The business case for autonomous transport in the port of Vlissingen

Public version

Living Lab Autonoom Transport Zeeland

LECTORAAT SUPPLY CHAIN INNOVATION

16-10-2023

HZ UNIVERSITY OF APPLIED SCIENCES

Ahmad Mir Mohammadi Kooshknow

Evelot Westerink-Duijzer

Lectoraat Supply Chain Innovation
16-10-2023
Vlissingen

This analysis is part of the project Living Lab Autonoom Transport Zeeland.

This project is made possible by the European Regional Development Fund, the Dutch government and the Province of Zeeland as part of OPZuid.

Picture front page: Beeldbank Living Lab Autonoom Transport Zeeland

Contents

EXECUTIVE SUMMARY

Automation of transport has several potential advantages, such as an increase in road capacity, in road safety and in driving comfort. In addition, automation offers a significant solution to the growing challenge of the driver shortage. In this report, we examine the impact of using autonomous vehicles in the port of Vlissingen, comparing performance with regular vehicles. We also identify the synergy effects that can be achieved with a shared pool of autonomous vehicles that can be used by multiple companies.

The results show that the implementation of autonomous vehicles brings several advantages, despite the initial increase in equipment costs. First of all, the implementation of autonomous vehicles leads to a reduction in personnel costs. Because the vehicles are self-driving, a single control room employee can monitor several vehicles simultaneously, resulting in significant savings on personnel.

In addition, we see that autonomous vehicles bring a substantial reduction in fuel costs. The fact that autonomous vehicles have an electric driveline ends dependency on fossil fuels and reduces fuel costs in the long run. This is not only financially attractive, but is also results in lower CO_2 emissions, thereby contributing to a greener and more environmentally friendly future.

We find that the operator-to-vehicle ratio is crucial for the economic attractiveness of autonomous transport. When this ratio increases, more control room employees will be needed and personnel costs will increase. Therefore, it is important to study this parameter carefully, as it directly affects the overall financial feasibility of implementing autonomous vehicles.

The results of our research show that the synergy effects of a pool of autonomous vehicles are limited. Small cost reductions can be achieved, because equipment can be used slightly more efficiently. This is particularly beneficial for the smaller companies, that would need only one or two autonomous terminal tractors for their own operations. Larger companies can already achieve efficient deployment of the vehicles on their own. The restricted potential for synergy is mainly caused by the high similarity in opening hours and peak demands over all companies.

Based on the findings in this report, we advise the companies in the port of Vlissingen to consider autonomous vehicles as a financially attractive alternative to regular terminal tractors. Larger companies can invest in this new technology themselves, but for smaller companies the investment might be a burden. Despite the limited financial advantages of a shared pool of autonomous vehicles, we see potential benefits of cooperation as a way to enable wider adoption of automated transport. Since cooperation is not directly in the interest of larger companies, initiative by an external party could be recommended, such as the port authorities or a company renting out the vehicles. The strategic adoption of autonomous vehicles by multiple companies in the port of Vlissingen strengthens the position of the port in the market while contributing to a greener and more sustainable future.

Chapter 1. Introduction

Nowadays, autonomy can be seen as an inevitable paradigm in the modern transportation and logistics sector. Increased road capacity, traffic safety, and driving comfort are generally considered to be potential benefits of automation. Furthermore, when it comes to the logistics sector, resolving the problem of the ever-increasing driver shortage is a big advantage autonomy can bring. Despite the potential benefits, the widespread operation of autonomous vehicles in the transportation sector has not come true yet. An important barrier to implementation is the financial investment needed to adopt autonomous vehicles.

In this report, which is published as part of the Living Lab Autonomous Transport Zeeland project, we investigate the possibilities for autonomous transport in the port of Vlissingen. The Living Lab Autonomous Transport Zeeland project is developing an open innovation system in which logistics companies, technology providers for autonomous vehicles, road authorities, and knowledge institutions jointly innovate and experiment with autonomous vehicles with mixed traffic in real-life logistics operations and on public roads. Part of this joint innovation is the analysis of business cases for the use of autonomous transport in complex traffic situations at various logistics service providers and for the whole port of Vlissingen.

