Moderate convoy length	Convoy length	10 veh.	20 veh.
3. Fast convoy length	Convoy length	10 veh.	30 veh.
4. Moderate convoy interval	Convoy interval	30 min	20 min
5. Fast convoy interval	Convoy interval	30 min	10 min
6. Fast convoy length & interval	Convoy length Convoy interval	10 veh. 30 min	30 veh. 10 min
7. Avoid rush hours road fastest	Avoid rush hours Convoy length Convoy interval	inactive 10 veh. 30 min	active 30 veh. 10 min
8. Avoid daytime road fastest	Avoid daytime Convoy length Convoy interval	inactive 10 veh. 30 min	active 30 veh. 10 min
9. Military vehicles only fastest	Empty roads Time factor Convoy length Convoy interval	inactive 0% 10 veh. 30 min	active 40% 30 veh. 10 min

Table 4.4: Experiments with alternative rail and IWW use

Alternative	Changed parameter	Base value	New value
11. Moderate train interval	Train interval	12h	8h
12. Fast train interval	Train interval	12h	4h
13. Avoid rush hours rail fastest	Avoid rush hours Train interval	inactive 12h	active 4h
14. Avoid daytime rail fastest	Avoid daytime Train interval	inactive 12h	active 4h
16. Moderate IWW interval	IWW interval	12h	8h
17. Fast IWW interval	IWW interval	12h	4h

Table 4.5: Parameter values for combining multiple modalities

Parameter	20a. Slow road and rail transit	21a. Slow all modality transit
Avoid rush hours	inactive	inactive
Avoid daytime	inactive	inactive
Road transport	active	active
Convoy length	10 veh.	10 veh.
Convoy interval	30 min	30 min
Convoy speed	65 km/h	65 km/h
Slow convoy overtaking	active	active
Empty roads	inactive	inactive
Empty roads time factor	-	-
Rail transport	active	active
Train interval	12h	12h
Train speed	80 km/h	80 km/h
IWW transport	inactive	active
IWW interval	-	12h
IWW speed	-	20 km/h

Table 4.6: Experiments with alternative use of multiple modalities

Alternative	Changed parameter	Base value	New value
20b. Fast road and rail transit	Convoy length	10 veh.	30 veh.
	Convoy interval	30 min	10 min
	Train interval	12h	4h
21b. Fast all modality transit	Convoy length	10 veh.	30 veh.
	Convoy interval	30 min	10 min
	Train interval	12h	4h
	IWW interval	12h	4h
22a. Avoid rush hours all modality slow	Avoid rush hours	inactive	active
22b. Avoid rush hours all modality fast	Avoid rush hours	inactive	active
	Convoy length	10 veh.	30 veh.
	Convoy interval	30 min	10 min
	Train interval	12h	4h
	IWW interval	12h	4h

Table 4.7: Experiments with multiple modalities and 8 arriving ships in 4 days

Alternative	Changed parameter	Base value	New value
23a. 8 ships all modality slow	Number of ships	1	8
	Ship interval	-	12h
23b. 8 ships all modality fast	Number of ships	1	8
	Ship interval	-	12h
	Convoy length	10 veh.	30 veh.
	Convoy interval	30 min	10 min
	Train interval	12h	4h
	IWW interval	12h	4h
24. Avoid rush 8 ships all modality fast	Avoid rush hours	inactive	active
	Number of ships	1	8
	Ship interval	-	12h
	Convoy length	10 veh.	30 veh.
	Convoy interval	30 min	10 min
	Train interval	12h	4h
	IWW interval	12h	4h
25. Avoid rush 8 ships road and rail fast	Avoid rush hours	inactive	active
	Number of ships	1	8
	Ship interval	-	12h
	Convoy length	10 veh.	30 veh.
	Convoy interval	30 min	10 min
	Train interval	12h	4h

4.2. Analysis of results

This section first discusses the effect of different parameters in detail and concludes with an overview of all alternatives, focusing on their total travel time loss and their transit time. The different parameters are analysed in groups of similar alternatives. For every group, a figure shows the travel time loss caused by military transit in the first 24 hours, and the duration time of the military transit operation. The figure shows the values for individual runs in blue and the mean of those values in red. All alternatives are compared with the first alternative in the figure, sometimes being the slow-road alternative or the slow-alternatives for rail and IWW. Appendix A provides tables with the numerical values behind the figures in this chapter, along with independent two-sample t-test results for comparing the alternatives to the base alternative of every figure.

Figure 4.1 first shows the three different modalities. These alternatives correspond with alternatives 1, 10, and 15 of table 4.2. In short, the figure shows that the road is the modality with the shortest transit time but at the cost of much travel time loss. The differences between travel time loss and transit time when using rail or IWW compared to road are significant. The insights that using trains results in slightly more travel time loss and takes 1 day (7%) shorter are also significant.

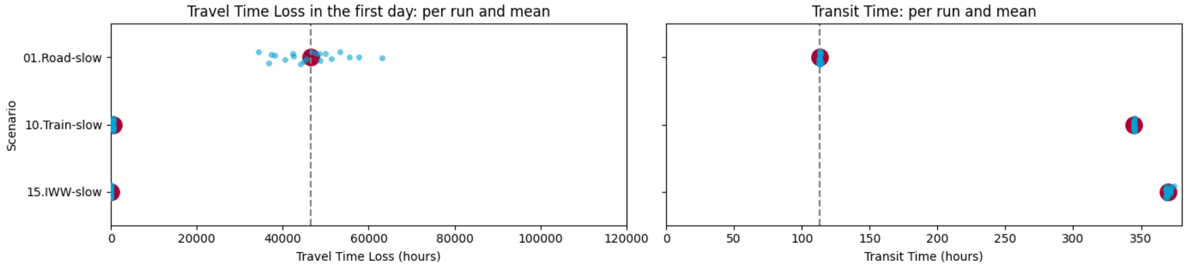

Figure 4.1: Results for experimentation with different modalities

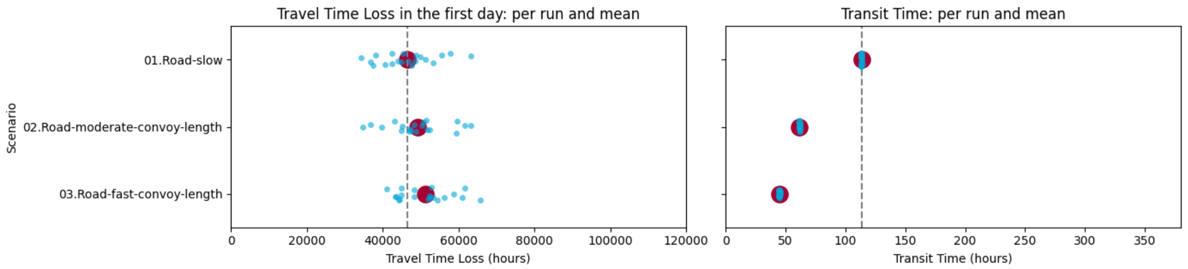

Figure 4.2: Results for experimentation with convoy lengths on the road

4.2.1. Road experiments

Figure 4.2 shows three alternatives for military transit via road, varying in convoy length. These alternatives correspond with alternatives 1 to 3 of tables 4.2 and 4.3. The figure shows that these alternatives differ minimally in travel time loss, and these differences are not significant. The spread in values per run can be explained by the randomness that is part of the network generation algorithm. However, the alternatives differ significantly in transit duration, which is as expected because an operation with an equal number of longer convoys takes less time to transit the same number of vehicles, which corresponds with the relationship as set out in figure 2.3. One can conclude that based on these two figures, it is preferable to have longer convoys, since they do not result in significantly more travel time loss, while they significantly speed up the transit operation.

