



Politecnico di Torino

Master of Civil Engineering

Infrastructures and Transportation Systems

A.Y. 2024/2025

**Performance Evaluation and Capacity Planning of
Port-Hinterland Transport Chains with
System Dynamics Modeling:
Analysis of the Road Network**

Relator:

Prof.ssa Claudia Caballini

Co-relator:

Dott.ssa Costanza Chiesa

Candidates:

Cardinale Sara, 322526

Abstract

Global supply chains today face the dual challenge of being efficient and competitive while also operating in a sustainable manner. Ports occupy a central position in this system, acting as pivotal hubs where the flow of goods can either facilitate or constrain the performance of the broader logistics network. The efficiency of port operations has a direct impact not only on the port itself but also on inland transportation, distribution, and ultimately on the reliability of supply chains worldwide. Among the various flows managed in a port, road transport is increasingly critical. Ensuring the rapid and uninterrupted movement of trucks is essential to prevent congestion and delays, which can cascade through the system and affect the timely delivery of goods to their final destinations.

Ports present unique operational challenges due to the coexistence of road and rail networks within a very limited and highly congested space. Trucks and trains share corridors, terminal access points, and intersections, making the coordination of these flows particularly complex. Any disruption or inefficiency in managing road traffic can quickly ripple through the entire port system, generating queues, delays, and in extreme cases, systemic congestion. This spatial constraint, combined with the dynamic interaction of multiple transport modes, makes the analysis and optimization of port operations a particularly challenging task.

This thesis aims to analyze, model, and simulate a port node, focusing on the road flows and the way it interacts with the railway network within these confined areas. Due to the non-linear dynamics and feedback mechanisms inherent in such systems, a System Dynamics (SD) approach has been adopted. SD is especially suitable for capturing interdependencies, delays, and feedback loops, offering a comprehensive perspective on how various components influence each other over time.

The study is grounded in a case study of an Italian port, relying on real operational data to ensure that the findings are both realistic and applicable. Several scenarios were examined, including standard operations, increased demand, and service disruptions. By simulating these scenarios, it was possible to identify the points of vulnerability in the port's operations and evaluate the resilience of its logistics flows under varying conditions.

Results indicate that the main bottlenecks occur at the entrance gates and where road and rail flows intersect. The latter are particularly sensitive areas because trains are granted regulatory priority,

often causing trucks to wait, generating queues, and producing cascading delays. In extreme cases, this can lead to systemic congestion that affects the efficiency of the entire port operation.

The model developed in this thesis proves to be an effective tool for identifying these critical areas and vulnerabilities. It provides insights that can inform operational decisions aimed at improving efficiency, capacity, and resilience, particularly in relation to managing road traffic within the port. Finally, the study contributes to a deeper understanding of the operational complexities faced by modern ports and offers practical insights for enhancing the management of critical infrastructure in highly constrained environments.

The present document was developed in six sections, briefly described below.

Chapter 1 - context of reference

Presents a theoretical background on multimodal transport, port logistics and hinterland connectivity. The chapter concludes with a review of the existing literature and establishes the innovative contribution of this thesis.

Chapter 2 - Methodology: System Dynamics Simulation

Describes the research methodology used, introducing simulation as a tool for analyzing complex port systems and comparing multiple approaches, justifying the selection of a System Dynamics (SD) given its ability to capture system's feedback loops and aggregate flows.

Chapter 3 – Case Study

Details the simulation model, based on a real Italian port case study. It explains the development of the road network, along as its crossing with the railway system, along with a description of the demand growth and disruption scenarios that were tested.

Chapter 4 – Results

Presents the simulation results, beginning with model validation. It analyzes the road network's performance under various scenarios and then quantifies the impact of rail-road interactions at crossings, focusing on system throughput and congestion.

Chapter 5 – Conclusions

Summarizes the key findings, identifying gate V3 and crossing X3 as the primary sources of bottlenecks. It concludes that rail priority at crossings reduces the road network's throughput revealing critical point of operational friction.

Chapter 6 – Scope and limitations

Outlines the study's boundaries clarifying that the model focuses on internal dynamics and uses necessary simplifications.

Acknowledgements

This thesis holds dual value for me: it's the result of many months of work and it marks the conclusion of my entire academic journey. It has been a long road; one I could not have faced with such determination without the support of the right people.

I want to express my deepest gratitude to everyone who supported me, starting with my advisors. To Professor Claudia Caballini, thank you for being a mentor from day one, for believing in my abilities, and for sharing the world of port logistics with such genuine and contagious passion. To Costanza Chiesa, I sincerely thank you for your constant support and for enriching my work with your valuable experience and insights. Thank you both for all the time and guidance you gave me.

A special and heartfelt thank you goes to my partner on this journey: Daniela. This thesis wouldn't exist without you. Thank you for sharing this experience with me, for pushing me to think more deeply, and for making every challenge less difficult and more inspiring.

I also want to thank Veronica Asta and Next Freight for the fantastic opportunity to collaborate on this project.

Finally, to my family, my partner, and my friends, thank you for being my pillars of support every step of the way. Your encouragement was the driving force that allowed me to reach this goal.

Contents

1.	Context of Reference	12
1.1.	Overview of freight transport.....	12
1.1.1.	Freight transport systems	12
1.1.2.	Multimodal and intermodal transport	14
3.2.3	Challenges in freight transport.....	16
1.2.	Shipping sector.....	18
1.2.1.	General overview of maritime transport	18
1.2.2.	Current economic situation of the maritime transport sector.....	19
1.2.1.	Demand and supply in ports	20
1.2.2.	Port operations: structure, stakeholders, and process	20
1.2.3.	Trends and innovations in maritime logistics	27
1.3.	The shipping sector and hinterland connectivity	28
1.3.1.	Port-hinterland concept.....	28
1.3.2.	Internal port logistics and layouts	29
1.3.3.	Integration with other modes of transport.....	31
1.3.4.	Challenges of linking ports to inland destinations.....	39
1.4.	Analysis of existing literature	41
1.5.	Innovative contribution of the Thesis	43
2.	Methodology: System Dynamics Simulation	44
2.1.	Different simulation approaches	44
2.2.	Software selection: Vensim PLE	47
3.	Case Study	48
3.1.	Port Description	48
3.2.	Generalities	49

3.2.1.	Overview of the models	49
3.2.2.	Development of the models	49
3.2.3.	Terminal infrastructure and specialization.....	49
3.2.4.	The crossing conflict problem	50
3.2.5.	Generalized scheme for the simulation models	51
3.2.6.	Cargo type aggregation	52
3.3.	Road network model	52
3.3.1.	Physical layout and operational rules	53
3.3.2.	The truck lifecycle	56
3.3.3.	System process flow	56
3.3.4.	Simulation parameters	57
3.3.5.	Model variables and equations.....	58
3.3.6.	Validation and calibration.....	74
3.3.7.	Scenarios modeled	74
3.4.	Crossings between networks models	84
3.4.1.	Model integration methodology.....	84
3.4.2.	Expected system dynamics	85
3.4.3.	Simulation parameters	85
3.4.4.	Model variables and equations.....	86
3.4.5.	Scenarios modeled	87
4.	Results.....	90
4.1.	Model validation	90
4.2.	Road network model results.....	92
4.2.1.	Baseline performance scenario	92
4.2.2.	Infrastructure expansion scenario	96

4.2.3.	Demand growth scenario	99
4.2.4.	Disruption scenarios.....	102
4.2.5.	Slow-down scenario.....	106
4.3.	Crossing between network models results.....	112
4.3.1.	Baseline performance scenario	112
4.3.1.	Slow-down scenario.....	115
5.	Conclusions.....	118
6.	Scope and limitations.....	120
7.	Bibliography	121

List of Figures

Figure 1: Point-to-point and hub-and-spoke networks [2].....	15
Figure 2: Fundamental physical elements of a port [14]	21
Figure 3: Port stakeholders [3].....	24
Figure 4: Layers of a port's hinterland reach [18]	30
Figure 5: Railway facilities in a port [3]	32
Figure 6: Different types of dry ports [14].....	36
Figure 7: Interaction between maritime and inland transport systems [14].....	38
Figure 8: Generalized scheme for the simulation model	51
Figure 9: Schematized Road network for Scenario 1	53
Figure 10: Truck lifecycle.....	56
Figure 11: Truck entrances for Scenario 1	57
Figure 12: Schematized Road network for Scenario 2	76
Figure 13: Truck entrances for Scenario 2.....	77
Figure 14: Truck entrances for Scenario 3.....	80
Figure 15: Schematized Road network for Scenario 4	81
Figure 16: Schematized Road network for Scenario 4bis.....	82
Figure 17: Train Presence at Crossings X1, X2, and X3 for Scenario 1	88
Figure 18: Train Presence at Crossings X1, X2, and X3 for Scenario 2	89
Figure 19: Trucks exited for validation	90
Figure 20: Outbound Terminal 2 for validation.....	91
Figure 21: Trucks exited via V2 and V3.....	92
Figure 22: Trucks waiting at V2 and V3	93
Figure 23: Occupancy VS capacity of segment P.....	94
Figure 24: Occupancy VS capacity of segment V	94
Figure 25: Occupancy VS capacity of Terminal 1.....	95
Figure 26: Occupancy VS capacity of T8.....	96
Figure 27: Trucks waiting at V3 - Base Scenario VS Scenario 2.....	97
Figure 28: Trucks waiting at V2 - Scenario 1 VS Scenario 2.....	97
Figure 29: Trucks exited via V3 - Scenario 1 VS Scenario 2.....	98
Figure 30: Trucks exited via V2, V3 and V4.....	98

Figure 31: Trucks on V outbound - Scenario 1 VS Scenario 2	99
Figure 32: Trucks waiting at V2 and V3 - Scenario 1 VS Scenario 3	100
Figure 33: Trucks on V outbound - Scenario 1 VS Scenario 3	101
Figure 34: Trucks exited via V2 and V3 - Scenario 1 VS Scenario 3	101
Figure 35: Occupancy VS capacity of segment V due to Disruption	102
Figure 36: Trucks in T8 - Scenario1 VS Scenario 4.....	103
Figure 37: Trucks exited via V3 - Scenario 1 VS Scenario 4.....	104
Figure 38: Trucks in T2 - Scenario 1 VS Scenario 4bis	105
Figure 39: Trucks on O Outbound - Scenario 1 VS Scenario 4bis	106
Figure 40: Trucks waiting at V2 and V3 due to system slow-down.....	107
Figure 41: Trucks on V outbound - Scenario 1 VS Scenario 5	108
Figure 42: Trucks in T8 - Scenario 1 VS Scenario 5.....	108
Figure 43: Trucks exited via V2 and V3 - Scenario 1 VS Scenario 5	109
Figure 44: Trucks in queue at Gate V2 for all scenarios	111
Figure 45: Trucks in queue at Gate V3 for all scenarios	111
Figure 46: Trucks exited via V2 and V3 for crossings	112
Figure 47: Crossing X1 - Inbound and outbound path	113
Figure 48: Trucks waiting at V2 for crossings model.....	113
Figure 49: Trucks waiting at V3 for crossings model.....	114
Figure 50: Crossing X3 - Inbound and outbound path	114
Figure 51: trucks exiting V2 and V3 under scenarios 1 and 2 for crossings model	115
Figure 52: Trucks in queue at Gate V2 for all Crossings scenarios.....	117
Figure 53: Trucks in queue at Gate V3 for all Crossings scenarios.....	117

List of Tables

Table A: Differences between simulation techniques (developed by the author)	45
Table B: Port terminals and their characteristics	50
Table C: Length, time and capacity of road segments.....	54
Table D: Entry and exit capacity of road terminals	54
Table E: Operational capacity of road terminals	55
Table F: Operational time at gate and inside road terminals	55
Table G: Proportion of arrivals for road terminals for Scenario 1	56
Table H: List of Vensim PLE parameters and constants for truck Scenario 1	60
Table I: List of Vensim PLE stock variables function for truck Scenario 1	64
Table J: List of Vensim PLE flow variables function for truck Scenario 1	73
Table K: List of Vensim PLE auxiliary variables function for truck Scenario 1	74
Table L: List of Vensim PLE lookup functions for truck Scenario 1	74
Table M: Scenarios for Road network model	75
Table N: Proportion of arrivals for road terminals for Scenario 2.....	77
Table O: List of Vensim PLE parameters and constants for truck Scenario 2	78
Table P: List of Vensim PLE stock variables function for truck Scenario 2	79
Table Q: List of Vensim PLE flow and auxiliary variables function for truck Scenario 2	79
Table R:List of Vensim PLE canceled variables for truck Scenario 2	79
Table S: List of Vensim PLE updated functions for truck Scenario 4.....	82
Table T: List of Vensim PLE updated functions for truck Scenario 4bis.....	83
Table U: Length, time, and capacity of road segments for Scenario 5	84
Table V: List of Vensim PLE parameters and constant for the crossings Model.....	86
Table W: List of Vensim PLE flow variables function for the crossings Model	87
Table X: Scenarios for Crossing between network models	88
Table Y: Scenarios and results for Road network model	110
Table Z: Scenarios and results for Crossing between network models	116

1. Context of Reference

Developed in collaboration with Daniela Restrepo Ruiz

1.1. Overview of freight transport

Freight transportation is a milestone in global trade, ensuring that goods move efficiently from producers to consumers across continents. Today, the rise of multimodal and intermodal transportation solutions is reshaping the industry, improving flexibility and connectivity while addressing growing challenges such as environmental pollution and the need for sustainable practices.

1.1.1. Freight transport systems

Freight transportation refers to the movement of goods and materials from one place to another and plays a crucial role in the global economy by providing a critically important service within supply chains, linking distant points of supply and demand. Over the years, freight flows have steadily increased due to various factors, such as population growth, reduced trade barriers, and decreasing transportation costs. In addition, increased consumption and growing demand for personalized products and services, as well as the development of online purchasing platforms, have further contributed to this expansion. This growth has also been supported by significant infrastructure developments, such as the expansion of roads, railways, waterways, ports, and storage and transshipment facilities. Nowadays, the effectiveness of freight transportation characterizes the competitiveness of countries, as it directly affects the cost and efficiency of international trade. [1]

Core components of transportation

According to Rodrigue, in its book “The Geography of Transport Systems” [2], there are four main components that are necessary for transportation to take place, and they are the same for freight and passenger transportation.

- *Modes*: they represent the vehicles used for activities; some vehicles are designed exclusively for transporting people or goods, while others can perform both functions.
- *Infrastructure*: they constitute the physical support of transportation assets and include both routes (such as railways, canals, or highways) and terminals (such as ports or airports). Infrastructure also includes superstructures, or movable assets; in the port context,

infrastructure refers to piers and shipping channels, while superstructures include cranes, handling equipment, and yard equipment.

- *Transportation networks*: they are systems consisting of interconnected locations that define the functional and spatial organization of mobility. Networks indicate which points are interconnected and how service occurs between them.
- *Flows*: they represent the movements of people, goods, and information through their respective networks. Each flow has an origin, possible intermediate stages, and a final destination.

Modes of transport

There are four main modes of freight transport: road transport, rail transport, sea transport, and air transport. The efficiency of freight transport modes varies greatly between them, and each mode has unique advantages and disadvantages.

Road transport provides high distribution capillarity, offers low costs over short distances, and provides fast and reliable service. However, it is constrained by transporting limited volumes of goods, is highly prone to congestion, has higher accident rates, and is the mode of transportation that contributes most to environmental pollution. [3]

Rail transport can move a significant amount of freight, allows scheduled operations, operates efficiently over medium to long distances, is considered safe and tends to be sustainable. However, it is limited to tracks, where passenger trains often take priority, requires cost and waiting time at terminals, and is suitable primarily for large volumes of lower-value raw materials. [3]

Sea transport can accommodate large quantities of cargo, adapting to a wide range of cargo types, is highly energy efficient, and is cost-effective for long-distance, high-volume shipments. However, it requires considerable time and cost for terminal operations, depends on large volumes of cargo to remain economically viable, and operates at relatively low transport speeds. [3]

Air transport allows minimal travel time over long distances and reduces the likelihood of goods being lost or damaged. On the other hand, it generates high environmental pollution, incurs higher costs than other modes, and is not suitable for all types of goods due to capacity and cost constraints. It tends to be used for the transport of high-value goods. [3]

Some other minor modes are, for example, inland waterways and pipelines.

1.1.2. Multimodal and intermodal transport

The evolution of global trade is driving significant changes in transportation strategies, and examples include intermodal and multimodal transportation. In particular, key trends such as: the continued globalization of the economy, the increasing demand for faster product delivery, the adoption of agile business practices, and the need for efficient supply chain management are reshaping the way companies move goods. These factors highlight the growing importance of flexible and integrated transportation solutions to meet modern business needs. [4]

Differences and benefits of multimodal and intermodal strategies

Multimodal freight transport refers to the movement of goods through a sequence of at least two different modes of transport. In this context, the transport unit can be of any type: a box, a container, a swap body, a road/rail vehicle or even a vessel.

Intermodal freight transport is a specific type of multimodal transport in which cargo is transported from origin to destination in a single standardized intermodal unit, such as a TEU container, without the goods being moved during mode changes. [5]

According to Gordon and Young [6], the main outcomes from the transportation market services embracing intermodalism are:

1. A key economic advantage is improved asset utilization, wherein equipment, whether ships, trucks, or railcars, is not unduly idled during the loading and unloading process.
2. Goods to be transported are secured within a vehicle at the origin and do not undergo intermediate transloading, a task that is typically a prime target for damage, theft, or tampering.
3. It speeds the movement of goods between producer and consumer, thereby reducing the volume of inventory in transit and its holding cost, which may be substantial.

Intermodal transport is often preferred because of its economic and environmental and social benefits. First of all, the use of the most appropriate means of transportation for different types of trips and loads gives the possibility to exploit the cost advantages of each mode; then, this type of system leads to less pollution and congestion. The main drawbacks of the intermodal cycle are linked to cost increase at terminals, long trans-shipment times, and greater vulnerability at nodes. Multimodal transport can be expensive as well, mainly because of the costs of managing and coordinating the passage of goods between one system and another. On the other hand, it allows

for superior geographic coverage, while intermodal can be more limited, especially if certain infrastructure, such as rail, is not available. Often, in intermodal cycles this problem is solved by operating the initial and final part of the transport by road. [3]

Hub and spoke networks

The hub and spoke systems are transportation models consisting of central nodes, called hubs, connected to surrounding nodes, called spokes. High-capacity transport services are frequently carried out between hubs, while low-capacity transport services are less frequently carried out between spokes. [3]

This type of model has developed as a result of the introduction of solutions related to intermodality and multimodality and has partly replaced the traditional point-to-point approach. Previously, in fact, transportation took place directly from producer to consumer, without taking advantage of intermediate stopping points or mode changes. [2]

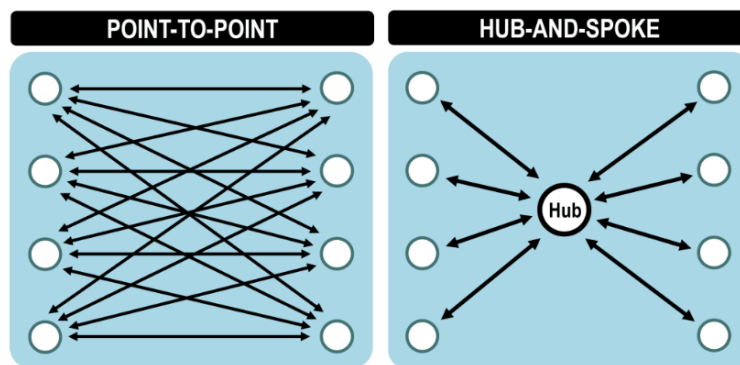


Figure 1: Point-to-point and hub-and-spoke networks [2]

Compared with point-to-point systems, hub-and-spoke models offer many advantages, which are able to improve operational efficiency and overall quality of transportation service (View Figure 1). Some of these advantages, according to Rodrigue [2] are:

1. Cost reduction, in the sense of lowering transportation costs for the individual unit, is achieved by concentrating traffic flows at hubs, which allows them to benefit from economies of scale.
2. Increased frequency of services, referring to the possibility of ensuring more regularity of connections to the hubs, allowing more daily departures between origin-destination pairs that would otherwise be underserved.

3. Expansion of network coverage, achieved by connecting peripheral nodes to central hubs, allowing access to more destinations without the need to activate direct connections for each terminal pair.
4. Operational simplification, the centralized nature of the system allows a reduction in management complexity compared to traditional management of multiple direct links.
5. Environmental benefits, resulting from the concentration of shipments and route optimization, contribute to the reduction of energy consumption and emissions.

Importance of transport mode integration for efficiency

Considering what has been discussed until now, it is possible to draw the conclusion that the integration of different modes of transport plays a key role in the overall improvement of the efficiency of transportation and logistics systems. Combining different modes of transport in a differentiated manner allows the best features of each to be exploited: the flexibility and capillarity of road transport, the sustainability of rail transport, and the high capacity of maritime transport. As can be deduced, even considering the case of introducing hub-and-spoke systems instead of traditional point-to-point systems, proper coordination of transportation allows optimizing its performance and thus, reducing overall costs, travel time, and the number of handling operations. There are several studies, one of which considers the case of an Italian company, which show how the modal shift from unimodal road transport in favor of combined transport brought several benefits. In particular, it is shown that one of the main benefits has been a significant reduction in generalized transportation costs on shipments, but also on the costs of negative externalities. Other remarkable benefits were a reduction in transportation time and an improvement in punctuality. Some modes of transport, such as rail transport, are less affected by delays due to traffic, for example, in the case of road transport. [7]

3.2.3 Challenges in freight transport

As the transportation sector expands to meet growing demand, it faces significant challenges that inhibit its performance and sustainability. There are four critical issues for which solutions are always being sought, and they are: infrastructure limitations, technology integration, and environmental sustainability.

Infrastructure limitations

Infrastructure is a critical bottleneck to achieving efficient freight transport. The main physical constraints that currently exist are: aging road networks, limited rail capacity, and congestion at transfer points. In general, infrastructure constraints lead to increased transit times, operational costs, and environmental impacts, as freight operators are forced to rely on less efficient modes of transportation, such as road transport, due to the lack of connections to other types of transportation considered more sustainable, such as rail. The problem could be solved through a comprehensive policy approach that prioritizes targeted investments in infrastructure improvements and the development of smart, integrated transportation hubs. Such improvements would enable a smoother modal shift and ensure that freight flows are less disrupted by capacity constraints, ultimately contributing to a more resilient and cost-effective transportation network.

Technology integration

Digitization is rapidly transforming the freight industry, enabling more efficient, data-driven decision making and operational optimization. The adoption of new technologies such as data analytics, Internet of Things (IoT) devices and other ICT solutions can greatly improve the operation of the industry. These technologies enable real-time monitoring of freight movements and more accurate forecasting of demand, which in turn helps logistics operators optimize routes and reduce unnecessary idle runs. However, despite these innovative solutions, there are still issues that limit them, including integration into pre-existing systems, data interoperability issues, and data privacy issues. Addressing these challenges requires coordination among industry stakeholders and policymakers, with a range of investments in both technology and training to facilitate a smoother digital transition. [8]

Environmental sustainability

Despite the many benefits of its development, freight flows have increasingly attracted public policy attention from an environmental and sustainability perspective in recent decades. This attention aims to reduce the negative impacts of freight growth, including local emissions affecting public health, greenhouse gas emissions, and traffic accidents. These issues that also concern passenger transport. [1]

According to the European Environment Agency (EEA), transport was responsible for approximately 25% of the European Union's total greenhouse gas emissions in 2020, ranking

second after the energy sector. Within this share, road transport alone generated more than 70 percent of transport-related emissions, ranking first as the main pollutant in the sector. [9]

The European Union has set itself the goal of becoming the first continent in the world to achieve climate neutrality by 2050, and to achieve this, it assumes that greenhouse gas emissions related to the transport sector will reach a 90% reduction by that deadline. To achieve this goal, different solutions have been devised so far, [10] the most effective ones consist of providing incentives for the use of low-emission lorries. [11]

1.2. Shipping sector

When talking about the transport sector, the concept of “shipping” is related to the transport of goods in ships. The core function of a port system is for the secure transfer of goods between sea and land modes of transport. [12]

1.2.1. General overview of maritime transport

Sea transport is the oldest means of transport of goods in mankind, and the current predominant way to transport goods internationally, representing 80% of the global volume of trade, or 70% in terms of value. [3] In a global context, the shipping sector has grown in the last decades and has been an indicator of the global economic trend. Both maritime transport and port management have had considerable evolution, and due to the increased competition between shipping lines and between ports, the costs of operations have gradually decreased. [10]

Ever since World War II, maritime trade has been expanding at a rapid pace, and world economies have become reliant on the efficiency of the shipping sector. Therefore, both the industry and the port operators are making great efforts to reduce the costs of operation, through strategies such as economies of scale, container handling, and, more recently, technological innovations that enhance efficiency. [10]

Regarding container handling, the containerization rate has been growing at a high pace, thanks to the possibility of efficiency and standardization in operations that these transport units allow. And with it, the maximum capacity of the vessels has increased to adapt to demand, though its growth remains constrained by port infrastructure limitations. [10]

On another hand, economies of scale contribute to a more effective transport system and are related to a core principle of transportation: the balance between massification and atomization. While massification involves higher capacity and larger terminals, it has limited flexibility. Yet,

atomization, related to lower quantities, leads to more expensive costs for moving but allows for greater flexibility. [3]

1.2.2. Current economic situation of the maritime transport sector

After understanding the overall role of port in global trade, it's possible to review deeper the recent situation of the shipping sector. Despite its rapid growth and continuous strategies to reduce operational costs, and enhance connectivity between ports around the world, recent challenges in maritime trade have intensified. Various elements shape shipping trends, including geopolitical conditions, economic fluctuations, and global factors such as e-commerce growth, the decentralization of production processes, the evolution of global supply chains, port and transport operations, and technological advances. [3]

Geopolitical tensions in key chokepoints and vulnerable economies to rising shipping costs are significantly impacting global trade flows. According to the Review of Maritime Transport by the UN [], checkpoints such as Suez and Panama channels had a reduction of about half of their transit during 2023, with further declines in 2024. In particular, the Panama channel disruptions, led to an increase in 31% of the sailing distances. Additionally, connectivity has also dropped, and small islands and developing countries have suffered the impact, with a drop in connectivity of 9%. [13] All these conditions caused rerouting, port congestion and rising operational costs, which led to increased freight rates during 2024, impacting mainly nations that highly rely on maritime transport, threatening stability and driving inflation. Although in 2023, global maritime trade had a growth of 2.4% achieving 12.3 billion tons transported, following a contraction in 2022, these disruptions call for actions, including the implementation of monitoring systems for detecting early disruptions in chokepoints, along with other actions such as international cooperation. [13]

In addition to these issues, another major one has arisen in the last decades: climate change. Shipping is responsible for 3% of the global greenhouse gas emissions. One of the possible strategies would be to renew fleets to more sustainable and efficient ones, but due to high costs this solution is developing very slowly. In contrast to the growth of cargo capacity, only 14% of new tonnage was fuel-alternative, which accentuates the failure to assess decarbonization. Moreover, due to policies implemented in relation to climate change, costs of operations have been impacted, since upon failure to assess decarbonization penalties are applied, which increases costs, and reduces competitiveness. [13]

1.2.1. Demand and supply in ports

As already mentioned, maritime transport plays a fundamental role and is tightly related to world economy. This leads to great importance of demand and supply at port level, influenced by multiple factors. In ports, and in general in transportation, demand is considered a derived demand, which means that it exists because of the need for another good or service, whether it is moving freight or passengers. [14]

Maritime transport arises meets different needs. In the case of freight, it is influenced by factors such as a country's Gross Domestic Product (GDP), how sensitive demand is to changes in price, transport costs, and alternatives of transport available. On another hand, for passenger transport, factors such as people's income, time for leisure, the purpose of passenger's journey, and the possibility to choose between different destinations are more determinant in alternative to GDP or price elasticity. [14]

Ports also serve as demand generators. This is accentuated if they offer a good range of port and related services of good quality, if they are specialized and facilitate transportation, and if they are well interconnected with landside networks. This may be evidence for example in containerized cargo, as they not only manage local economy goods, but also intermediate goods that require other services such as storage, transshipment, or assembly nearby. [14]

1.2.2. Port operations: structure, stakeholders, and process

Ports represent a complex system with dynamic operations related to handling, transporting, and storing the units of goods, becoming critical nodes in global supply chains.

General port functioning

Generally, ports are composed of maritime access to either a natural or artificial area. This access goes to the basins that are surrounded by breakwater to reduce the hit of waves in the area, and then inland they include surfaces and piers. The fundamental physical elements are the following seen in Figure 2:



Figure 2: Fundamental physical elements of a port [14]

- *Harbor*: a sheltered natural or artificial area where port operations take place, having careful control regarding depth and navigation.
- *Anchorage areas*: designated areas for ships to anchor while waiting for an available berth. Delimited with buoys, and in some cases located within the harbor.
- *Breakwaters*: protective barriers built in harbors to shield them against strong waves, tides, winds, and currents.
- *Navigation channels*: routs that guide ships to the harbor, including outer access channels, and inner approach channels. Their depth is controlled, and navigation is assisted by pilots and tugboats.
- *Turning basin*: A circular area where vessels are able to turn around with the help of tugboats, with at least twice the length of the largest that is allowed.
- *Berthing basin* also known as docks, is the area next to a berth where ships are moored. It is important that they ensure enough capacity, length, and depth.
- *Berths*: docking structures that support both berthing and mooring.
- *Wharves*: structures made up of one or more berths parallelly aligned with the shore.
- *Piers*: structures that extend into the harbor as an extension of the terminal facility, often equipped with storage facilities such as storage sheds and warehouses.
- *Jetties*: thin docking structures that extend to the sea in order to support loading and unloading of cargo into ships.
- *Dry docks*: enclosed basins that may be filled or emptied to allow ship construction, maintenance and repairing.

Their characteristics, logistics and organization differ according to aspects such as flow of goods, service categories, functionality, among others. [14]

Classification of services

Regarding service categories, shipping may be divided into two. First, tramp services which handle bulk shipping of both liquid and solid bulk on demand, including petroleum, chemical products, food, coal, minerals, among others. On the other hand, liner services are related to both general cargo and passengers, with pre-established regular lines. General cargo may be conventional for elements like wood or cars, or containerized for goods such as finished products, components, machinery, and food. Meanwhile, passengers may be transported through ferries or cruises.

These services may be done through different types of ships, which may handle several amounts of goods, including deep-sea vessels, feeder ships, and barges. The last are for transport in the hinterlands through rivers or canals. As for which ship is used, an important distinction has to be done: hub and spoke networks. As mentioned before, and applying it to the case of maritime transport, this concept is related to connectivity between ports, in such a way that the number of connections needed is reduced. In this case, smaller or less important ports (spokes) are all connected to main ones (hubs), which have the most frequent and higher capacity services. For these, ships such as deep-sea vessels with capacities of up to 24,300 TEUs serve hub ports, while feeder ships of 800-2800 TEUs serve smaller regional ports. This also implies that hubs need infrastructure for bigger ships, which affects the depth, logistics, size, among other factors of its design and management. Also, in relation to the flow of goods, they may be classified as: gateway ports where flow is given between ship and trucks or trains either as import or export, or as transshipment ports, when flow goes from bigger ships to smaller ones (hubs) that are feeder vessels. [3]

Finally, regarding the general functioning and classification of ports, it is also useful to understand the institutional models, for which three categories may be defined. The private model has both property of the land and provisions of services in private way, while public model has both public. In this order of ideas, private models allow for better flexibility and quicker response to demand but less government oversight which could be the example of United Kingdom. While for public models there are more regulations and public funding, but a more rigid operation, which is usually seen in regions such as Africa and Latin America. In Italy, before 1994, the model adopted was public, but as it created a lack of efficiency and competitiveness, the land-lord model was

introduced. This last model consists of public property of land either at regional or national level, and private provision of services. In this way, the new law in Italy separated two roles: port authorities as public entities who manage infrastructure and regulate port activities without a direct involvement in operations, and terminal operators as private companies that become responsible for economic and commercial services under concession. [3]

Main stakeholders in port operations

To better understand the stakeholders involved in such a complex process, it is useful to divide them into three main groups: seaside, port or terminal, and landside or hinterland. Within each of these phases, and in the interaction between them, both public and private bodies play essential roles. (View Figure 3) [3]

First, starting with the seaside, two main stakeholders are involved. First, *port guards*, a public authority responsible for administrative activities related to maritime safety, whose main task is to ensure safety in port activities and safeguarding of human life in the sea. The second major stakeholder in seaside is the shipping line, which is a private company in charge of transporting goods by sea on behalf of a specific client, either with ships they own or chartered ones. *Shipping lines* may be composed of different figures: the shipowner, responsible for ship's operation and technical safety compliance, the owner who actually possesses the vessel's holdings, the renter who leases the ship if shipowner is not the direct owner, and the carrier who has the contractual obligation of delivering goods by sea under a bill of lading. Finally, supporting the shipping line is the *ship agent*, a private actor with the task of administrative, operational and commercial formalities related to ship arrival and departure, in charge of representing the interests of the shipowner before institutions and port authorities. [3]

Regarding the connection between vessels and port infrastructure, *technical-nautical services* play a fundamental role. Though public in nature, they are carried out by private companies operating under concession, who are in charge of three main activities: piloting, where a specialized port pilot is authorized to perform navigation within port waters to guide it safely to berth, towing which involves using cables or tugboats to assist vessels without propulsion, and mooring, related to securing and releasing ships at the dock and its movement within the port. [3]

Then, regarding the terminal domain, three main actors take part. The *port authority* is responsible for managing the governance of port areas, planning, coordinating, and promoting operations, overseeing, and granting authorizations and concessions when needed to *terminal operators*. These

last, usually private, are responsible for the core logistics such as handling, loading, and unloading of cargo along ship to storage areas and vice versa. These functions are supported by the stevedores, who do the physical labor related to cargo handling. [3]

For a proper transition between the port and inland destinations, additional stakeholders operate. *Inspectorates and customs* are in charge of verifying compliance I information, classification, and documentation of goods. [3]

Finally, regarding the hinterland side, transport operations include multiple critical actors, such as the *railway infrastructure manager* who is a public company that must construct and maintain the rail infrastructure, the *shunting company* which operates diesel locomotives for the movement of goods between the terminals and the intermodal yards, the actual *rail operator* that conducts the rail freight transport service by itself, and *road carriers*: which are responsible for accepting orders, loading and unloading, movement of cargo, among others. [3]

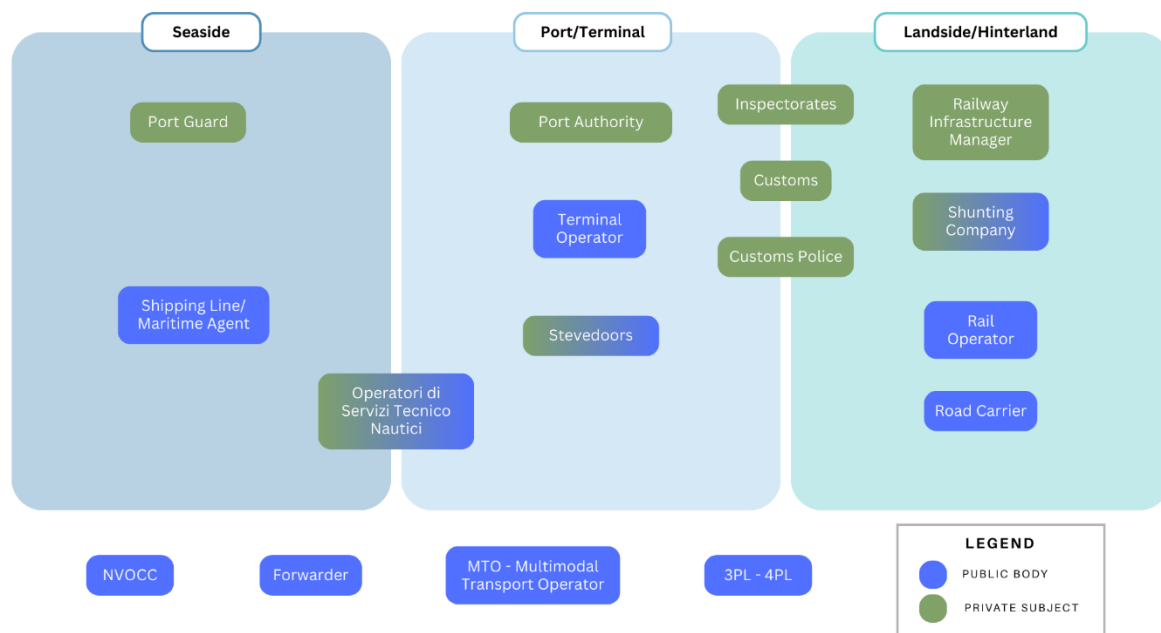


Figure 3: Port stakeholders [3]

Additional to these actors, other important stakeholders operate not on a specific activity but mostly throughout the entire logistics process, like the case of the *Non-Vessel Operating Common Carrier (NVOCC)*, which acts as a type of maritime carrier but without owning any vessels but instead shopping portions of cargo space from actual shipowners and issuing their own bill of lading. Regarding the *freight forwarder* they manage the overall logistic chain across multiple transport modes, coordinate interactions among the agents and carriers, optimize transport without

actually owning vessels or cargo, etc. In more complex and large-scale logistics operations, a *multimodal transport operator (MTO)* may be involved in overseeing the integrated transport services and managing the entire flow of transport for the entire cycle. Finally, both *third party logistics (3PL)* and *fourth party logistics (4PL)* offer coordination of multiple service providers and optimize the entire supply chain on behalf of the client. [3]

Types of cargo handling technologies and systems

Handling of the goods may be done in two ways: LO-LO (Lift-on/Lift-off) a technique where cranes are used to move the loading units, like for example with containers. Or, RO-RO (Roll-on/Roll-off), a technique that does not use cranes, as vehicles get on the ship by themselves with the goods loaded by using ramps. This last way of transport may be either accompanied in which the driver stays during the ship trip (or train trip), or unaccompanied, where the driver loads the vehicle to the ship or train and then leaves it there, until the next destination where a new driver receives it. [3]

As mentioned before, containerization has emerged and settled as a useful and efficient solution. Beginning in 1952, it allowed for a reinvention of managing merch. Containerization allows for higher efficiency, as it lowers costs by 35% and loading and discharging time by more than 80%. [15]

As introduced before, intermodal transport does not handle directly goods, but handles intermodal transport units, which may be containers, swap bodies, and semitrailers. Containers are mainly useful for maritime transport and were introduced as a standardized box for transportation, revolutionizing freight transport and giving importance to maritime transport which thanks to this became cheaper and more agile. [16]

A container is a rectangular prism with corner fittings for handling it, a bottom and side rail, and multiple other elements that allow movement and handling of it. They can be stacked, which allows for an optimal organization in storage, and are usually handled using cranes. They are given by three measurements. The most used are TEU, related to 20 ft length containers. Their width and height are usually between 8 and 9 ft. [16]

There are two main container handling systems: Indirect Transfer System (ITS) and Direct Transfer System (DTS). In ITS containers are moved in stages by using yard cranes and trucks before reaching the final spot where they are stored, being a space-efficient system. On the other

hand, in DTS, containers are picked up and placed directly with specialized vehicles without needing extra cranes, which requires more space but is faster and common in European ports. [12] Bulk handling, on the other hand, consists of carrying out loose cargo. The load is defined by the size of the ship and the storage capacity in port and is handled in a different way depending on whether its liquid or dry bulk. Therefore, each bulk terminal specializes in a specific commodity, for example natural gas, grain, coal, among others, as they require different techniques and infrastructure. [14]

Key port operation activities

Along the whole logistical process from the arrival of the ship up to the internal procedures, the activities could be classified into three main groups of processes: waterside, yard, and landside; the same classification framework used to categorize the stakeholders involved in each phase. [3] [17]

- **Waterside operations**

They include all activities occurring from the arrival of the vessel near to the port up to the preparation for cargo operations. The main operations are: arrival and berthing, piloting, towing, mooring, and initial clearance procedures.