1.1 Port of Vlissingen

The port of Vlissingen is part of North Sea Port, which is the third largest port of the Netherlands. This port environment is not too complex and the roads around the port are still limited in traffic and complexity, which makes this port area particularly suitable for experimenting with autonomous transport on site and on public roads.

Multiple companies in the port of Vlissingen are investigating the possibilities of implementing autonomous transport on their terminals. For smaller companies, which would only need a few autonomous vehicles, the required investments might be a bottleneck. Compared to large parties that deploy dozens of vehicles, these smaller companies can benefit less from economies of scale. In addition, the occupancy rate of their vehicles is expected to be lower. As a result, it is more difficult for smaller companies to keep up with this innovation and they can lose their competitive position. In this article, we therefore study two scenarios. First, we analyze the business case for company-owned autonomous vehicles. In addition, we also determine the synergy that can be achieved when companies make use of a shared pool of autonomous vehicles. By sharing the vehicles, investment costs can be spread and the vehicles can be used more efficiently.

1.2 Autonomous transport

When discussing the implementation of autonomous transport, it is good to define what we mean with autonomy. The Society of Automotive Engineers (SAE) identifies different levels of autonomous driving, ranging from level 0 (fully manual) to level 5 (fully autonomous) (SAE International, 2021). In this report we consider autonomous transport at level 4 or 5. At these levels no driver is needed in the vehicle and the vehicle can drive autonomously in specific areas and conditions (level 4) or under all circumstances (level 5). At these levels the automated system has taken over all human tasks in the vehicle. This only concerns the driver tasks that relate to driving the vehicle. Any other actions performed by the driver, such as assistance with loading and unloading, have to be handled in another way and are not taken over by the autonomous vehicle.

1.3 Safety

Safety is an important prerequisite for the success of autonomous transport. The switch from human-driven transport to autonomous transport has various impacts on safety. We briefly discuss three aspects of safety: the safety of other road users, driver safety, and the safety of the cargo.

The safety of other road users

Similar to a human-driven vehicle, an autonomous vehicle comes into contact with all kinds of road users. In the port of Vlissingen this is not limited to users on private property but may extend to public road users. Safety must be guaranteed for all these road users. Guidelines for machine safety can be applied on-site. When entering public roads, official permission from authorities such as the road authority and the RDW is required.

Driver safety

In regular transport, the driver is responsible for driving the vehicle and in some cases also for assistance with loading and unloading. This can results in environments in which vehicles and pedestrians move simultaneously, which brings about safety risks. With a shift to autonomous transport, these risks are considerably decreased as we are removing the drivers from the vehicles.

The safety of the cargo

Drivers are usually aware of the way the cargo is loaded and thereby adapt their driving style to reduce the risk of damage to the cargo. This can be a challenge for an autonomous vehicle, especially if an emergency stop has to be made. This could mean that an autonomous vehicle acts differently than a driver, possibly with a higher risk of damage to the load. The cargo damage risk decreases when the load is containerized, which is the case for part of the transport in the port of Vlissingen.

1.4 Structure report

The remainder of this report is structured as follows. In Chapter 2, we discuss the port of Vlissingen and the companies included in the analysis of this report. Chapter 3 discusses the scope of the study and the used methodology. The results of the business case and comparison of costs are provided in Chapter 4. Finally, the report comes to the concluding discussions in Chapter 5.

Chapter 2. Autonomous transport in the port of Vlissingen

In this chapter, we discuss the port of Vlissingen which is used as a case study in this report. We first describe the layout of the port in Section 2.1 and introduce the companies included in our analysis. Section 2.2 explains the concept of the Central Gate. Finally, we give an overview of the transport flows of the included companies in Section 2.3.

2.1 Port of Vlissingen

In this report we analyse the implementation of autonomous terminal tractors in the port of Vlissingen. Together with the port of Terneuzen, Vlissingen is part of North Sea Port. After Rotterdam and Amsterdam this is the third largest port in the Netherlands, with a transshipment volume of 38.3 million ton in 2021 (CBS, 2021). North Sea Port participates in the project Living Lab Autonomous Transport Zeeland and is interested in investigating the possibilities of using autonomous terminal tractors within its port.