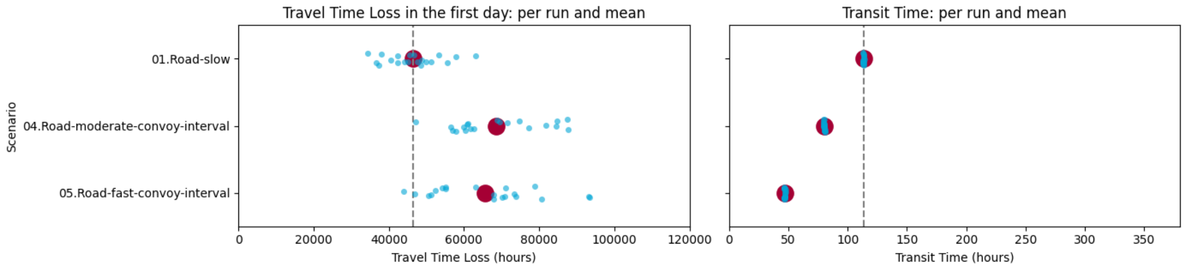

Figure 4.3: Results for experimentation with convoy intervals on the road

Figure 4.3 shows three alternatives for military transit via road, varying in convoy interval time; e.g. the time between the departure of two convoys. These alternatives with shorter intervals correspond with alternatives 4 and 5 of table 4.3. The figure shows that the alternatives with a shorter interval result in more travel time loss and this difference is significant. The benefit of these alternatives is that they significantly shorten the transit time, which corresponds with the relationship as set out in figure 2.3. The conclusion is therefore, that one should trade-off the travel time loss and transit time when it comes to determining the interval.

Figure 4.4 shows three alternatives for military transit via road, corresponding with alternatives 7a and 8a of table 4.3. The differences with the base alternative are the avoidance of driving during rush hour in alternative 7a, and driving during daytime in alternative 8a. Both alternatives show less travel time loss

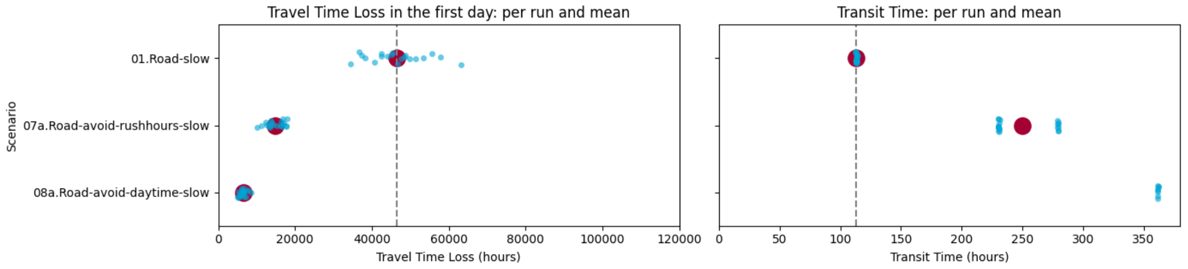

Figure 4.4: Results for experimentation with prioritisation

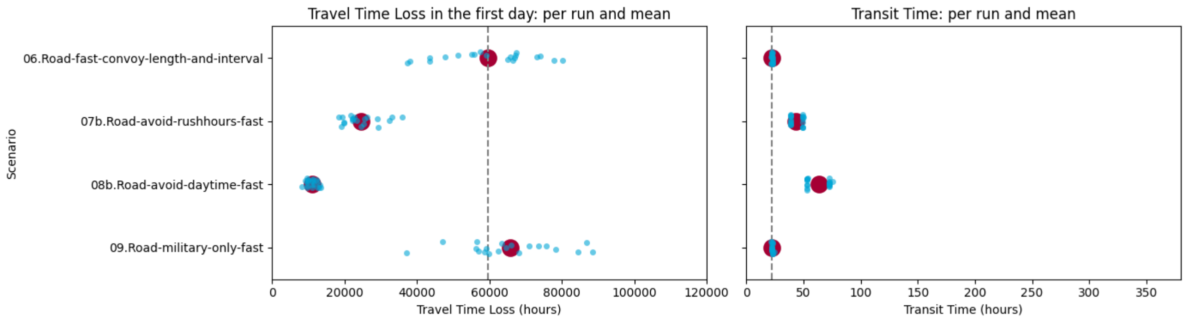

Figure 4.5: Results for experimentation with prioritisation with faster transit

than the base alternative, which is understandable, as most travel time loss was expected in rush hour and during daytime, which are avoided in these scenarios. However, this comes at the cost of much more transit time. These findings correspond with the relationships as set out in figure 2.3, although they are not all mentioned explicitly.

Figure 4.5 shows similar alternatives that experiment with prioritisation, however, this figure and the alternatives use alternative 6 as base scenario, which includes a quicker convoy interval and longer convoy length. Similar to the other figure, alternatives 7b and 8b show significantly less travel time loss than this base scenario. Although avoiding rush hours and daytime increases the transit time, alternatives 7b and 8b are significantly faster than alternative 1, respectively 61% and 51 %. This figure also shows alternative 9, in which roads used by military vehicles are reserved just for them. However, this alternative does not significantly differ in travel time loss or transit time, compared to alternative 6.

4.2.2. Rail and IWW experiments

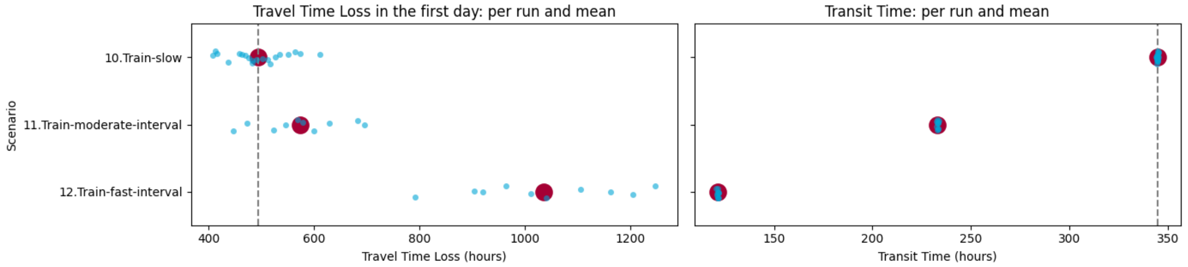

Figure 4.6: Results for experimentation with trains

In figure 4.6, three alternatives that use trains in different intervals are presented and compared with the base scenario. These alternatives correspond with alternatives 10 to 12 of tables 4.2 and 4.4. The figure shows very big, significant changes in travel time loss but this comes at a cost of significant increases in transit time, compared to the base alternative, which corresponds with with the relationship as set out in figure 2.4. Scenario 12 still takes significantly longer but this increase is less than 4% of the slow road alternative's transit time.

Figure 4.7 is comparable to figure 4.6 but shows alternatives that use barge ships instead, corresponding with alternatives 15 to 17 of tables 4.2 and 4.4. The figure shows zero travel time loss, based on one of the assumptions in the model. This comes with the same cost as in the train alternatives: very long transit times. The fastest alternative, in which a barge ship departs every 4 hours, is still 25 % slower than the slow road alternative.

4.2.3. Multimodal experiments

Figures 4.8 and 4.9 show alternatives 18 to 22b, respectively with the slow and fast variant in which road and rail modalities are combined. When using the slow dimensions, adding rail to the road modality significantly increases travel time loss and decreases the transit time. When combining all three