Upon arrival, vessels arrive to berths, with the coordination between ship and port authorities. In most ports, it is compulsory for a different pilot to guide the boat through internal waters for safe maneuvering, as piloting is more complex than in open water. For bigger ships or for any ship with limited maneuvering, tugboats may provide propulsion support for vessels, this is known as towing. Following the arrival to the berth, the vessel must be secured using mooring lines. Finally, vessels undergo control checks in order to have initial clearance prior to cargo handling. [3] [17]

- **Yard operations**

Inside the yard or terminal area an interface between vessel and inland transport systems is given. In this zone key processes such as cargo handling, storage, internal transfer, and customs and clearance procedures consolidate the terminal operations.

Continuing from the process finished in the waterside, the goods must be loaded and unloaded, which depends on the cargo type. Handling technologies include cranes, straddle carriers, Ro-

Ro ramps, grabs, suction systems, or pipelines. After discharge, goods need to be stored temporarily in designated terminal areas, which also depend on the cargo requirements, but usually are container stacks, warehouses, silos, among others. During this phase internal transfers are performed between the vessels and the storage facilities throughout the gate areas, through vehicles such as terminal tractors, forklifts, or conveyor systems. In this moment, customs and clearance procedures may be done, in which documentation is controlled, goods are classified, and inspections are performed before the cargo may continue inland. As mentioned before, the terminal operations are handled by terminal operators and supported by stevedores. [3] [17]

- **Landside operations**

Once cargo is cleared for inland movement, it's annexed to the hinterland logistics chain, which includes activities such as: gate operations, modal transfer, inland distribution, and support services.

In this final process, first the cargo must exit the port area through controlled access points. Here, additional checks to documentation, weight and safety are performed. For this, a modal transfer must be done depending on the mode of transport selected, either trucks, trains, or barges, or for the case of bulk: pipelines, conveyors or trucks. At this point inland distribution begins to deliver to the final destination. [3] [17]

1.2.3. Trends and innovations in maritime logistics

Port management has been in constant evolution over the past decades, leading to new technologies and a shift in trade patterns. For instance, thanks to Information Technology, satellite systems and software's are being used to facilitate communication between ports, ships and along the supply chain, which enables better cargo handling, operations and monitoring for better performance. Among strategies, the use of locations beacons is an important tool, including Automatic Identification System (AIS) to locate vessels emergency location beacons, transponders, radios, among others.

The maritime sector has responded to changes at a macroeconomic level given by globalization, relocation of production activities and consumption changes. Between the responses, one would be naval gigantism and technology advances in disciplines such as ship design and engineering and in ship operations, in order to adapt to port requirements and to be able to accommodate the

client's requirements through efficient and safe operations. Another significant change would be unitization given by containerization, which as mentioned before, is able to increase significantly efficiency as it reduces loading and discharging times and costs. In relation to this, nowadays ports must have container handling facilities and appropriate equipment that allow for economies of scale by greater productivity, increased ship size and lower traffic. [3] [15] Another recent phenomenon to respond to macroeconomic changes is transshipment, in which the system is given by hub-and-spoke, where main and bigger ports are fed by smaller ports. [3]

It is of great importance to understand that nowadays globalization and the development of the maritime sector allow for supply chains to concentrate not in a single country or region but to have a global reach, with multiple headquarters and supplies coming from different countries. [3]

1.3. The shipping sector and hinterland connectivity

1.3.1. Port-hinterland concept

Ports have a role of gateways to inland networks, in which nodes are formed in between transport between intercontinental and continental flows. Thanks to containerization, larger container vessels and economies of scale, the role of ports as major gateways has expanded significantly. This, along with intermodal transport implementation, has allowed for a greater reach of the hinterlands. [14]

The study of operations and logistics in the hinterland is crucial, given the fact that the majority of transport costs happen inland and not at sea, even though sea journeys are longer. Inland logistics, including port connectivity with road and rail networks, often represent the most complex and expensive part of the supply chain. [14]

Port connectivity refers to the ability to connect ports and cities through logistics and transport networks such as road and rail, playing a crucial role in the efficiency of transport in a country. [3]

A port hinterland, is a strategic component for the supply chain, and refers to the piece of land over which a port extends its influence and operations regarding its activities and interaction with the users. Therefore, they encompass both business activities and customer areas. Nevertheless, it is not easy to objectively define the limit of a port hinterland, since they vary according to the type of commodities, season, economic cycles, and transport technologies. For instance, for the case of dry and liquid bulk it is more common to have customers within close proximity to the port, as inland transportation has high costs and is complex. Usually, it involves one direction only of

flows, either incoming or outgoing, along with a low number of market players and destinations. On the contrary, containerized cargo involves bidirectional flow directions as multiple origins and destinations are scattered over the hinterland, therefore involving more competitors and economic players. This results in bigger hinterland areas for container terminals. [14]

In fact, containerization has fundamentally changed the hinterlands' dynamics. Before containers were invented, goods were transported between where they were produced to the closest port, meaning ships would have to stop in many ports along the way to have good coverage. In this way, ports served their own territory and nearby area, known as captive hinterland, and did not actually compete between each other. Then, with the rise of containerization, goods became easier to move in ships, trucks and trains, so goods may travel longer distances in a faster and more economical way, resulting in ports now reaching farther inland and attracting goods from bigger areas. This meant that hinterlands between ports started to intersect, so now businesses get to choose between which ports to use, leading to more competitiveness between ports, in which their success depends greatly on their hinterland access and connectivity. Larger ships stopping at fewer ports also means that inland distribution must be cost-effective for customers further away, reinforcing the importance of inland transport systems. [14]

1.3.2. Internal port logistics and layouts

Port connectivity and internal transport

Port regionalization is a phenomenon in which maritime transport and inland freight transport systems are integrated, instead of them evolving separately, thanks especially to intermodal transportation opportunities. This phase happens after an integration of transshipment hubs and is characterized by the formation of regional load center networks with multimodal logistics platforms in its hinterland. Port regionalization is achieved through developing rails and corridors between a port and a network of inland load centers. These corridors facilitate freight transportation in an uninterrupted and continuous way. It addresses two important issues: externalization of local constraints in relation to growth and efficiency such as lack of available land or increased port traffic, supply chain integration. [14]

The transport connection between ports and inland areas is shaped by four key components which, in relation to maritime-land connectivity, are particularly important in long-distance trade. First, the foreland which represents the sea routes and connection that a port has with other ports around

the world. Then, the port system, referring to the infrastructure that connects the port to the inland. Third, the transport modes, including ships, trains, trucks, and barges that move the goods inland. Finally, the hinterland, which as mentioned before, refers to the inland area that the port serves. [14]

Following this logic, to further understand a port's hinterland reach, four interrelated layers may be analyzed as shown in Figure 4: locational, infrastructural, transport and logistical. The first is the location layer, which considers the geographical location of a port relative to main maritime routes, productions or consumption centers and demand hubs. The second is the infrastructure layer, which allows port dynamics by providing basic infrastructure for both links and nodes in the system such as roads and railways in links, or terminals in nodes. In this layer, accessibility materialized and relies on availability of capital. Then, the third one is the transport layer, which are the actual services that operate on links and corridors within the system. Finally, the logistical layer involves the organization of transport chains and their integration with broader logistics systems. Each layer provides added value to the one before it, contributing additional value and enhancing the port's accessibility and competitiveness. [14]

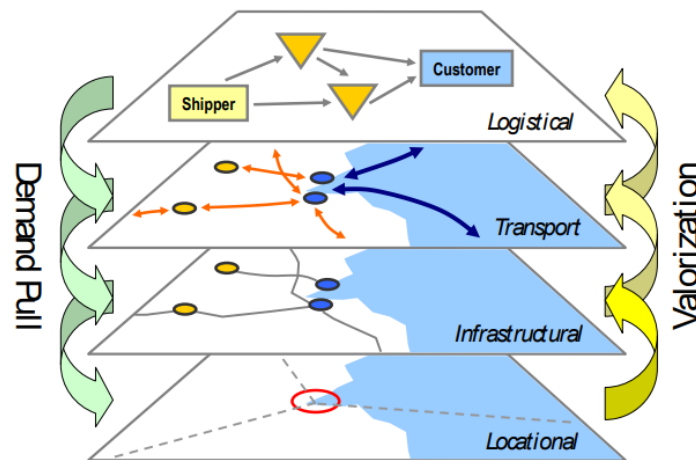


Figure 4: Layers of a port's hinterland reach [18]

From a logistical standpoint, transport organization can be viewed through two perspectives. Outside-In or import logistics, is a port driven form of development that seeks to serve the port terminal in a more effective way. While the Inside-Out or export logistics refers to a method focused not on the port sector but on their accessibility to global trade. In terms of flows, inland flows have two main directions: inbound or outbound. Inbound traffic consists of goods arriving at the hinterland, often for local consumption mainly of finished products. On the other hand, flow

leaving the hinterland, usually for export of raw materials or manufactured goods, is known as *outbound traffic*. [14]

1.3.3. Integration with other modes of transport

At the interface between maritime and inland transportation systems, ports must manage complex logistical operations. An access from the port to the industrial complexes ensures a complete chain of transport and requires enough infrastructure either with fluvial barges, rail unit trains or roads which usually handle heavy traffic. To understand this connection, connectivity with both rail and road internally at port level is explained below.

Port-rail connectivity and transport corridors

Port-rail interfaces are the strategic and physical locations where maritime and rail transportation systems connect, facilitating the transfer of goods and information between these two systems; in the intermodal context, the port-rail interface is of particular strategic importance.

In this precise intermodal system, one of the most important operators is the shunting operator and railway infrastructure managers, who enable the port to benefit from this type of service. In a port context, the railway infrastructure managers are identified as the company that operates the railway line, while the shunting operators are those who take care, usually using diesel locomotives, of transporting the cargo from the yard where the goods are stored to the electric line, where the exchange between locomotives takes place. [3]

Nevertheless, several stakeholders are involved regarding hinterland access, including national and regional authorities, carriers, stevedoring companies, logistic service providers, port authorities and shipper and cargo owners. [14]

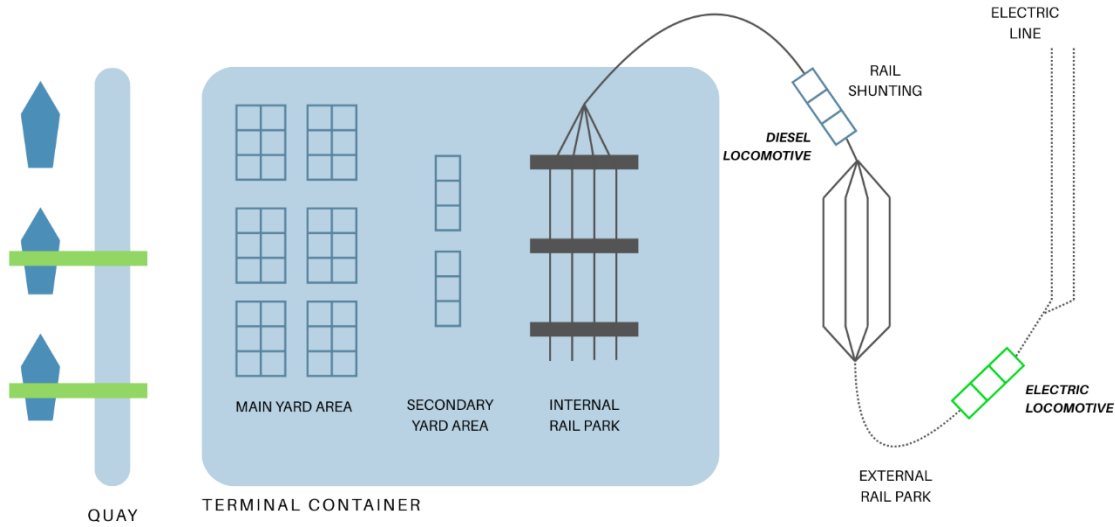


Figure 5: Railway facilities in a port [3]

Upon arrival at the port, the unloading and transfer of cargo onto the national rail network follows a series of carefully managed steps to ensure both efficiency and safety as can be seen in Figure 5. First, cargo is lifted out of the ship's hold and placed in the landing area alongside the vessel. Next, forklifts and terminal tractors move the cargo to the port's marshalling yard, where port authorities carry out all necessary documents.

In the marshalling yard, shipments are then sorted by type and destination. At this stage, shunting operators take over, employing diesel locomotives provided by specialized companies or third-party rail operators. These operators manually couple the wagons, and cargo loading onto the wagons is performed using either cranes or automated spreaders. The wagons are then hauled along a non-electrified line until they reach the electrified mainline.

The traction changeover occurs in a dedicated exchange zone: the diesel locomotive is uncoupled and replaced by an electric locomotive for onward movement over the national network. Finally, once the train has been fully assembled and inspected, it departs for the hinterland under the authority of the rail infrastructure manager.

Port regionalization and hinterland transport are also closely tied up to the concept of transport corridors. These corridors refer to an orientation of transport routes and flows in such a way that they connect origins, destinations and points of transshipment. When talking about the movement of goods, it refers to freight corridors, which need the support of infrastructure such as roads,

railways or ports. These, both through land and sea, are essential for port connectivity with inland areas and distribution networks. [14]

Specifically, rail corridors are important to analyze, not only on the perspective in which they complement the articulation and connectivity of ports, but also as competitors, since in particular, long distance rail corridors appear as competitors with maritime routes. [14]

Port-rail connectivity in the European context

Recently, in the European context, ports with rail infrastructure have begun to gain special attention, mainly because of the environmental benefits of rail freight transport. Shifting freight transport from road to rail is increasingly seen as important for reducing emissions caused by logistics and transportation. Several countries in Europe have already introduced road restrictions for trucks for years, thus incentivizing the shift to modal transport by rail. [19]

The European Union has developed several initiatives to encourage sea-rail connections in the ports of member countries. Examples of these initiatives are:

- *TEN-T (Trans-European Transport Network)*, a project that aims to create a set of integrated transport infrastructures, promoting multimodality.
- *Shift2Rail*, a public-private partnership that aims to renew the European railway network, also contributing to increasing the competitiveness of the Union.
- *European Green Deal*, a set of political initiatives with the aim of reducing emissions and zeroing the climate impact of the European Union by 2050.

Currently, the largest rail port in Europe is the port of Hamburg. In 2023, 45.6 million tons of goods, out of 78 million total, were transported by rail; it is the highest ratio among ports in the Union. The rail network stretches 300 kilometers and can accommodate more than 5500 wagons per day, making it one of the most important in Germany. [20] Several European ports have taken the port of Hamburg as a model to follow, trying to achieve the same statistics from the point of view of ship-to-rail integration.

Other ports in Europe that exploit this type of multimodal link are the port of Antwerp (Netherlands) and the HAROPA port system (Le Havre-Rouen-Paris, France). Although equipped with a good rail link, only less than 10 percent of freight takes advantage of this connection in these ports; they have established a target of reaching 20 and 15 percent, respectively, in the coming years. [21]

Among Italian ports, the one that stands out most for domestic multimodal transport is the port of Trieste, from which about half of the containers and 40 percent of the semi-trailers are forwarded by rail to Central-Eastern Europe. On the other hand, as far as the ports on the Tyrrhenian side are concerned (and thus, mainly, Genoa, La Spezia and Livorno), rail transport, although present, does not turn out to be as high performing as in the previous case. Ports in Liguria, in particular, are particularly disadvantaged in this context, as the number of trains adopted is shorter than European standards. [22]

Port-road connectivity

Within the spectrum of intermodal and multimodal solutions examined until now, road transport recurs in almost all cases, due to its capillary nature, and thus the ability to reach every destination. Ports, in particular, rely essentially on road routes, and hinterland traffic is dominated by trucks in the majority of ports: in most logistics' chains, in fact, road transportation covers the initial and final stages of the freight journey. Port-road connectivity, therefore, refers to the integration between the maritime and road systems, aimed at optimizing the flow of goods, especially along the last mile and the first mile of transportation.

From yard to landside, the connection with road transport is facilitated through designated access roads to the port. These roads typically have gated entry points where documentation is checked and compliance with port regulations is verified. Access is restricted to authorized personnel, and entry is granted only to those who have the correct permits, which control not only who can enter the port, but also regulate the date and duration of their stay and ensure adherence to all laws and regulations within the port.

One of the main issues is that in these access points bottlenecks are generated. They may happen due to three different factors: political or legal, operational inefficiency, or physical capacity constraints. Regarding policies it could include regulations or political decisions related to environmental standards or regulations for access, rules or nighttime bans, among others. Operational inefficiency may happen due to transport operators or by the logistics service. Finally, regarding capacity, it is given by both the infrastructure in place and in the nodes. It is important to understand that having enough capacity regarding infrastructure does not guarantee steady operations. Many conditions impact steadiness, including: the mix of freight and passenger flows, weather, incidents, peaks in supply and demand, among others. [18]

Port-related Road congestion emerges as one of the main issues related to this connectivity, affecting not only port activities but also impacting life in the cities and traffic nearby the port. One of the principal strategies to mitigate traffic is to target the inactive trucks at port gates, specifically with truck appointment systems, incentives for off-peak traffic, and virtual container yard systems. [18]

Truck appointment systems are based on a system of scheduling appointments for trucks who choose to have one, for which preferential treatment is given. This system, which may be optional or enforced, allows for better planning and distribution of trucks along the day, such that the accumulated queue is reduced, and prior activities necessary upon the arrival may be performed in advance. On the other hand, incentives for off-peak traffic, achieved through extended gate hours, also allow for better traffic distribution throughout the day in a different way. Another alternative is to improve the connecting infrastructure. Finally, virtual container yards systems are also being used to reduce unnecessary container movements, in which, instead of returning empty containers to the port and then picking up the net one, a truck can be directly reassigned to pick up and export load nearby and in a certain way to recycle containers withing the chain to avoid redundant trips. [18] It is important to understand that the success of these strategies is not always achieved, as it depends on market, political and other factors.

Another key element in relation to road transport is parking management within port areas, which have designated parking facilities in the yards, especially for the vehicles involved in freight and cargo handling, as parking is necessary to guarantee efficient queuing and maneuvering. They are usually equipped with security and monitoring, temporary parking spots, and have operations all day. For instance, in the case of Ro-Ro activities, they require a lot of space for parking.

Dry ports and inland terminals

The evolution of freight distribution networks has gradually shifted the focus from maritime port terminals to inland solutions supporting coastal operations. In particular, “dry ports,” or inland ports, originated as rail or barge terminals, connected with regular services to the seaport, taking on a role as a true onshore extension of port functions. These integrated nodes offer a range of logistics activities; from warehouses and storage facilities to distribution centers and value-added services, enabling them to overcome the capacity and congestion limitations of coastal ports.

Underlying the growth of inland ports are several factors: high land and labor costs in port areas incentivize the relocation of some operations to areas with lower rents and wages; congestion and

the increasing energy consumption of road transport require the massification of flows via rail or river corridors; the need to penetrate ever-larger inland markets pushes ports to extend their catchment area through high-capacity connections to the hinterland; finally, dedicated economic and customs policies can facilitate the transfer of port functions inland, creating favorable conditions for the development of free zones and inland logistics centers. [14]

Three main types of dry ports shown in Figure 6, often combined, can be identified:

- Satellite terminals, located in close proximity (less than 100 km) to the port, handle ancillary functions such as empty container storage and freight sorting, easing the operational impact on the coastal terminal.
- Freight distribution clusters (load centers), large intermodal hubs integrated into logistics parks or free zones, act as collection and distribution centers for regional markets, with warehousing activities and related services.
- Transshipment facilities, located along international corridors or near borders, enable freight handling operations between different modes of transport (rail-truck, barge-truck) and often perform integrated customs procedures.

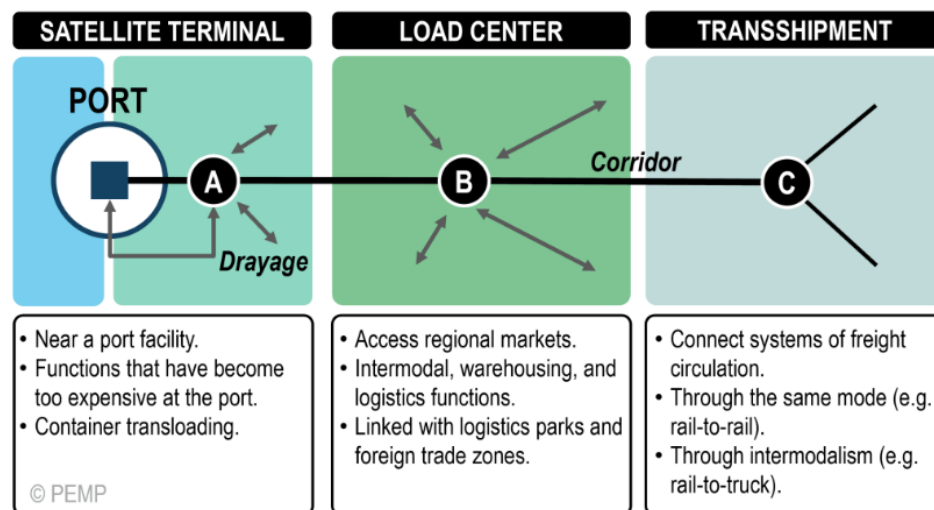


Figure 6: Different types of dry ports [14]

In terms of regional impacts, inland ports extend the reach of seaports, fostering the development of logistics hubs inland and contributing to more efficient freight distribution. In Europe and North America, where the phenomenon is more mature, articulated networks of rail terminals and inland ports connected via barge and rail corridors are observed; in East Asia, the focus has grown especially on load centers along major rivers or along the Eurasian Landbridge. Looking to the

future, the role of dry ports is likely to increase further: they will be crucial in handling growing container volumes, optimizing the repositioning of empty space, and exploiting new intermodal technologies, although residual risks of overinvestment require careful governance and strategies tailored to each economic and regulatory context. [14]

Dry ports and inland terminals in the European context

In Europe, dry ports and inland terminals have evolved from simple intermodal terminals to full-scale logistics hubs extended inland, supported by high-capacity multimodal corridors and innovative operating models. The heart of this system lies in the Rhine-Scheldt delta, where ports such as Rotterdam and Antwerp stretch via the Rhine to integrated logistics clusters (Dordrecht, Moerdijk, Duisburg). Here, boat and rail terminals not only ease coastal traffic, but house container depots, distribution centers and value-added services, configuring themselves as “extended gates” that transport many of the port operations directly to the hinterland. [14]

In Italy, the main dry ports are Turin-Orbassano and Bologna, and they take use of the TEN-T corridors to connect to the ports of Genoa and Trieste. [3]

Looking ahead, shared governance between port authorities, private operators and EU institutions will play a crucial role in defining sustainable dry port models. Key prospects for the future include the adoption of digital solutions for intermodal tracking, integrated customs incentive schemes, and public-private partnerships to finance green infrastructure that can shift more and more traffic from road to rail and barge. The goal would be to consolidate inland terminals as pillars of European logistics, while maintaining high adaptability to regional specificities and the needs of local markets.

Interaction between different Hinterland Transport Modes

Each transportation system has its own traffic and limits and therefore it is necessary for ports to organize in such a way that the different modes are carefully separated and get their own area in the terminal, which is somehow shown in Figure 7. This separation implies also a temporary differentiation, as each transport should be able to work on its own schedule. This last consideration leads to the need for space of storage while goods waiting to be moved known as buffer zones between ship operations and inland transport. [14]

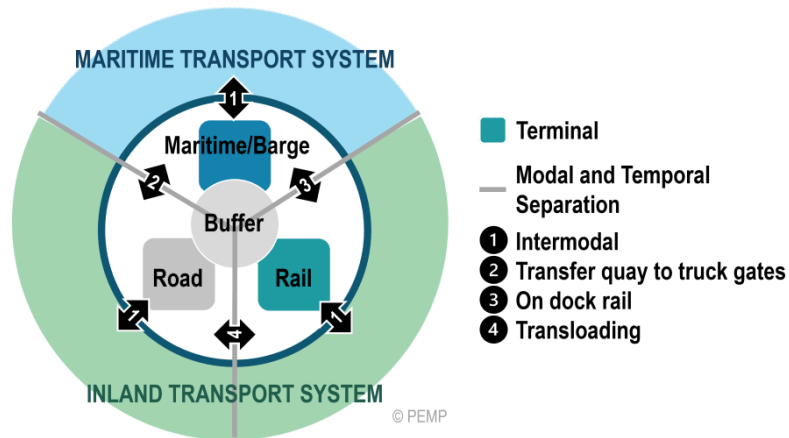


Figure 7: Interaction between maritime and inland transport systems [14]

When different transport modes intersect in the port Hinterland, vertical or horizontal separation elements are used to ensure smooth flow, safety and efficiency. The choice between level crossing, overpass, underpass or underground track depends mainly on cost, traffic volumes, service continuity and spatial constraints. [2] [14]

The main elements that are used to ensure efficient connections are listed below.

- *Level crossings*: represent the cheapest but also the least protected intersection between rail and road; they allow direct crossing with barriers and signals but quickly become unsustainable beyond a certain threshold of vehicle or rail traffic, due to delays, accident risks and congestion.
- *Overpasses and underpasses*: achieve complete flow separation; eliminate conflicts between rail and road vehicles, allowing independent schedules and increasing safety. However, they are characterized by much higher initial investment and require space for approach ramps, which are often chosen in urban settings with encumbrances and elevation constraints.
- *Underground tracks and tunnels*: these are usually adopted in densely built-up or environmentally valuable areas; this solution, the most expensive per kilometer, frees up surface area for urban uses, reduces noise pollution and barriers to the urban fabric, but involves lengthy designs and complex ventilation and safety systems.

The choice of the type of solution is determined by a counterbalance of four main factors. Firstly, traffic and capacity define the threshold beyond which level crossings become inadequate in terms of both efficiency and safety, imposing elevated or underground solutions; secondly, costs and construction time for elevated or underground works, which are significantly higher than for a

simple level crossing, make the latter preferable only in low-flow contexts with ample space available; moreover, spatial and environmental constraints, typical of densely built-up urban areas or protected sites, push toward underground solutions to limit the impact on the territory and preserve the continuity of the landscape; finally, the evolution of safety regulations on rail-road intersections, which are increasingly stringent especially along high traffic corridors or near intermodal terminals, favors the complete separation of traffic levels. [2] [14]

1.3.4. Challenges of linking ports to inland destinations

Linking seaports to inland destinations is obstructed by three interconnected challenges, which are congestion at terminals and on access routes, limited capacity of rail and river infrastructure, and environmental and regulatory constraints. Congestion reduces the reliability of logistics chains, with average delays of more than an hour per vehicle at port gates, while the scarcity of dedicated tracks and adequate barge corridors prevents the transfer of large volumes of freight by rail and water. Finally, procedures for environmental assessments and national regulations lengthen the time it takes to build new hinterland connections. Again, an effective strategy would combine digital solutions, targeted investment in intermodal infrastructure, and regulatory simplification. [2] [14]

Congestion at port terminals and access roads

Congestion is most pronounced at terminal access gates and on adjacent arterial roads, where trucks can wait an average of more than 60 minutes before entering. This phenomenon is aggravated by the absence of coordinated reservation systems and the low capacity of near-dock yards, which force vehicles to make longer stops on access roads. The result is increased operating costs, reduced asset utilization, and higher emissions due to prolonged operation of parked engines. [2] [14] Some elements that could address these issues are:

- Appointment systems are integrated with Port Community Systems, which distribute access slots throughout the day and reduce traffic peaks.
- Inland ports/dry ports placed along rail and river corridors, to move the loading/unloading point inland and decongest the main port area.
- IoT platforms for real-time monitoring of vehicular flow and predictive traffic management systems, enabling better coordination between port operators and local authorities.

Limited rail and inland waterway capacity

Rail infrastructure dedicated to freight traffic is often underpowered relative to the needs of containerized and bulk movement: many rail-on-dock terminals have limited tracks, inadequate tunnel profiles, and an absence of high-capacity corridors. Similarly, barge service encounters frequent bottlenecks due to river ports with obsolete docks, variable depths, and overloaded locks. Poor interoperability among network operators and the absence of central coordination further complicates the optimization of intermodal flows. Two interventions that would improve this condition are the creation of dedicated freight rail corridors, with upgraded tracks and double track, capable of supporting longer and heavier freight trains; and the modernization and presence of regular dredging along major navigable waterways to maintain consistent depth levels and carrying capacity. [2]

Environmental and regulatory constraints

The construction of new port-hinterland connections is often slowed by environmental impact assessment (EIA) processes, EU directives on air/water emissions, and national regulations that limit the freedom of service barge between regions. In addition, the multiplicity of regional and national offices and approvals generates a “regulatory drag” that can last for years, discouraging investment in “green” infrastructure such as fully electrified terminals or photovoltaic docks. This process could be streamlined by the presence of incentives linked to the hinterland link's ability to reduce emissions (such as modulated subsidies based on km-bar, as envisioned in the Green Deal), to promote low-emission technologies and the use of sustainable modes. [2]

Dead leg or empty return

Another issue related to inland connectivity is related to the management of containers after they are emptied and need to be returned to the port. It is common for them to return empty to its destination, causing a significative issue in the logistics chain when there is no cargo to transport on the way back, increasing traffic, costs and pollution, longer times for containers to be reused, unnecessary pressure to port and road infrastructure. Strategies to reduce empty trips have been implemented. For instance, triangulation, which means that instead of the container to be taken back empty to the port, it could be used nearby for another export load, but it's challenging in terms of coordination. Another strategy is sharing containers between different shipping lines or using containers for local deliveries. [17]

1.4. Analysis of existing literature

An analysis was made to review existing literature related to the objective and sector of the current study, in order to evaluate the state of the art, and understand in which areas there is need for further studying and how this thesis fills those blanks.

Recent academic literature focuses on the optimization of port logistic systems, driven by the need to manage increasingly complex global supply chains. Ports are no longer seen as isolated entities, but as a complex network made up of interdependencies between the different stakeholders involved, in which the efficiency of one of them has effects on the entire system. Given the nature of these systems, they are well-suited for being analyzed through simulation modeling.

Dragović, Tzannatos, and Park [12] performed a comprehensive literature review, in which they confirmed that simulation is currently being studied as a methodology for analyzing operations within ports and container terminals. In their work, the studies found were systematically categorized based on the subsystem that was being analyzed such as berth allocation, quay crane scheduling and yard management. As a common factor, most studies focused on the identification of operational bottlenecks and evaluation of the performance of terminals under different scenarios. Therefore, a strong precedent on use of simulation as analytical tool on this domain is established, aligning with the objectives of the present thesis.