Previous research has been done by students from HZ University of Applied Sciences in order to identify the size of transportation flows in the port of Vlissingen (Van den Dries, Van Hekke, & Vermeulen, 2021). In this report we use their data in the business case calculations. Included in their analysis are six companies: Verbrugge, Lineage Logistics, Access World, Vopak, MSP Onions and Van Keulen. Figure 1 shows the layout of the port and including the geographical location of each of these companies.

Figure 1: Layout of the port of Vlissingen including the locations of the companies involved and the Central Gate.

As can be seen in Figure 1 we distinguish between two locations for Verbrugge: the Zeeland Terminals (VZT) and the Scaldia Terminals (VST). Lineage Logistics, Vopak and Access World all have a single location within the port of Vlissingen. MSP Onions is located just outside the port. The figure does not show the location of Van Keulen, since this is a transport company located in Middelburg. In our analysis, we include trips performed by Van Keulen that take place within the port of Vlissingen.

We realize that our analysis is limited by the fact that we do not have data available of the road transport of all companies in the port of Vlissingen. However, the six selected companies together are responsible for around 70% of all incoming and outgoing transshipments by road in the port of Vlissingen (North Sea Port, 2023). They thereby represent the majority of road transport and we assume they constitute a representative sample.

2.2 Central Gate

North Sea Port is located in a rapidly changing environment with transitions in the field of energy and climate, logistics, technology and digitization. Continued innovation in these domains is therefore of great importance. Part of these important innovations is the concept of a possible central gate. The central gate is a central point on the edge of the port of Vlissingen that will serve as a (de)coupling point to keep the external traffic (regular trucks) outside the port. Currently, the port of Vlissingen does not have a central gate, but a potential location has been identified by North Sea Port. This potential location is indicated with a 'P' in Figure 1.

In our analysis we investigate multiple scenarios for autonomous transport, assuming the existence of the central gate where trucks will leave their load and autonomous vehicles will pick up the loads and move them inside the port. To make a fair comparison between the different scenarios with and without autonomous vehicles, we assume that the trips performed in each scenario are the same. That implies that also in the situation without autonomous vehicles, we assume that the load is dropped off at the central gate and transported into the port with regular terminal tractors. Our analysis only includes transport generated by the six included companies. Assumptions on the trips performed by other companies are therefore not needed. Hence, the question whether they also visit the central gate or not is outside the scope of our report.

The concept of the central gate is extensively studied within the CATALYST project. More information on this project can be found online (TNO, 2020). Within this project a simulation study is performed exploring the possibilities of performing first- and last-mile transport with autonomous terminal tractors (Distribute, 2021). The simulation study provides insights into the logistic performance of the central gate, assuming a fixed number of trucks arriving uniformly over the day. In our business case analysis we use more realistic data and also include variation in demand over time.

2.3 Data

In this report, we distinguish between three types of transport flows:

- **Shuttle:** vehicles moving on the premises of one company,
- **Intraportal:** vehicles moving between companies in port of Vlissingen,
- **In/outbound[1]:** vehicles coming in and going out of port of Vlissingen.

Figure 2 presents a schematic overview of these three transport flows.

[1] In this report the term in/outbound refers to inbound OR outbound trip.

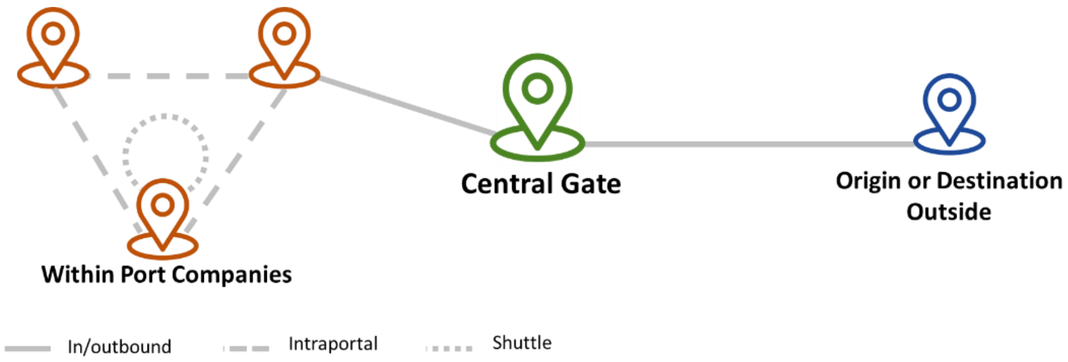

Figure 2: Visualization of the three types of transport: in/outbound, intraportal and shuttle.