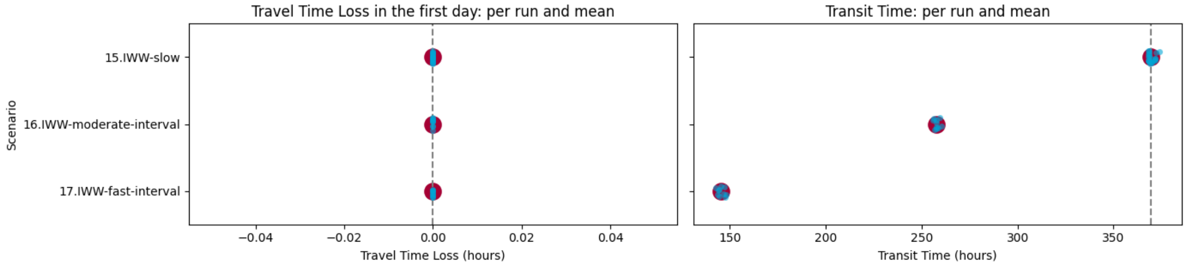

Figure 4.7: Results for experimentation with barge ships

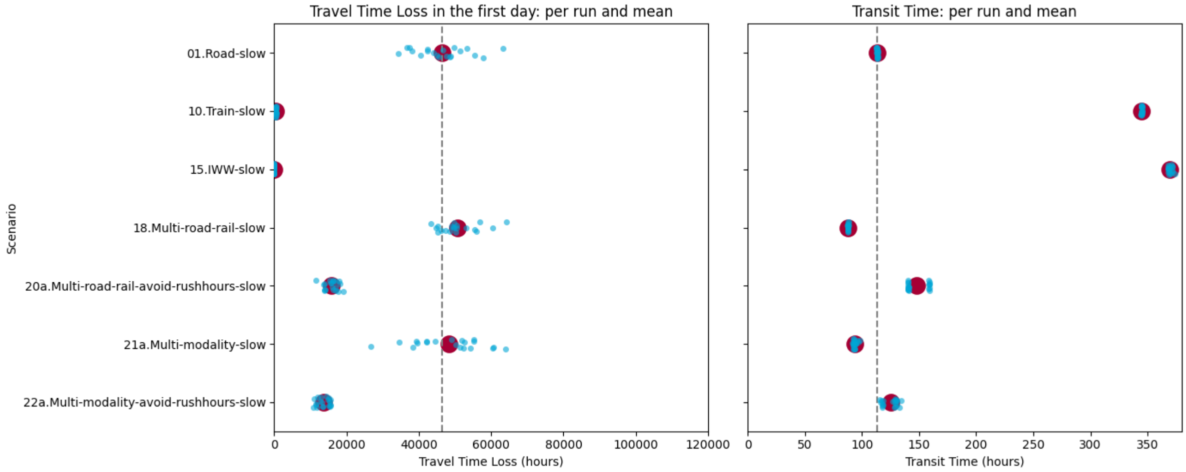

Figure 4.8: Results for experimentation combining road, rail and IWW (slow)

modalities, the transit time decreases significantly but the travel time loss does not differ significantly from the slow road alternative.

In the fast dimensions, only the small decrease in transit time is significant when combining road and rail. This decrease is larger when all three modalities are combined, during which the travel time loss does not significantly change from the fast road alternative.

When combining the two or three modalities with the avoidance of rush hours, there is always a huge and significant drop in travel time loss compared to alternatives without this avoidance. In the slow alternatives, transit time increases significantly when combining road and rail and is unchanged when combining all modalities. In the fast dimension an increase in transit time (both significant).

In figure 4.10, 4 multimodal alternatives that process 8 arriving ships in 4 days are compared with the slow road alternative. The figure shows that the alternative that combines road, rail, and the avoidance of rush hours, takes around the same transit time for 8 ships as the base alternative takes for 1 ship of military equipment. Additionally, the travel time loss per day for the alternatives that avoid rush hours are lower than that of the base alternative.

4.2.4. Results overview

Figure 4.11 shows an overview of all alternatives, except for those with 8 arriving ships in 4 days. In this figure, the experiments are sorted on their increasing total travel time loss, which is shown in the blue bars. The red bars show the corresponding transit time. Note that the total travel time loss in this figure is not the travel time loss in the first day, like in the previous figure, but the cumulative travel time loss throughout the transit period. This is important to consider because if a transit operation takes multiple days, the travel time loss also lasts multiple days.

Based on this figure, the alternatives can roughly be divided into four categories. The first category consists alternatives with no or relatively limited travel time loss, which are the alternatives that use

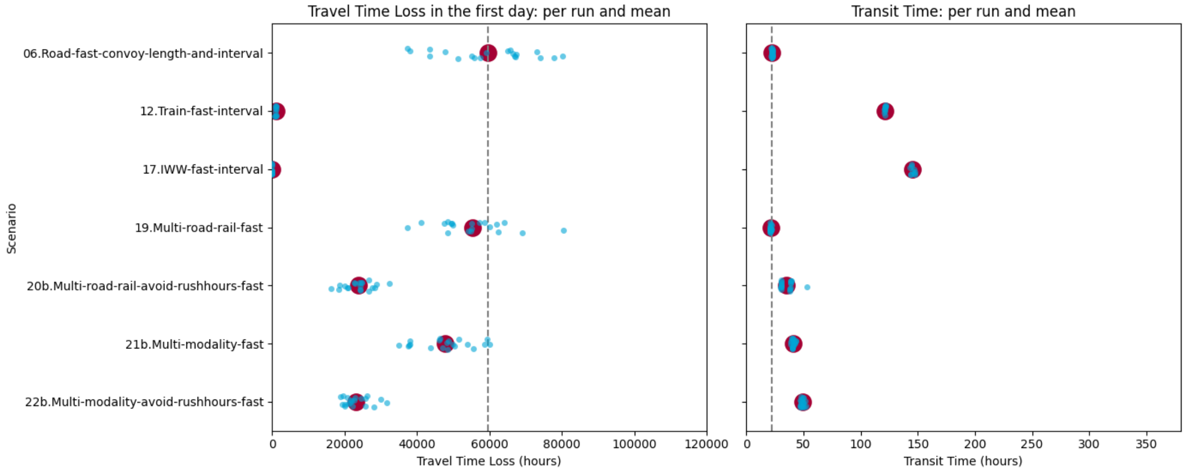

Figure 4.9: Results for experimentation combining road, rail and IWW (slow)

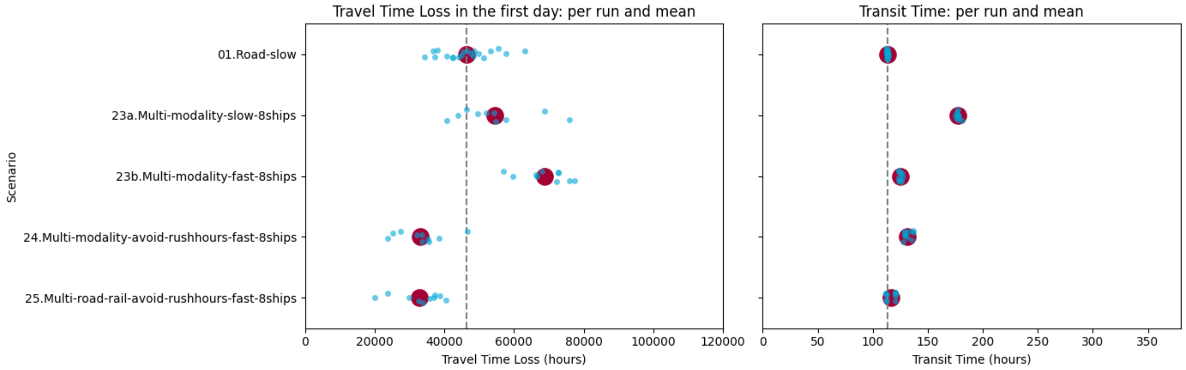

Figure 4.10: Results for experimentation with 8 arriving ships in 4 days

trains or barge ships and are shown at the top of the figure. Their transit time is relatively long but those alternatives with fast intervals are quite average.

The second category are alternatives with a very short transit time, such as alternative 19, 6 and 9, all shown in the middle of the figure. Their total travel time loss is substantial but quite average.

There are also alternatives that stand out because they have unwanted high values for both measures, such as alternative 8a, 7a, and 1, shown at the bottom of the figure, which form the third category. The fourth and last category consists of alternatives with below average values for both measures, such as 8b, 22b, 20b, and 7b. This are alternatives that use multiple transport modalities and/or avoid rush hours and/or daytime.

This figure shows that there are some alternatives that should be avoided in practice, because their underlying transit approaches don't benefit either of the two measures (third category). Other alternatives, in the first and second category, benefit one of the two measures strongly, and can therefore be used when one of the two measures is more important than the other. Lastly, their are alternatives that balance the two measures, that can be used when both measures are equally important.

Figure 4.12 is similar to figure 4.11 but shows the four alternatives that have been used for processing 8 ships in 4 days. Similar to the categories derived from figure 4.11, this figure shows an alternative with relatively little travel time loss (24), relatively little transit time (25), an alternative in which both values are relatively average (23b) and one in which both values are unwanted (23a).