Nevertheless, there is a wide range of possibilities within simulation modeling. In recent decades, System Dynamics (SD) simulation has gained popularity in the port sector, as a well-suited methodology for analyzing non-linear behaviors where operational complexity requires tools capable of representing interactions, delays, and feedback loops between different components. For instance, Liu, Zhang and Zeyi [23] analyzed through SD the collaborative operations between the different stakeholders including port authority, customs and terminal operators. Their model, built with Vensim software, was able to quantify the way in which changes in micro-level operational rules and infrastructure constraints alter the overall throughput of the port, therefore concluding that the efficiency of the port ecosystem is very sensitive to the operation policies and strategies. This includes interconnected activities such as the scheduling of vessel arrivals, allocation of berths, yard operations, customs inspection efficiency, among others.

A significant contribution in this area is a study by Caballini, Saccone and Siri [24], who interpret ports as a “system of systems”. In other words, a port can be conceived as a set of autonomous subsystems that share resources and must coordinate to ensure the smooth functioning of the

whole, including for example, customs, sea-side operations, land interface, handling and storage areas. The management of such contexts is made more complex by the presence of actors with different interests, non-uniform procedures, and uneven levels of digitization. Within their framework they highlight the importance of optimizing the rail cycle into a more sustainable means of transport. Their study presents a SD model using Power Sim Studio's software that reproduces the railway cycle of three Italian container terminals including phases such as loading/unloading, storage and customs check, finding that the terminals were not fully exploiting their rail capacity. The study evaluated potential improvements such as implementing new technology, moving operations to a dry port and increasing resources, finding that simply investing in infrastructure or equipment had little effect on the reduction of delays, since the main obstacles resulted in work organization, document management and poor synchronization between actors involved. This contribution serves as an example of the application of SD to real cases, showing, with empirical data, that better organization and inter-organizational cooperation can have a more significant effect on overall performance than infrastructure interventions alone.

In a more granular approach, Sacone and Siri [25] focused on the internal management of a rail freight terminal, with a model used to analyze operational variables such as the available shunting locomotives, the length of receiving and departure tracks, impact of train arrival schedules on internal congestion, among others. This work approaches the importance of more specific operational details such as the service time in hubs and dwell time in terminals as critical factors on the system's efficiency.

In order to further understand the contribution of this thesis, the existing literature on port simulation can be broadly categorized into two levels of analysis: micro and macro level.

On one hand, macro-level studies focus on a strategic perspective, and on ports as an aggregated node within a larger economic or logistical network. These models are concerned with overall flows and interactions between major components. In this order of ideas, Liu, Zhang and Zeyi [23] present a macro-level port as it analyses interactions between the stakeholders rather than the physical movement of the assets.

In contrast, micro-level studies focus on detailed processes and physical constraints within a specific subsystem of the port. Therefore, these models are concerned with a more granular and particular performance. The study by Sacone and Siri [25] is a clear example of this, by focusing on a single rail freight terminal and the flows on it.

Finally, the work by Caballini, Sacone and Siri [24] could be classified in both perspectives, as it begins with a macro framework when approaching the port as a system of systems, but building the actual simulation model in a specific operational process as is the railway cycle within the container terminal.

1.5. Innovative contribution of the Thesis

While the existing literature provides valuable foundations, it is notable that most studies tend to analyze road and rail operations as separate systems on either macro or micro-level processes. Few works have developed integrated SD models explicitly designed to capture the mutual influence between rail and road traffic flows at critical intersection points within a port. The novelty of this thesis is articulated in the following points:

- The development of an integrated SD model that directly couples the dynamics of the rail and road networks, thus enabling the analysis of interaction effects such as cascading delays and capacity constraints.
- The introduction of a methodology to use the results of the rail network simulation as input for the road network model, creating a dynamic interaction rather than one based on static assumptions.

This thesis focuses on an internal operative context of both the rail and road network. Granular variables are analyzed, and capacity of terminals, tracks and hubs become a critical variable of analysis. It was developed considering the complex interdependencies between modes of transport; an increasingly necessity as ports evolve toward more sustainable and coordinated logistics systems.

2. Methodology: System Dynamics Simulation

Developed in collaboration with Daniela Restrepo Ruiz

Ports and their intermodal connections with the hinterland are complex and interdependent systems, characterized by continuous interaction between resources and flows. The variety of factors that influence these systems makes studying their behavior using purely analytical methods particularly complex. In this context, simulation stands out as an effective tool that is well suited to this type of problem.

The goal of simulation is to replicate real-world processes in a digital and controlled environment. This offers the possibility to observe the behavior of the system, test hypotheses, and evaluate the impact of potential changes without the costs, risks, or operational disruptions that a physical implementation would entail.

In the port operations sector, simulation is an important decision-making support tool; it allows planners to explore different possible scenarios, identify bottlenecks, and evaluate strategies under varying operational and demand conditions.

2.1. Different simulation approaches

In the study of logistics and transportation, several simulation methodologies are available. Three main modeling approaches are used: System Dynamics (SD), Discrete Event Simulation (DES), and Agent-Based Simulation (ABS).

While they share the common goal of reproducing real dynamics, each of these approaches is based on different modeling principles, which make them more suitable for certain cases and not useful for others depending on the nature of the problem being analyzed.

The fundamental difference between these methodologies lies in their level of abstraction and in their core unit. Table A below summarizes the main aspects of each of them.

- SD focuses on the stock as a core unit, which represents an accumulation of resources (such as trains or trucks), [26]
- DES focuses on events, which are a specific occurrence at a point in time that changes the state of the system. An event in the port sector could be a train arriving at a signal or a crane starting to unload or load a container. [27]
- ABS focuses on agents, which are autonomous, decision-making entities (such as a truck driver or a shipping line). Each agent has its own set of behavior and rules. [28]

Aspect	Discrete Event Simulation (DES)	Agent-Based Modeling (ABM)	System Dynamics (SD)
Description	Focuses on the performance of a system based on a chronological sequence of events. Core unit: the event	Models a system as a set of autonomous interacting agents focusing on how they interact and behave. Core unit: the agent	Models feedback loops, flows, and time delays to analyze the behavior of a system over time. Core unit: the stock
Level of Abstraction	High operational detail: it models at a micro level (e.g., position of the train at each moment).	Medium to high (behavioral detail).	Aggregated: models at macro-level, not focused on single elements but focused on flows.
Best For	Decision making for systems with well-defined processes and with predictable events.	For systems with complex interactions, where individual behavior impacts the overall system.	Modeling the long-term trends for systems with complex relationships and feedback loops (chains of cause-effect relationships).

Table A: Differences between simulation techniques (developed by the author)

In the port logistics context, each of them serves for different applications under certain strengths and weaknesses:

- System Dynamics (SD) focuses on capturing the aggregate behavior of a system over time by analyzing feedback loops, stocks, and flows. It is particularly effective for representing high-level interactions and long-term trends. It is typically used for: strategic planning, demand forecasting, policy impacts, bottlenecks, capacity analysis, modal shift scenarios, CO2 impact of port policies, among others. An advantage is that it is easy to visualize feedback loops, and it needs less data as it is at aggregate level, but as it also gives results at this level, it ends up having lack of operational detail. It works with trend-level data, and general causal relationships. [26]
- Discrete Event Simulation (DES) models the system as a sequence of discrete events occurring at specific points in time. This approach is particularly suitable for detailed operational modeling, where the exact timing of events and resource allocation are critical. It is used for analyzing terminal operations, queuing, berth/crane scheduling, gate congestion, yard operations, among others. It is a very realistic process modeling and allows to quantify queues and delays, but it requires high quantity of detailed data and becomes complex for larger systems. It needs data related to process times, resources, use, among others. [27]

- Agent-Based Simulation (ABS) models the system as a set of autonomous agents, each with individual behaviors and decision-making rules. ABS is useful when the heterogeneity of actors and behaviors emerging from local interactions are central elements of the analysis. Therefore, it is used for behavior modeling, routing, interaction of stakeholders, truck driver choices, logistics chain decision. This kind of modeling captures heterogeneity and has flexibility for “What-If” scenarios, but it is very data-intensive and presents difficulties during validation and calibration. It needs data related to agent rules and interactions. [28]

The choice of methodology is critical as it defines the scope of the analysis and the types of questions that may be answered with it. It has to be aligned with the specific objectives and the nature of the system that is being investigated. For this thesis, which analyses the complex interaction between a port’s rail network, road network and their critical intersection points, the most appropriate framework was to choose System Dynamics (SD)

Although DES and ABS approaches have proven valid in port operations research (e.g., in the simulation of ship scheduling or yard operations), their strength lies in the granular representation of processes. The main objective of this thesis, on the other hand, is to understand the behavior at the system level and the long-term effects of interactions between road and rail networks within the port environment.

System Dynamics is particularly well suited to this purpose for several reasons:

1. Focus on aggregate flows. The goal is to capture the evolution of traffic and resource utilization at the systemic level, rather than modeling individual vehicles or events.
2. Representation of feedback mechanisms. The model must take into account causal loops, such as congestion affecting delays and delays affecting productivity; SD is inherently designed to handle such dynamics.
3. Exploration of strategic scenarios. The study requires testing strategic interventions and assessing their impact over extended time horizons, a typical strength of SD models.
4. Simplified data requirements. Compared to DES or ABS, SD can provide strategic insights even with less detailed operational data sets, making it a viable choice in contexts where granular data is difficult to obtain.

In such way, System Dynamics was selected due to its core principles that align with the research objectives and data availability.

2.2. Software selection: Vensim PLE

The selection of an appropriate software tool is fundamental for the implementation of a simulation model. For this thesis, Vensim PLE (Personal Learning Edition) was chosen to develop it. The decision was driven by three main reasons: it's direct alignment with the System Dynamics methodology, its strong feature set availability, and its widespread use for academic purposes.

This software package is specifically designed for System Dynamics models, and therefore it was developed around the principles of its paradigm. Its strengths lay on its visual modeling interface which allow for visual diagrams such as causal loop and stock and flow maps. The graphical interface is very intuitive and allows to communicate better both the structure of the model and the results.

Regarding its simulation engine it is optimized for solving systems of non-linear differential equations, which are the core of SD models, ensuring that the model is implemented with software with numerical stability and precision.

Finally, the software includes comprehensive analysis built-in tools that allow a better understanding of the results, such as dynamic graphing and tabular data output. These features allowed for a better analysis of the multiple scenarios simulated, to visualize a direct comparison of the different operational policies and infrastructural changes.

In such way, the complexity and size of the model implemented, fit sufficiently within the operational limits of the PLE version, and allow for a precise and efficient simulation with the SD methodology from its conceptualization and implementation to the final analysis of the results.

3. Case Study

The quantitative analysis developed in this thesis is based on a simulation model built with Vensim PLE, a System Dynamics framework. The aim is to study the functioning of a road network and its interaction with the rail network within a port context. The simulation is intended to assess the overall productivity of the system, identify the main bottlenecks, and understand how well the network is able to manage variable flows, also taking into account various operational constraints and alternative scenarios.

The model was developed using a continuous flow approach, which allows for an aggregate analysis of resource use, queue formation, and overall behavior, rather than tracking individual units one by one. This makes it a useful tool for assessing the resilience and efficiency of infrastructure, but also for exploring the impact of possible changes, such as new operational policies or infrastructure interventions.

3.1. Port Description

The information used in this chapter and the following chapters concerns a real port and has been provided by Next Freight. For confidentiality reasons, the name of the port in question will not be disclosed.



The case study chosen for this research concerns a large multimodal and multiterminal port in Northern Italy, selected for its strategic role as one of the main maritime hubs for national industry and European trade. Its historical evolution has given rise to a complex structure characterized by space constraints, elements that make it particularly interesting for the study of operational criticalities that emerge in transport networks and in the interaction between different modes.

From a physical point of view, the port extends along a narrow coastal strip close to urban areas, where several specialized terminals are located. The compact configuration means that roads and railways often share limited space, creating several points of intersection.

Port operations are supported by modern infrastructure, such as latest-generation cranes, ramps for Ro-Ro traffic, internal transfer vehicles, and shunting locomotives. Thanks to this equipment, the port is able to handle over 2 million TEUs, more than 3 million linear meters of Ro-Ro traffic, and over 5 million tons of general and bulk cargo each year.

The high volume of traffic, combined with the variety of cargo types and space constraints, makes this port a case study for analyzing the challenges of intermodal efficiency, conflicts between road and rail traffic, and bottlenecks that arise in the functioning of the port.

The high volume of traffic, combined with the variety of types of goods and spatial constraints, makes this port a prime example for analyzing the challenges associated with intermodal efficiency, conflicts between road and rail traffic, and bottlenecks that arise in the operation of different transport networks.

3.2. Generalities

3.2.1. Overview of the models

As previously anticipated, the port's infrastructure is designed to handle a diverse range of freight, broadly classified as containers, bulk, and Ro-Ro units. Its landside logistical operations are managed through a complex internal network of roads and railways.

Access to the port is facilitated through three primary entry/exit points: one dedicated rail entrance (V1) and two separate road entrances (V2 and V3). The coexistence of these two transport systems within a confined operational area gives rise to specific logistical challenges, most notably in terminals and at points where the road and rail networks intersect. This chapter provides a detailed description of the port's constituent terminals and the nature of these network conflicts, which form the basis of the viability analysis presented in this thesis.

3.2.2. Development of the models

Three separate models were created in order to better understand the dynamics inside it:

1. Rail network Model, developed by Daniela Restrepo Ruiz;
2. Road network Model, analyzed further on in this thesis;
3. Crossings between networks Model, developed in collaboration with Daniela Restrepo Ruiz and analyzed further on in this thesis.

Before entering into detail for each of these models, some clarifications and decisions had to be made which are explained below.

3.2.3. Terminal infrastructure and specialization

The port is composed of different terminals, for this analysis nine of them are considered, each with varying specializations in terms of freight handling and modal connectivity. The

heterogeneity of these terminals is a key feature of the port's operational landscape. A detailed breakdown is as follows:

- Terminal 1 (T1): a multi-modal terminal handling container, with connections to both the road and rail networks.
- Terminal 2 (T2): specializes in Ro-Ro freight and is served exclusively by the road network.
- Terminal 3 (T3): handles bulk goods and is connected only to the road network.
- Terminal 4 (T4): a multi-modal terminal for bulk freight, accessible via both road and rail.
- Terminal 5 (T5): a dedicated container terminal connected exclusively to the rail network.
- Terminal 6 (T6): handles bulk cargo and is served only by the road network.
- Terminal 7 (T7): a specialized liquid bulk terminal with an exclusive connection to the rail network.
- Terminal 8 (T8): a large multi-modal terminal for containers, with both road and rail access.
- Terminal 9 (T9): a container terminal served exclusively by the road network.

This distribution highlights a mix of specialized, single-mode terminals and flexible, multi-modal terminals. Below, Table B summarizes the characteristics of each terminal.

ID Terminal	Cargo Type	Road Connection	Rail Connection
T1	Containers	YES	YES
T2	Ro-Ro	YES	NO
T3	Bulk	YES	NO
T4	Bulk	YES	YES
T5	Containers	NO	YES
T6	Bulk	YES	NO
T7	Bulk	NO	YES
T8	Containers	YES	YES
T9	Containers	YES	NO

Table B: Port terminals and their characteristics

3.2.4. The crossing conflict problem

A central challenge to the port's internal viability is the existence of level crossings, where the road and rail networks intersect. These conflict points can become significant bottlenecks, as port regulations dictate that rail traffic has absolute priority over road traffic. When a train occupies a

crossing, all road vehicle movement is halted, which can lead to queue formation and cascading delays throughout the road network.

There are three critical crossings within the port's infrastructure:

1. Crossing 1 (X1): Located on the network intersection serving the access routes to Terminal 1.
2. Crossing 2 (X2): Positioned on the main trunk line in the vicinity of the road-based terminals, including Terminal 3.
3. Crossing 3 (X3): Situated near the V3 road entrance, affecting vehicles entering or exiting from this point.

The management of these crossings is therefore a crucial factor in determining the efficiency and capacity of the port's landside operations.

3.2.5. Generalized scheme for the simulation models

To analyze the interactions and dependencies within the port, a generalized model is proposed. The schematic diagram in Figure 8 represents the logical layout of the port, abstracting from the precise geographical details. It illustrates the terminals, the road and rail networks, the external entrances, and the critical crossing points that will be used for the simulation analysis.

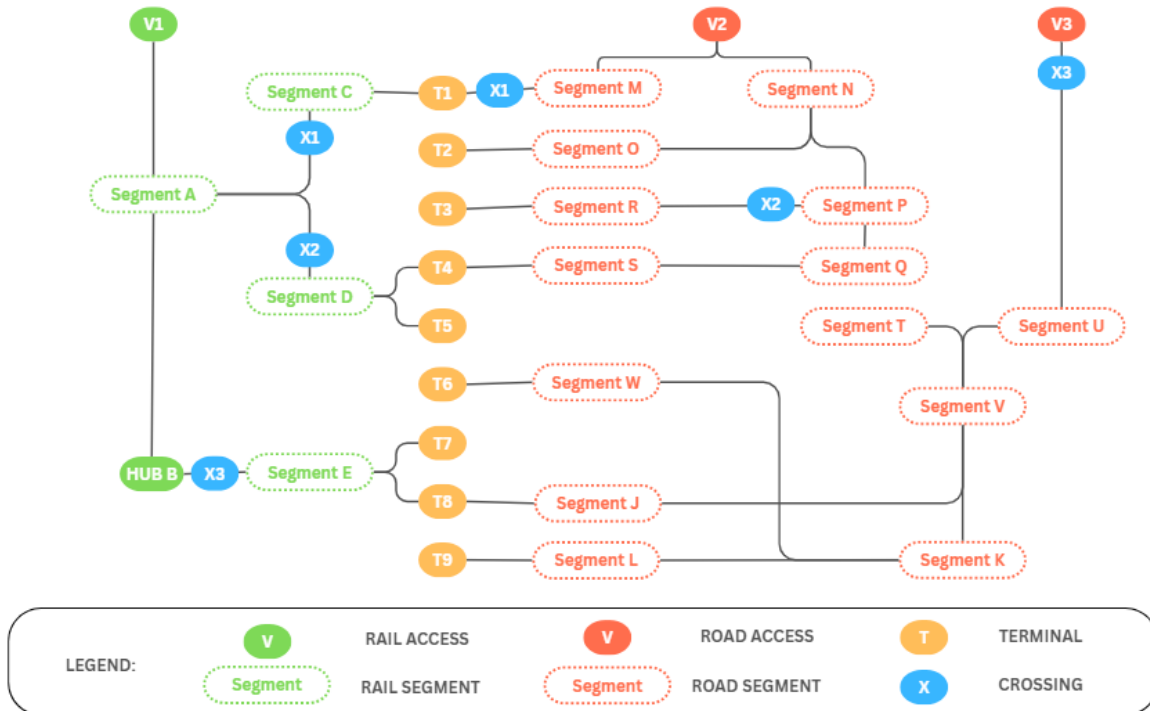


Figure 8: Generalized scheme for the simulation model

3.2.6. Cargo type aggregation

One of the main methodological choices adopted in constructing the model concerns the aggregation of all trains and trucks into a single homogeneous flow, regardless of the type of load (Ro-Ro, bulk goods, containers, etc.).

As cited above, the primary objective of this study is to analyze the flows, interactions, and productivity of road infrastructure and shared infrastructure. Particular attention is paid to common rail and road segments, since in these shared contexts the operational behavior of a train or truck does not vary according to the nature of the cargo being transported. The speed and occupancy of a single road segment follow the same rules of signaling, sorting, and capacity, regardless of the goods being transported.

Consequently, introducing a distinction between different types of cargo would have added complexity to the model without bringing significant benefits to the analysis of congestion and flow dynamics in the shared network.

However, it should be noted that the main operational differences related to the type of cargo arise within the terminals, particularly during loading, unloading, and internal handling operations. To take this variability into account without introducing excessive complexity into the model, terminal operating times were not considered as constant values but were modeled as random variables derived from a uniform distribution within a predefined range.

This made it possible to effectively represent the variability of internal logistics processes, including both relatively fast operations, such as those involving containers, and slower procedures, such as those involving bulk goods, without having to explicitly distinguish between different types of cargo throughout the model.

3.3. Road network model

According to the principles of System Dynamics, the model is designed to investigate the operational behavior of a complex port road network. The primary objective of this simulation is to analyze the system's throughput, identify and quantify operational bottlenecks, and evaluate the network's capacity to manage truck flows under a comprehensive set of constraints. Later on, the simulation will be enriched through the development of a new model, which also considers intersections with the existing railway inside the port.

3.3.1. Physical layout and operational rules

The port's road network consists of two primary entry/exit points, designated V2 and V3. These gates connect to a network of seven destination terminals (T1, T2, T3, T4, T6, T8, T9) via a series of interconnected, two-lane road segments, indicated with a capital letter. A key feature of the network is that several segments are shared resources, forming common paths for trucks traveling to different destinations. Figure 9 captures graphically this setting.

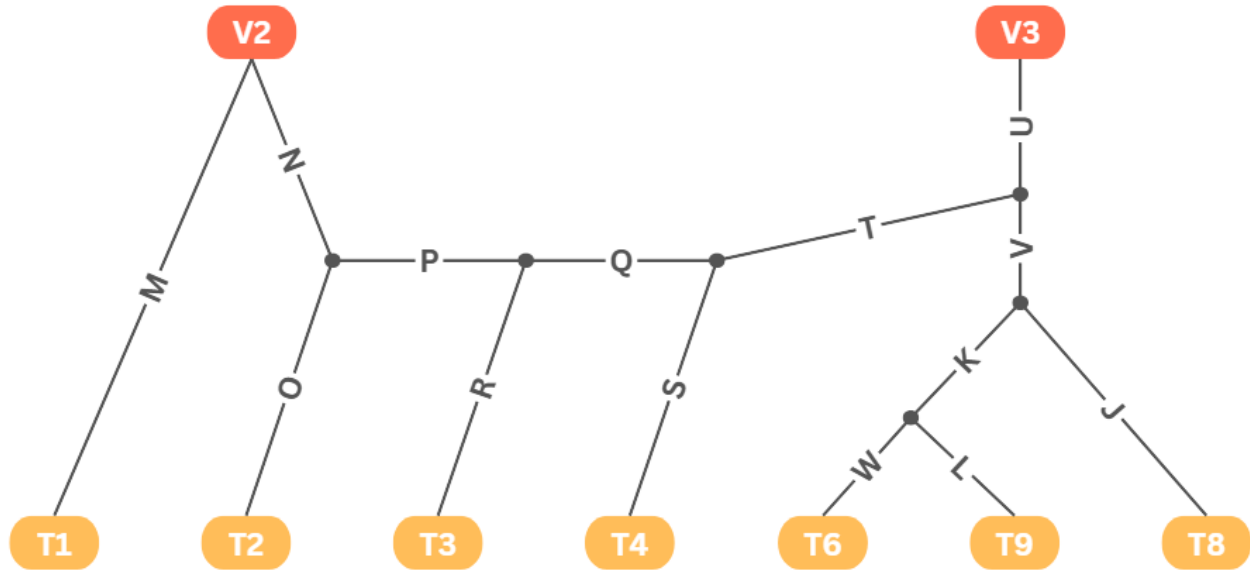


Figure 9: Schematized Road network for Scenario 1

The terminal accessibility from each gate is defined as follows:

- From Gate V2 trucks can access Terminals 1, 2, 3, and 4.
- From Gate V3 trucks can access Terminals 2, 3, 4, 6, 8, and 9.

The operational rules governing the system are:

- All road segments are modeled with two lanes, one for each direction of travel. The capacity of each lane is finite and defined as a fixed number of trucks. This capacity, as seen in Table C, was calculated by measuring the physical length of each road segment using Google Earth and dividing by an assumed 18-meter length per truck, which accounts for both the vehicle's size and a safety distance.

Segment	Length	Time	Capacity
<i>[-]</i>	<i>[km]</i>	<i>[min]</i>	<i>[Trucks]</i>
M	0.145	2	8

Segment	Length	Time	Capacity
<i>[-]</i>	<i>[km]</i>	<i>[min]</i>	<i>[Trucks]</i>
N	0.703	9	39
O	0.244	3	13
P	0.381	5	21
Q	0.313	4	17
R	0.066	1	3
S	0.161	2	8
T	0.227	3	12
U	0.048	1	2
V	0.777	10	43
K	0.215	3	11
W	0.025	1	1
L	0.341	5	18
J	0.656	8	36

Table C: Length, time and capacity of road segments

- Each terminal has a dedicated gate area for processing inbound and outbound trucks. These gates have distinct, finite capacities for entry and exit flows as seen in Table D, allowing for simultaneous processing.

Terminal	Entry Capacity	Exit Capacity
<i>[-]</i>	<i>[Trucks]</i>	<i>[Trucks]</i>
T1	2	1
T2	3	2
T3	1	1
T4	2	1
T6	2	2
T8	3	2
T9	2	2

Table D: Entry and exit capacity of road terminals

- The internal operational area of each terminal has a fixed capacity, limiting the maximum number of trucks that can be serviced at any given time.

Terminal	Operational Capacity
<i>[-]</i>	<i>[Trucks]</i>
T1	15
T2	18
T3	5

Terminal	Operational Capacity
<i>[-]</i>	<i>[Trucks]</i>
T4	8
T6	15
T8	20
T9	15

Table E: Operational capacity of road terminals

- Trucks are subject to mandatory processing times at terminal gates and operational dwell times within the terminals themselves. These durations are modeled as stochastic variables, drawn from uniform distributions to represent real-world variability.

Terminal	Time at Gate	Range Inside T	
<i>[-]</i>	<i>[min]</i>	<i>[min]</i>	
T1	3	10	40
T2	3	25	40
T3	3	45	100
T4	3	45	100
T6	3	45	100
T8	3	15	30
T9	3	10	40

Table F: Operational time at gate and inside road terminals

- Truck movement from entry points to the different destinations is governed by a probabilistic routing mechanism. This approach disaggregates a total departing truck flow into multiple outbound paths based on a predefined set of probabilities.
- Truck movement from entry points to the different destinations is governed by a probabilistic routing mechanism. This approach disaggregates a total departing truck flow into multiple outbound paths based on a predefined set of probabilities seen in Table G.

Entrance	Terminal	Probability
<i>[-]</i>	<i>[-]</i>	<i>[%]</i>
V2	T1	64%
	T2	13%
	T3	11%
	T4	12%
V3	T2	25%
	T3	8%
	T4	10%

Entrance	Terminal	Probability
<i>[-]</i>	<i>[-]</i>	<i>[%]</i>
	T6	14%
	T8	29%
	T9	14%

Table G: Proportion of arrivals for road terminals for Scenario 1

3.3.2. The truck lifecycle

Every truck follows a mandatory, sequential lifecycle from its entry into the port to its exit. This journey involves navigating the road network to a specific terminal, undergoing service, and returning via the same path to its original point of entry. The simplified conceptual scheme is illustrated below in Figure 10.

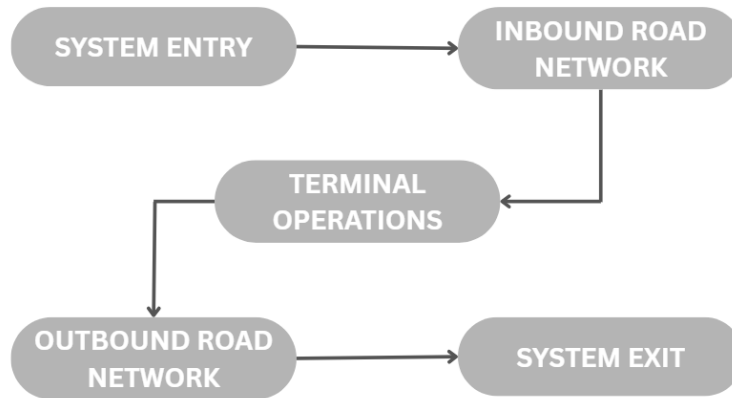


Figure 10: Truck lifecycle

3.3.3. System process flow

On Vensim PLE, the journey of a truck is modeled as a logical sequence of states (represented as Stocks) and transitions (represented as Flows).

1. *System Entry*. Trucks arrive at the V2 and V3 gates at a variable rate defined by a time-dependent lookup table. They accumulate in initial queues if the first road segment is at capacity.
2. *Inbound Journey*. Trucks are dispatched from the entry queues onto the road network, subject to the capacity of the subsequent road segments. The model uses parallel stocks to represent traffic streams with different origins or destinations traveling on the same physical road segment.

3. *Terminal Entry and Service.* Upon reaching their destination, trucks first enter a queue for the terminal gate. After being processed at the gate, they move into the main terminal area, where they dwell for a stochastic duration to complete operations.
4. *Outbound Journey and Exit.* After completing terminal operations, trucks begin the return journey. For dual-access terminals the exit flow has two options: if the route back towards the truck's original entry gate is not occupied, the trucks should follow it. If the route is congested, trucks should follow the alternative one. The outbound journey mirrors the inbound path, utilizing a separate set of "outbound" stocks to model two-way traffic. Finally, trucks arrive at their exit gate and are removed from the system, accumulating in stocks that measure total throughput.

3.3.4. Simulation parameters

The simulation is configured with the following global parameters:

- *Time units:* hours
- *Simulation horizon:* 168 hours (one week)
- *Integration timestep (TIME STEP):* 0.01 hours, to ensure numerical precision and stability with the complex feedback loops.

The total weekly arrivals for Scenario 1 are implemented in the model through *some lookup functions*, and they are presented in the graph below.

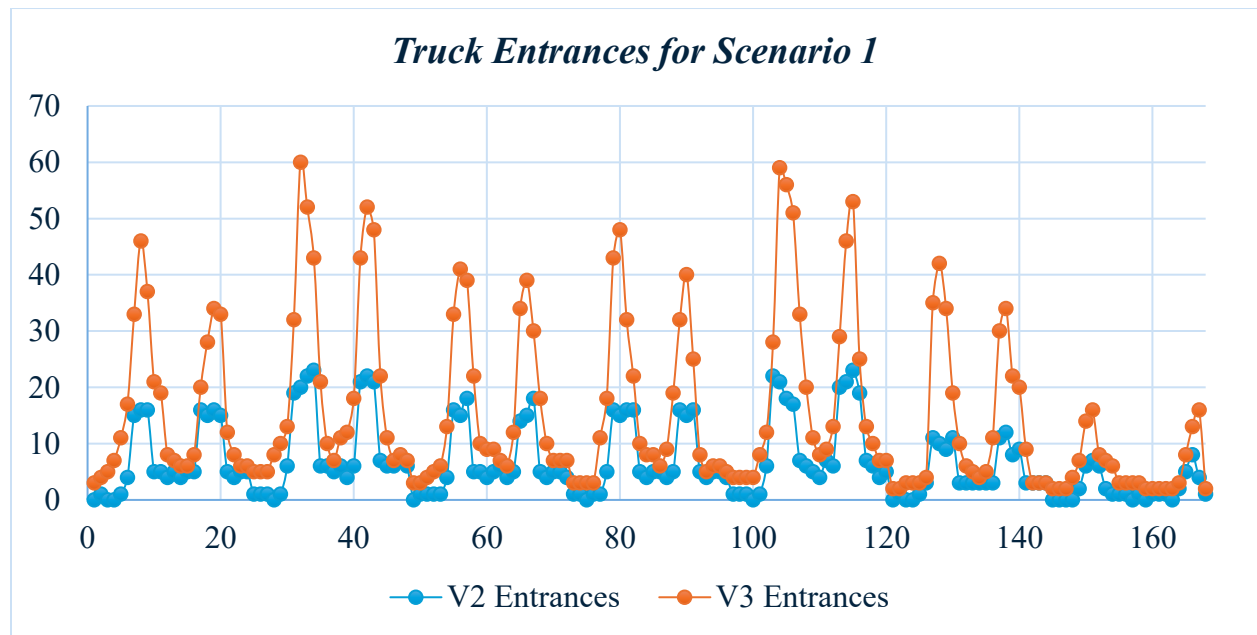


Figure 11: Truck entrances for Scenario 1

3.3.5. Model variables and equations

The following tables (Table H, Table I, Table J, Table K and Table L) provide a complete dictionary of all variables and equations used in the model, organized by their function.

Model parameters and constants

These are fixed values that define the model's characteristics.

Variable Name	Formula/Value	Units	Description
Capacity of Segment J	36	Trucks	Road capacity of segment J
Capacity of Segment K	11	Trucks	Road capacity of segment K
Capacity of Segment L	18	Trucks	Road capacity of segment L
Capacity of Segment M	8	Trucks	Road capacity of segment M
Capacity of Segment N	39	Trucks	Road capacity of segment N
Capacity of Segment O	13	Trucks	Road capacity of segment O
Capacity of Segment P	21	Trucks	Road capacity of segment P
Capacity of Segment Q	17	Trucks	Road capacity of segment Q
Capacity of Segment R	3	Trucks	Road capacity of segment R
Capacity of Segment S	8	Trucks	Road capacity of segment S
Capacity of Segment T	12	Trucks	Road capacity of segment T
Capacity of Segment U	2	Trucks	Road capacity of segment U
Capacity of Segment V	43	Trucks	Road capacity of segment V
Capacity of Segment W	1	Trucks	Road capacity of segment W
Capacity of T1 Gate Inbound	2	Trucks	Inbound gate capacity for terminal T1
Capacity of T1 Gate Outbound	1	Trucks	Outbound gate capacity for terminal T1
Capacity of T1 Ops	15	Trucks	Operations capacity of terminal T1
Capacity of T2 Gate Inbound	3	Trucks	Inbound gate capacity for terminal T2
Capacity of T2 Gate Outbound	2	Trucks	Outbound gate capacity for terminal T2
Capacity of T2 Ops	18	Trucks	Operations capacity of terminal T2
Capacity of T3 Gate Inbound	1	Trucks	Inbound gate capacity for terminal T3
Capacity of T3 Gate Outbound	1	Trucks	Outbound gate capacity for terminal T3
Capacity of T3 Ops	5	Trucks	Operations capacity of terminal T3
Capacity of T4 Gate Inbound	2	Trucks	Inbound gate capacity for terminal T4
Capacity of T4 Gate Outbound	1	Trucks	Outbound gate capacity for terminal T4
Capacity of T4 Ops	8	Trucks	Operations capacity of terminal T4
Capacity of T6 Gate Inbound	2	Trucks	Inbound gate capacity for terminal T6
Capacity of T6 Gate Outbound	2	Trucks	Outbound gate capacity for terminal T6
Capacity of T6 Ops	15	Trucks	Operations capacity of terminal T6
Capacity of T8 Gate Inbound	3	Trucks	Inbound gate capacity for terminal T8
Capacity of T8 Gate Outbound	2	Trucks	Outbound gate capacity for terminal T8

Variable Name	Formula/Value	Units	Description
Capacity of T8 Ops	20	Trucks	Operations capacity of terminal T8
Capacity of T9 Gate Inbound	2	Trucks	Inbound gate capacity for terminal T9
Capacity of T9 Gate Outbound	2	Trucks	Outbound gate capacity for terminal T9
Capacity of T9 Ops	15	Trucks	Operations capacity of terminal T9
Prob T1 from V2	0.64	Dmnl	Probability of a truck from V2 going to T1
Prob T2 from V2	0.13	Dmnl	Probability of a truck from V2 going to T2
Prob T2 from V3	0.25	Dmnl	Probability of a truck from V3 going to T2
Prob T3 from V2	0.11	Dmnl	Probability of a truck from V2 going to T3
Prob T3 from V3	0.08	Dmnl	Probability of a truck from V3 going to T3
Prob T4 from V2	0.12	Dmnl	Probability of a truck from V2 going to T4
Prob T4 from V3	0.1	Dmnl	Probability of a truck from V3 going to T4
Prob T6 from V3	0.14	Dmnl	Probability of a truck from V3 going to T6
Prob T8 from V3	0.29	Dmnl	Probability of a truck from V3 going to T8
Prob T9 from V3	0.14	Dmnl	Probability of a truck from V3 going to T9
Prop of T2 Traffic for V2	0.342	Dmnl	Proportion of T2 traffic originating from V2
Prop of T3 Traffic for V2	0.579	Dmnl	Proportion of T3 traffic originating from V2
Prop of T4 Traffic for V2	0.546	Dmnl	Proportion of T4 traffic originating from V2
Time at Gate T1	3/60	Hour	Processing time at gate T1
Time at Gate T2	3/60	Hour	Processing time at gate T2
Time at Gate T3	3/60	Hour	Processing time at gate T3
Time at Gate T4	3/60	Hour	Processing time at gate T4
Time at Gate T6	3/60	Hour	Processing time at gate T6
Time at Gate T8	3/60	Hour	Processing time at gate T8
Time at Gate T9	3/60	Hour	Processing time at gate T9
Time Flow	1	Dmnl	Rate of flow for the custom timer
Time in T1	RANDOM UNIFORM (min, max, 1)	Hour	Time spent in terminal T1 operations
Time in T2	RANDOM UNIFORM (min, max, 2)	Hour	Time spent in terminal T2 operations
Time in T3	RANDOM UNIFORM (min, max, 3)	Hour	Time spent in terminal T3 operations
Time in T4	RANDOM UNIFORM (min, max, 4)	Hour	Time spent in terminal T4 operations
Time in T6	RANDOM UNIFORM (min, max, 5)	Hour	Time spent in terminal T6 operations
Time in T8	RANDOM UNIFORM (min, max, 6)	Hour	Time spent in terminal T8 operations
Time in T9	RANDOM UNIFORM (10/40, 40/60, 7)	Hour	Time spent in terminal T9 operations
Time Segment J	8/60	Hour	Travel time for segment J
Time Segment K	3/60	Hour	Travel time for segment K

Variable Name	Formula/Value	Units	Description
Time Segment L	5/60	Hour	Travel time for segment L
Time Segment M	2/60	Hour	Travel time for segment M
Time Segment N	9/60	Hour	Travel time for segment N
Time Segment O	3/60	Hour	Travel time for segment O
Time Segment P	5/60	Hour	Travel time for segment P
Time Segment Q	4/60	Hour	Travel time for segment Q
Time Segment R	1/60	Hour	Travel time for segment R
Time Segment S	2/60	Hour	Travel time for segment S
Time Segment T	3/60	Hour	Travel time for segment T
Time Segment U	1/60	Hour	Travel time for segment U
Time Segment V	10/60	Hour	Travel time for segment V
Time Segment W	1/60	Hour	Travel time for segment W
Unit Aux	0.1	Hour	An auxiliary time unit for calculations

Table H: List of Vensim PLE parameters and constants for truck Scenario 1

Stock variables

They represent accumulations within the system and are defined using the INTEG function.