We use the data collected by the students (Van den Dries, Van Hekke, & Vermeulen, 2021). We note that this is historical data covering truck movements in 2020. Their results showed that the port has substantially more outbound trucks than inbound trucks. On weekdays on average 500 outbound trucks visit the port, which is roughly twice the amount of inbound trucks. Lineage Logistics and Verbrugge are the largest companies. Together they account for more than 90% of trip durations in our dataset.

The six companies included in our analysis have different transport flows, indicated in Table 1. The first four companies are terminals, visited by many inbound and outbound trucks. Verbrugge and Lineage Logistics are the largest two terminals and they also have terminal trucks driving on their own premises, labelled as shuttle services. MSP Onions is an exporting company that sends trucks to the terminal of Lineage on a daily basis. Since both MSP Onions and Lineage are located in or close to the port of Vlissingen, we consider this transport to be intraportal. Finally, we have Van Keulen, a transport company that performs all kinds of trips. From their data we have the start and end location of each trip, which enables us to determine whether the trips is in/outbound, intraportal or shuttle.

	Shuttle	Intraportal	Inbound/Outbound	Share of all workloads
1. Verbrugge	✓		✓	32 %
2. Lineage Logistics	✓		✓	61 %
3. Access World			✓	1 %
4. Vopak			✓	1 %
5. MSP Onions		✓		2 %
6. Van Keulen	✓	✓	✓	3 %

Table 1: Overview of the types of trips included in our analysis for each company.

Table 1 presents some summary statistics of the data on which our results are based. The last column in Table 1 shows that the vast majority of trips in our dataset is connected to Lineage Logistics. Verbrugge is responsible for almost a third of all workload. The remaining four companies together account for the remaining 7%. Figure 3 gives an overview of the average number of trips for the various days of the week and the hours of the day.

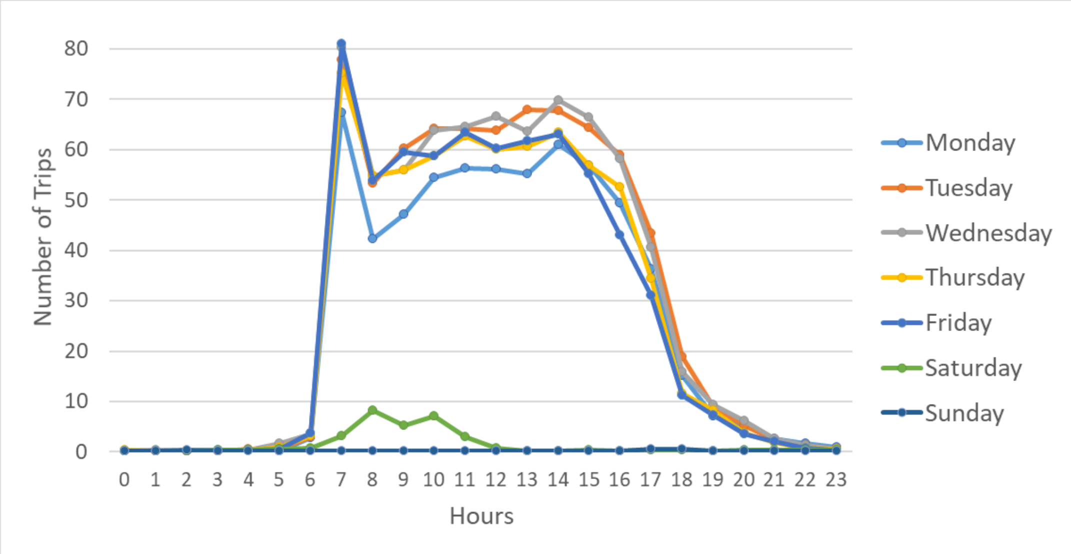

Figure 3: Average number of trips in the port of Vlissingen per hour of the day and day of the week.

Figure 3 shows that most trips take place during weekdays between 7 AM and 18 PM. There is a peak at 7 AM when the terminals open, after that there are on average 60 trips per hour until terminals close around 18 AM.