4.3. Sensitivity analysis

This sensitivity analysis focuses on model parameters that are not directly varied in the experiments but may still influence the model's behaviour. Its purpose is to reveal how sensitive the model outcomes are to these underlying assumptions. Since the experimental results must be interpreted with the model's assumptions and limitations in mind, understanding these sensitivities is essential for accurately presenting the findings of this research. The sensitivity analysis is organized separately for the road, rail, and IWW elements of the model. In each analysis, a specific parameter is first increased by 10% and then decreased by 10% relative to its original value. In some cases these values have to be rounded because the model only allows discrete values. The corresponding results are shown in the figures throughout this section.

Figure 4.13 shows the outcome of the sensitivity analysis for the road modality. A few model parameters stand out in this figure and a 10 % change in their values caused significantly different outcomes: civil intensity, max80, border-destination distance and convoy speed.

A change in civil intensity causes significant changes in travel time loss. This is in line with the causal relation diagram of section 2.4, which shows that both an increase in civil intensity and in military intensity leads to more travel time loss.

The max80 parameter activates the calculations behind the assumption that the speed is capped at 80 km/h on roads with two lanes used by a military road convoy (section 3.3.3). This sensitivity analysis shows that this mechanism accounts for almost all travel time loss calculated in the model, indicating this is an assumption with a lot of effect on the outcome of the model.

The border-destination distance parameter significantly changes the military transit time when changed by 10%. Although this change is significant, the change in military transit time is limited to 28 minutes for a decrease in the parameter and 50 minutes for an increase in the parameter. The convoy speed also significantly changes the military transit time with about one hour if changed by 10%.

Figure 4.14 presents the sensitivity analysis for the rail modality. Two of the parameters in this analysis require attention: the port-border distance and the train capacity. Some other factors significantly change the transit time but these changes are less than an hour for a transit time of 5 days, which is not found relevant.

A short port-border distance significantly decreases the travel time loss by 19 %. The effect of increased port-border distance is limited to a 6% change, which is not significant.

The train capacity was not incorporated as factor in the experimentation because it is seen as value that can hardly be influenced and that does not affect the travel time. This sensitivity analysis confirms the last argument as there are no significant changes in the travel time loss. However, the transit time is 10% (half a day) shorter when the train capacity is increased with 10 %. This can be explained by realising that less trains are needed if a train has more capacity, for which the transit time is shorter.

Figure 4.15 shows the sensitivity analysis for the IWW modality. Caused by the assumption that military use of barge ships has no effect on civilian barge ships, the analysis shows no changes in travel time loss. The attention is drawn to port-border distance, border-destination distance, ship speed and ship capacity. These four parameters significantly affect the military transit time when changed by 10%.

For the port-border distance, this is only the case when the parameter is increased. In that case, the transit time changes with 4 hours (3%). For the border-destination, both an increase and decrease significantly change the transit time, with respectively 2,5 to 3 hours.

The model is more sensitive to the speed of barge ships. If this is increased, the transit time significantly decreases with 2,5 hours and when it is decreased, transit takes 14 hours longer. The model is most sensitive to the ship capacity, just like the earlier mentioned train capacity. Transit is changed by 12,5 to 14 hours if this capacity is changed.