Variable Name	Formula/Value	Units	Description
Custom Time	INTEG (Time Flow, 0)	Hour	A custom timer for the model
Truck on S from V2	INTEG (Depart Q for S from V2 - Arrive at Gate T4 from V2, 0)	Trucks	Trucks on segment S coming from V2
Truck on S from V3	INTEG (Depart T for S - Arrive at Gate T4 from V3, 0)	Trucks	Trucks on segment S coming from V3
Trucks at Gate T1 Inbound	INTEG (Arrive at Gate T1 - Start Gate T1 Inbound Process, 0)	Trucks	Trucks waiting at the inbound gate of T1
Trucks at Gate T2 Inbound	INTEG (Arrive at Gate T2 from V2 + Arrive at Gate T2 from V3 - Start Gate T2 Inbound Process, 0)	Trucks	Trucks waiting at the inbound gate of T2
Trucks at Gate T3 Inbound	INTEG (Arrive at Gate T3 from V2 + Arrive at Gate T3 from V3 - Start Gate T3 Inbound Process, 0)	Trucks	Trucks waiting at the inbound gate of T3
Trucks at Gate T4 Inbound	INTEG (Arrive at Gate T4 from V2 + Arrive at Gate T4 from V3 - Start Gate T4 Inbound Process, 0)	Trucks	Trucks waiting at the inbound gate of T4
Trucks at Gate T6 Inbound	INTEG (Arrive at Gate T6 - Start Gate T6 Inbound Process, 0)	Trucks	Trucks waiting at the inbound gate of T6
Trucks at Gate T8 Inbound	INTEG (Arrive at Gate T8 - Start Gate T8 Inbound Process, 0)	Trucks	Trucks waiting at the inbound gate of T8
Trucks at Gate T9 Inbound	INTEG (Arrive at Gate T9 - Start Gate T9 Inbound Process, 0)	Trucks	Trucks waiting at the inbound gate of T9

Variable Name	Formula/Value	Units	Description
Trucks Exited via V2	INTEG (Arrive at V2 Exit from N + Arrive at V2 for Exit from M, 0)	Trucks	Total trucks that have exited via V2
Trucks Exited via V3	INTEG (Arrive at V3 Exit from U, 0)	Trucks	Total trucks that have exited via V3
Trucks in T1	INTEG (Enter T1 - Start Exit from T1, 0)	Trucks	Trucks inside terminal T1 for operations
Trucks in T2	INTEG (Enter T2 - Start Exit from T2, 0)	Trucks	Trucks inside terminal T2 for operations
Trucks in T3	INTEG (Enter T3 - Start Exit from T3, 0)	Trucks	Trucks inside terminal T3 for operations
Trucks in T4	INTEG (Enter T4 - Start Exit from T4, 0)	Trucks	Trucks inside terminal T4 for operations
Trucks in T6	INTEG (Enter T6 - Start Exit from T6, 0)	Trucks	Trucks inside terminal T6 for operations
Trucks in T8	INTEG (Enter T8 - Start Exit from T8, 0)	Trucks	Trucks inside terminal T8 for operations
Trucks in T9	INTEG (Enter T9 - Start Exit from T9, 0)	Trucks	Trucks inside terminal T9 for operations
Trucks on J Inbound	INTEG (Depart V to J - Arrive at Gate T8, 0)	Trucks	Inbound trucks on segment J
Trucks on J Outbound	INTEG (Depart Gate T8 Outbound - Depart J for V Outbound, 0)	Trucks	Outbound trucks on segment J
Trucks on K Inbound	INTEG (Depart V to K - Depart K, 0)	Trucks	Inbound trucks on segment K
Trucks on K Outbound	INTEG (Depart L for K Outbound + Depart W for K Outbound - Depart K for V Outbound, 0)	Trucks	Outbound trucks on segment K
Trucks on L Inbound	INTEG (Depart K for L - Arrive at Gate T9, 0)	Trucks	Inbound trucks on segment L
Trucks on L Outbound	INTEG (Depart Gate T9 Outbound - Depart L for K Outbound, 0)	Trucks	Outbound trucks on segment L
Trucks on M Inbound	INTEG (Depart V2 for T1 - Arrive at Gate T1, 0)	Trucks	Inbound trucks on segment M
Trucks on M Outbound	INTEG (Depart Gate T1 Outbound - Arrive at V2 for Exit from M, 0)	Trucks	Outbound trucks on segment M
Trucks on N Inbound	INTEG (Depart V2 for T2 + Depart V2 for T3 + Depart V2 for T4 - Depart N, 0)	Trucks	Inbound trucks on segment N
Trucks on N Outbound	INTEG (Depart O for N Outbound + Depart P Outbound - Arrive at V2 Exit from N, 0)	Trucks	Outbound trucks on segment N
Trucks on O from V2	INTEG (Depart N for O - Arrive at Gate T2 from V2, 0)	Trucks	Trucks on segment O from V2
Trucks on O from V3	INTEG (Depart P for O from V3 - Arrive at Gate T2 from V3, 0)	Trucks	Trucks on segment O from V3
Trucks on O Outbound	INTEG (Depart Gate T2 Outbound - Depart O Outbound, 0)	Trucks	Outbound trucks on segment O
Trucks on P from V2	INTEG (Depart N for P - Depart P from V2, 0)	Trucks	Trucks on segment P from V2

Variable Name	Formula/Value	Units	Description
Trucks on P from V3	INTEG (Depart Q for P from V3 - Depart P for O from V3, 0)	Trucks	Trucks on segment P from V3
Trucks on P Outbound for V2	INTEG (Depart R for P Outbound + Depart Q for P Outbound - Depart P Outbound, 0)	Trucks	Outbound trucks on segment P heading to V2
Trucks on P Outbound for V3	INTEG (Depart O for P Outbound - Depart P Outbound to V3, 0)	Trucks	Outbound trucks on segment P heading to V3
Trucks on Q from V2	INTEG (Depart P for Q - Depart Q for S from V2, 0)	Trucks	Trucks on segment Q from V2
Trucks on Q from V3	INTEG (Depart T for Q - Depart on Q from V3, 0)	Trucks	Trucks on segment Q from V3
Trucks on Q Outbound	INTEG (Depart S for Q Outbound - Depart Q for P Outbound, 0)	Trucks	Outbound trucks on segment Q
Trucks on Q Outbound to V3	INTEG (Depart P Outbound to V3 + Depart R for Q Outbound - Depart Q Outbound to V3, 0)	Trucks	Outbound trucks on segment Q heading to V3
Trucks on R from V2	INTEG (Depart P for R - Arrive at Gate T3 from V2, 0)	Trucks	Trucks on segment R from V2
Trucks on R from V3	INTEG (Depart Q for R from V3 - Arrive at Gate T3 from V3, 0)	Trucks	Trucks on segment R from V3
Trucks on R Outbound	INTEG (Depart Gate T3 Outbound - Depart R Outbound, 0)	Trucks	Outbound trucks on segment R
Trucks on S Outbound	INTEG (Depart Gate T4 Outbound - Depart S Outbound, 0)	Trucks	Outbound trucks on segment S
Trucks on T Inbound	INTEG (Depart U for T - Depart T, 0)	Trucks	Inbound trucks on segment T
Trucks on T Outbound to V3	INTEG (Depart Q Outbound to V3 + Depart S for T Outbound - Depart T Outbound to V3, 0)	Trucks	Outbound trucks on segment T heading to V3
Trucks on U Inbound	INTEG (Depart V3 for T2 + ... + Depart V3 for T9 - Depart U, 0)	Trucks	Inbound trucks on segment U
Trucks on U Outbound	INTEG (Depart T Outbound to V3 + Depart V for U Outbound - Arrive at V3 Exit from U, 0)	Trucks	Outbound trucks on segment U
Trucks on V Inbound	INTEG (Depart U for V - Depart V, 0)	Trucks	Inbound trucks on segment V
Trucks on V Outbound	INTEG (Depart J for V Outbound + Depart K for V Outbound - Depart V for U Outbound, 0)	Trucks	Outbound trucks on segment V
Trucks on W Inbound	INTEG (Depart K for W - Arrive at Gate T6, 0)	Trucks	Inbound trucks on segment W
Trucks on W Outbound	INTEG (Depart Gate T6 Outbound - Depart W for K Outbound, 0)	Trucks	Outbound trucks on segment W
Trucks Processing at Gate T1	INTEG (Start Gate T1 Inbound Process - Enter T1, 0)	Trucks	Trucks currently processing at T1 inbound gate
Trucks Processing at Gate T1 Outbound	INTEG (Start T1 Gate Outbound Process - Depart Gate T1 Outbound, 0)	Trucks	Trucks currently processing at T1 outbound gate

Variable Name	Formula/Value	Units	Description
Trucks Processing at Gate T2	INTEG (Start Gate T2 Inbound Process - Enter T2, 0)	Trucks	Trucks currently processing at T2 inbound gate
Trucks Processing at Gate T2 Outbound	INTEG (Start T2 Gate Outbound Process - Depart Gate T2 Outbound, 0)	Trucks	Trucks currently processing at T2 outbound gate
Trucks Processing at Gate T3	INTEG (Start Gate T3 Inbound Process - Enter T3, 0)	Trucks	Trucks currently processing at T3 inbound gate
Trucks Processing at Gate T3 Outbound	INTEG (Start T3 Gate Outbound Process - Depart Gate T3 Outbound, 0)	Trucks	Trucks currently processing at T3 outbound gate
Trucks Processing at Gate T4	INTEG (Start Gate T4 Inbound Process - Enter T4, 0)	Trucks	Trucks currently processing at T4 inbound gate
Trucks Processing at Gate T4 Outbound	INTEG (Start T4 Gate Outbound Process - Depart Gate T4 Outbound, 0)	Trucks	Trucks currently processing at T4 outbound gate
Trucks Processing at Gate T6	INTEG (Start Gate T6 Inbound Process - Enter T6, 0)	Trucks	Trucks currently processing at T6 inbound gate
Trucks Processing at Gate T6 Outbound	INTEG (Start T6 Gate Outbound Process - Depart Gate T6 Outbound, 0)	Trucks	Trucks currently processing at T6 outbound gate
Trucks Processing at Gate T8	INTEG (Start Gate T8 Inbound Process - Enter T8, 0)	Trucks	Trucks currently processing at T8 inbound gate
Trucks Processing at Gate T8 Outbound	INTEG (Start T8 Gate Outbound Process - Depart Gate T8 Outbound, 0)	Trucks	Trucks currently processing at T8 outbound gate
Trucks Processing at Gate T9	INTEG (Start Gate T9 Inbound Process - Enter T9, 0)	Trucks	Trucks currently processing at T9 inbound gate
Trucks Processing at Gate T9 Outbound	INTEG (Start T9 Gate Outbound Process - Depart Gate T9 Outbound, 0)	Trucks	Trucks currently processing at T9 outbound gate
Trucks Queued at Gate T1 Outbound	INTEG (Start Exit from T1 - Start T1 Gate Outbound Process, 0)	Trucks	Trucks queued for outbound processing at T1
Trucks Queued at Gate T2 Outbound	INTEG (Start Exit from T2 - Start T2 Gate Outbound Process, 0)	Trucks	Trucks queued for outbound processing at T2
Trucks Queued at Gate T3 Outbound	INTEG (Start Exit from T3 - Start T3 Gate Outbound Process, 0)	Trucks	Trucks queued for outbound processing at T3
Trucks Queued at Gate T4 Outbound	INTEG (Start Exit from T4 - Start T4 Gate Outbound Process, 0)	Trucks	Trucks queued for outbound processing at T4
Trucks Queued at Gate T6 Outbound	INTEG (Start Exit from T6 - Start T6 Gate Outbound Process, 0)	Trucks	Trucks queued for outbound processing at T6

Variable Name	Formula/Value	Units	Description
Trucks Queued at Gate T8 Outbound	INTEG (Start Exit from T8 - Start T8 Gate Outbound Process, 0)	Trucks	Trucks queued for outbound processing at T8
Trucks Queued at Gate T9 Outbound	INTEG (Start Exit from T9 - Start T9 Gate Outbound Process, 0)	Trucks	Trucks queued for outbound processing at T9
Trucks Waiting at V2	INTEG (V2 Arrivals - Depart V2 for T1 - ... - Depart V2 for T4, 0)	Trucks	Trucks waiting at entry point V2
Trucks Waiting at V3	INTEG (V3 Arrivals - Depart V3 for T2 - ... - Depart V3 for T9, 0)	Trucks	Trucks waiting at entry point V3

Table I: List of Vensim PLE stock variables function for truck Scenario 1

Flow variables

They represent the rate of change in the system.

Variable Name	Formula/Value	Units	Description
Arrive at Gate T1	Trucks on M Inbound/Time Segment M	Trucks/Hour	Arrival rate of trucks at T1 gate
Arrive at Gate T2 from V2	Trucks on O from V2/Time Segment O	Trucks/Hour	Arrival rate at T2 gate from V2
Arrive at Gate T2 from V3	Trucks on O from V3/Time Segment O	Trucks/Hour	Arrival rate at T2 gate from V3
Arrive at Gate T3 from V2	Trucks on R from V2/Time Segment R	Trucks/Hour	Arrival rate at T3 gate from V2
Arrive at Gate T3 from V3	Trucks on R from V3/Time Segment R	Trucks/Hour	Arrival rate at T3 gate from V3
Arrive at Gate T4 from V2	Truck on S from V2/Time Segment S	Trucks/Hour	Arrival rate at T4 gate from V2
Arrive at Gate T4 from V3	Truck on S from V3/Time Segment S	Trucks/Hour	Arrival rate at T4 gate from V3
Arrive at Gate T6	Trucks on W Inbound/Time Segment W	Trucks/Hour	Arrival rate of trucks at T6 gate
Arrive at Gate T8	Trucks on J Inbound/Time Segment J	Trucks/Hour	Arrival rate of trucks at T8 gate
Arrive at Gate T9	Trucks on L Inbound/Time Segment L	Trucks/Hour	Arrival rate of trucks at T9 gate
Arrive at V2 Exit from N	Trucks on N Outbound/Time Segment N	Trucks/Hour	Rate of trucks arriving at V2 for exit from N
Arrive at V2 for Exit from M	Trucks on M Outbound/Time Segment M	Trucks/Hour	Rate of trucks arriving at V2 for exit from M

Variable Name	Formula/Value	Units	Description
Arrive at V3 Exit from U	Trucks on U Outbound/Time Segment U	Trucks/Hour	Rate of trucks arriving at V3 for exit from U
Depart Gate T1 Outbound	MIN (Trucks Processing at Gate T1 Outbound / Time at Gate T1, MAX (0, Capacity of Segment M - Trucks on M Outbound) / Time at Gate T1)	Trucks/Hour	Departure rate from T1 outbound gate
Depart Gate T2 Outbound	MIN (Trucks Processing at Gate T2 Outbound / Time at Gate T2, MAX (0, Capacity of Segment O - Trucks on O Outbound) / Time at Gate T2)	Trucks/Hour	Departure rate from T2 outbound gate
Depart Gate T3 Outbound	MIN (Trucks Processing at Gate T3 Outbound / Time at Gate T3, MAX (0, Capacity of Segment R - Trucks on R Outbound) / Time at Gate T3)	Trucks/Hour	Departure rate from T3 outbound gate
Depart Gate T4 Outbound	MIN (Trucks Processing at Gate T4 Outbound / Time at Gate T4, MAX (0, Capacity of Segment S - Trucks on S Outbound) / Time at Gate T4)	Trucks/Hour	Departure rate from T4 outbound gate
Depart Gate T6 Outbound	MIN (Trucks Processing at Gate T6 Outbound / Time at Gate T6, MAX (0, Capacity of Segment W - Trucks on W Outbound) / Time at Gate T6)	Trucks/Hour	Departure rate from T6 outbound gate
Depart Gate T8 Outbound	MIN (Trucks Processing at Gate T8 Outbound / Time at Gate T8, MAX (0, Capacity of Segment J - Trucks on J Outbound) / Time at Gate T8)	Trucks/Hour	Departure rate from T8 outbound gate
Depart Gate T9 Outbound	MIN (Trucks Processing at Gate T9 Outbound / Time at Gate T9, MAX (0, Capacity of Segment L - Trucks on L Outbound) / Time at Gate T9)	Trucks/Hour	Departure rate from T9 outbound gate
Depart J for V Outbound	MIN (Trucks on J Outbound / Time Segment J, MAX (0, Capacity of Segment V - Trucks on V Outbound) / Unit Aux)	Trucks/Hour	Departure rate from J towards V (outbound)
Depart K	Trucks on K Inbound/Time Segment K	Trucks/Hour	Departure rate from segment K

Variable Name	Formula/Value	Units	Description
Depart K for L	$\text{MIN (Depart K * Prob T9 from V3 / Prob K Split, MAX (0, Capacity of Segment L - Trucks on L Inbound) / Unit Aux)}$	Trucks/Hour	Departure rate from K towards L
Depart K for V Outbound	$\text{MIN (Trucks on K Outbound / Time Segment K, MAX (0, Capacity of Segment V - Trucks on V Outbound) / Unit Aux)}$	Trucks/Hour	Departure rate from K towards V (outbound)
Depart K for W	$\text{MIN (Depart K * Prob T6 from V3 / Prob K Split, MAX (0, Capacity of Segment W - Trucks on W Inbound) / Unit Aux)}$	Trucks/Hour	Departure rate from K towards W
Depart L for K Outbound	$\text{MIN (Trucks on L Outbound / Time Segment L, MAX (0, Capacity of Segment K - Trucks on K Outbound) / Unit Aux)}$	Trucks/Hour	Departure rate from L towards K (outbound)
Depart N	Trucks on N Inbound/Time Segment N	Trucks/Hour	Departure rate from segment N
Depart N for O	$\text{MIN (Depart N * Prob T2 from V2 / Prob N Split, MAX (0, Capacity of Segment O - Total Occupancy of O) / Unit Aux)}$	Trucks/Hour	Departure rate from N towards O
Depart N for P	$\text{MIN (Depart N * (Prob T3 from V2 + Prob T4 from V2) / Prob N Split, MAX (0, Capacity of Segment P - Total Occupancy of P) / Unit Aux)}$	Trucks/Hour	Departure rate from N towards P
Depart O for N Outbound	$\text{MIN (Depart O Outbound * Prop of T2 Traffic for V2, MAX (0, Capacity of Segment N - Trucks on N Outbound) / Unit Aux)}$	Trucks/Hour	Departure rate from O towards N (outbound)
Depart O for P Outbound	$\text{MIN (Depart O Outbound * (1 - Prop of T2 Traffic for V2), MAX (0, Capacity of Segment P - Trucks on P Outbound for V3) / Unit Aux)}$	Trucks/Hour	Departure rate from O towards P (outbound)
Depart O Outbound	Trucks on O Outbound/Time Segment O	Trucks/Hour	Outbound departure rate from segment O
Depart on Q from V3	Trucks on Q from V3/Time Segment Q	Trucks/Hour	Departure rate from Q originating from V3
Depart P for O from V3	$\text{MIN (Trucks on P from V3 / Time Segment P, MAX (0, Capacity of Segment O - Total Occupancy of O) / Unit Aux)}$	Trucks/Hour	Departure rate from P towards O (from V3 traffic)

Variable Name	Formula/Value	Units	Description
Depart P for Q	$\text{MIN (Depart P from V2 * Prob T4 from V2 / Prob P Split V2, MAX (0, Capacity of Segment Q - Total Occupancy of Q) / Unit Aux)}$	Trucks/Hour	Departure rate from P towards Q
Depart P for R	$\text{MIN (Depart P from V2 * Prob T3 from V2 / Prob P Split V2, MAX (0, Capacity of Segment R - Total Occupancy of R) / Unit Aux)}$	Trucks/Hour	Departure rate from P towards R
Depart P from V2	Trucks on P from V2/Time Segment P	Trucks/Hour	Departure rate from P originating from V2
Depart P Outbound	$\text{MIN (Trucks on P Outbound for V2 / Time Segment P, MAX (0, Capacity of Segment N - Trucks on N Outbound) / Unit Aux)}$	Trucks/Hour	Outbound departure rate from segment P
Depart P Outbound to V3	$\text{MIN (Trucks on P Outbound for V3 / Time Segment P, MAX (0, Capacity of Segment Q - Trucks on Q Outbound to V3) / Unit Aux)}$	Trucks/Hour	Outbound departure rate from P towards V3
Depart Q for P from V3	$\text{MIN (Depart on Q from V3 * Prob T2 from V3 / Prob Q Split V3, MAX (0, Capacity of Segment P - Total Occupancy of P) / Unit Aux)}$	Trucks/Hour	Departure rate from Q towards P (from V3 traffic)
Depart Q for P Outbound	$\text{MIN (Trucks on Q Outbound / Time Segment Q, MAX (0, Capacity of Segment P - Trucks on P Outbound for V2) / Unit Aux)}$	Trucks/Hour	Departure rate from Q towards P (outbound)
Depart Q for R from V3	$\text{MIN (Depart on Q from V3 * Prob T3 from V3 / Prob Q Split V3, MAX (0, Capacity of Segment R - Total Occupancy of R) / Unit Aux)}$	Trucks/Hour	Departure rate from Q towards R (from V3 traffic)
Depart Q for S from V2	$\text{MIN (Trucks on Q from V2 / Time Segment Q, MAX (0, Capacity of Segment S - Total Occupancy of S) / Unit Aux)}$	Trucks/Hour	Departure rate from Q towards S (from V2 traffic)
Depart Q Outbound to V3	$\text{MIN (Trucks on Q Outbound to V3 / Time Segment Q, MAX (0, Capacity of Segment T - Trucks on T Outbound to V3) / Unit Aux)}$	Trucks/Hour	Outbound departure rate from Q towards V3
Depart R for P Outbound	$\text{MIN (Depart R Outbound * Prop of T3 Traffic for V2, MAX (0, Capacity of Segment P - Trucks on P Outbound for V2) / Unit Aux)}$	Trucks/Hour	Departure rate from R towards P (outbound)

Variable Name	Formula/Value	Units	Description
Depart R for Q Outbound	$\text{MIN (Depart R Outbound} * (1 - \text{Prop of T3 Traffic for V2}), \text{MAX (0, Capacity of Segment Q - Trucks on Q Outbound to V3) / Unit Aux)}$	Trucks/Hour	Departure rate from R towards Q (outbound)
Depart R Outbound	Trucks on R Outbound/Time Segment R	Trucks/Hour	Outbound departure rate from segment R
Depart S for Q Outbound	$\text{MIN (Depart S Outbound} * \text{Prop of T4 Traffic for V2}, \text{MAX (0, Capacity of Segment Q - Trucks on Q Outbound) / Unit Aux)}$	Trucks/Hour	Departure rate from S towards Q (outbound)
Depart S for T Outbound	$\text{MIN (Depart S Outbound} * (1 - \text{Prop of T4 Traffic for V2}), \text{MAX (0, Capacity of Segment T - Trucks on T Outbound to V3) / Unit Aux)}$	Trucks/Hour	Departure rate from S towards T (outbound)
Depart S Outbound	Trucks on S Outbound/Time Segment S	Trucks/Hour	Outbound departure rate from segment S
Depart T	Trucks on T Inbound/Time Segment T	Trucks/Hour	Departure rate from segment T
Depart T for Q	$\text{MIN (Depart T} * (\text{Prob T2 from V3} + \text{Prob T3 from V3}) / \text{Prob T Split}, \text{MAX (0, Capacity of Segment Q - Total Occupancy of Q) / Unit Aux)}$	Trucks/Hour	Departure rate from T towards Q
Depart T for S	$\text{MIN (Depart T} * \text{Prob T4 from V3} / \text{Prob T Split}, \text{MAX (0, Capacity of Segment S - Total Occupancy of S) / Unit Aux)}$	Trucks/Hour	Departure rate from T towards S
Depart T Outbound to V3	$\text{MIN (Trucks on T Outbound to V3} / \text{Time Segment T}, \text{MAX (0, Capacity of Segment U - Trucks on U Outbound) / Unit Aux)}$	Trucks/Hour	Outbound departure rate from T towards V3
Depart U	Trucks on U Inbound/Time Segment U	Trucks/Hour	Departure rate from segment U
Depart U for T	$\text{MIN (Depart U} * (\text{Prob T2 from V3} + \text{Prob T3 from V3} + \text{Prob T4 from V3}), \text{MAX (0, Capacity of Segment T - Trucks on T Inbound) / Unit Aux)}$	Trucks/Hour	Departure rate from U towards T
Depart U for V	$\text{MIN (Depart U} * (\text{Prob T6 from V3} + \text{Prob T8 from V3} + \text{Prob T9 from V3}), \text{MAX (0,}$	Trucks/Hour	Departure rate from U towards V

Variable Name	Formula/Value	Units	Description
	Capacity of Segment V - Trucks on V Inbound) / Unit Aux)		
Depart V	Trucks on V Inbound/Time Segment V	Trucks/Hour	Departure rate from segment V
Depart V for U Outbound	MIN (Trucks on V Outbound / Time Segment V, MAX (0, Capacity of Segment U - Trucks on U Outbound) / Unit Aux)	Trucks/Hour	Departure rate from V towards U (outbound)
Depart V to J	MIN (Depart V * Prob T8 from V3 / Prob V Split, MAX (0, Capacity of Segment J - Trucks on J Inbound) / Unit Aux)	Trucks/Hour	Departure rate from V towards J
Depart V to K	MIN (Depart V * (Prob T6 from V3 + Prob T9 from V3) / Prob V Split, MAX (0, Capacity of Segment K - Trucks on K Inbound) / Unit Aux)	Trucks/Hour	Departure rate from V towards K
Depart V2 for T1	MIN ((Trucks Waiting at V2/Unit Aux) * Prob T1 from V2, MAX (0, Capacity of Segment M - Trucks on M Inbound) / Unit Aux)	Trucks/Hour	Departure rate from V2 towards T1
Depart V2 for T2	MIN ((Trucks Waiting at V2/Unit Aux) * Prob T2 from V2, MAX (0, Capacity of Segment N - Trucks on N Inbound) / Unit Aux)	Trucks/Hour	Departure rate from V2 towards T2
Depart V2 for T3	MIN ((Trucks Waiting at V2/Unit Aux) * Prob T3 from V2, MAX (0, Capacity of Segment N - Trucks on N Inbound) / Unit Aux)	Trucks/Hour	Departure rate from V2 towards T3
Depart V2 for T4	MIN ((Trucks Waiting at V2/Unit Aux) * Prob T4 from V2, MAX (0, Capacity of Segment N - Trucks on N Inbound) / Unit Aux)	Trucks/Hour	Departure rate from V2 towards T4
Depart V3 for T2	MIN ((Trucks Waiting at V3/Unit Aux) * Prob T2 from V3, MAX (0, Capacity of Segment U - Trucks on U Inbound) / Unit Aux)	Trucks/Hour	Departure rate from V3 towards T2
Depart V3 for T3	MIN ((Trucks Waiting at V3/Unit Aux) * Prob T3 from V3, MAX (0, Capacity of	Trucks/Hour	Departure rate from V3 towards T3

Variable Name	Formula/Value	Units	Description
	Segment U - Trucks on U Inbound) / Unit Aux)		
Depart V3 for T4	MIN ((Trucks Waiting at V3/Unit Aux) *Prob T4 from V3, MAX (0, Capacity of Segment U - Trucks on U Inbound) / Unit Aux)	Trucks/Hour	Departure rate from V3 towards T4
Depart V3 for T6	MIN ((Trucks Waiting at V3/Unit Aux) *Prob T6 from V3, MAX (0, Capacity of Segment U - Trucks on U Inbound) / Unit Aux)	Trucks/Hour	Departure rate from V3 towards T6
Depart V3 for T8	MIN ((Trucks Waiting at V3/Unit Aux) *Prob T8 from V3, MAX (0, Capacity of Segment U - Trucks on U Inbound) / Unit Aux)	Trucks/Hour	Departure rate from V3 towards T8
Depart V3 for T9	MIN ((Trucks Waiting at V3/Unit Aux) *Prob T9 from V3, MAX (0, Capacity of Segment U - Trucks on U Inbound) / Unit Aux)	Trucks/Hour	Departure rate from V3 towards T9
Depart W for K Outbound	MIN (Trucks on W Outbound / Time Segment W, MAX (0, Capacity of Segment K - Trucks on K Outbound) / Unit Aux)	Trucks/Hour	Departure rate from W towards K (outbound)
Enter T1	MIN (Trucks Processing at Gate T1 / Time at Gate T1, MAX (0, Capacity of T1 Ops - Trucks in T1) / Time at Gate T1)	Trucks/Hour	Rate of entering T1 operations area
Enter T2	MIN (Trucks Processing at Gate T2 / Time at Gate T2, MAX (0, Capacity of T2 Ops - Trucks in T2) / Time at Gate T2)	Trucks/Hour	Rate of entering T2 operations area
Enter T3	MIN (Trucks Processing at Gate T3 / Time at Gate T3, MAX (0, Capacity of T3 Ops - Trucks in T3) / Time at Gate T3)	Trucks/Hour	Rate of entering T3 operations area
Enter T4	MIN (Trucks Processing at Gate T4 / Time at Gate T4, MAX (0, Capacity of T4 Ops - Trucks in T4) / Time at Gate T4)	Trucks/Hour	Rate of entering T4 operations area
Enter T6	MIN (Trucks Processing at Gate T6 / Time at Gate T6, MAX (0, Capacity of T6 Ops - Trucks in T6) / Time at Gate T6)	Trucks/Hour	Rate of entering T6 operations area

Variable Name	Formula/Value	Units	Description
Enter T8	MIN (Trucks Processing at Gate T8 / Time at Gate T8, MAX (0, Capacity of T8 Ops - Trucks in T8) / Time at Gate T8)	Trucks/Hour	Rate of entering T8 operations area
Enter T9	MIN (Trucks Processing at Gate T9 / Time at Gate T9, MAX (0, Capacity of T9 Ops - Trucks in T9) / Time at Gate T9)	Trucks/Hour	Rate of entering T9 operations area
Start Exit from T1	Trucks in T1/Time in T1	Trucks/Hour	Rate of trucks beginning to exit T1 operations
Start Exit from T2	Trucks in T2/Time in T2	Trucks/Hour	Rate of trucks beginning to exit T2 operations
Start Exit from T3	Trucks in T3/Time in T3	Trucks/Hour	Rate of trucks beginning to exit T3 operations
Start Exit from T4	Trucks in T4/Time in T4	Trucks/Hour	Rate of trucks beginning to exit T4 operations
Start Exit from T6	Trucks in T6/Time in T6	Trucks/Hour	Rate of trucks beginning to exit T6 operations
Start Exit from T8	Trucks in T8/Time in T8	Trucks/Hour	Rate of trucks beginning to exit T8 operations
Start Exit from T9	Trucks in T9/Time in T9	Trucks/Hour	Rate of trucks beginning to exit T9 operations
Start Gate T1 Inbound Process	MIN (Trucks at Gate T1 Inbound / Unit Aux, MAX (0, Capacity of T1 Gate Inbound - Trucks Processing at Gate T1) / Unit Aux)	Trucks/Hour	Rate of starting inbound processing at T1 gate
Start Gate T2 Inbound Process	MIN (Trucks at Gate T2 Inbound / Unit Aux, MAX (0, Capacity of T2 Gate Inbound - Trucks Processing at Gate T2) / Unit Aux)	Trucks/Hour	Rate of starting inbound processing at T2 gate
Start Gate T3 Inbound Process	MIN (Trucks at Gate T3 Inbound / Unit Aux, MAX (0, Capacity of T3 Gate Inbound - Trucks Processing at Gate T3) / Unit Aux)	Trucks/Hour	Rate of starting inbound processing at T3 gate

Variable Name	Formula/Value	Units	Description
Start Gate T4 Inbound Process	MIN (Trucks at Gate T4 Inbound / Unit Aux, MAX (0, Capacity of T4 Gate Inbound - Trucks Processing at Gate T4) / Unit Aux)	Trucks/Hour	Rate of starting inbound processing at T4 gate
Start Gate T6 Inbound Process	MIN (Trucks at Gate T6 Inbound / Unit Aux, MAX (0, Capacity of T6 Gate Inbound - Trucks Processing at Gate T6) / Unit Aux)	Trucks/Hour	Rate of starting inbound processing at T6 gate
Start Gate T8 Inbound Process	MIN (Trucks at Gate T8 Inbound / Unit Aux, MAX (0, Capacity of T8 Gate Inbound - Trucks Processing at Gate T8) / Unit Aux)	Trucks/Hour	Rate of starting inbound processing at T8 gate
Start Gate T9 Inbound Process	MIN (Trucks at Gate T9 Inbound / Unit Aux, MAX (0, Capacity of T9 Gate Inbound - Trucks Processing at Gate T9) / Unit Aux)	Trucks/Hour	Rate of starting inbound processing at T9 gate
Start T1 Gate Outbound Process	IF THEN ELSE (Trucks Processing at Gate T1 Outbound < Capacity of T1 Gate Outbound, Trucks Queued at Gate T1 Outbound / Unit Aux, 0)	Trucks/Hour	Rate of starting outbound processing at T1 gate
Start T2 Gate Outbound Process	IF THEN ELSE (Trucks Processing at Gate T2 Outbound < Capacity of T2 Gate Outbound, Trucks Queued at Gate T2 Outbound / Unit Aux, 0)	Trucks/Hour	Rate of starting outbound processing at T2 gate
Start T3 Gate Outbound Process	IF THEN ELSE (Trucks Processing at Gate T3 Outbound < Capacity of T3 Gate Outbound, Trucks Queued at Gate T3 Outbound / Unit Aux, 0)	Trucks/Hour	Rate of starting outbound processing at T3 gate
Start T4 Gate Outbound Process	IF THEN ELSE (Trucks Processing at Gate T4 Outbound < Capacity of T4 Gate Outbound, Trucks Queued at Gate T4 Outbound /Unit Aux, 0)	Trucks/Hour	Rate of starting outbound processing at T4 gate
Start T6 Gate Outbound Process	IF THEN ELSE (Trucks Processing at Gate T6 Outbound < Capacity of T6 Gate Outbound, Trucks Queued at Gate T6 Outbound /Unit Aux, 0)	Trucks/Hour	Rate of starting outbound processing at T6 gate
Start T8 Gate Outbound Process	IF THEN ELSE (Trucks Processing at Gate T8 Outbound < Capacity of T8 Gate Outbound, Trucks Queued at Gate T8 Outbound /Unit Aux, 0)	Trucks/Hour	Rate of starting outbound processing at T8 gate

Variable Name	Formula/Value	Units	Description
Start T9 Gate Outbound Process	IF THEN ELSE (Trucks Processing at Gate T9 Outbound < Capacity of T9 Gate Outbound, Trucks Queued at Gate T9 Outbound /Unit Aux, 0)	Trucks/Hour	Rate of starting outbound processing at T9 gate
V2 Arrivals	Truck Arrivals at V2	Trucks/Hour	Arrival rate of trucks at entry point V2
V3 Arrivals	Truck Arrivals at V3	Trucks/Hour	Arrival rate of trucks at entry point V3

Table J: List of Vensim PLE flow variables function for truck Scenario 1

Auxiliary variables

These variables are used for intermediate calculations to simplify other equations.