2.4 Shifts

Most companies officially open between 7:00 AM and 7:30 AM, with their operating hours extending at least until 3:00 PM. Some companies close between 17:00 PM and 17:30 PM, while others maintain official hours until 23:30 PM or even operate 24 hours a day. Table 2 provides detailed information about the official open hours of these companies.

Company	Open hours
Vopak	24 hours
MSP Onions	7:30-17:00
Access World	7:00-15:00
Lineage	7:00-17:00
VZT	7:30-23:30
VST	7:30-23:30
van Keulen	9:00-17:30

Table 2: Official open hours of companies (from google)

However, despite the official working hours outlined in Table 2, which were obtained through a Google search, the available data indicate that for certain companies, such as Lineage and Verbrugge, there are reports of trips during the midnight hours.

In this report, we have established generic shifts that are standardized across all companies. The historical data of their activities determines whether each company adheres to a particular shift or not. The shifts identified in this report are as follows:

- Shift 1: 7:00 – 15:00
- Shift 2: 15:00 – 23:00
- Shift 3: 23:00 – 7:00

Chapter 3. Principles

This section elaborates on the principles, assumptions and scenarios of the business case analysis for autonomous transport in the port of Vlissingen.

3.1 Scenarios

This report considers three scenarios for transporting goods in the port of Vlissingen. The scenarios are images of the port future in which a central gate is built and plays important role in logistics of the port. The following three scenarios are evaluated and compared, where scenario A makes use of regular terminal tractors (TTs) and scenario B and C use autonomous terminal tractors (ATTs).

- **Scenario A - Non-autonomous transport:** This scenario is the continuation of the current procedures and non-autonomous transport in the presence of the central gate.
- **Scenario B - Company-owned ATTs:** This scenario describes and situation in which each company owns a number of ATTs and performs the port transport with the new technology.
- **Scenario C - Pool of ATTs:** This scenario is an image of a port future in which a company (called third party in the current report) will own and monitor/control a number of ATTs. Other companies pay this third party for using vehicles to perform their logistics operations.

The aim of the analysis is to compare the three scenarios and find the scenario with minimum total costs.

3.2 Pooling Scheme

There are four potential schemes for pooling autonomous terminal tractors (ATTs) at the port of Vlissingen, which we study in Scenario C. One way of pooling is to charge companies based on the kilometers their ATTs drive (pay per use scheme). Another option is to rent vehicles at a fixed price for fixed periods (rental scheme). It is also possible to lease vehicles with all-in monthly prices for a minimum period of time (operational lease). Finally, companies can jointly purchase vehicles and share them among themselves (joint purchase scheme).

In this analysis, the rental scheme is selected as the pooling scheme. In this scheme, companies pay the rent for using vehicles. This rent includes costs for charging vehicles at the lower price (own-station price) in the charging stations of the third party.

3.3 Assumptions

To obtain our results, we make the following assumptions:

- External trucks are either decoupled or unloaded at central gate and the rest of journey takes place by (autonomous) terminal tractors.
- A trip is considered to be a one-way trip including (un)loading at the terminal and (de)coupling at the central gate.
- Detours to reach a charging station and waiting times in case of queues at charging stations are neglected.
- It takes 21 minutes for a vehicle to be loaded/unloaded and coupled/decoupled. When the (un)loading + (de)coupling takes more than 21 minutes, the vehicle will not stay with the load. This is in line with the assumptions in earlier studies, assuming 15 minutes dwell time for the terminal tractor on the terminal and 6 minutes (de)coupling time (Distribute, 2021).
- For scenario A we assume that the driver has one hour of resting time per shift. During that hour, the vehicle also stands still. We assume that autonomous vehicles in scenario B and C do not have resting time, and they can drive the entire shift.

- For scenario C (ATT pool), the rental price for all shifts and all days is the same. The idea behind this assumption is that ATTs can potentially work 24/7 and without encountering scarcity of drivers. The demand for control room operators may add to costs of the nights or weekends shifts, but the abundance of non-utilized vehicles in those shifts can reduce the price of using the vehicles.
- For scenario C, it is assumed that the third party already has the pooling platform for collaboration and it only needs to cover costs of material, personnel, and charging stations.
- For scenario C, the third party's operators handle the movement of ATTs for all subscribers.
- Due to unavailable data, for intraportal trips of van Keulen and shuttle trips of Lineage and Verbrugge, we assume that the engine of vehicles is always ON during the trips, both during driving and during (un)loading and (de)coupling.