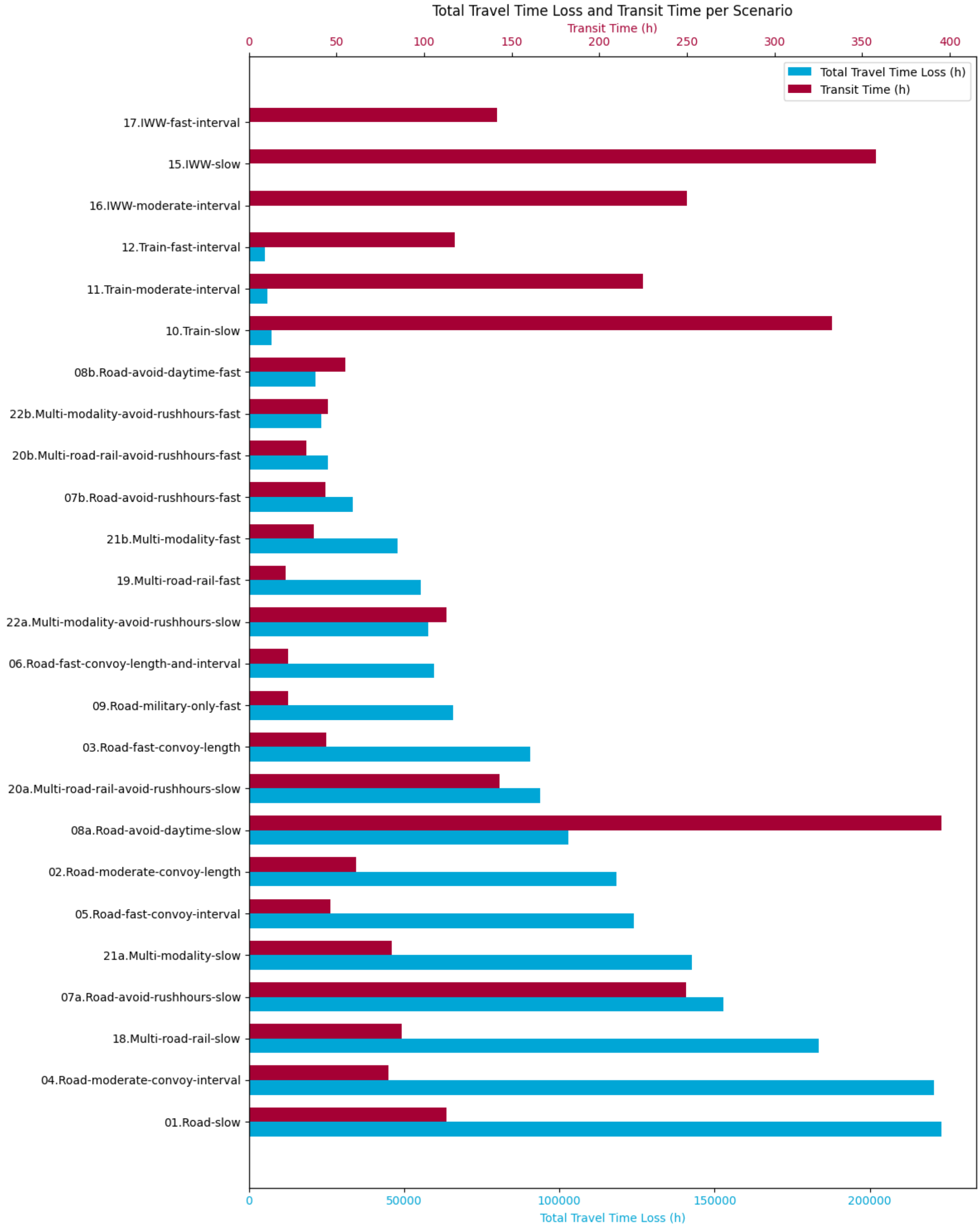

Figure 4.11: Overview of all alternatives with 1 arriving ship

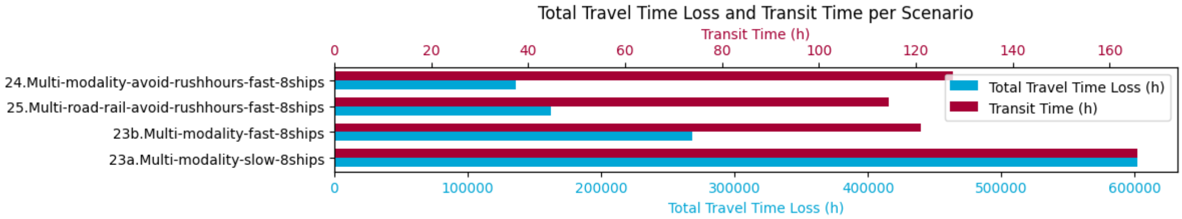

Figure 4.12: Overview of all alternatives with 8 arriving ships in 4 days

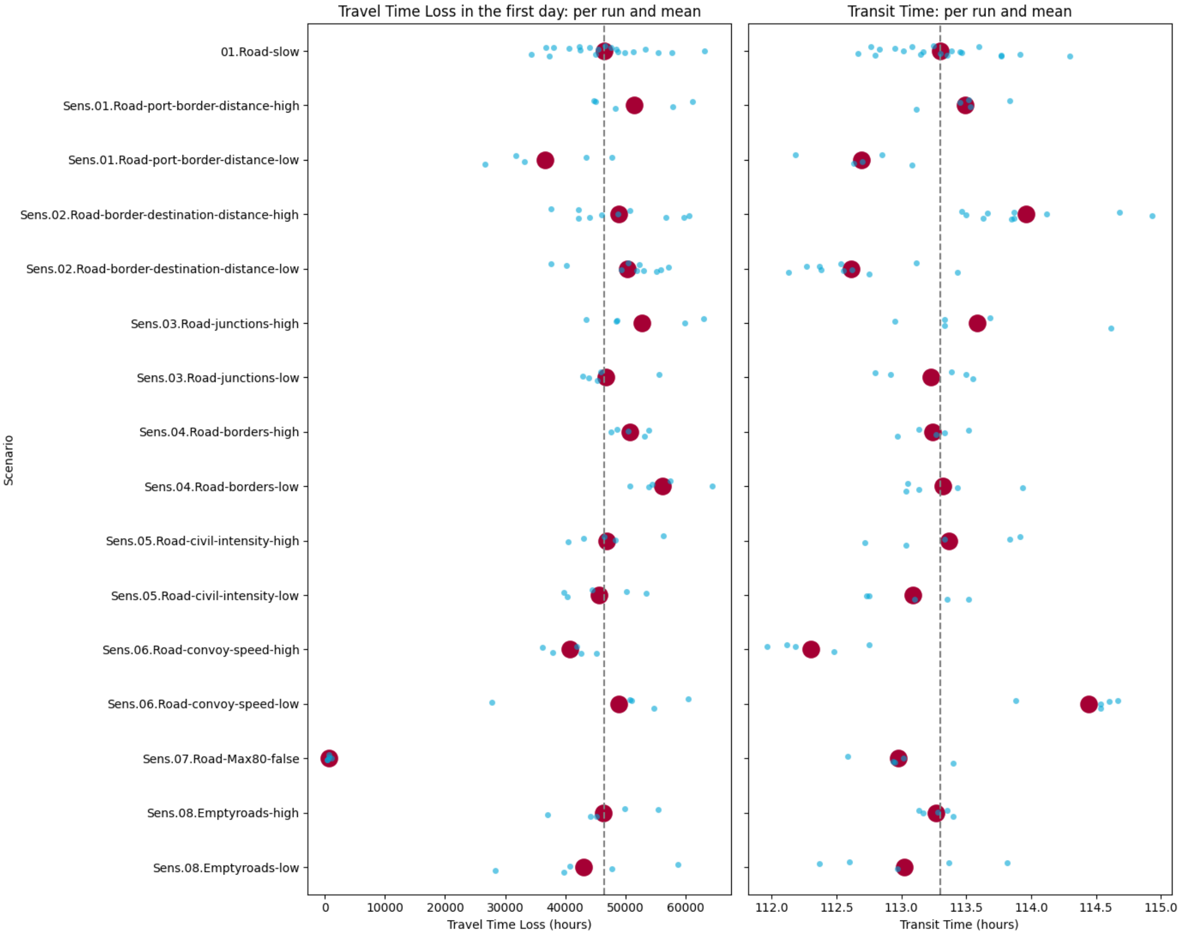

Figure 4.13: Results for sensitivity analysis for road modality

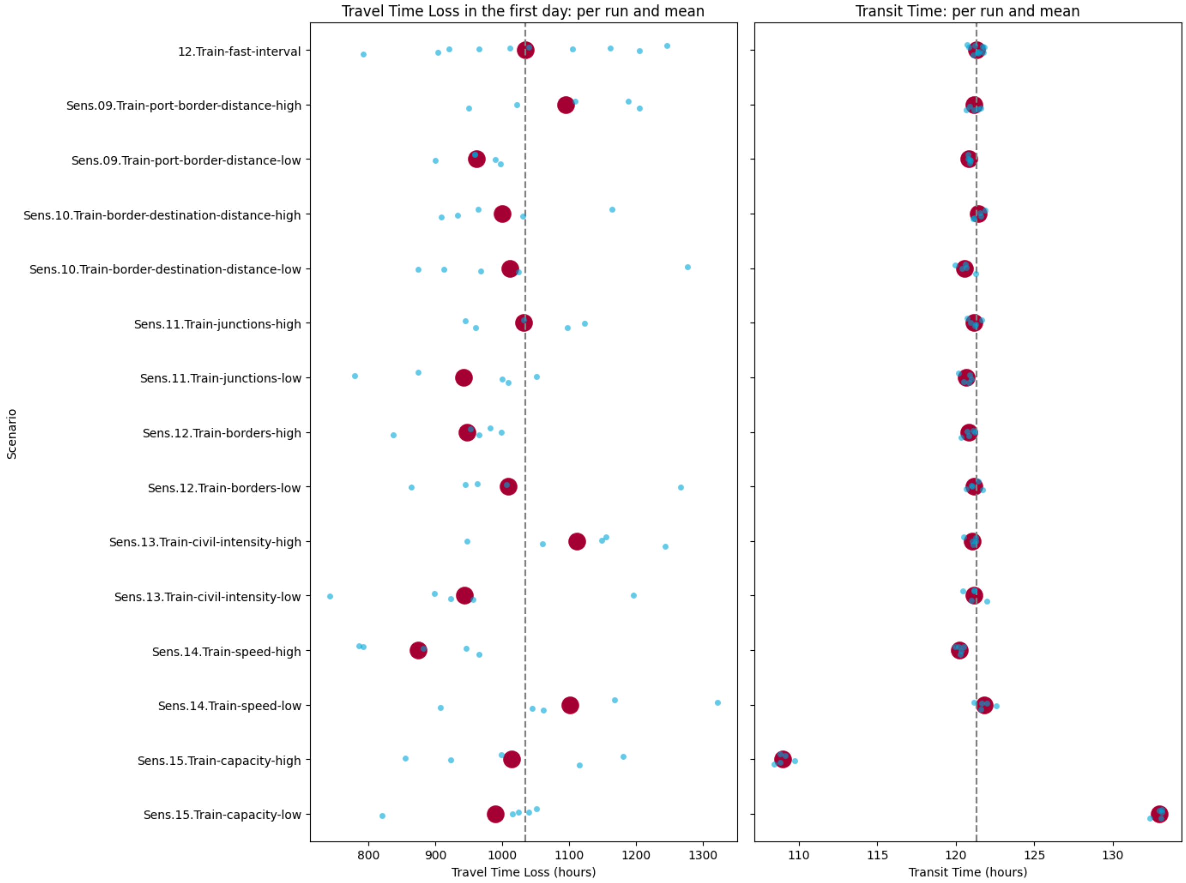

Figure 4.14: Results for sensitivity analysis for rail modality

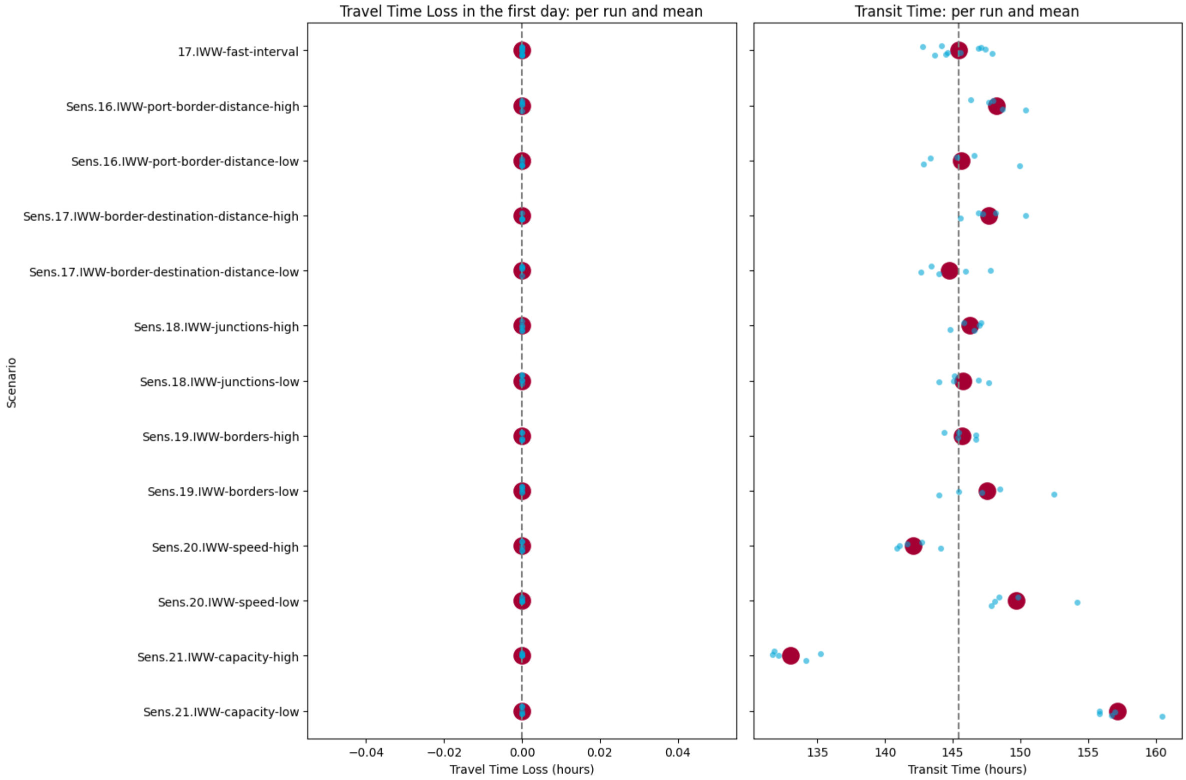

Figure 4.15: Results for sensitivity analysis for IWW modality

5

Conclusion and discussion

This research aimed to explore the impact of simultaneous infrastructure use by military and civilian vehicles and identify options for balancing that impact. After a system analysis, this report presented the development of a mesoscopic model representing a multi-modal transportation system, which is used to experiment with alternative strategies for military transit. This chapter answers the research questions as discussed in chapter 1, and discusses the relevance and limitations of the work.

5.1. Conclusion of (sub-)research questions

The first sub-question of this research was: ”How can military mobility influence the Dutch civil transportation system?” The introduction and system analysis addressed this question by explaining that military mobility sometimes transits the Netherlands on the way from other continents to their destinations in Europe. In the absence of dedicated military infrastructure, the military equipment is transported via infrastructure that is also used for civilian mobility, such as roads, railways, and inland waterways, as well as seaports and airports. Section 2.1 examined how military traffic, especially road convoys, behaves differently from civilian traffic, which could result in a slower speed flow. Military trains likely cause waiting times for civilian trains, and Inland Waterways (IWW) are not likely to impact civilian use, because of the underutilization of the current capacity. This study focused solely on infrastructure use, not on vehicle availability.

The second sub-question was: ”What are the different scenarios for military mobility demand in the Netherlands?” Initially, this question was intended to explore scenarios of military transport volumes within a certain period. However, due to ambiguity in the literature, the focus shifted to the order of magnitude of transit operations, which is around 2000 equipment pieces that arrive in the Netherlands per individual ship. Additionally, it was found that in an expanded scenario, 8 ships with a total of 16000 pieces could arrive in 4 days.

The third sub-question was: ”In what way can the Dutch Ministry of Defence influence military transportation?” With the help of analogical literature on managing multi-modal transport and traffic, section 2.3 identified several intervention methods for how the Dutch Ministry of Defence (DMoD) can influence military transportation. These are: traffic demand management, congestion avoidance, prioritisation of traffic modes, collaborative driving strategies, and integrating multiple transport modalities. This set of interventions has all been included in the development of the model to gain insights on their effects, except for collaborative driving strategies, which were found to be infeasible.

The fourth sub-question was: ”How can the transportation system be modelled to experiment with the influence of the Dutch Ministry of Defence?” The literature on modelling of transportation systems in section 3.1 resulted in the conclusion that a mesoscopic transportation model would be suitable to research the system-wide effects of individual military vehicles. This approach also accounts for multimodality both in transport choice (transport) and shared infrastructure (traffic).