Variable Name	Formula/Value	Units	Description
Prob K Split	Prob T6 from V3 + Prob T9 from V3	Dmnl	Combined probability for splitting traffic at K
Prob N Split	Prob T2 from V2+Prob T3 from V2+Prob T4 from V2	Dmnl	Combined probability for splitting traffic at N
Prob P Split V2	Prob T3 from V2+Prob T4 from V2	Dmnl	Combined probability of splitting traffic at P from V2
Prob Q Split V3	Prob T2 from V3 + Prob T3 from V3	Dmnl	Combined probability for splitting traffic at Q from V3
Prob T Split	Prob T2 from V3 + Prob T3 from V3 + Prob T4 from V3	Dmnl	Combined probability of splitting traffic at T
Prob V Split	Prob T6 from V3 + Prob T8 from V3 + Prob T9 from V3	Dmnl	Combined probability for splitting traffic at V
Total Occupancy of O	Trucks on O from V2 + Trucks on O from V3	Trucks	Total trucks currently on road segment O
Total Occupancy of P	Trucks on P from V2 + Trucks on P from V3	Trucks	Total trucks currently on road segment P
Total Occupancy of Q	Trucks on Q from V3 + Trucks on Q from V2	Trucks	Total trucks currently on road segment Q
Total Occupancy of R	Trucks on R from V3 + Trucks on R from V2	Trucks	Total trucks currently on road segment R

Variable Name	Formula/Value	Units	Description
Total Occupancy of S	Truck on S from V3 + Truck on S from V2	Trucks	Total trucks currently on road segment S

Table K: List of Vensim PLE auxiliary variables function for truck Scenario 1

Lookup tables

Variable Name	Formula/Value	Units	Description
Truck Arrivals at V2	WITH LOOKUP (Custom Time, ((0,0) -(168,23)],))	Trucks/Hour	Time-based arrival pattern of trucks at V2
Truck Arrivals at V3	WITH LOOKUP (Custom Time, ((0,0) -(168,60)],))	Trucks/Hour	Time-based arrival pattern of trucks at V3

Table L: List of Vensim PLE lookup functions for truck Scenario 1

3.3.6. Validation and calibration

In order to validate the model and evaluate its dynamic behavior under intense but plausible load conditions, a controlled impulse test was conducted. The objective of this test was to assess the model's response to conditions and see how it reacted and to adjust, if necessary, in order to fulfill all constraints and logical needs. The experiment involved introducing a known volume of traffic for each of the two main entrances for duration of one hour as explained below:

- Impulse magnitude: equal to 100 trucks/hour for each of the two main entrances (V2 and V3)
- Impulse duration: 1 hour
- Timing: hour 50 of the simulation.

This validation will be further discussed in the results section as it allows to understand better how quickly congestion forms and dissipates in the system.

3.3.7. Scenarios modeled

In order to evaluate the impact of changes, growth, disruptions or other changing factors in the model, several scenarios have been considered.

Scenario	Case	Description
Scenario 1	Baseline performance	Two port gates (V2 and V3), normal traffic conditions

Scenario	Case	Description
Scenario 2	Infrastructure expansion	Three port gates (V2, V3 and V4), normal traffic conditions
Scenario 3	Demand growth	Two port gates (V2 and V3), intense traffic conditions (+1000 trucks/week)
Scenario 4	Network disruption	Two port gates (V2 and V3), normal traffic conditions, closure of segment V for 2 hours on Thursday afternoon due to an accident
Scenario 4bis	Terminal disruption	Two port gates (V2 and V3), normal traffic conditions, and the closure of terminal T2 for 12 hours on Thursday afternoon due to an accident.
Scenario 5	Slow down	Two port gates (V2 and V3), normal traffic conditions, speed reduction of 50% due to bad weather conditions.

Table M: Scenarios for Road network model

Scenario 1 (Base Scenario): Two port gates

The base scenario is developed under the logic presented before by loading the system with normal traffic conditions and allowing only entrance of traffic through port gates V2 and V3 as shown above.

Scenario 2: Three port gates

To evaluate potential improvement, this alternative scenario was developed. This scenario introduces a third entry/exit gate, V4, which serves as a dedicated access point exclusively for Terminal 8.

- **Changes in physical layout and operational rules**

In this scenario, the physical layout is altered as shown on Figure 12:

- A new gate, V4, is added to the system.
- Terminal 8 is disconnected from the main road network (specifically from segment 'V') and is now connected directly to V4 via road segment 'I'.
- All other terminals and road segments remain connected as in the base scenario.

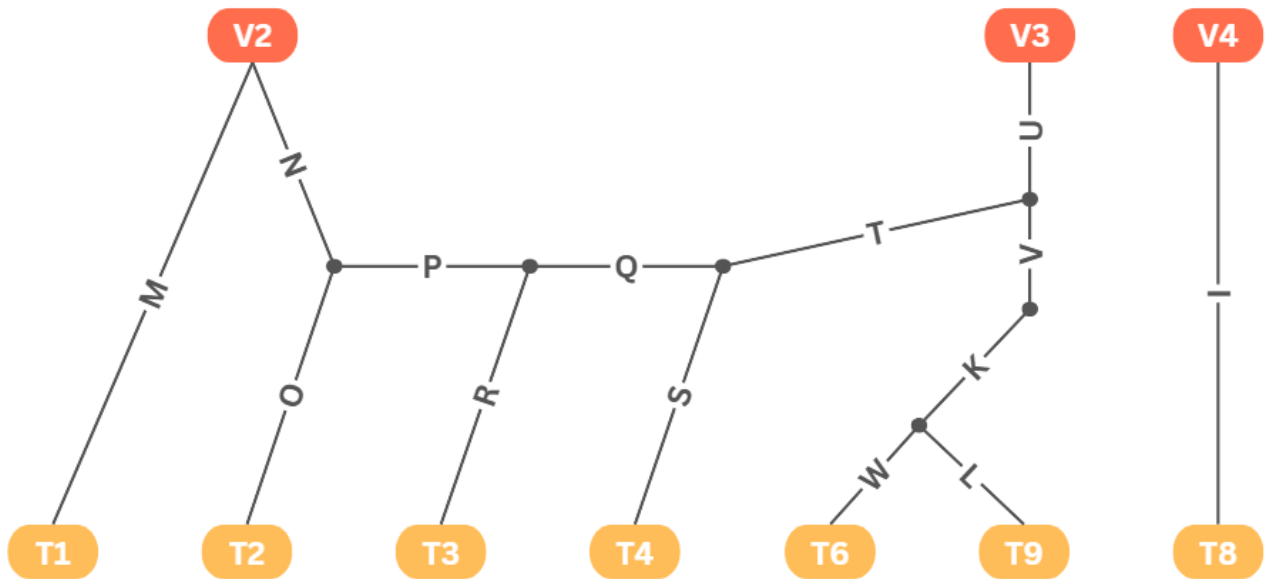


Figure 12: Schematized Road network for Scenario 2

This change modifies the operational rules:

- All traffic destined for Terminal 8 must now enter and exit through V4.
- Terminal 8 is no longer accessible from V3. Consequently, the traffic distribution from V3 is re-allocated among the remaining six terminals.
- **Simulation parameters for Scenario 2**

Adjusting the model for the alternative scenario also altered the behavior of the probabilistic routing mechanism.

Entrance	Terminal	Probability
<i>[-]</i>	<i>[-]</i>	<i>[%]</i>
V2	T1	55%
	T2	15%
	T3	15%
	T4	15%
V3	T2	34%
	T3	9%
	T4	13%
	T6	22%
	T9	22%
V4	T8	100%

Table N: Proportion of arrivals for road terminals for Scenario 2

The other global parameters were considered the same as Scenario 1.

The total weekly arrivals for Scenario 2 are implemented in the model through *some Lookup functions*, and they are presented in the graph below.

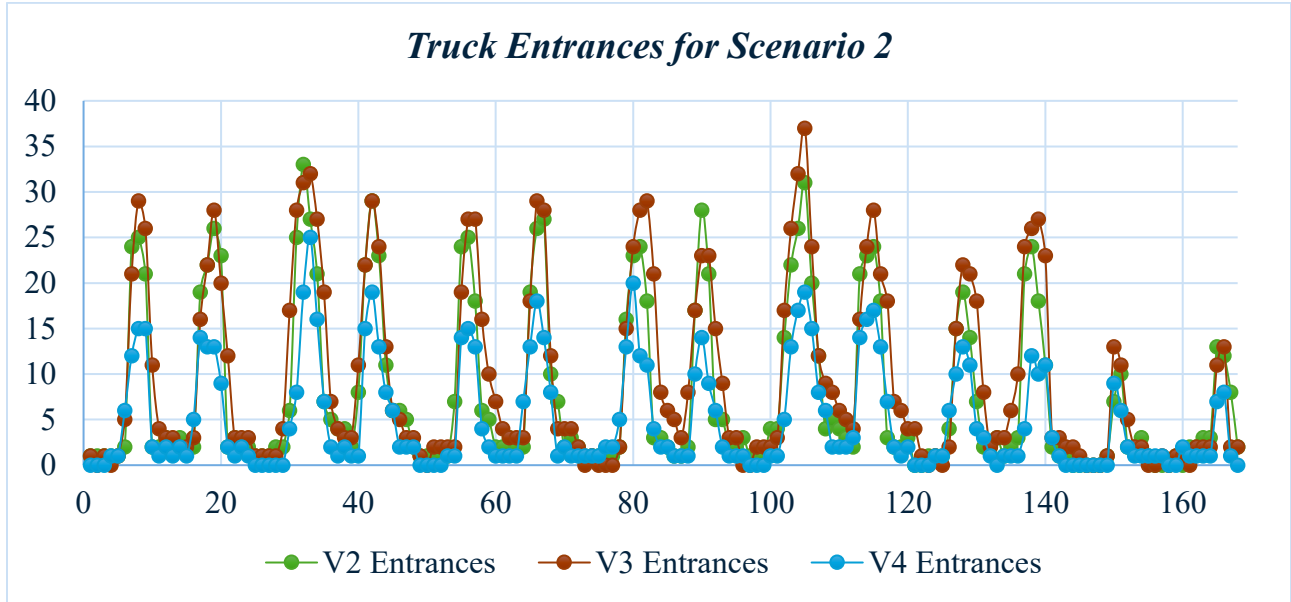


Figure 13: Truck entrances for Scenario 2

- **Model variables and equations**

To adapt the model for Scenario 2, the following variables were added, modified, or canceled. All other equations remain as defined in the base scenario. (Table P, Table Q and Table R)

New Parameters and Constants			
Variable Name	New Equation	Units	Description
Capacity of Segment I	33	Trucks	Road capacity of segment I
Time Segment I	8/60	Hour	Travel time for segment I
V4 Arrivals	Truck Arrivals at V4	Trucks/Hour	Total truck arrivals at entry point V4
Prob T1 from V2	0.55	Dmnl	Probability of traffic from V2 going to T1
Prob T2 from V2	0.15	Dmnl	Probability of traffic from V2 going to T2
Prob T2 from V3	0.34	Dmnl	Probability of traffic from V3 going to T2

New Parameters and Constants			
Variable Name	New Equation	Units	Description
Prob T3 from V2	0.15	Dmnl	Probability of traffic from V2 going to T3
Prob T3 from V3	0.09	Dmnl	Probability of traffic from V3 going to T3
Prob T4 from V2	0.15	Dmnl	Probability of traffic from V2 going to T4
Prob T4 from V3	0.13	Dmnl	Probability of traffic from V3 going to T4
Prob T6 from V3	0.22	Dmnl	Probability of traffic from V3 going to T6
Prob T8 from V3	0.22	Dmnl	Probability of traffic from V3 going to T8
Prop of T2 Traffic for V2	0.306	Dmnl	Proportion of T2 outbound traffic destined for V2
Prop of T3 Traffic for V2	0.625	Dmnl	Proportion of T3 outbound traffic destined for V2
Prop of T4 Traffic for V2	0.536	Dmnl	Proportion of T4 outbound traffic destined for V2

Table O: List of Vensim PLE parameters and constants for truck Scenario 2

New Stocks			
Variable Name	New Equation	Units	Description
Trucks Waiting at V4	INTEG (V4 Arrivals - Depart V4 to T8, 0)	Trucks	Queue of trucks waiting at entry point V4
Trucks on I Inbound	INTEG (Depart V4 to T8 - Arrive at Gate T8, 0)	Trucks	Number of trucks on segment I (inbound)
Trucks on I Outbound	INTEG (Depart Gate T8 Outbound - Arrive at V4 Exit from I, 0)	Trucks	Number of trucks on segment I (outbound)
Trucks Exited via V4	INTEG (Arrive at V4 Exit from I, 0)	Trucks	Total trucks that have exited through V4
Modified Stocks			
Variable Name	New, Modified, or Canceled Equation	Units	Description
Trucks on U Inbound	INTEG (Depart V3 for T2 + Depart V3 for T3 + Depart V3 for T4 + Depart V3 for T6 + Depart V3 for T9 - Depart U, 0)	Trucks	Number of trucks on segment U (inbound)
Trucks on V Outbound	INTEG (Depart K for V Outbound - Depart V for U Outbound, 0)	Trucks	Number of trucks on segment V (outbound)
Trucks Waiting at V3	INTEG (V3 Arrivals - Depart V3 for T2 - Depart V3 for T3 - Depart V3	Trucks	Queue of trucks waiting at entry point V3

	for T4 - Depart V3 for T6 - Depart V3 for T9, 0)		
--	--	--	--

Table P: List of Vensim PLE stock variables function for truck Scenario 2

New Flows			
Variable Name	New Equation	Units	Description
Depart V4 to T8	MIN (Trucks Waiting at V4 / Unit Aux, MAX (0, Capacity of Segment I - Trucks on I Inbound) / Unit Aux)	Trucks/Hour	Departure rate from V4 towards T8
Arrive at V4 Exit from I	Trucks on I Outbound / Time Segment I	Trucks/Hour	Arrival rate at V4 exit from segment I
Modified Flows & Auxiliaries			
Variable Name	New, Modified, or Canceled Equation	Units	Description
Arrive at Gate T8	Trucks on I Inbound / Time Segment I	Trucks/Hour	Arrival rate at Gate T8
Depart Gate T8 Outbound	MIN (Trucks Processing at Gate T8 Outbound / Time at Gate T8, MAX (0, Capacity of Segment I - Trucks on I Outbound) / Time at Gate T8)	Trucks/Hour	Departure rate from Gate T8 outbound
Prob V Split	Prob T6 from V3 + Prob T9 from V3	Dmnl	Combined probability for split at V
Depart U for V	MIN (Depart U * (Prob T6 from V3 + Prob T9 from V3), MAX (0, Capacity of Segment V - Trucks on V Inbound) / Unit Aux)	Trucks/Hour	Departure rate from segment U towards V

Table Q: List of Vensim PLE flow and auxiliary variables function for truck Scenario 2

Canceled Variables	
Depart V3 for T8	<i>This flow is deleted from the model</i>
Prob T8 from V3	<i>This parameter is deleted from the model</i>
Depart V to J	<i>This flow is deleted from the model</i>
Trucks on J Inbound	<i>This stock is deleted from the model</i>
Trucks on J Outbound	<i>This stock is deleted from the model</i>
Depart J for V Outbound	<i>This flow is deleted from the model</i>

Table R: List of Vensim PLE canceled variables for truck Scenario 2

Scenario 3: Heavy traffic conditions

Starting from the basic configuration of the base scenario, Scenario 3 was developed to assess the resilience and behavior of the system under stress. The primary objective of this scenario is to determine how the road network reacts to a significant increase in traffic load and to identify the threshold beyond which new bottlenecks appear.

This methodology allows to isolate the effect of the traffic increase alone on system performance.

- **Changes in physical layout, operational rules, and simulation parameters**

The network layout, terminal accessibility, and operating rules are the same as in Scenario 1. The only change is in the input data, specifically the arrival rates of trucks at gates V2 and V3.

- The total number of weekly arrivals has been increased by 1000 units from the normal traffic conditions.
- To maintain realistic flow patterns, the increase has been distributed proportionally between the two gates, preserving the original traffic ratio.

The total weekly arrivals for Scenario 3 are implemented in the model through *some Lookup functions*, and they are presented in the table below.

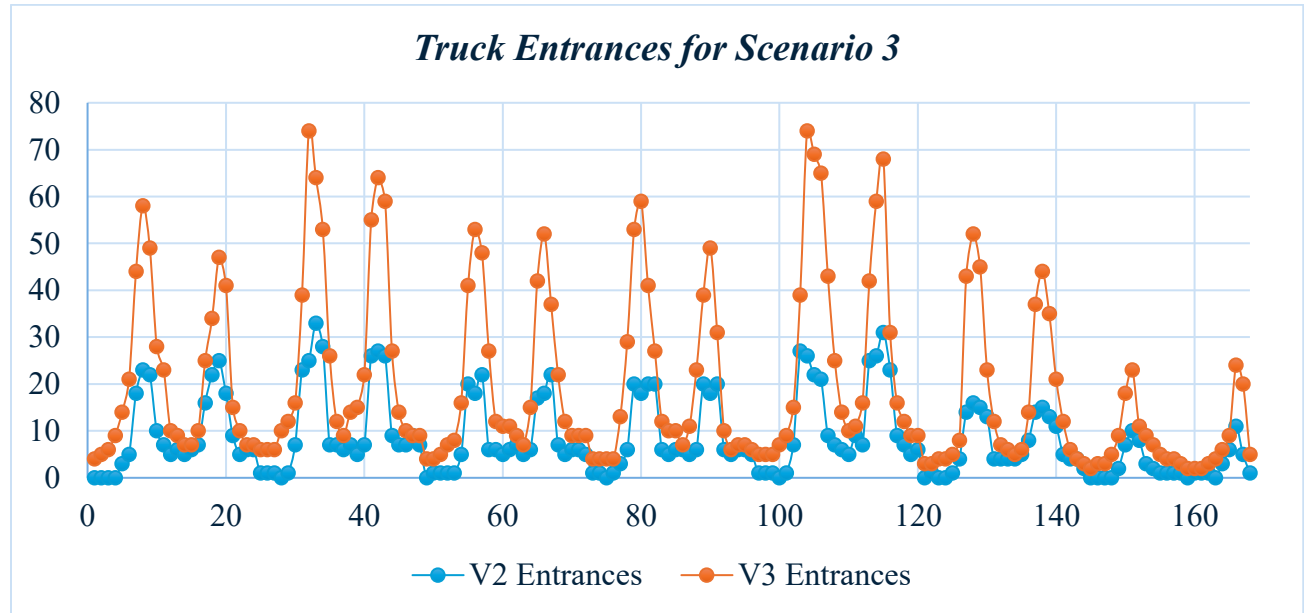


Figure 14: Truck entrances for Scenario 3

All other simulation parameters, including segment capacities, terminal capacities, and process times, remain unchanged from Scenario 1.

Scenario 4: Road network disruption

Scenario 4 was designed to test the robustness of the system and its ability to recover following an unexpected event. This scenario simulates an accident that causes the temporary closure of a critical artery of the network, segment V, while maintaining the normal traffic conditions of Scenario 1. The objective is to analyze the propagation of congestion and measure the time it takes for queues to dissipate once operations are restored. (Figure 15)

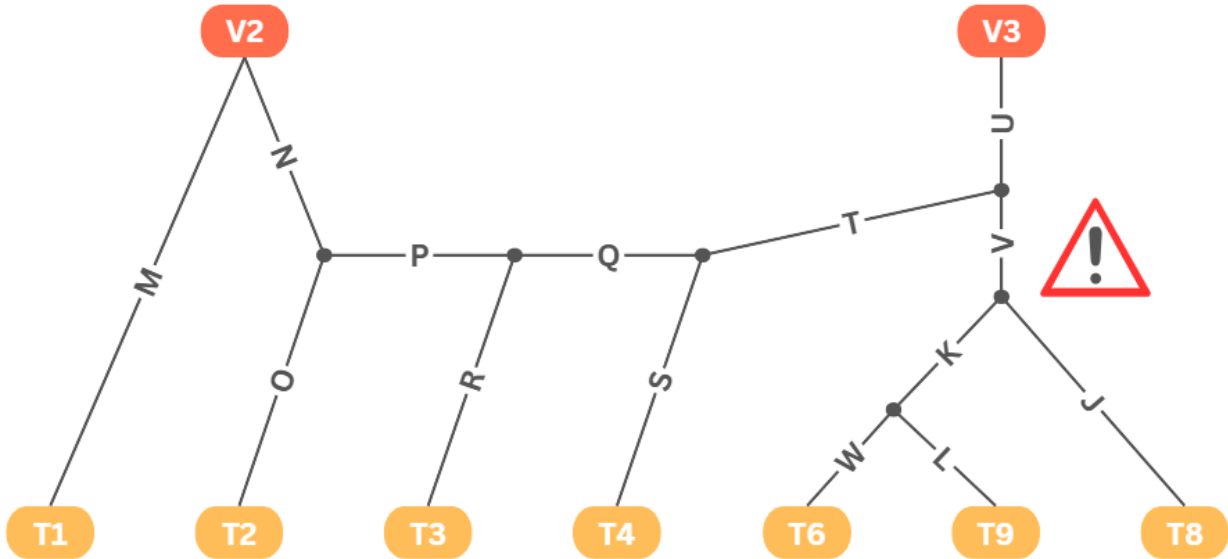


Figure 15: Schematized Road network for Scenario 4

In particular, the analysis of this variant focuses on quantifying the queues that form prior to the blockage (especially in segment U and at gate V3), the impact that this blockage has on accessibility to terminals T6, T8, and T9, and the dynamics with which the system clears the accumulated congestion after the segment reopens.

- **Changes in physical layout, operational rules, and simulation parameters**

The physical configuration and weekly traffic volumes are the same as in the base scenario. The key change is the introduction of a dynamic and temporary interruption of a model parameter.

- The complete, bidirectional closure of segment V was simulated for a duration of two hours.
- The incident was scheduled for Thursday afternoon, with the closure beginning at hour 88 and ending at hour 90 of the simulation.

To achieve this event, the Capacity of Segment V variable was modified using a *lookup function* dependent on the Custom Time variable. During the specified time interval, the segment capacity was set to 0, effectively preventing any transit. Outside this interval, the capacity is maintained at its nominal value of 43 trucks.

Variable Name	Formula/Value	Units	Description
Capacity of Segment V	WITH LOOKUP (Custom Time, $[(0,0) - (168,43)],)$)	Trucks	Time-based capacity pattern of trucks for segment V

Table S: List of Vensim PLE updated functions for truck Scenario 4

Scenario 4bis: Terminal disruption

This scenario is designed to evaluate the system's response to a significant internal bottleneck, distinct from the network-level disruption in Scenario 4. It simulates the complete closure of Terminal T2 for a continuous period of 12 hours on a Thursday afternoon. (Figure 16)

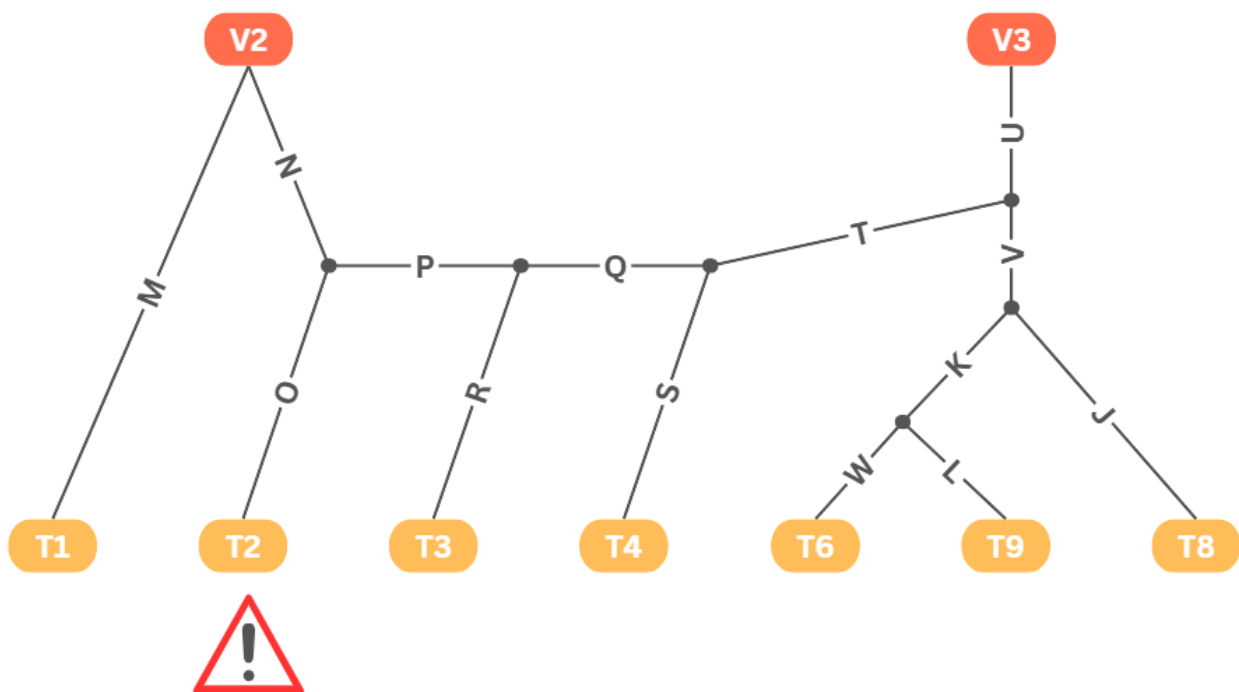


Figure 16: Schematized Road network for Scenario 4bis

As Terminal T2 is a key shared resource accessible from both port gates, this test is designed to measure the upstream impact of a critical processing node becoming unavailable and to evaluate the system's ability to recover from a prolonged internal failure.

- **Changes in physical layout, operational rules, and simulation parameters**

The physical configuration and weekly traffic volumes are again the same as in the base scenario. The main difference, like in Scenario 4, is the introduction of a dynamic and temporary interruption of a model parameter.

- The complete closure of Terminal 2 was simulated for a duration of twelve hours.
- The incident was scheduled for Thursday afternoon, with the closure beginning at hour 84 and ending at hour 96 of the simulation.

To achieve this event, the Capacity of T2 Ops variable was modified using a *lookup function* dependent on the Custom Time variable. During the specified time interval, the segment capacity was set to 0, effectively preventing any transit. Outside this interval, the capacity is maintained at its nominal value. (Table T)

Variable Name	Formula/Value	Units	Description
Capacity of T2 Ops	WITH LOOKUP (Custom Time, ((0,0) -(168, max)],))	Trucks	Time-based pattern of operations capacity of terminal T2

Table T: List of Vensim PLE updated functions for truck Scenario 4bis

Scenario 5: System slowdown due to adverse weather

This scenario models the impact of a global, systemic degradation of operational efficiency, such as that caused by adverse weather conditions. Rather than a localized failure, this scenario assumes that all truck movements are impaired. This allows for an analysis of the system's sensitivity to widespread slowdowns, testing how overall productivity, throughput, and congestion levels are affected when the entire network is operating at a reduced capacity under normal traffic volumes.

- **Changes in physical layout, operational rules, and simulation parameters**

While the physical configuration and weekly traffic are maintained the same as in the base scenario, a 50% reduction in travel speed is applied to all road segments throughout the network for the entire duration of the simulation, this change doubles the travel time between any two points. Also, the travel times obtained with the 50% increase were then rounded up to the nearest integer to avoid decimals. The updated values for each segment are listed in Table U

Segment	Length	Time	Capacity
<i>[-]</i>	<i>[km]</i>	<i>[min]</i>	<i>[Trucks]</i>
M	0.145	3	8
N	0.703	14	39
O	0.244	5	13
P	0.381	8	21
Q	0.313	6	17
R	0.066	2	3
S	0.161	3	8
T	0.227	5	12
U	0.048	2	2
V	0.777	15	43
K	0.215	5	11
W	0.025	2	1
L	0.341	8	18
J	0.656	12	36

Table U: Length, time, and capacity of road segments for Scenario 5

3.4. Crossings between networks models

After analyzing the road network and importing the results of the model related to the rail network (developed by Daniela Restrepo Ruiz), a third integrated model was developed, capable of providing an overview of all land transport operations in the port. The aim is to move beyond the isolated analysis of the two systems and to investigate the emerging behaviors that result from their interaction.

In particular, this model focuses on analyzing the dynamic conflicts that occur at level crossings (X1, X2, and X3), assessing the impact of giving priority to rail traffic over road traffic, and identifying how localized disruptions can propagate throughout the entire system. By coupling rail and road simulations, it is possible to obtain a more realistic representation of phenomena typical of complex multimodal contexts, such as cascading delays and the formation of prolonged queues.

3.4.1. Model integration methodology

The integration between the two models was achieved by using the outputs of the rail simulation as dynamic inputs for the road model. The core of the process lies in modeling the presence of trains at the three critical crossings and thereby conditioning the road flow according to the rail schedule.

- The occupancy data for the railway segments corresponding to the crossings (segments C, D, and E) were extracted and converted into three lookup table variables: *Train Presence at Crossing X1*, *Train Presence at Crossing X2*, and *Train Presence at Crossing X3*. These variables express at what times during the simulated week a train occupies a given crossing.
- To regulate the passage of heavy vehicles, binary ‘permission’ variables (*Trucks Permission to Cross X1, X2, X3*) were introduced, calculated using an *IF–THEN–ELSE function*. When the probability of a train being present exceeds a pre-set threshold (0.01), the permission variable takes the value 0, preventing transit; otherwise, it remains equal to 1, allowing passage.

The integration of these variables into the flow equations allows the movement of trucks at occupied intersections to be instantly reset to zero, realistically simulating the effect of a temporary closure.

3.4.2. Expected system dynamics

Given the structure of the model, the following dynamics are anticipated:

- Queues are expected to develop immediately upstream of intersections subject to closure, with the most significant occurrences predicted on segment M for X1, segment P for X2, and segment U for X3.
- Locally generated queues may propagate along the network, such as a slowdown at X3 extending to gate V3, increasing the stock of *Trucks Waiting at V3* and affecting all incoming traffic from that gate, regardless of destination.
- Interruptions are likely to reduce the effective capacity of the affected segments, leading to a decrease in overall throughput for the terminals served (T1, T3, and those accessed via V3), with the magnitude of this reduction representing one of the main outputs of the simulation.

3.4.3. Simulation parameters

The simulation is configured with the following global parameters:

- *Time units*: hours
- *Simulation horizon*: 168 hours (one week)
- *Integration timestep (TIME STEP)*: 0.01 hours, to ensure numerical precision and stability with the complex feedback loops.

The total weekly arrivals for trucks are implemented in the model through *some lookup functions*. The distribution is the same as the one adopted for Scenario 1 of the road network model.

3.4.4. Model variables and equations

To adapt the road network model to include the crossing conflicts, new variables were introduced to handle the logic of train presence, and several existing flow equations were modified. All other parameters, stocks, and flows remain as defined in the base road network model.

- **New Parameters and Constants**

These variables introduce the external data from the rail model and translate it into the control logic for the road network. (Table V)

Variable Name	Formula/Value	Units	Description
Train Presence at Crossing X1	WITH LOOKUP (Custom Time, ...)	Dmnl	Time-based lookup table representing the occupancy of the rail segment at crossing X1, taken as input from the rail model.
Train Presence at Crossing X2	WITH LOOKUP (Custom Time, ...)	Dmnl	Time-based lookup table for the occupancy of the rail segment at crossing X2.
Train Presence at Crossing X3	WITH LOOKUP (Custom Time, ...)	Dmnl	Time-based lookup table for the occupancy of the rail segment at crossing X3.
Trucks Permission to Cross X1	IF THEN ELSE (Train Presence at Crossing X1 > 0.01, 0, 1)	Dmnl	A binary switch that is 0 if a train is present at X1 and 1 otherwise.
Trucks Permission to Cross X2	IF THEN ELSE (Train Presence at Crossing X2 > 0.05, 0, 1)	Dmnl	A binary switch that is 0 if a train is present at X2 and 1 otherwise.
Trucks Permission to Cross X3	IF THEN ELSE (Train Presence at Crossing X3 > 0.05, 0, 1)	Dmnl	A binary switch that is 0 if a train is present at X3 and 1 otherwise.