3.4 Scope

The business case analysis in this report covers the comparison of annual operational costs and CO_2 emissions among three scenarios of using autonomous transport (company-owned and pool) and using conventional transport in the port of Vlissingen.

The current analysis concentrates on the main items in material, personnel and energy costs, and does not include other cost type. In this analysis time-value of money, taxes, depreciations, risks and social impact analysis is not covered. In addition, the following items are not included in this analysis:

- the cost of infrastructural changes required to allow autonomous vehicles to drive safely along the intended route;
- the cost of infrastructural changes required to have sufficient network capacity available;
- the costs for integration of IT systems, such as ERP or WMS systems;
- the costs of automating certain processes, such as automatic loading and unloading;
- the costs of digitizing transport documentation;
- any other costs that may result from the implementation of autonomous vehicles.

Chapter 4. Business case

The current business case analysis contains the following sections. In Section 4.1, we present an overview of the required number of vehicles. Next we conduct an economic analysis (Section 4.2) and a sensitivity analysis on the important parameters (Section 4.3). In Section 4.4, the environmental analysis can be found. The methodology we used to obtain our results is explained in detail in Appendix A.

4.1 Required number of vehicles

The business case depends on the required number of trucks for all scenarios. In order to calculate the number of required trucks it is important to find the total hours required to perform companies' tasks. This depends on the total distances that vehicles should drive and their average speed. For in/outbound trips we have data on the average distance per trip for most companies, but for shuttle trips and some intraportal trips we have no data on the driven distances per trip. We therefore obtain travel times from expert opinions (by interview for Lineage and Verbrugge) or by using data on the operational time of the vehicles to directly calculate travel times (for Van Keulen).

4.1.1 Distance and travel times

For in/outbound trips, average distances for a one-way trip is equal to distance between companies and the central gate. These distances are presented in Table 3.

Average one-way in/outbound trip distance (km)				
Vopak	**Access World**	**Lineage**	**VZT**	**VST**
4	5,6	5,2	7,5	3,6

Table 3: Average distance for inbound/outbound trips.

Van Keulen is by nature a transporting company and its in/outbound trips are not always the same, therefore the average distance per trip cannot be calculated with the available data. However, it is possible to calculate travelled distance per shifts of different day types. Based on such calculations, and assumption that in each shift there is only one long trip, the distances of in/outbound trips of Van Keulen can be presented as presented in Table 4

Average distance for a hypothetical in/outbound trip of van Keulen (km)	
Weekdays - Shift 1	106,36
Weekdays - Shift 2	29,74
Weekdays - Shift 3	21,31
Weekends - Shift 1	0
Weekends - Shift 2	22,2
Weekends - Shift 3	18,25

Table 4: Average distance for inbound/outbound trips by Van Keulen.

Given the distances, the average driving time per trip for vehicles can be obtained by dividing distances over the speeds. The average speed on conventional terminal tractors and autonomous terminal tractors are assumed to be 35 km/h and 20 km/h, respectively. Average time per trip is the average driving time plus 21 minutes average (un)loading and (de)coupling time for all trips. Generally, the total trip durations equal to sum of moving duration and waiting duration. In this analysis, it is assumed that each trip has zero waiting time as no data is available to make other assumptions.

The next class of trips in this study are intraportal trips. For MSP Onions' intraportal trips, we have two different routes for the company's busiest and less busy months (see Appendix A.3). To find the average one-way trip distance for each period, we assume it is half of the path for the respective route. For the peak months, the path is a weighted average of two loops (see Appendix A.3). As a result, the average one-way distances are 4.86 km for peak months and 3.4 km for non-peak months. Similar to in/outbound trips, given the distances, the average driving time per trip for MSP Onions can be obtained by dividing distances over the speeds. In addition, total trip durations can be obtained by adding travel times with (un)loading and (de)coupling times.

In addition, we have intraportal trips by Van Keulen. For the intraportal trips of Van Keulen the distances are not known, but the travel times per different types of shifts can be obtained from the historical data as presented in Table 5.