The model is developed as an Agent-Based Model (ABM), using the NetLogo software, and contains both a network generation algorithm and a transportation model. The goal of the network generation algorithm was to avoid revealing sensitivities in the Dutch infrastructure system, while still enabling studying a Dutch-like network. This also reduced the dependency on data from the Dutch transportation system. Instead, key parameters on the system are used to generate a similar system every model run.

With the help of this model, it was possible to address the fifth sub-question: ”What is the effect of the Ministry’s influence on civil travel time loss and the military transit time?” As set out in section 4.2, there are four categories within the more than 30 experiments that have been conducted:

1. Alternatives with limited travel time loss but long transit time. These alternatives involve rail or inland waterway modalities only and minimise disruption to civil traffic.
2. Alternatives with short transit time but moderate travel time loss. These alternatives involve the combination of short intervals, long convoys, combining road and rail, and reserving roads for military vehicles only, all to speed up the transit operation.
3. Alternatives with high values for both indicators. These alternatives involve the road modality with slow intervals, sometimes combined with avoiding rush hours and daytime, or the rail modality with slow intervals.
4. Alternatives with relatively average or low values for both indicators. These alternatives excel in balancing the two metrics and rely on factors such as high intervals, long convoys, multiple modalities, and always in combination with avoiding rush hours or daytime.

Regarding these categories, it can be concluded that it is important to identify the intent of a transit operation before setting the parameters of the operation’s execution. For example, if a short military transit time is of the utmost importance, this requires different choices than in a situation where limiting disruption to civilian life is the most important. Even a situation where both elements are equally important can be accommodated, but again requires different choices. It speaks for itself that situations within the third category are to be avoided, as they harm both the travel time loss, as well as the transit time.

Additionally, the experiments show that different intervention methods, related to both the transport market and the traffic market, should be combined to maximise their effects. For example, avoiding rush hours and daytime in a road-only operation leads to longer transit times and only reduces the travel time loss by about 75%. Shortening the interval of such an operation by 67% reduces both measures, but combining these two methods results in one of the four shortest transit times and one far below average travel time loss. Similar conclusions can be drawn for combining measures with multiple modalities.

Together with the detailed results found in chapter 4, these findings lead to the overview depicted in figure 5.1. This shows guidelines for military transit operations with the aim of minimising travel time loss, minimising transit time, or balancing those two. Additionally, the figure mentions that short convoys are not beneficial for either of the factors and that roads should only be reserved if required for the operation because it does not serve a purpose in either of the two measures.

The figure also contains an arrow that symbolises the scale of military threats, as referred to in chapter 1. This is not a conclusion but an indication that when the level of military threats increases, it is more likely that the intent of transit operations shifts towards prioritising short transit times.

At the end of section 4.2, this methodology has been applied to experiment with 8 arriving ships in 4 days. This experimentation showed that when combining road and rail in their fastest configurations and also avoiding rush hours, it is possible to transport this military equipment within 5 days. Although avoiding rush hours limits travel time loss, these operations still significantly disrupt civilian traffic, with about 150.000 hours of travel time loss for the full operation.