Table V: List of Vensim PLE parameters and constant for the crossings Model

- **Modified Flows**

The following flow equations were modified from the original road network model. The multiplication by the Trucks Permission to Cross variable is the key change that enables the simulation of crossing interruptions. (Table W)

Variable Name	Modified Formula/Value	Units	Description
Arrive at V2 for Exit from M	(Trucks on M Outbound/Time Segment M) * Trucks Permission to Cross X1	Trucks/Hour	Rate of trucks arriving at V2 for exit, now conditional on X1 being clear.
Arrive at V3 Exit from U	(Trucks on U Outbound/Time Segment U) * Trucks Permission to Cross X3	Trucks/Hour	Rate of trucks arriving at V3 for exit, now conditional on X3 being clear.
Depart P for R	MIN(...) * Trucks Permission to Cross X2	Trucks/Hour	Departure rate from P towards R, now conditional on X2 being clear.
Depart R for P Outbound	MIN(...) * Trucks Permission to Cross X2	Trucks/Hour	Outbound departure rate from R towards P, now conditional on X2 being clear.
Depart V2 for T1	MIN(...) * Trucks Permission to Cross X1	Trucks/Hour	Departure rate from V2 towards T1, now conditional on X1 being clear.
Depart V3 for T2	MIN(...) * Trucks Permission to Cross X3	Trucks/Hour	Departure rate from V3 towards T2, now conditional on X3 being clear.
Depart V3 for T3	MIN(...) * Trucks Permission to Cross X3	Trucks/Hour	Departure rate from V3 towards T3, now conditional on X3 being clear.
Depart V3 for T4	MIN(...) * Trucks Permission to Cross X3	Trucks/Hour	Departure rate from V3 towards T4, now conditional on X3 being clear.
Depart V3 for T6	MIN(...) * Trucks Permission to Cross X3	Trucks/Hour	Departure rate from V3 towards T6, now conditional on X3 being clear.
Depart V3 for T8	MIN(...) * Trucks Permission to Cross X3	Trucks/Hour	Departure rate from V3 towards T8, now conditional on X3 being clear.
Depart V3 for T9	MIN(...) * Trucks Permission to Cross X3	Trucks/Hour	Departure rate from V3 towards T9, now conditional on X3 being clear.

Table W: List of Vensim PLE flow variables function for the crossings Model

By implementing these modifications, the integrated model can accurately simulate the stop-and-go dynamics imposed on the road network, allowing for a detailed analysis of throughput reduction and queue propagation caused by rail priority.

3.4.5. Scenarios modeled

To evaluate the impact of rail traffic on the road network under different operational conditions, two distinct scenarios were simulated. In both scenarios, the road network's configuration, and the truck arrival distribution (as shown in Figure 17) remain constant. The sole difference between the

scenarios is the train schedule, which is imported as an external input from the corresponding simulations of the rail network model. This approach allows for the direct isolation and analysis of the effects of rail disruptions on road traffic.

The scenarios taken in consideration are summarized in the table below:

Scenario	Case	Description
Scenario 1	Road + Rail	Base demand for road interrupted by train's flow.
Scenario 2	Road + Rail (adverse weather)	Base demand for road interrupted by train's flow under adverse weather conditions

Table X: Scenarios for Crossing between network models

Scenario 1: Base Conditions

This scenario serves as the baseline for performance analysis, representing the port's landside operations under normal, everyday conditions. The train schedule is derived from the base scenario of the rail network model, which assumes standard train speeds, loading/unloading times, and no unplanned disruptions. The resulting train presence distributions at the three crossings for the simulated week are depicted in the graph below (Figure 17). This schedule reflects the standard operation of the port's rail system.

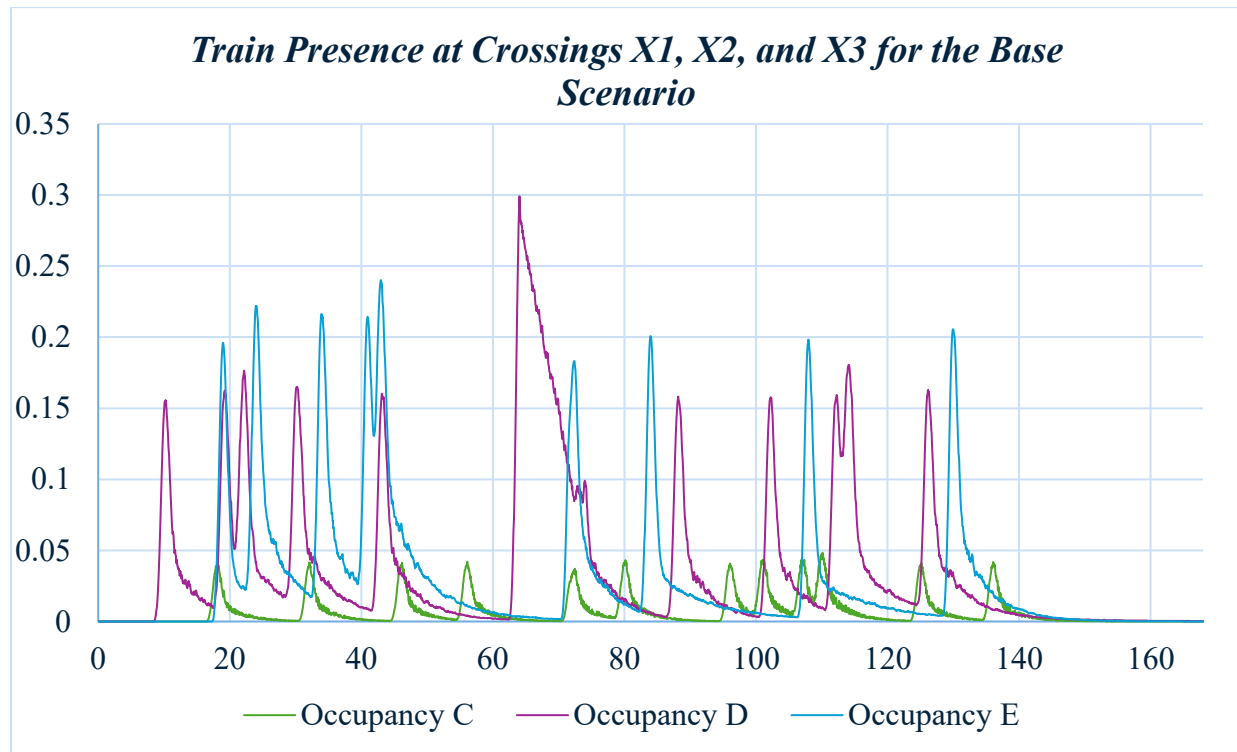


Figure 17: Train Presence at Crossings X1, X2, and X3 for Scenario 1

Scenario 2: Adverse Weather Conditions

This scenario is designed to test the resilience of the port's road network when the rail system is under stress. It simulates the impact of adverse weather conditions, which are assumed to primarily affect the efficiency of rail operations. In the rail network model, this was simulated by increasing the time trains spend at terminals and slightly reducing their travel speed, leading to delays and increased track occupancy for the entire duration of the simulation.

The resulting train schedule is significantly different from the baseline. As shown in Figure 18, the crossings are occupied for longer and more frequent intervals, representing a more disruptive pattern of rail movements. By comparing the results of this scenario to the baseline, it is possible to quantify the cascading effects of rail delays on truck queues, waiting times, and overall terminal throughput.

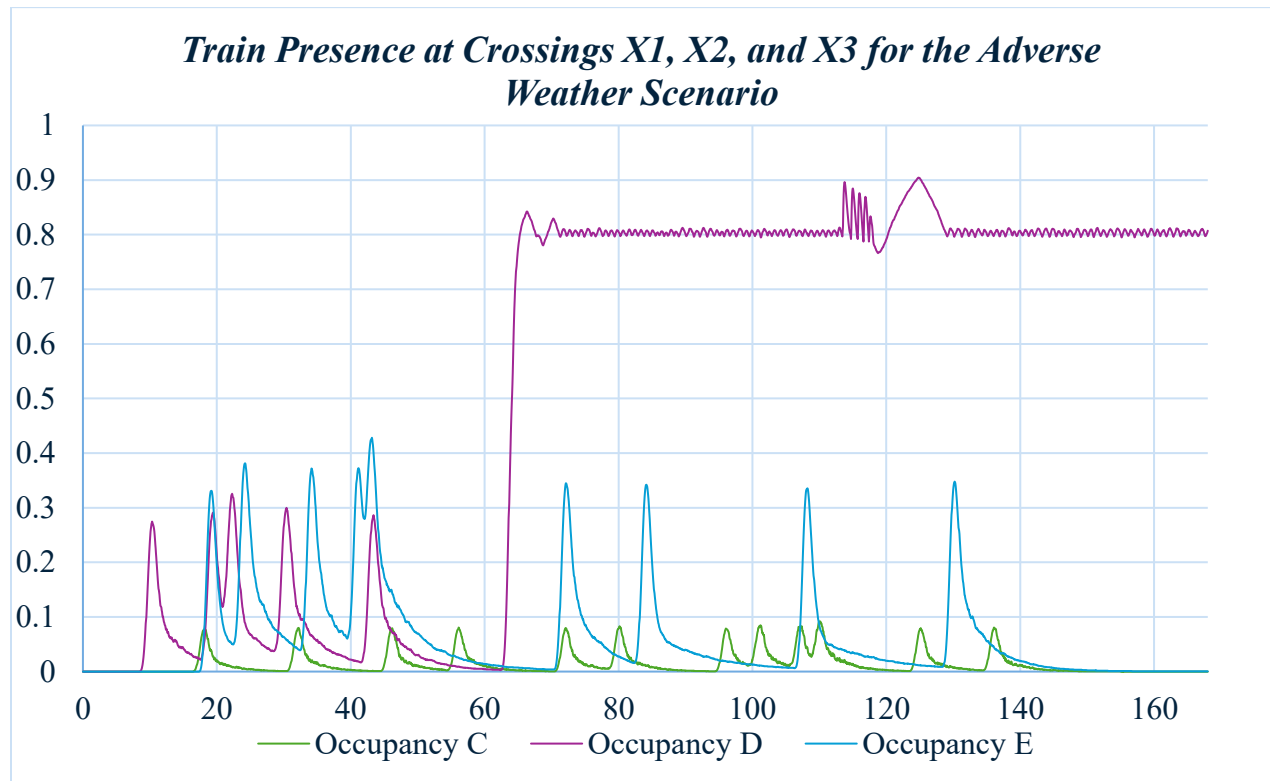


Figure 18: Train Presence at Crossings X1, X2, and X3 for Scenario 2

4. Results

4.1. Model validation

To verify the model's logical consistency and structural integrity, a controlled impulse test was performed. The test involved injecting a high-volume, short-duration pulse of 100 trucks per hour for one hour at each of the two main entrances (V2 and V3). The objective was to assess the model's response to stress and confirm that all entities were conserved throughout the simulation. The results confirmed the structural integrity of the model. The entire traffic pulse was processed without permanent blockages, and all 200 trucks introduced were correctly recorded at their respective exits. As shown in Figure 19, the model demonstrated a perfect separation of flows for an uncongested network: vehicles that entered from V2 exited from V2, and likewise for V3.

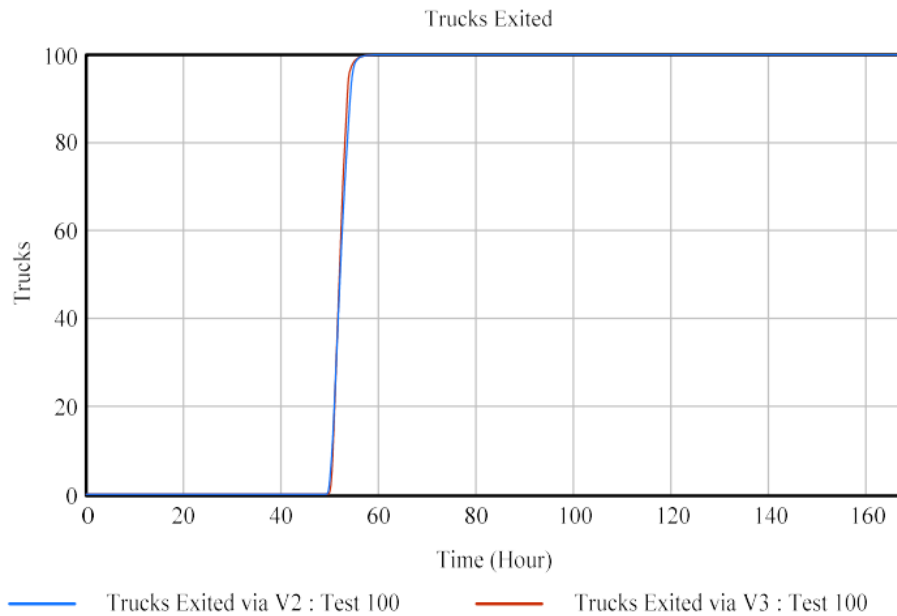


Figure 19: Trucks exited for validation

A deeper analysis of the model's behavior revealed that this flow separation is not governed by explicit rules but is an emergent property arising from the network's structural asymmetry:

- Entrance V2: wide access gate, with immediate division of the flow into two segments (M and N) with a total initial capacity of 47 slots.

- Entrance V3: access funnel that channels all traffic into Segment U alone, characterized by a critical capacity of 2 slots.

This initial bottleneck in V3 causes a marked slowdown in traffic flow, altering the arrival times at shared terminals compared to vehicles coming from V2. This time difference triggers congestion downstream, particularly on specific exit routes, like the one coming from Terminal T2.

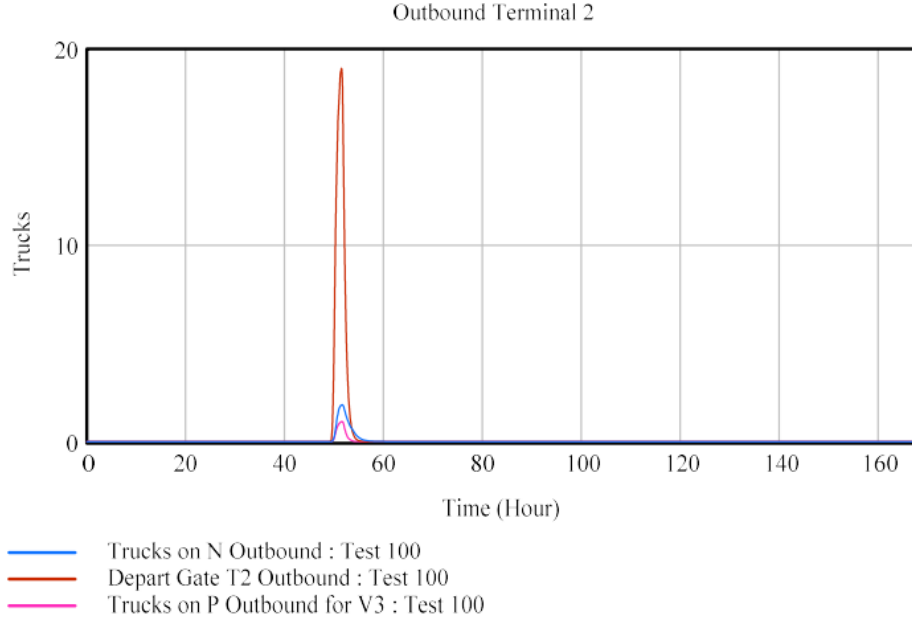


Figure 20: Outbound Terminal 2 for validation

As shown in Figure 20, when mixed flows attempt to depart from a shared terminal, the outbound route corresponding to the more congested V3 origin (in pink) becomes temporarily saturated. Consequently, trucks are forced to use the only available uncongested path, which corresponds to their original point of entry (in blue).

It should therefore be highlighted that, in the case of heavy and concentrated traffic, the model revealed an emerging property of considerable importance: congestion itself acts as an implicit routing mechanism, keeping flows separate without the need for explicit sorting rules.

In summary, the test confirmed both the internal consistency and robustness of the model and its ability to reproduce complex and counterintuitive dynamics, fully processing the initial 200 trucks and ensuring perfect separation of flows thanks to a regulating effect determined by the network structure and induced congestion.

4.2. Road network model results

4.2.1. Baseline performance scenario

Scenario 1 establishes the baseline performance of the port network under normal traffic conditions. The analysis focuses on overall system throughput and the identification of operational bottlenecks.

The primary measure of the system's performance is its ability to process arriving trucks in a timely manner. The cumulative throughput for gates V2 and V3 over the simulation period in Figure 21 shows that the system successfully processes all incoming traffic by the end of the week.

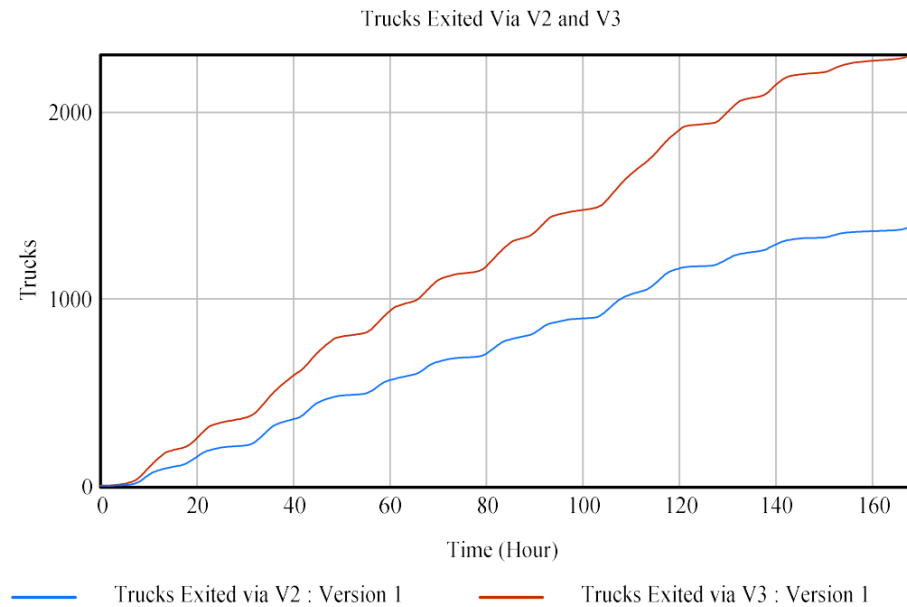


Figure 21: Trucks exited via V2 and V3

(Version 1 stands for Scenario 1)

However, an analysis of queue formation at the entry gates reveals significant congestion during peak arrival periods. Figure 22 illustrates the number of trucks waiting to enter the network at V2 and V3.

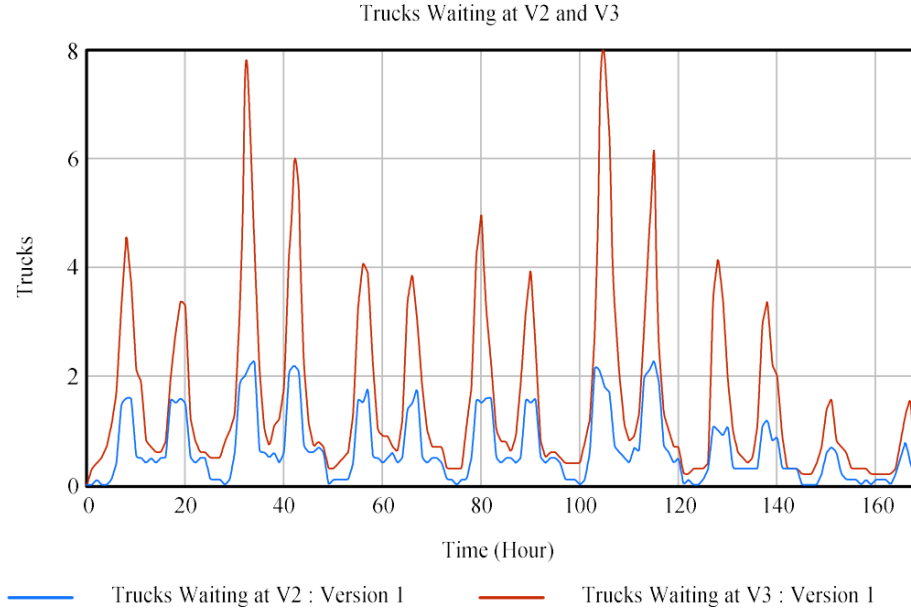


Figure 22: Trucks waiting at V2 and V3

(Version 1 stands for Scenario 1)

The data clearly indicates that Gate V3 experiences substantially more congestion than V2. The queue at V3 is consistently larger and persists for longer durations. This can be directly attributed to the limited capacity of the initial road segment (Segment U). This finding establishes the V3 entrance as the primary constraint on the entire road network's performance under baseline conditions.

An analysis of the individual road segments shows that, for the most part, the internal network has sufficient capacity to handle the baseline traffic flow. The occupancy levels of critical shared segments, such as P and Q, remain well below their capacity limits throughout the simulation. (Figure 23)

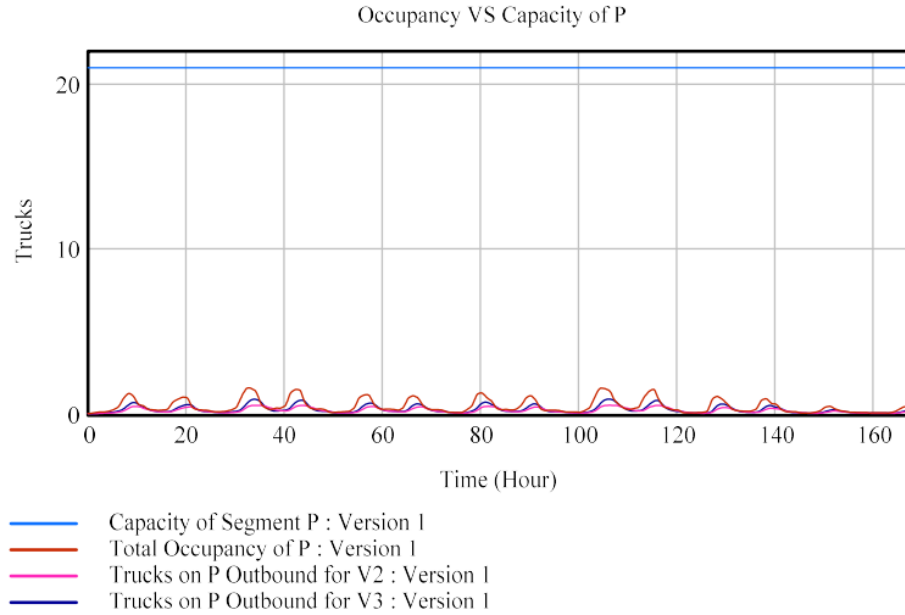


Figure 23: Occupancy VS capacity of segment P
(Version 1 stands for Scenario 1)

This indicates that the core road infrastructure is not a source of significant delay. Even the segments immediately downstream from the congested V3 gate operate comfortably within their capacity, however, an analysis of Segment V reveals a counter-intuitive dynamic resulting from downstream constraints evidenced in Figure 24.

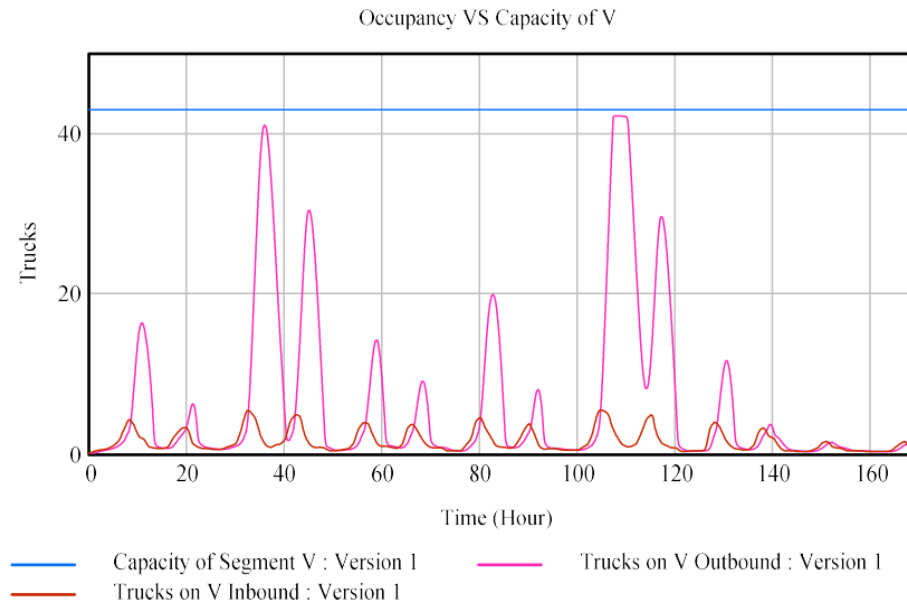


Figure 24: Occupancy VS capacity of segment V
(Version 1 stands for Scenario 1)

As shown in Figure 53, the number of Trucks on V Outbound (pink line) is significantly higher than the Trucks on V Inbound (red line). This indicates that trucks are experiencing more significant queues on their way out of the port. This is not due to a problem within Segment V itself, but rather a gridlock effect caused by the extremely limited capacity of the subsequent segment, Segment U.

As established, Segment U can only hold two trucks and serves as the final channel for all traffic exiting via Gate V3. When this small segment is full, it prevents trucks from leaving Segment V, causing a backlog that propagates backward. Therefore, the high number of outbound trucks shown on Segment V represents a queue waiting for access to the congested Segment U. This confirms that the congestion is not a series of isolated incidents, but a systemic issue rooted in the structural bottleneck at the V3 gate, which impacts mostly outbound flows.

The final stage of the inbound journey is terminal processing. The analysis of terminal utilization indicates that under baseline traffic conditions, none of the terminals constitute a significant bottleneck. The number of trucks being serviced within each terminal's operational area consistently remains far below the designated capacity as seen in Figure 25 and Figure 26. This suggests that the terminal processing times, and gate capacities are adequate for the current arrival patterns.

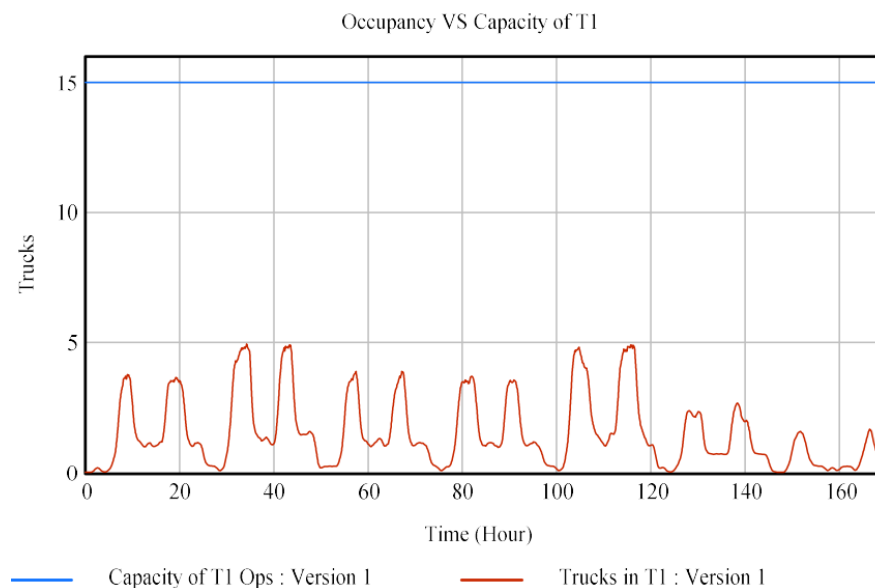


Figure 25: Occupancy VS capacity of Terminal 1

(Version 1 stands for Scenario 1)

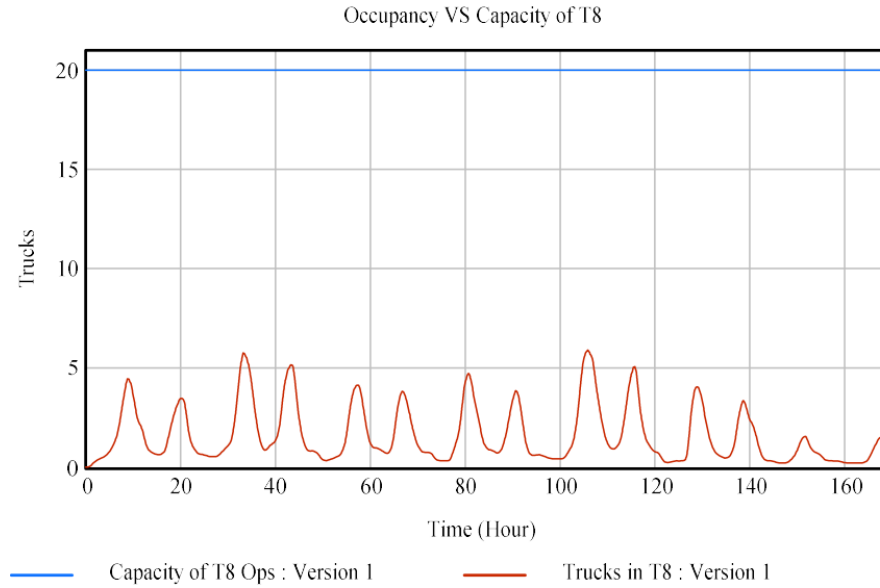


Figure 26: Occupancy VS capacity of T8

(Version 1 stands for Scenario 1)

The baseline scenario demonstrates the port's road network and terminals are capable of handling the current workload, even though the system's overall efficiency is constrained by a clear and significant bottleneck at the V3 entry point. Any strategic initiative aimed at improving system performance should therefore prioritize addressing the capacity limitations at this specific location.

4.2.2. Infrastructure expansion scenario

Scenario 2 assesses the impact of a significant infrastructure investment: the addition of a third port gate, V4. The objective is to determine if this expansion can improve the primary bottleneck identified in the baseline scenario at Gate V3 and the overall efficiency of the road network. The total traffic volume remains constant, with a portion of the arrivals re-distributed to the new gate. The most direct measure of the new gate's effectiveness is its impact on queue lengths at the existing entry points. As established in the baseline scenario, Gate V3 represents the system's most significant constraint.

The comparative analysis shown in Figure 27 below reveals an important improvement: the introduction of Gate V4 leads to a substantial reduction in both the magnitude and duration of queues at V3. Peak congestion is reduced by more than 50% (from nearly 8 trucks to around 3), and the queues dissipate much more rapidly.

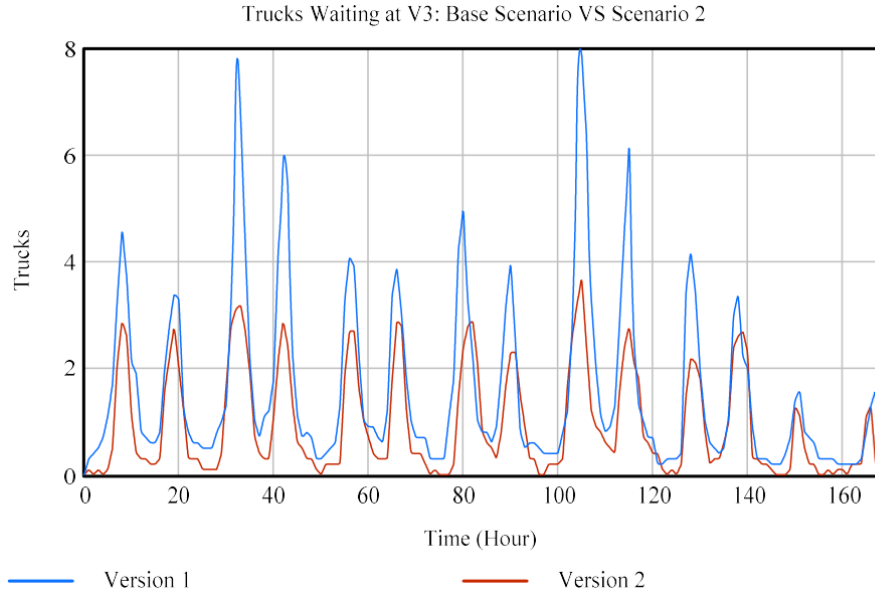


Figure 27: Trucks waiting at V3 - Base Scenario VS Scenario 2

(Version 1 stands for Scenario 1 and Version 2 stands for Scenario 2)

On the other hand, Gate V2 experiences a slight increase in congestion, with queues reaching slightly higher peaks than in the baseline scenario as shown on Figure 28. This is an important secondary effect, suggesting that while the overall system pressure is lower, the altered traffic dynamics may place a marginally higher load on the V2 entrance.

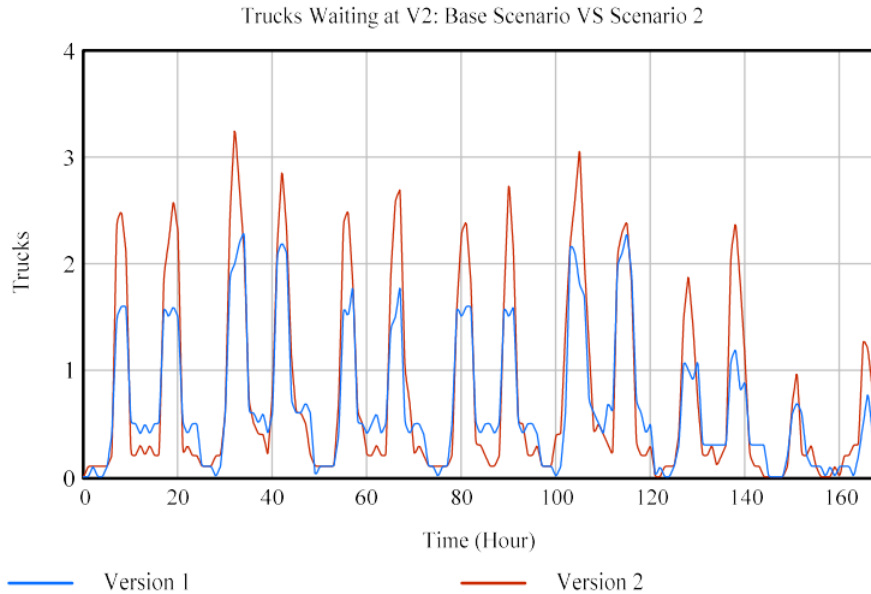


Figure 28: Trucks waiting at V2 - Scenario 1 VS Scenario 2

(Version 1 stands for Scenario 1 and Version 2 stands for Scenario 2)

The reduction in congestion at V3 is a direct result of rerouting a significant portion of its traffic. The total number of trucks processed through Gate V3 over the week is significantly lower in Scenario 2 compared to the baseline as illustrated by Figure 29 and Figure 30. The newly introduced Gate V4 successfully absorbs this diverted traffic, processing a substantial number of trucks that would have otherwise been routed through V3.