Van Keulen Average average time per intraportal trips (h/trip)	
Weekdays-Shift 1	8,54
Weekdays-Shift 2	1,15
Weekdays-Shift 3	0,48
Weekends-Shift 1	0,91
Weekends-Shift 2	4,63
Weekends-Shift 3	0,00

Table 5: Average travel time for inbound/outbound trips by Van Keulen

For shuttle trips, we have data available from Verbrugge and Lineage, indicating total yearly travel times. To estimate the workload per shift and day, we assume that the distribution of these trips among different shifts of weekdays and weekends mirrors that of inbound and outbound trips. It is important to note that throughout this report, we maintain a clear distinction between Verbrugge Zeeland Terminal (VZT) and Verbrugge Scaldia Terminal (VST) because, for shuttle trips, trucks cannot be present at both locations simultaneously. Annual shuttle travel times are provided in Table 6.

Total yearly shuttle trip hours (h/y)	**Lineage**	**VZT**	**VST**
Weekdays-Shift 1	20.258,85	9.331,64	2.575,94
Weekdays-Shift 2	7.963,67	3.138,40	734,97
Weekdays-Shift 3	48,60	3.138,40	4,64
Weekends-Shift 1	527,66	0,00	0,00
Weekends-Shift 2	1,22	0,00	0,00
Weekends-Shift 3	0,00	0,00	0,00

Table 6: Total travel time for shuttle trips by Verbrugge and Lineage.

4.1.2 Number of Trips

To obtain yearly workload (travel time) of in/outbound, and intraportal trips, it is necessary to multiply the average trip durations by number of trips. The average number of trips for in/outbound trips are presented in Table 7. For Van Keulen, as we have total travelled distance for trips, we assume that in each shift there is only one long hypothetical trip that represents all the trips.

Average number of in/outbound trips per shift (trip/shift)	**Vopak**	**Access World**	**Lineage**	**Verbrugge VZT**	**Verbrugge VST**
Weekdays - Shift 1	9,52	5,80	289,55	100,50	27,74
Weekdays - Shift 2	3,4	0,20	113,80	33,80	7,92
Weekdays - Shift 3	1,36	0,00	0,70	0,56	0,05
Weekends- Shift 1	1,36	0,00	13,01	0,00	0,00
Weekends- Shift 2	1,36	0,00	0,07	0,00	0,00
Weekends- Shift 3	1,36	0,00	0,00	0,00	0,00

Table 7: Average number of inbound/outbound trips per shift.

For intraportal trips, the number of MSP Onions' trips are provided in Table 8. For van Keulen we analyze the trips assuming that this is only one hypothetical long trip per shift. In addition, for shuttle trips, no data is available on the number of trips and we consider only total travelled times as presented before in Table 6.

Average number of Intraportal trips per shift (trip/shift)	MSP Onions (peak)	MSP Onions (non-peak)
Weekdays - Shift 1	28,8	14,4
Weekdays - Shift 2	10,8	5,4
Weekdays - Shift 3	0,0	0,0
Weekends- Shift 1	0,0	0,0
Weekends- Shift 2	0,0	0,0
Weekends- Shift 3	0,0	0,0

Table 8: Average number of intraportal trips per shift.

4.1.3 Required vehicles

Based on the previous data, the required number of vehicles in each shift of a certain day type can be calculated. We refer to Appendix A for the details of our calculations. The average required number of vehicles per shift is usually a decimal number, and for scenarios A and B, for each shift the values are rounded up to obtain integer numbers of vehicles. Here, for both scenarios, the total required TTs and ATTs in the whole system is 57 (see Table 9 and Table 10). Note that, in the tables , we count the maximum of numbers per each shift type for MSP Onions, comparing peak and non-peak season.

The reason that the numbers are so close to each other in scenarios A and B is that despite the higher speed of TTs, it is assumed that one hour per each shift in scenario A is spend for resting of drivers which is not applicable for ATTs. Hence, the lower speed of ATTs is compensated by the fact that they can continue to drive during breaks.

Required TT per shift	Vopak	Access World	MSP Onions	Lineage	VZT	VST	van Keulen	Total in port
Weekdays-Shift 1	1	1	3	32	14	4	2	57
Weekdays-Shift 2	1	1	1	13	5	1	1	23
Weekdays-Shift 3	1	0	0	1	2	1	1	6
Weekends-Shift 1	1	0	0	2	0	0	1	4
Weekends-Shift 2	1	0	0	1	0	0	1	3
Weekends-Shift 3	1	0	0	0	0	0	1	2
Required TTs	**1**	**1**	**3**	**32**	**14**	**4**	**2**	**57**

Table 9: Required number of vehicles in scenario A.