The conclusion that it is possible to transit this amount of equipment within such a short period confirms *that* the Netherlands can ”facilitate simultaneous use of infrastructure by civilian and military traffic with attention to the interests of both.” Figure 5.1 and the remarks that it is important to identify the intent of an

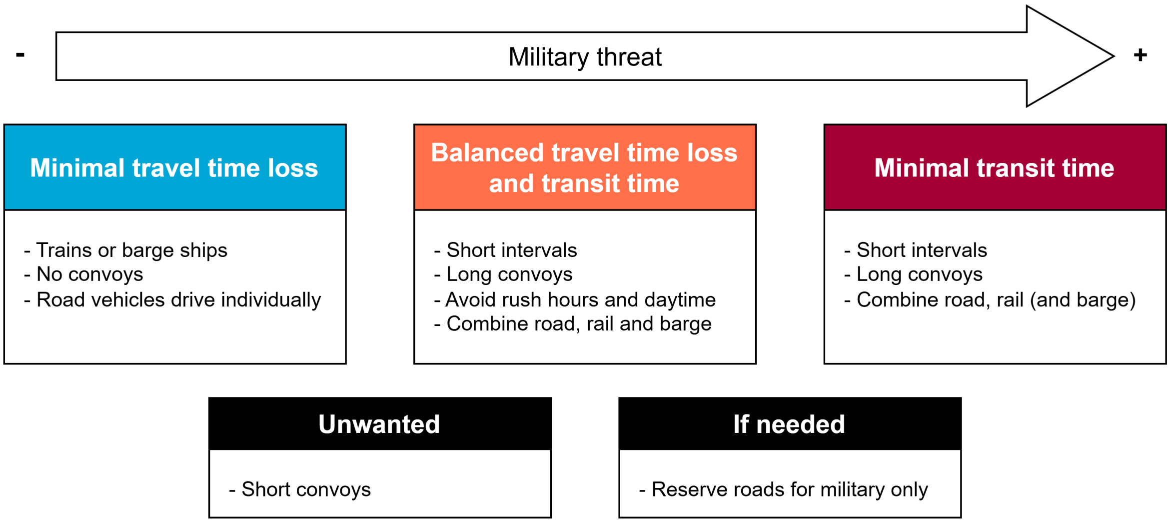

Figure 5.1: Overview of guidelines per intent for military transit operations

individual transit operation and combine intervention methods for maximal result answer the question *how* the Dutch Ministry of Defence can do this, which is the answer to the main research question.

5.2. Discussion of findings and conclusions

The findings and conclusions reported in the previous section must be interpreted with reservations as they are based on a model-based study that contains various assumptions and simplifications. This section, therefore, addresses the performed sensitivity analysis and discusses the limitations of this research. Additionally, the study is positioned in the scientific field of transportation modelling and multi-modal transportation and suggests additional research.

5.2.1. Sensitiviteis and limitations

The sensitivity analysis presented in section 4.3 revealed that the findings are subject to several model sensitivities. The model is especially sensitive to the assumption that the speed of civil vehicles on two-lane roads used by military convoys is capped at 80 km/h (see section 3.3.3). This assumption alone accounts for 98% of the observed travel time loss on the road network. Although the assumption is grounded in the system analysis of military influence on the transportation system and supported by the understanding that traffic modes interact non-linearly, this sensitivity implies that if the assumption proves inaccurate, the research outcomes may differ significantly.

Another sensitivity concerns the capacity of trains and barge ships, which directly affects the duration of transit operations. Similarly, the speed of military vehicles impacts both transit time and travel time loss. Furthermore, the model shows sensitivity to the distance between the port and the border, and the border and the final destination. While this confirms the model's potential for application in other geographical contexts beyond the Dutch infrastructure network, it also highlights the need to validate whether core components such as the network generation algorithm and travel time calculations are transferable to those contexts.

The mentioned sensitivities suggest that the results are dependent on the underlying assumptions. Given the limited availability of literature on simultaneous military and civilian infrastructure use, validating these assumptions requires additional research. For instance, microscopic research into the interaction between civilian and military road users could provide much-needed insight, but lies beyond the scope of the present study. Research could also be focused on exploring measures that ensure certain assumptions do not hold, such as a ban on overtaking for trucks or the use of only three-lane roads.

The sensitivity to vehicle capacities also touches upon a broader limitation of the study: the exclusion of vehicle availability and loading/unloading times. While these omissions do not undermine the main conclusions regarding simultaneous infrastructure use, they do place constraints on the operational feasibility of specific recommendations. For example, the promotion of rail and IWW as alternatives to road use require the availability of sufficient transport vehicles, which has not been modelled here. Additionally, certain simplifying assumptions, such as only considering passenger trains, may limit the representativeness of the model. Furthermore, the model abstracts away from other real-world factors such as road accidents or infrastructure works, which can also cause congestion and might interact differently with military mobility.

This study contributes to ongoing research in transportation modelling, particularly in the context of agent-based modelling (ABM). It confirms the insight, highlighted by earlier research, that ABM allows for meaningful simulation in the absence of comprehensive transportation data. The model also illustrates how ABM can be extended towards a mesoscopic approach, whereby part of the traffic is modelled macroscopically and part microscopically.

5.2.2. Positioning in the scientific field

In the domain of multimodal transport interventions, this study demonstrated the potential of three out of four analysed categories of managing multi-modality: traffic demand management, congestion avoidance, and integrating multiple transport modalities. Prioritisation of roads for military vehicles, however, did not result in significant system-wide benefits in this context.

Concerning the scientific field of transportation modelling, as explored in section 3.1, this study confirmed several insights from other researchers. For example, the insight that ABM allows for transportation modelling without the availability of all data that transportation models normally require is confirmed by the development and usability of this model. Additionally, this approach can also be applied to a mesoscopic model, in which part of the traffic is viewed macroscopically and part microscopically.

A notable contribution lies in the development of the network generation algorithm, which has not been identified in prior literature. Although its development was initially motivated by the confidentiality of information on military mobility but the elaboration and development of this idea also shows benefits in other areas. The conducted sensitivity analysis revealed the possibilities of such an algorithm, for example, in experimentation with the number of seaports. Additionally, the number of researched intervention methods and following experiments and sensitivity analysis show that ABM allows for a very flexible model in which many different factors can be broad together.

5.2.3. Recommendations for future research

This research has demonstrated the value and flexibility of agent-based modelling for assessing multimodal transportation strategies involving military mobility. At the same time, several critical assumptions and omissions call for caution in interpreting the results, especially when used for policy advice or operational planning. Several recommendations for future research emerge from the sensitivities and limitations mentioned above. Microscopic research on the interaction between convoys (of varying lengths) and civilian vehicles is essential since assumptions on this topic cause such a big part of the travel time loss in the model. At the same time, the flexibility that is inherent to ABM and is amplified by the network generation algorithm, provides researchers hereafter to modify the model, apply it to different contexts and incorporate new insights or research questions. The conclusions would benefit such efforts on topics such as vehicle availability, capacity, and speed, and travel time loss due to accidents and infrastructure repairs, for which the developed simulation model can function as a starting point.

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A

Additional experiment result analysis

Table A.1: Comparison of alternatives with different modalities

Scenario	Runs	Travel time loss (h)			Transit time (h)		
		Value	△	p-value	Value	△	p-value
01.Road-slow	20	46448	None	None	112.80	None	None
10.Train-slow	20	495	-99%	0.000	332.86	195%	0.000
15.IWW-slow	20	0	-100%	0.000	357.73	217%	0.000
10.Train-slow	20	495	None	None	332.86	None	None
15.IWW-slow	20	0	-100%	0.000	357.73	7%	0.000

Table A.2: Comparison of road-based alternatives

Scenario	Runs	Travel time loss (h)			Transit time (h)		
		Value	△	p-value	Value	△	p-value
01.Road-slow	20	46448	None	None	112.80	None	None
02.Road-moderate-convoy-length	20	49142	6%	0.268	61.12	-46%	0.000
03.Road-fast-convoy-length	20	51179	10%	0.045	44.36	-61%	0.000
04.Road-moderate-convoy-interval	20	68647	48%	0.000	79.83	-29%	0.000
05.Road-fast-convoy-interval	20	65662	41%	0.000	46.71	-59%	0.000
07b.Road-avoid-rushhours-fast	20	24652	-47%	0.000	43.56	-61%	0.000
08a.Road-avoid-daytime-slow	20	6443	-86%	0.000	395.29	250%	0.000
08b.Road-avoid-daytime-fast	20	11029	-76%	0.000	54.81	-51%	0.000
9. Road-military-only-fast	20	65764	40 %	0.000	22.43	-80%	0.000
06.Road-fast-convoy-length-and-interval	20	59666	None	None	22.36	None	None
07b.Road-avoid-rushhours-fast	20	24652	-59%	0.000	43.56	95%	0.000
08b.Road-avoid-daytime-fast	20	11029	-82%	0.000	54.81	145%	0.000
9. Road-military-only-fast	20	65764	10 %	0.145	22.43	0%	0.659