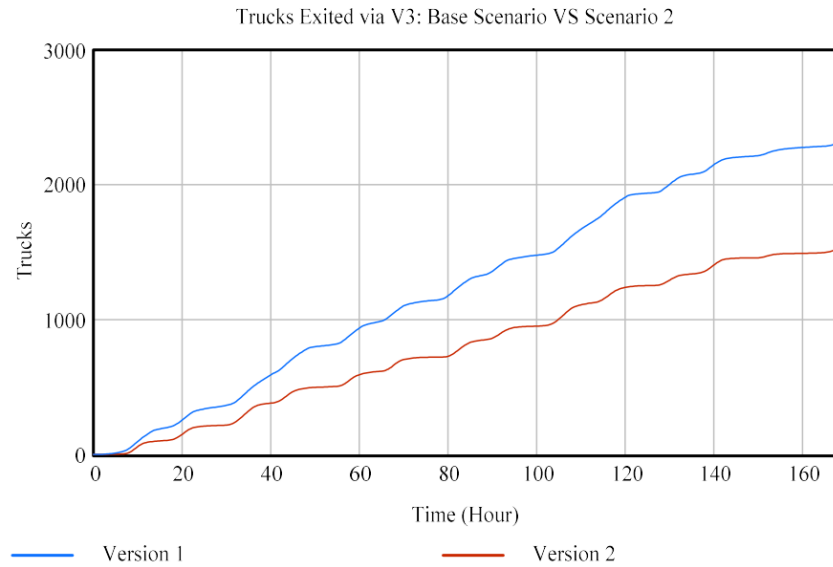


Figure 29: Trucks exited via V3 - Scenario 1 VS Scenario 2

(Version 1 stands for Scenario 1 and Version 2 stands for Scenario 2)

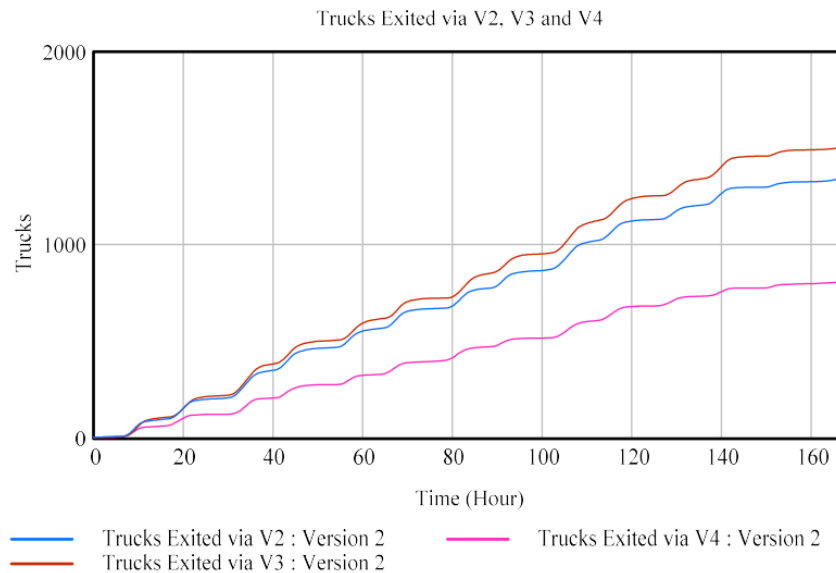


Figure 30: Trucks exited via V2, V3 and V4

(Version 2 stands for Scenario 2)

The benefits of reducing the V3 bottleneck extend beyond the entry gate and into the internal road network. With fewer trucks entering through V3, downstream road segments that were previously under pressure now operate with significantly more spare capacity.

For example, the outbound traffic on Segment V (Figure 31), a critical artery, is substantially lower and less volatile compared to the base scenario.

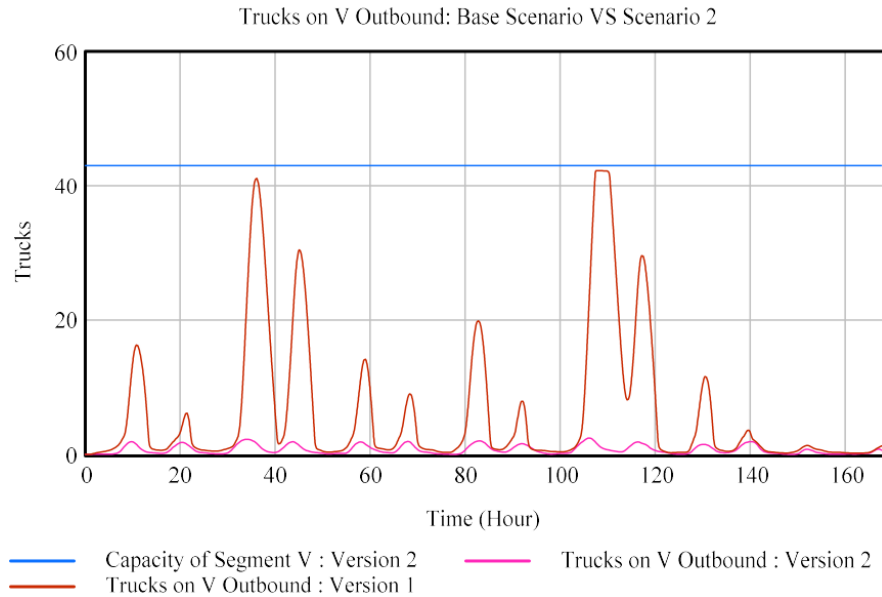


Figure 31: Trucks on V outbound - Scenario 1 VS Scenario 2

(Version 1 stands for Scenario 1 and Version 2 stands for Scenario 2)

The addition of Gate V4 proves to be a highly effective strategy for improving the port's performance. The investment successfully mitigates the primary bottleneck at Gate V3, leading to a reduction in entry point congestion and a more balanced distribution of traffic across the network. This positive effect propagates, reducing stress on internal road segments and resulting in a more efficient and resilient system overall.

4.2.3. Demand growth scenario

Scenario 3 is designed to stress-test the port network and identify its operational breaking points. The total traffic volume is increased of 1000 trucks, to 4715 trucks per week, simulating a period of high demand while maintaining the existing two-gate infrastructure (V2 and V3). The analysis focuses on identifying the emergence of new bottlenecks and determining the system's maximum sustainable capacity.

The primary consequence of the increased traffic is the development of severe congestion at the entry gates, particularly at the known bottleneck of V3. As shown in Figure 32, the queues at Gate V3 reach a peak of 30 trucks, a nearly three times increase compared to the base scenario; this value is dangerous, as 30 trucks in queue highly impact city traffic in areas surrounding the port. While the system does eventually process all arriving trucks, the queues at V3 remain consistently high and take much longer to clear between arrival peaks. This indicates that the gate is operating very near its maximum processing capacity for extended periods. The system is still functional, but the level of service is substantially degraded, with trucks experiencing significant delays before even entering the main network.

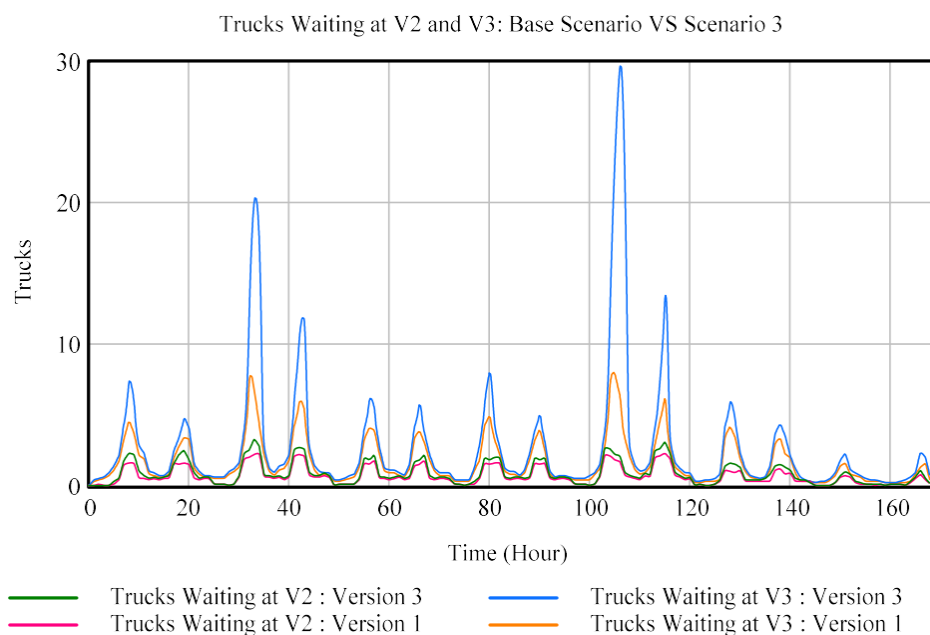


Figure 32: Trucks waiting at V2 and V3 - Scenario 1 VS Scenario 3

(Version 1 stands for Scenario 1 and Version 3 stands for Scenario 3)

A critical finding in this scenario is the propagation of congestion from the entry gate into the internal road network. Under the intense traffic load, downstream segments that previously had spare capacity now become secondary bottlenecks.

Considering again Segment V in Figure 33, it was possible to observe how the segment now operates at its maximum physical capacity for prolonged durations. This saturation of an internal route is a significant development; it means the congestion is no longer contained at the entrance but is now creating internal gridlock, which in turn would cause major delays for any traffic utilizing this path.

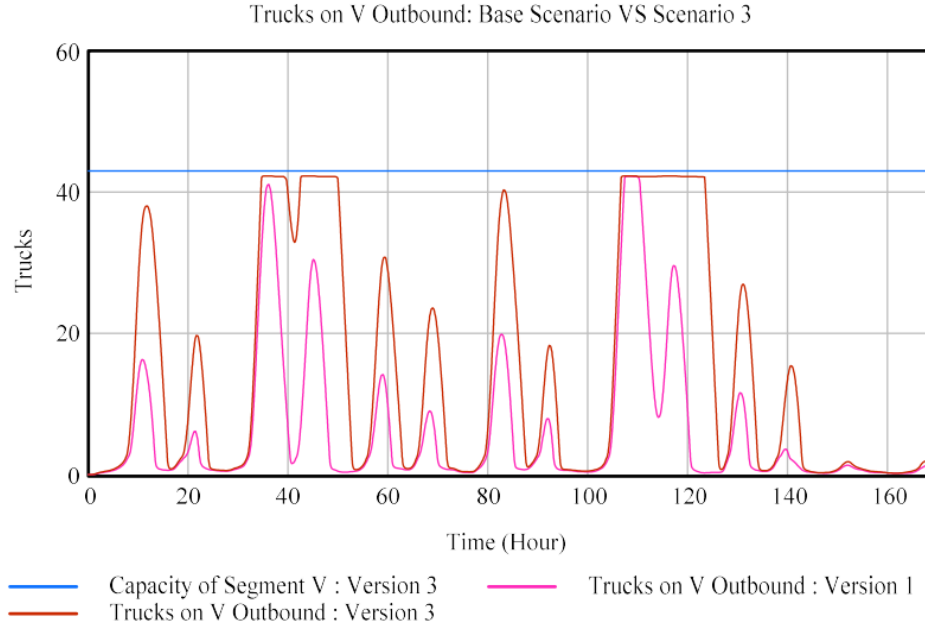


Figure 33: Trucks on V outbound - Scenario 1 VS Scenario 3

(Version 1 stands for Scenario 1 and Version 3 stands for Scenario 3)

Despite the severe congestion observed, the system successfully processes the entire increased volume of 4715 trucks over the week. The throughput graph (Figure 34) confirms that all trucks that enter also exit, demonstrating the model's robustness.

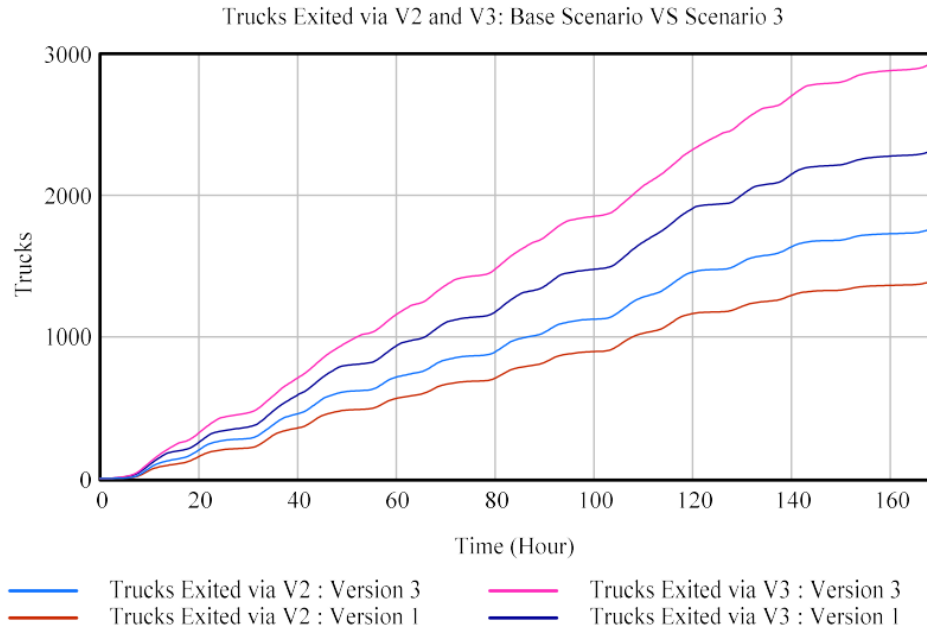


Figure 34: Trucks exited via V2 and V3 - Scenario 1 VS Scenario 3

(Version 1 stands for Scenario 1 and Version 3 stands for Scenario 3)

This scenario demonstrates that while the port's two-gate system can technically handle a high increase in traffic, it does so at the cost of severe levels of congestion.

The system does not fail, but its efficiency is dramatically reduced. The queues at Gate V3 and the saturation of internal segments like V indicate that the network is operating at the limit of its viability. While sustainable from a modeling perspective, such conditions in a real-world context would lead to significant delays.

4.2.4. Disruption scenarios

This section evaluates the port network's resilience by analyzing its response to two distinct types of operational failures: a short-term network blockage (Scenario 4) and a prolonged terminal shutdown (Scenario 4bis). The primary objective is to assess how the system absorbs and recovers from these disruptions while operating under normal traffic conditions.

Network disruption: Scenario 4

This scenario simulates a 2-hour closure of Segment V on a Thursday afternoon. As a critical artery for terminals T6, T8, and T9, its temporary unavailability tests the system's ability to handle a sudden stop and subsequent surge of traffic.

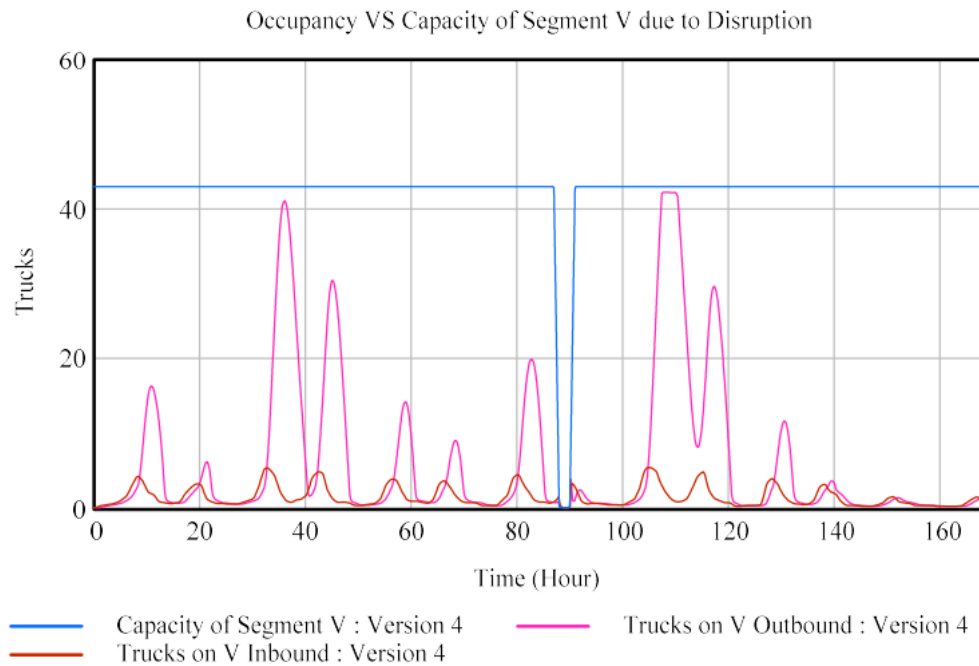


Figure 35: Occupancy VS capacity of segment V due to Disruption

(Version 4 stands for Scenario 4)

Figure 35 clearly shows the disruption, with all traffic on Segment V ceasing for the two-hour duration. Upon reopening, a surge of queued trucks is released into the network.

The immediate effect of this network disruption is felt at the downstream terminals. For Terminal T8, a noticeable spike in the number of trucks is visible shortly after Segment V reopens. However, the terminal's operational capacity is never reached.

A deeper analysis of the post-disruption traffic reveals a more complex dynamic. As shown in Figure 36, the expected surge of delayed trucks does not arrive as a single, massive wave. Instead, the Version 4 (blue) data show the initial post-disruption peak from Version 1 (red) being split into two smaller, distinct peaks. The cumulative volume of these two groups is equivalent to the single original peak.

This split is caused by a conflict at the already congested Gate V3. As the system began clearing the large backlog of trucks that had accumulated during the closure, a new wave of regularly scheduled traffic arrived at the gate. The system had to manage both of these flows simultaneously, which briefly interrupted the release of the backlogged trucks. This pause in the flow is what created the gap between the two peaks, causing the delayed traffic to arrive at Terminal T8 as two separate, smaller waves instead of one large one.

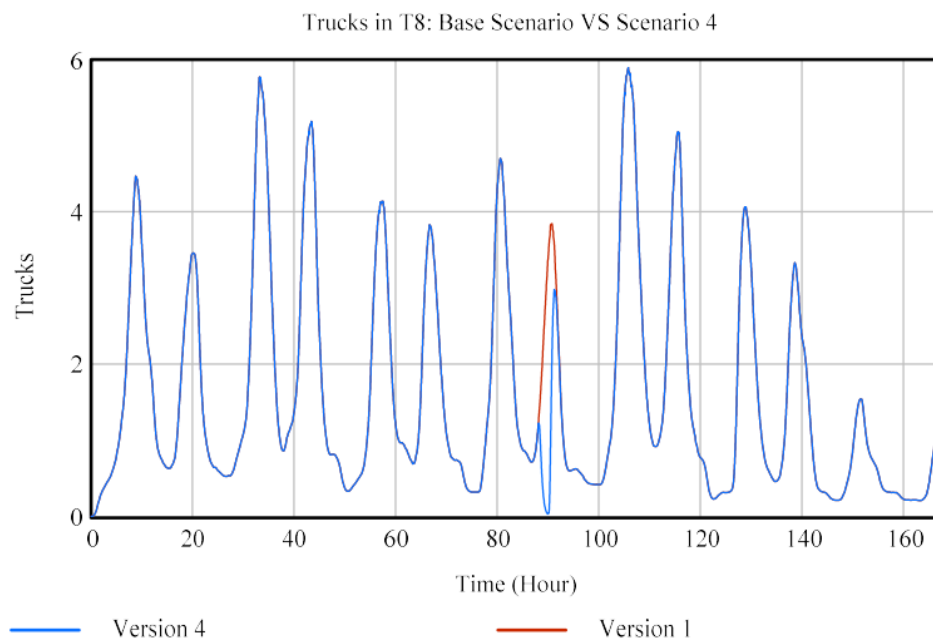


Figure 36: Trucks in T8 - Scenario 1 VS Scenario 4

(Version 1 stands for Scenario 1 and Version 4 stands for Scenario 4)

The overall impact on the port's weekly throughput is minimal. The cumulative number of trucks exiting via V3 at the end of the week is only slightly lower than in the baseline scenario as observed through Figure 37. The system recovers from the two-hour delay with remarkable efficiency, confirming a high degree of network resilience.

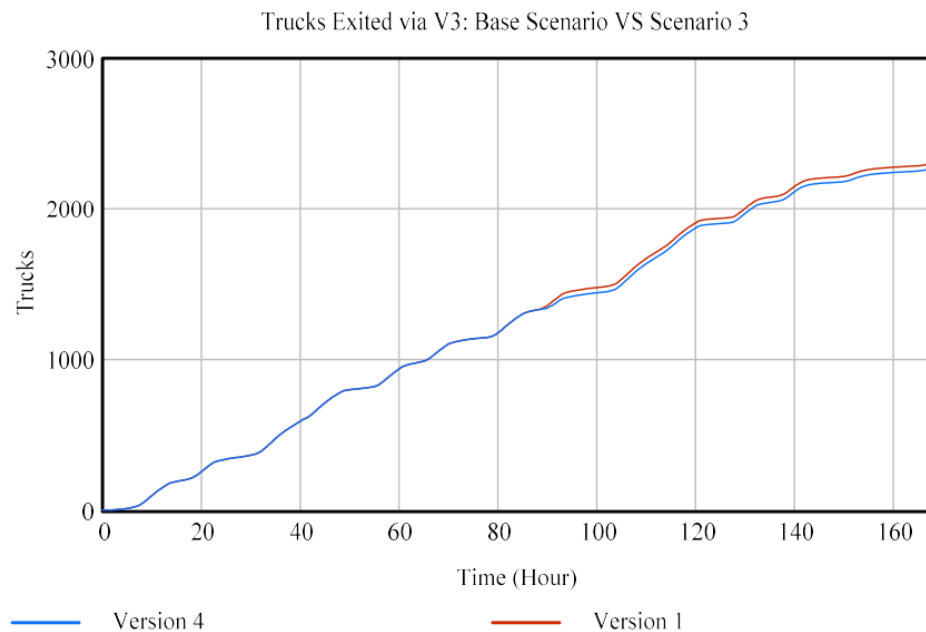


Figure 37: Trucks exited via V3 - Scenario 1 VS Scenario 4

(Version 1 stands for Scenario 1 and Version 4 stands for Scenario 4)

Terminal disruption: Scenario 4bis

This scenario presents a more severe and prolonged challenge: the complete shutdown of Terminal 2 for 12 hours. As a key terminal accessible from both gates, its closure tests the system's ability to adapt to the loss of a major processing hub.

Following, Figure 38 illustrates the closure event; the number of trucks within T2 drops to zero during the 12-hour disruption. Immediately upon reopening, a large queue of trucks that had been waiting at the gate begins to be processed, causing a sharp spike in the terminal's occupancy.

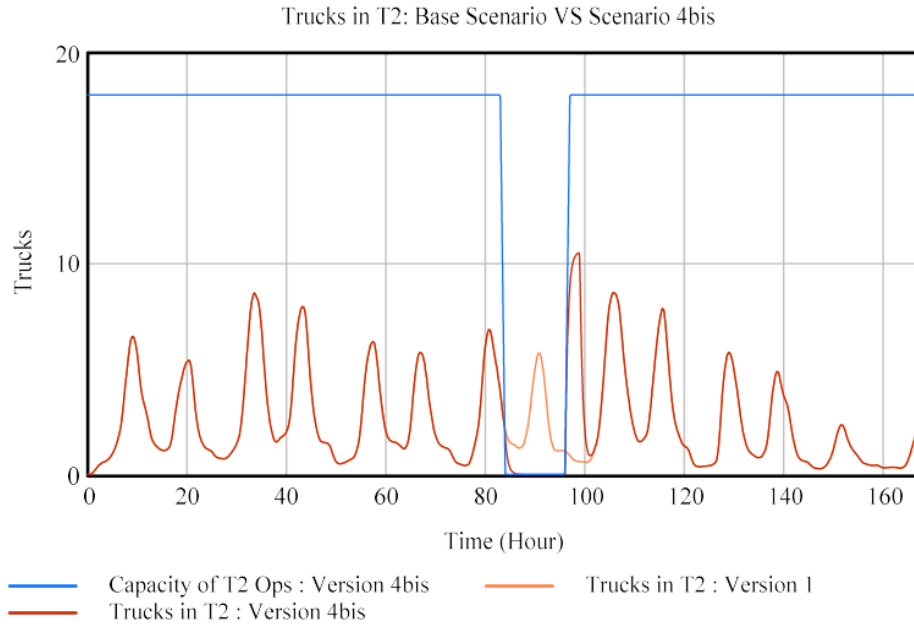


Figure 38: Trucks in T2 - Scenario 1 VS Scenario 4bis

(Version 1 stands for Scenario 1 and Version 4bis stands for Scenario 4bis)

Despite the intensity of this recovery, the system's internal logic prevents overload. The number of trucks inside T2 peaks but never exceeds its operational capacity. This demonstrates that the system is inherently stable and can manage the clearing of a significant backlog without violating its own constraints.

The prolonged closure has a noticeable but contained impact on the upstream network. Considering, for example, the outbound traffic on Segment O (Figure 39), it is possible to observe how it ceases during the closure. After reopening, the traffic flow is slightly more volatile as the backlog is processed, but it remains well within the segment's capacity limits.

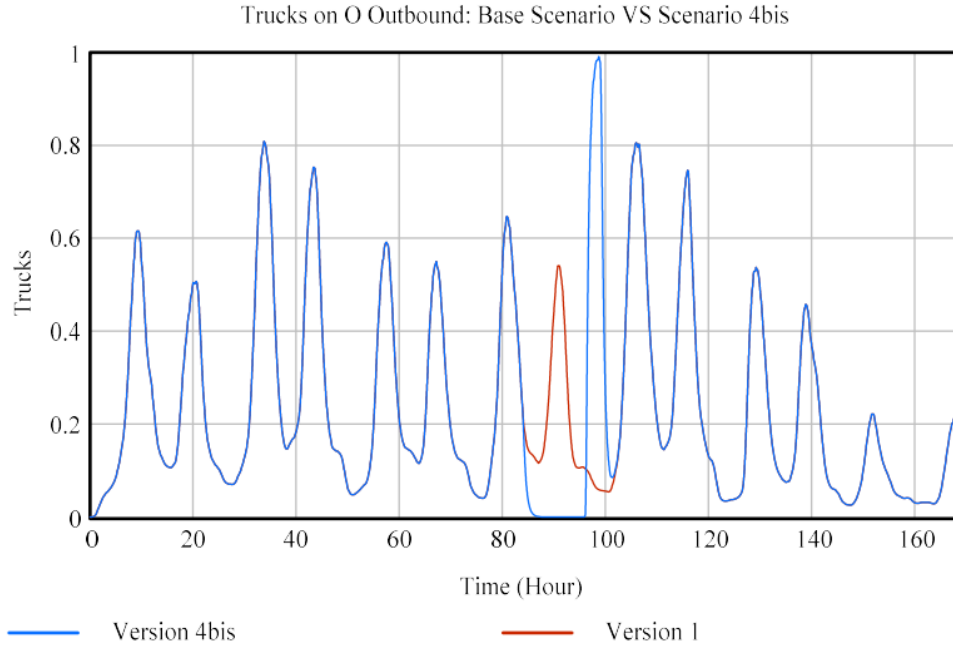


Figure 39: Trucks on O Outbound - Scenario 1 VS Scenario 4bis

(Version 1 stands for Scenario 1 and Version 4bis stands for Scenario 4bis)

The analysis of both disruption scenarios leads to a clear conclusion: the port's road network is highly resilient. It effectively manages both short-term, high-impact network failures and prolonged, localized shutdowns. In both cases, the system demonstrates an ability to absorb backlogs without violating capacity constraints, and the overall impact on weekly throughput is negligible. This robustness suggests a well-designed system with sufficient buffer capacity to handle common operational disruptions.

4.2.5. Slow-down scenario

The final scenario, Scenario 5, analyzes the impact of a global degradation in operational efficiency, such as would be caused by adverse weather conditions. A 50% increase was applied to all travel and processing times, which were then rounded up to the nearest integer to avoid decimals. This effectively simulates a significant slowdown across the network while maintaining the baseline traffic volume. The objective is to assess the system's sensitivity to a widespread slowdown and its effect on the overall level of service.

The most immediate and severe consequence of the system-wide slowdown is the formation of massive, unresolved queues at the entry gates. With trucks taking twice as long to clear the initial road segments, the entry points become catastrophically congested as illustrated in Figure 40.

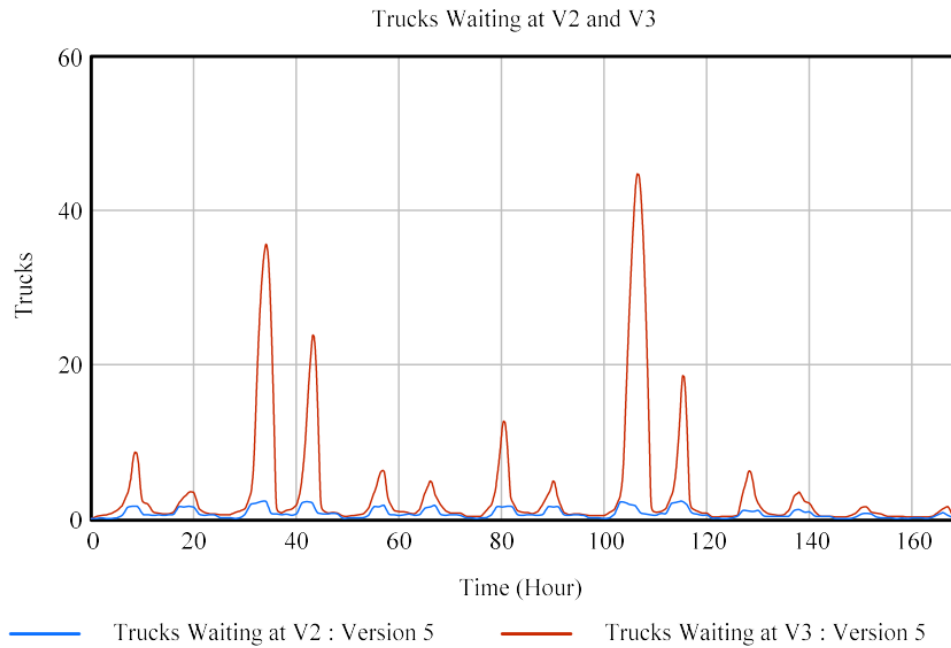


Figure 40: Trucks waiting at V2 and V3 due to system slow-down

(Version 5 stands for Scenario 5)

The graph in Figure 40 shows that the queue at Gate V3, which was already identified as the main system's bottleneck, grows to over 40 trucks. More importantly, the queue never fully dissipates, indicating a complete failure of the gate to process trucks at a rate sufficient to keep up with arrivals. Even the more efficient Gate V2 experiences significantly larger and more persistent queues than in any previous scenario.

Slower travel speeds mean that individual trucks occupy space on road segments for longer periods, drastically reducing the effective throughput of the network. This leads to the saturation of key internal arteries. Segment V, which was already under pressure in the intense traffic scenario, now operates at its maximum capacity for the majority of the simulation, as shown in Figure 41.

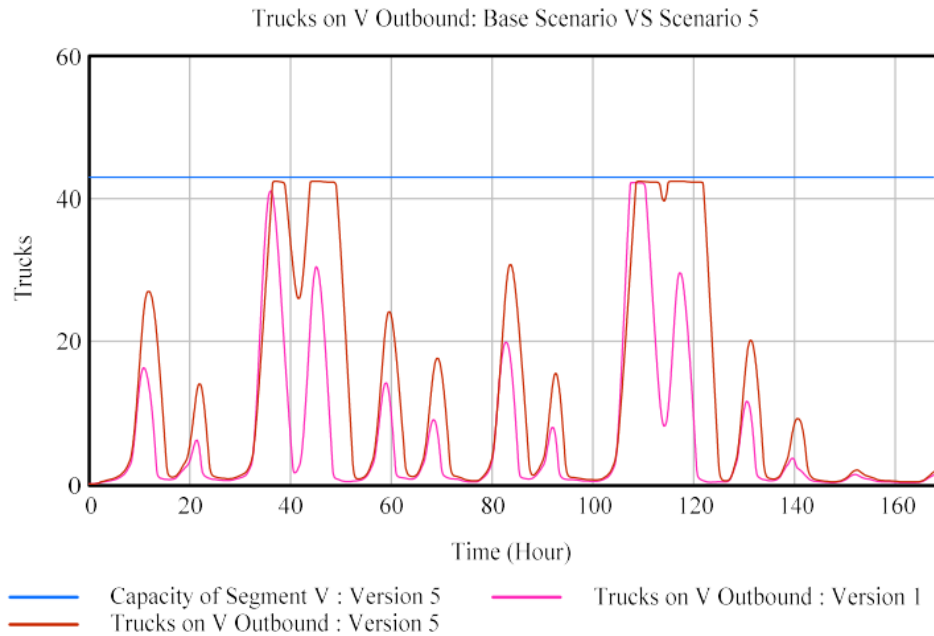


Figure 41: Trucks on V outbound - Scenario 1 VS Scenario 5

(Version 1 stands for Scenario 1 and Version 5 stands for Scenario 5)

The effects of the slowdown are also reflected at the terminal level, where the peaks of activity are delayed and suppressed, but the overall volume is still processed, evidenced in Figure 42.

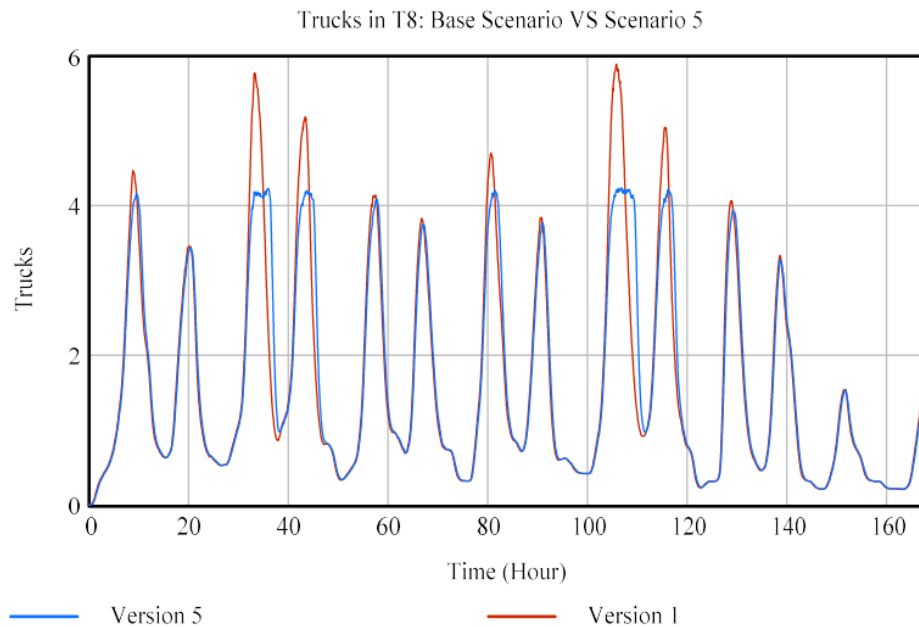


Figure 42: Trucks in T8 - Scenario 1 VS Scenario 5

(Version 1 stands for Scenario 1 and Version 5 stands for Scenario 5)

An interesting finding of this scenario is that, despite the severe congestion, the system demonstrates its robustness by successfully processing nearly the entire weekly traffic volume as noticed in Figure 43; the cumulative number of trucks exited by the end of the simulation is very identical to the baseline scenario for Gate V2, and mostly similar for Gate V3.