Table A.3: Comparison of rail and IWW alternatives

Scenario	Runs	Travel time loss (h)			Transit time (h)		
		Value	△	p-value	Value	△	p-value
10.Train-slow	20	495	None	None	332.86	None	None
11.Train-moderate-interval	10	574	16%	0.015	225.08	-32%	0.000
12.Train-fast-interval	10	1035	109%	0.000	117.33	-65%	0.000
15.IWW-slow	20	0	None	None	357.73	None	None
16.IWW-moderate-interval	10	0	nan	nan	249.72	-30%	0.000
17.IWW-fast-interval	10	0	nan	nan	141.46	-60%	0.000

Table A.4: Comparison of multi-modal road-rail alternatives

Scenario	Runs	Travel time loss (h)			Transit time (h)		
		Value	△	p-value	Value	△	p-value
01. Road-slow	20	26448	None	None	112.80	None	None
18.Multi-road-rail-slow	20	50818	9%	0.041	87.28	-23%	0.000
19.Multi-road-rail-fast	20	55285	19%	0.003	21.13	-81%	0.000
20a.Multi-road-rail-avoid-rushhours-slow	20	15846	-66%	0.000	143.11	27%	0.000
20b.Multi-road-rail-avoid-rushhours-fast	20	23914	-49%	0.000	32.56	-71%	0.000

Table A.5: Comparison of multimodal alternatives

Scenario	Runs	Travel time loss (h)			Transit time (h)		
		Value	Δ	p-value	Value	Δ	p-value
01.Road-slow	20	46448	None	None	112.80	None	None
21a.Multi-modality-slow	20	48261	4%	0.508	81.61	-28%	0.000
21b.Multi-modality-fast	20	47759	3%	0.586	37.01	-67%	0.000
22a.Multi-modality-avoid-rushhours-slow	20	13578	-71%	0.000	112.96	0%	0.910
22b.Multi-modality-avoid-rushhours-fast	20	23284	-50%	0.000	45.00	-60%	0.000
21b.Multi-modality-fast	20	47759	None	None	37.01	None	None
22b.Multi-modality-avoid-rushhours-fast	20	23284	-51%	0.000	45.00	22%	0.000

Table A.6: Comparison of alternatives with 8 ships arriving

Scenario	Runs	Travel time loss (h)			Transit time (h)		
		Value	Δ	p-value	Value	Δ	p-value
01.Road-slow	20	46448	None	None	112.80	None	None
23a.Multi-modality-slow-8ships	10	54385	17%	0.059	165.72	47%	0.000
23b.Multi-modality-fast-8ships	10	68849	48%	0.000	121.00	7%	0.000
24.Multi-modality-avoid-rushhours-fast-8ships	10	33134	-29%	0.000	127.69	13%	0.000
25.Multi-road-rail-avoid-rushhours-fast-8ships	10	32946	-29%	0.000	114.44	1%	0.059
23b.Multi-modality-fast-8ships	10	68849	None	None	121.00	None	None
24.Multi-modality-avoid-rushhours-fast-8ships	10	33134	-52%	0.000	127.69	6%	0.000
25.Multi-road-rail-avoid-rushhours-fast-8ships	10	32946	-52%	0.000	114.44	-5%	0.000

Table A.7: Overview of senstivity analyses

Scenario	Runs	Travel time loss (h)			Transit time (h)		
		Value	**∆**	**p-value**	**Value**	**∆**	**p-value**
01.Road-slow	20	46448	None	None	112.80	None	None
Sens.01.Road-port-border-distance-low	5	36581	-21%	0.063	112.19	-1%	0.009
Sens.01.Road-port-border-distance-high	5	51430	11%	0.237	112.99	0%	0.227
Sens.02.Road-border-destination-distance-low	10	50318	8%	0.158	112.12	-1%	0.000
Sens.02.Road-border-destination-distance-high	10	48870	5%	0.432	113.46	1%	0.002
Sens.03.Road-junctions-low	5	46718	1%	0.926	112.73	-0%	0.714
Sens.03.Road-junctions-high	5	52712	13%	0.178	113.08	0%	0.386
Sens.04.Road-borders-low	5	56179	21%	0.008	112.82	0%	0.931
Sens.04.Road-borders-high	5	50763	9%	0.050	112.74	-0%	0.680
Sens.05.Road-civil-intensity-low	5	45617	-2%	0.800	112.59	-0%	0.290
Sens.05.Road-civil-intensity-high	5	46930	1%	0.883	112.81	0%	0.963
Sens.06.Road-convoy-speed-low	5	48946	5%	0.687	113.94	1%	0.000
Sens.06.Road-convoy-speed-high	5	40769	-12%	0.030	111.80	-1%	0.000
Sens.07.Road-Max80-false	5	669	-99%	0.000	112.48	-0%	0.077
Sens.08.Emptyroads-low	5	43046	-7%	0.548	112.52	-0%	0.365
Sens.08.Emptyroads-high	5	46364	-0%	0.982	112.77	-0%	0.766
12.Train-fast-interval	10	1035	None	None	117.33	None	None
Sens.09.Train-port-border-distance-low	5	961	-7%	0.157	116.84	-0%	0.002
Sens.09.Train-port-border-distance-high	5	1095	6%	0.393	117.16	-0%	0.412
Sens.10.Train-border-destination-distance-low	5	1011	-2%	0.786	116.57	-1%	0.017
Sens.10.Train-border-destination-distance-high	5	1000	-3%	0.602	117.44	0%	0.573
Sens.11.Train-junctions-low	5	942	-9%	0.203	116.68	-1%	0.009
Sens.11.Train-junctions-high	5	1032	-0%	0.954	117.15	-0%	0.370
Sens.12.Train-borders-low	5	1009	-3%	0.760	117.16	-0%	0.435
Sens.12.Train-borders-high	5	947	-9%	0.126	116.85	-0%	0.034
Sens.13.Train-civil-intensity-low	5	943	-9%	0.321	117.13	-0%	0.489
Sens.13.Train-civil-intensity-high	5	1111	7%	0.289	117.03	-0%	0.128
Sens.14.Train-speed-low	5	1101	6%	0.452	117.79	0%	0.137
Sens.14.Train-speed-high	5	874	-16%	0.018	116.24	-1%	0.000
Sens.15.Train-capacity-low	5	990	-4%	0.487	128.92	10%	0.000
Sens.15.Train-capacity-high	5	1015	-2%	0.792	104.99	-11%	0.000
17.IWW-fast-interval	10	0	None	None	141.46	None	None
Sens.16.IWW-port-border-distance-low	5	0	nan	nan	141.60	0%	0.921
Sens.16.IWW-port-border-distance-high	5	0	nan	nan	144.22	2%	0.010
Sens.17.IWW-border-destination-distance-low	5	0	nan	nan	140.75	-1%	0.534
Sens.17.IWW-border-destination-distance-high	5	0	nan	nan	143.65	2%	0.056
Sens.18.IWW-junctions-low	5	0	nan	nan	141.76	0%	0.741
Sens.18.IWW-junctions-high	5	0	nan	nan	142.25	1%	0.277
Sens.19.IWW-borders-low	5	0	nan	nan	143.50	1%	0.244
Sens.19.IWW-borders-high	5	0	nan	nan	141.71	0%	0.732
Sens.20.IWW-speed-low	5	0	nan	nan	145.67	3%	0.019
Sens.20.IWW-speed-high	5	0	nan	nan	138.09	-2%	0.002
Sens.21.IWW-capacity-low	5	0	nan	nan	153.16	8%	0.000
Sens.21.IWW-capacity-high	5	0	nan	nan	129.00	-9%	0.000