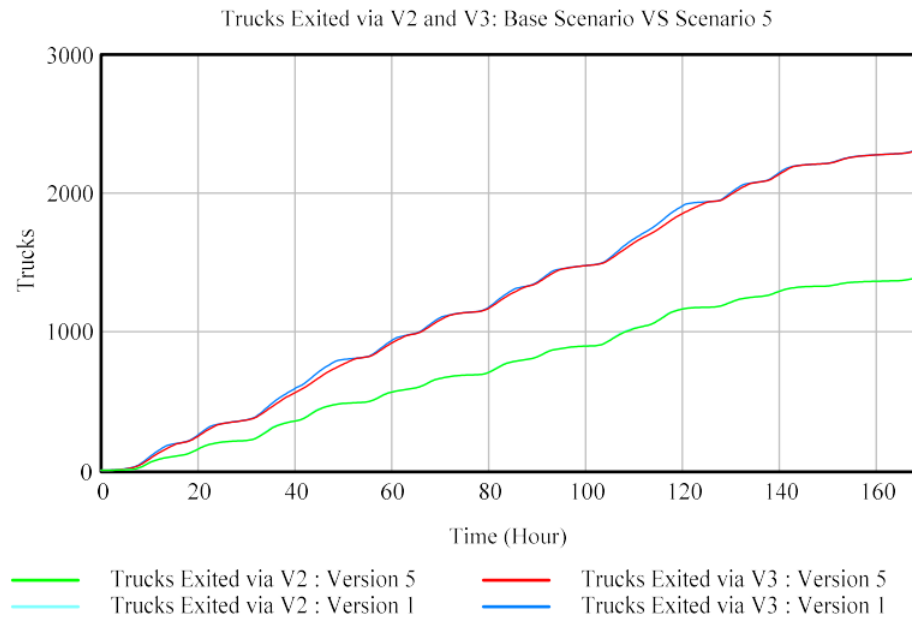


Figure 43: Trucks exited via V2 and V3 - Scenario 1 VS Scenario 5

(Version 1 stands for Scenario 1 and Version 5 stands for Scenario 5)

The analysis of Scenario 5 reveals that the port network is remarkably robust, able to process its standard weekly traffic volume even with a 50% reduction in operational speed. However, it does so at the cost of a severe degradation in the level of service. The extreme and persistent queues at the entry gates, combined with higher internal congestion, would lead to operationally unacceptable delays, and would highly impact on the infrastructures nearby the port.

Interestingly this outcome, characterized by severe congestion combined with eventual success in processing the total volume, is very similar to the results observed in Scenario 3, where an additional 1000 trucks were added to the system. This suggests that a systemic 50% slowdown places a comparable level of stress on the network as a 27% increase in traffic volume. In both cases, while the system does not fail, its efficiency is compromised to a degree that would render it ineffective in the real world where, inevitably, it would also cause serious consequences for city traffic near the port area.

To summarize:

Scenario	Case	Description	Trucks processed	Max number of trucks at Gate V2	Max number of trucks at Gate V3
Scenario 1	Baseline performance	Two port gates (V2 and V3), normal traffic conditions	100%	2	8
Scenario 2	Infrastructure expansion	Three port gates (V2, V3 and V4), normal traffic conditions	100%	3	4
Scenario 3	Demand growth	Two port gates (V2 and V3), intense traffic conditions (+1000 trucks/week)	100%	3	30
Scenario 4	Network disruption	Two port gates (V2 and V3), normal traffic conditions, closure of segment V for 2 hours on Thursday afternoon due to an accident	100%	2	8
Scenario 4bis	Terminal disruption	Two port gates (V2 and V3), normal traffic conditions, and the closure of terminal T2 for 12 hours on Thursday afternoon due to an accident.	100%	2	8
Scenario 5	Slow down	Two port gates (V2 and V3), normal traffic conditions, speed reduction of 50% due to bad weather conditions.	100%	2	44

Table Y: Scenarios and results for Road network model

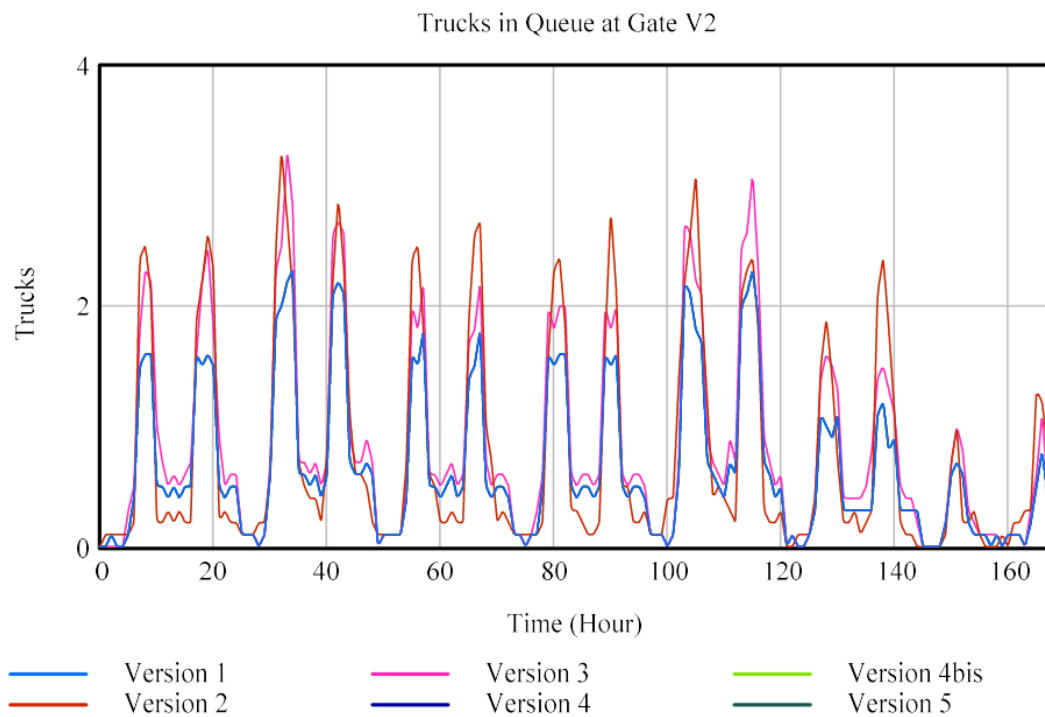


Figure 44: Trucks in queue at Gate V2 for all scenarios

(Version stands for Scenario)

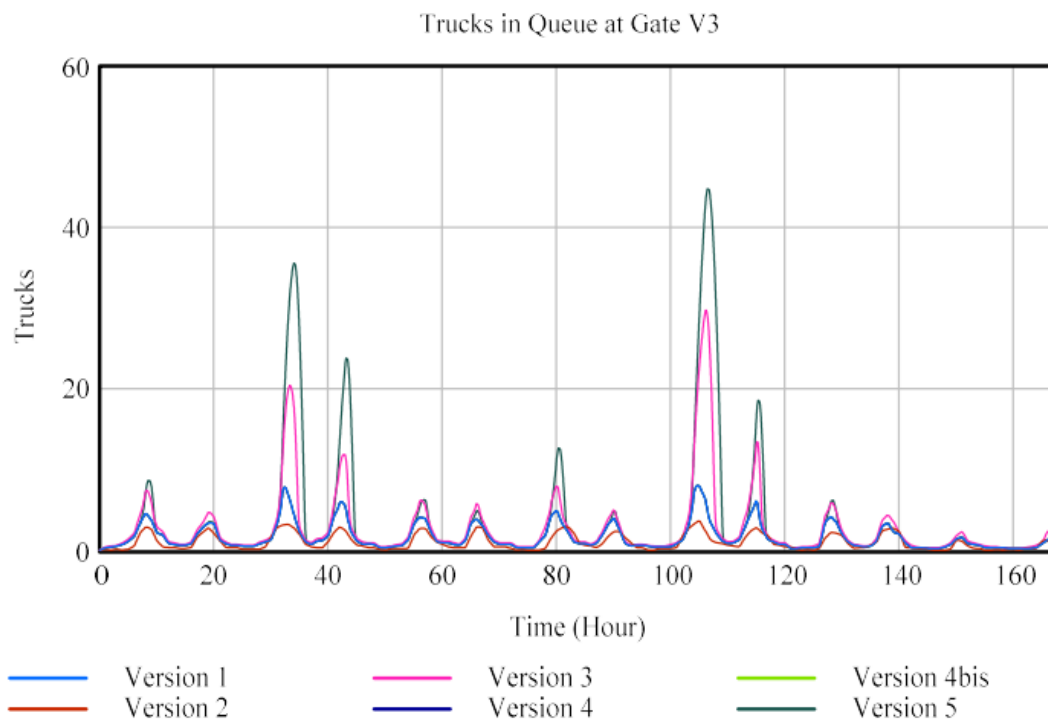


Figure 45: Trucks in queue at Gate V3 for all scenarios

(Version stands for Scenario)

4.3. Crossing between network models results

Developed in collaboration with Daniela Restrepo Ruiz

4.3.1. Baseline performance scenario

For Scenario 1, the analysis focused on quantifying the impact of normal train traffic on the road network's throughput and congestion levels. The results of this scenario are compared directly against "Version 1" of the road network model, which represents the ideal state with no rail interference.

The primary finding of the integrated model is that even under normal conditions, the priority given to rail traffic causes a significant reduction in the road network's overall efficiency. The graph below (Figure 46) compares the cumulative number of trucks exiting the port in the integrated model against the standalone road model.

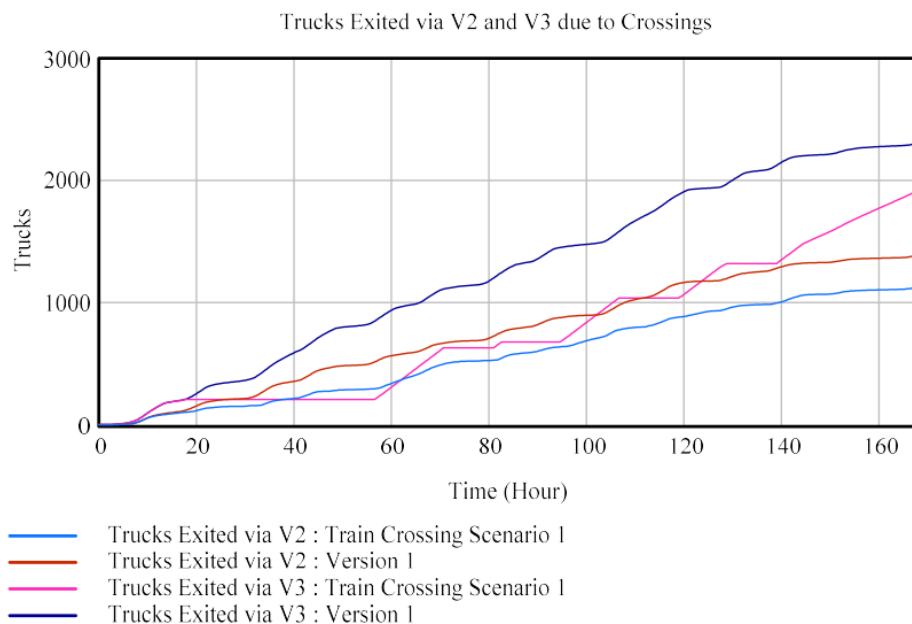


Figure 46: Trucks exited via V2 and V3 for crossings

The road network's total throughput is reduced by approximately 25%, from almost 3700 trucks to almost 2800 trucks over the week. The interference from train crossings prevents the road system from ever catching up, resulting in an important loss of capacity.

The closures at Crossing X1 create observable but manageable disruptions. The graph in Figure 47 shows the "Trucks Permission to Cross" variable (dotted red line) dropping to zero when a train

is present, which momentarily alters the corresponding inbound and outbound truck flows (blue and pink lines).

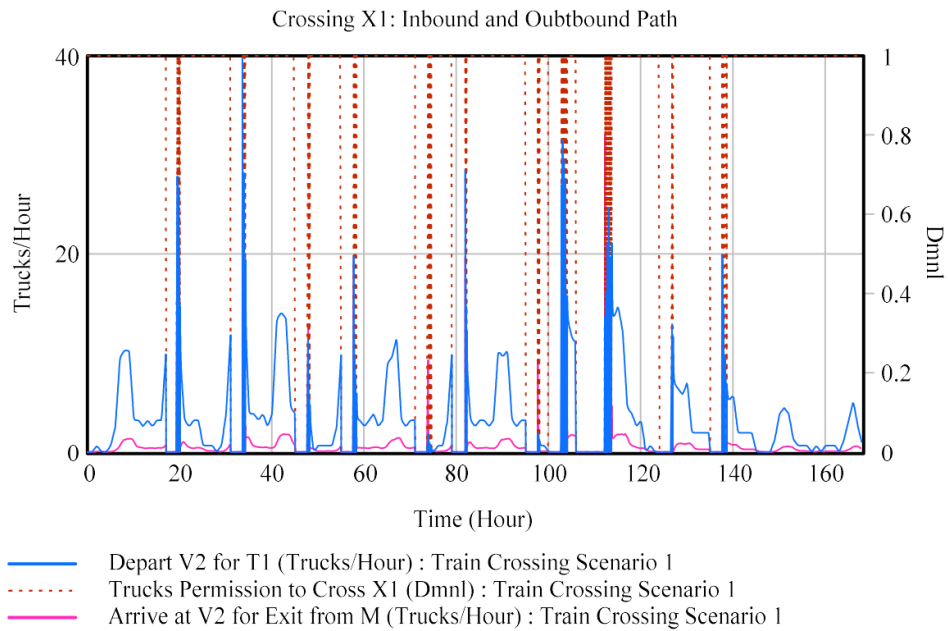


Figure 47: Crossing X1 - Inbound and outbound path

These interruptions cause minor, localized increases in queue lengths at the preceding segments. However, Figure 48 shows that the overall impact on the queue at Gate V2 is minimal when compared to the baseline, indicating that the network has sufficient capacity to absorb these short delays.

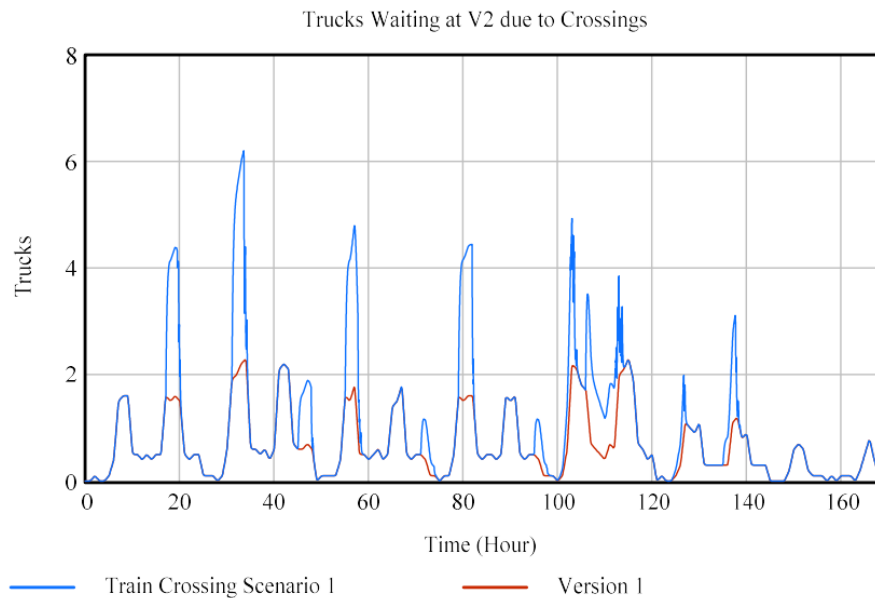


Figure 48: Trucks waiting at V2 for crossings model

The same does not apply to Gate V3, which was previously identified as one of the most concerning points of the road network and now is characterized by an enormous queue of over 600 vehicles. (Figure 49)

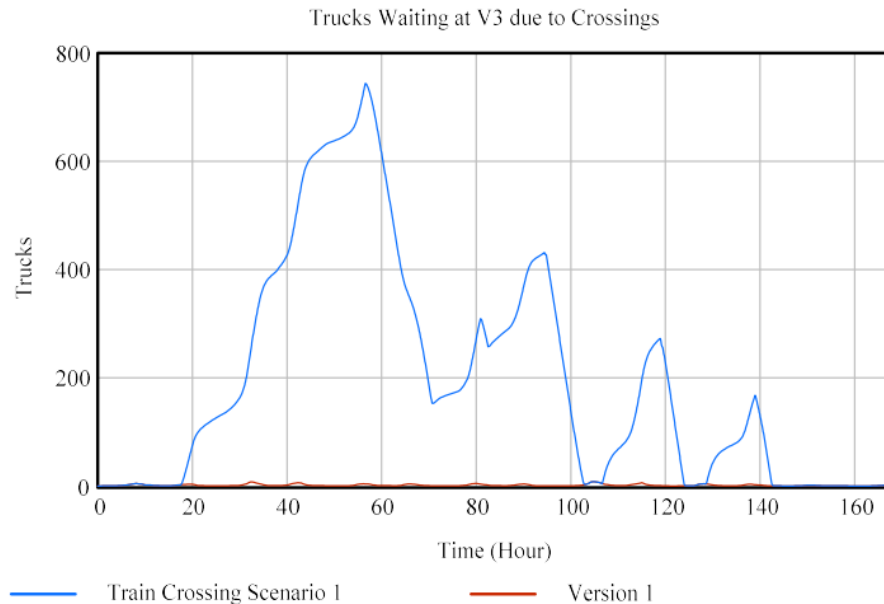


Figure 49: Trucks waiting at V3 for crossings model

Gate V3 is highly influenced by Crossing X3, that appears to be a critical point of failure for the entire network, being occupied by trains for the majority of the simulation, as abstracted from Figure 50.

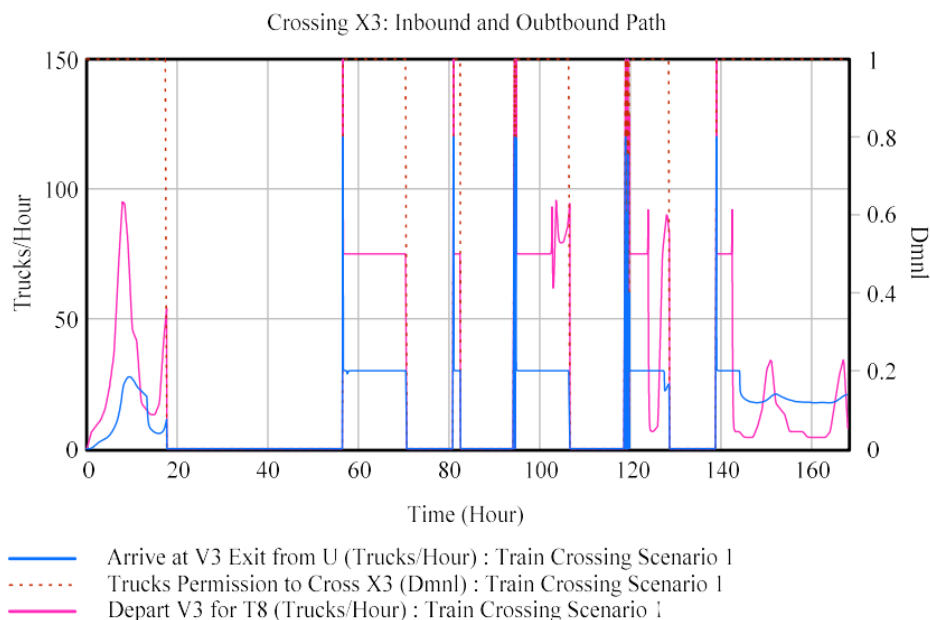


Figure 50: Crossing X3 - Inbound and outbound path

This integrated model demonstrates that the interaction with the rail network is the single most significant constraint on the port's landside performance under normal conditions. The analysis reveals a critical vulnerability that is not apparent when studying the road network in isolation.

4.3.1. Slow-down scenario

When analyzing the scenario in which both rail and road systems are under adverse weather conditions, the system starts from a heavier occupation of the facilities, which as one could expect, leads to greater occupancy of the shared system and a decrease in its throughput or capacity. The following graph (Figure 51) shows how scenario 2 has a great impact on the total trucks that are available to exit the system (in continues lines) with respect to a scenario where no trains disrupt the crossings in normal weather conditions (dashed lines), and a scenario where trains disrupt the crossings in normal weather conditions (dotted lines).

It can be seen in Figure 51 that in the case of V2 the impact is slightly lower than for the case of V3, which reaffirms what was mentioned earlier regarding the vulnerability of access point 3, presenting an additional reduction in capacity of processing of 24% and 40% respectively against the previous scenario.

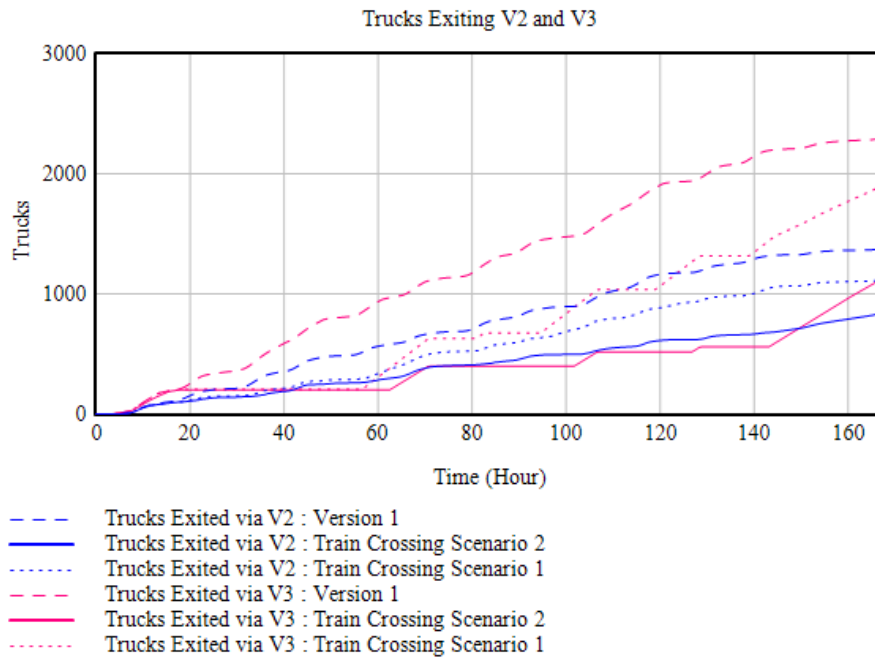


Figure 51: trucks exiting V2 and V3 under scenarios 1 and 2 for crossings model

(Version 1 stands for Scenario 1 of the Road network model)

To further understand the impact, the queues generated around the crossings were observed just like in the previous scenario, in which only slight increments were observed in crossings 1 and 2, and a greater impact in crossing 3, which confirms previous results that associate V3 to a critical point.

Finally, by analyzing the number of trucks waiting at both access points, it was seen that for V2 the results remained relatively similar with slightly higher queues, while for the case of V3 queues more than 1600 vehicles waiting to pass due to the presence of trains in crossings in adverse weather conditions.

These two scenarios of the crossings allow to understand the sensitivity of the road network to the presence of trains, and to speed and occupation of both the tracks and the road system. An important and key aspect to take into consideration is that for all scenarios that considered adverse weather conditions, only internal impacts were evaluated, but in real life the impact is widespread throughout the entire network inside and outside of the port and actual impacts are expected to be greater. Nevertheless, the scenarios simulated give an insight into internal disruption.

To summarize:

Scenario	Case	Description	Trucks processed	Max number of trucks at Gate V2	Max number of trucks at Gate V3
Scenario 1	Road + Rail	Base demand for road interrupted by train's flow.	83%	6	1609
Scenario 2	Road + Rail (adverse weather)	Base demand for road interrupted by train's flow under adverse weather conditions	54%	7	742

Table Z: Scenarios and results for Crossing between network models

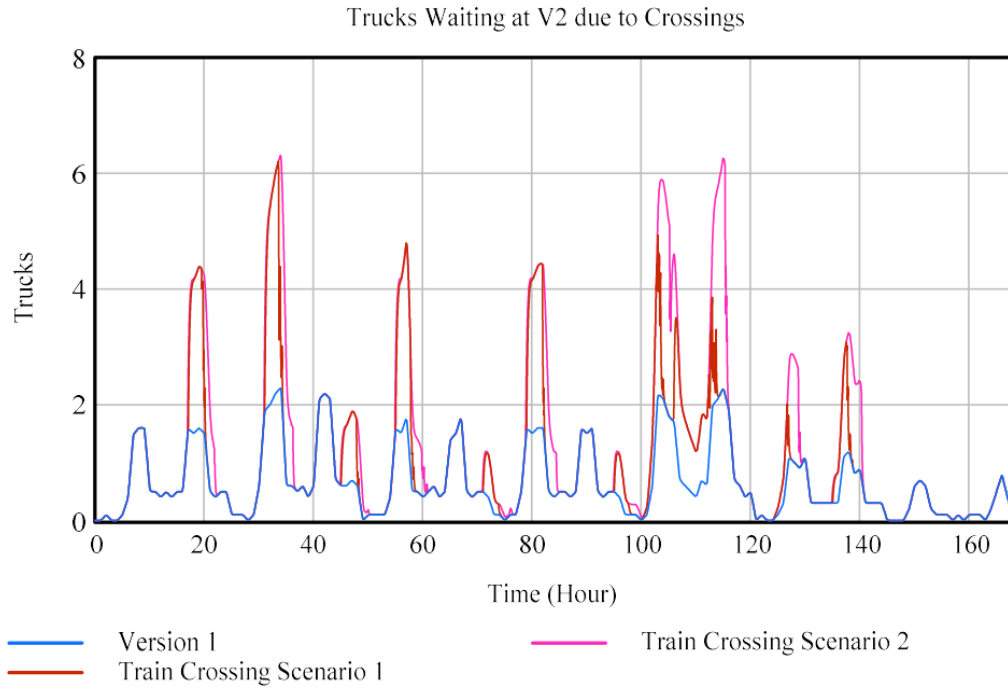


Figure 52: Trucks in queue at Gate V2 for all Crossings scenarios
(Version 1 stands for Scenario 1 of the Road network model)

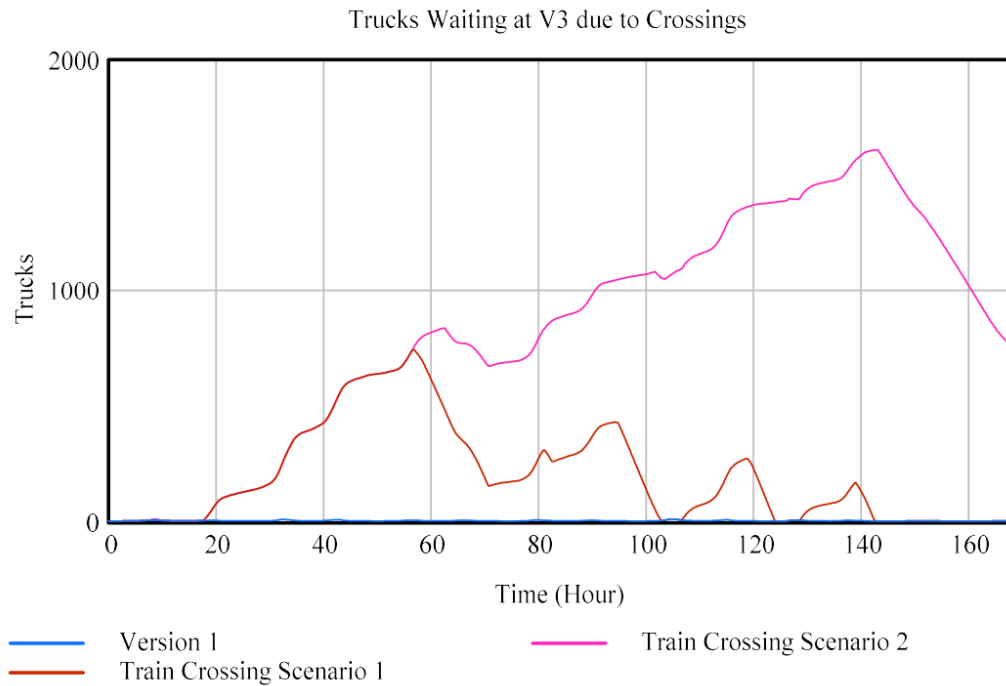


Figure 53: Trucks in queue at Gate V3 for all Crossings scenarios
(Version 1 stands for Scenario 1 of the Road network model)

5. Conclusions

This study focused on the road network of a major port in Northern Italy, analyzing both the road system itself and its intersections with the railway network. The aim was to understand the dynamics of traffic flows, identify critical points, and explore how road and rail interactions affect overall port operations. By simulating different scenarios, the research evaluated possible interventions, providing practical insights to improve the management of a port that is critical for the national industrial system.

Starting from the road network alone, the results offer both diagnostic and strategic insights. On the strategic side, Scenario 2 showed the positive impact of adding a new access point, Gate V4. This change increased the network's capacity to manage and distribute traffic, reducing pressure on existing gates and lowering the risk of congestion. This is more than a simple improvement; it represents a strategic adjustment that strengthens both the resilience and the overall capacity of the port.

From a diagnostic perspective, stress-test scenarios revealed the network's vulnerabilities under extreme conditions. Scenario 3, which added 1000 extra trucks, showed that waiting times increased sharply, especially at Gate V3. Scenario 5, simulating adverse weather, showed that even small reductions in efficiency led to a measurable drop in overall port performance.

A key insight comes from comparing the robustness of the simulation with the real-world system. While the model handled extreme loads without problems, in reality, such congestion could cause complete operational paralysis. The effects would extend beyond the port, causing congestion on surrounding roads and disrupting the wider urban network. This demonstrates how exceeding critical thresholds can have wide-reaching consequences.

Road-rail intersections were identified as the main source of operational friction. In the limited space of the port, trains and trucks share crossings, and every train passing temporarily stops road traffic. Under normal conditions, rail priority reduces road throughput by about 25%. Queues of waiting trucks often extend far enough to block other intersections, showing that even short rail operations can create long-lasting congestion inside and outside the port.

Crossing X3 and Gate V3 were the most critical points. Even under normal conditions, queues at the gate reached over 600 trucks, while in the slow-down scenario caused by bad weather, queues exceeded 1600, reducing throughput by an additional 40%.

Overall, the study shows that port efficiency depends not only on the capacities of road and rail networks individually, but also on how they interact. Shared intersections are the main source of congestion and operational problems. The analysis identified a hierarchy of bottlenecks, with road-rail crossings, shared rail sections, and vulnerable road segments at Gate V3 being the most critical. Finally, port performance deteriorates significantly under pressure. Although the model never encountered total blockages, moderate increases in demand cause minor delays, but extreme scenarios can trigger cascading congestion. By identifying these bottlenecks, the study provides guidance for targeted interventions aimed at improving efficiency, preventing disruptions, and strengthening the competitiveness of Italian ports in national and European logistics networks.

6. Scope and limitations

Although this simulation provides a solid framework, it is important to recognize that it involves certain simplifications and has a limited scope. The model focuses on a localized system boundary, considering only internal dynamics and not accounting for external factors such as congestion on major highways, accidents, or delays on the national rail network. While these factors are outside the model's scope, they could still influence the performance of the internal port network.

To maintain computational efficiency, the model simplifies operational complexity by grouping flows together and keeping some parameters constant, such as fixed service times and randomly assigned dwell times, which in reality can vary more widely. As a result, while the model effectively identifies system bottlenecks, it does not capture every fine-grained detail. Future research could improve the model by adding more detail in specific procedures or by introducing a more advanced traffic management logic.

Despite these limitations, the model successfully achieves its main goal: it identifies critical points in the network's behavior and provides a powerful, practical tool for evaluating the impact of strategic interventions within the port system.

7. Bibliography

- [1] L. D. J. Tavasszy, *Modelling Freight Transport*, 1st edition ed., London: Elsevier, 2014.
- [2] J.-P. Rodrigue, *The Geography of Transport Systems*, 6th edition ed., New York: Routledge, 2024.
- [3] C. Caballini, *Handouts*, Politecnico di Torino: Master Degree of Civil Engineering, 2024-2025.
- [4] B. Rondinelli, "Multimodal transportation, logistics, and the environment: managing interactions in a global economy," vol. 18, no. 4, pp. 398-410, 2000.
- [5] D. N. V. W. & R. SteadieSeifi, "Multimodal freight transportation planning: A literature review," vol. 233, no. 1, pp. 1-15, 2014.
- [6] G. Y. Gordon, *Securing Integrated Transportation Networks*, 1st edition ed., San Diego: Elsevier, 2024.
- [7] T. C. Rotaris, "Combined transport: Cheaper and greener. A successful Italian case study," vol. 43, 2022.
- [8] M. B. T. Giusti, "Sychromodal logistics: An overview of critical success factors, enabling technologies, and open research issues," vol. 129, pp. 92-110, 2019.
- [9] EEA, "Transport and Mobility," 10th February 2025. [Online]. Available: <https://www.eea.europa.eu/en/topics/in-depth/transport-and-mobility>.
- [10] G. H. R. Pálsson, *Port and Maritime Transport Challenges in West and Central Africa*, Washington D.C.: World Bank, 2007.
- [11] EU, "Green Deal: Greening freight for more economic gain with less environmental impact," 11th July 2023. [Online]. Available: https://commission.europa.eu/index_en.
- [12] B. T. E. P. N. K. Dragovic, "Simulation modelling in ports and container terminals: Literature overview and analysis by research field, application area and tool," vol. 29, 2017.
- [13] UNCTAD, "Review of Maritime Transport 2024," 22nd October 2024. [Online]. Available: <https://unctad.org/publication/review-maritime-transport-2024>.
- [14] P. R. Notteboom, *Port Economics, Management and Policy*, New York: Routledge, 2022.

- [15] M. G. Burns, *Port Management and Operations*, 1st edition ed., Boca Raton, FL: CRC Press, 2015.
- [16] B. Dalla Chiara, *Handouts*, Politecnico di Torino: Master Degree of Civil Engineering, 2023-2024.
- [17] A. McKinnon, "Efficient hinterland transport infrastructure and services for large container ports," no. 19, 2013.
- [18] A. R. De Palma, "Port Hinterland Connectivity," *International Transport Forum Discussion Papers*, no. 13, 2015.
- [19] C. G. S. S. T. T. Borruso, "Rail Ports as Nodal Gateways in the Sea: Land Connections and the Challenges of Sustainable Globalized Markets: The Case of Adriafer and the Port of Trieste," p. 425–441, 2023.
- [20] HHM, "Europe's largest rail port," Hafen Hamburg Marketing, 2024. [Online]. Available: <https://www.hafen-hamburg.de/>.
- [21] ERA, "Fostering the Railway Sector through the European Green Deal: Rail Ports Synergies," EU, 10th October 2020. [Online]. Available: <https://www.era.europa.eu/>.
- [22] RAM S.p.a., "Rapporto di Sintesi: Porti e Traffici Intermodali," 2022. [Online]. Available: <https://www.ramspa.it/>.
- [23] Z. Z. Liu, "Analysis of collaborative operation of port logistics system based on system dynamics," 2024.
- [24] S. S. Caballini, "The port as a system of systems: A System Dynamics simulation approach," pp. 191-196, 2012.
- [25] S. Sacone, "An integrated simulation-optimization framework for the operational planning of seaport container terminals.," vol. 15, p. 275–293.
- [26] UiB, "What is System Dynamics?," 14th August 2025. [Online]. Available: <https://www.uib.no/en>.
- [27] W. G. Rieder, "Simulation and Modeling," in *Encyclopedia of Physical Science and Technology*, 3rd edition ed., Robert A. Meyers, 2003, pp. 815-835.
- [28] The AnyLogic Company, "What is Agent-Based Simulation Modeling?," [Online]. Available: <https://www.anylogic.com/>.

- [29] M. Cristopher, Logistics and supply chain management, 4th edition ed., Harlow: Pearson, 2011.
- [30] R. W. K. Shibasaki, Global and International Logistics, Basel, Switzerland: MDPI - Multidisciplinary Digital Publishing Institute, 2021.

Attachment 1 - Road network model