Required ATTs per shift	Vopak	Access World	MSP Onions	Lineage	VZT	VST	Van Keulen	Total in port
Weekdays-Shift 1	1	1	3	32	14	4	2	57
Weekdays-Shift 2	1	1	1	13	5	1	1	23
Weekdays-Shift 3	1	0	0	1	2	1	1	6
Weekends-Shift 1	1	0	0	2	0	0	1	4
Weekends-Shift 2	1	0	0	1	0	0	1	3
Weekends-Shift 3	1	0	0	0	0	0	1	2
Required ATTs	1	1	3	32	14	4	2	57

Table 10: Required number of vehicles in scenario B.

For scenario C, the number of required vehicles per shift is permitted to be decimal as sharing is possible. However, the sum number of ATTs per each shift of a certain day type is rounded to its ceiling integer value to calculate the required ATTs to be purchased by the third party. The required ATTs for scenario C is equal to maximum of required ATTs for all shifts of all day types which is 55 (see Table 11) which saves 2 vehicles compared to scenario B.

Required ATT for pool per shift	Vopak	Access World	MSP Onions	Lineage	VZT	VST	van Keulen	Pool
Weekdays-Shift 1	0,65	0,46	2,14	31,82	13,59	3,08	1,44	55
Weekdays-Shift 2	0,23	0,02	0,80	12,51	4,57	0,88	0,28	20
Weekdays-Shift 3	0,09	0,00	0,00	0,08	1,56	0,01	0,17	2
Weekends-Shift 1	0,09	0,00	0,00	1,63	0,00	0,00	0,11	2
Weekends-Shift 2	0,09	0,00	0,00	0,01	0,00	0,00	0,69	1
Weekends-Shift 3	0,09	0,00	0,00	0,00	0,00	0,00	0,10	1
Max requirement per company	0,65	0,46	2,14	31,82	13,59	3,08	1,44	55

Table 11: Required number of vehicles in scenario C

4.2 Economic Analysis

In the economics analysis, three types of costs are considered in order to calculate the total costs of the system. The costs included material costs (costs of purchasing and maintaining vehicles), personnel costs (costs of relevant drivers/operators), and energy costs (costs of refueling/charging vehicles and building charging stations). All the costs are calculated in the form of uniform yearly costs.

4.2.1 Material Costs

Material costs include the purchase cost, insurance costs, and maintenance cost. Yearly purchase costs mainly depends on the number of required trucks, prices of vehicles, and life time of vehicles. Insurance costs is proportional to purchase price, and maintenance cost depends on the time vehicles are in use.

Based on discussions with a vehicle manufacturer we were able to derive estimates of the purchasing price for both TTs and ATTs. These values are confidential, but the purchasing price of an ATT is about three times larger than the purchasing price of regular TT. In addition, the lifetimes of a TT and ATT are 7 and 10 years, respectively, which we use to translate the purchasing price into yearly uniform purchasing costs. The annual insurance cost is taken as 3.5% of the purchasing price of the vehicle (Top Sector Logistics, 2019). Moreover, it is assumed that cost of maintenance of a TT and ATT in each hour is €2,5 and €1,7 per hour, respectively. Therefore, the maintenance cost for each company is calculated as the multiplication of total travel duration per year and the hourly maintenance costs.

Table 12, Table 13 and Table 14 present details of the yearly material costs in all three scenarios. We note that purchasing costs and insurance costs are not displayed separately because of their relation with purchasing prices which are confidential.

Material Costs: Scenario A	Vopak	Access World	MSP Onions	Lineage	Verbrugge	van Keulen
Maintenance costs (€/y)	4.802,01	1.989,00	8.591,93	204.638,55	107.289,15	10.519,18
Total material costs (€/y)	21.805,59	18.992,57	59.602,64	748.752,83	413.353,44	44.526,33
Total	1.307.033,39					

Table 12: Yearly material costs in Scenario A.

Material Costs: Scenario B	Vopak	Access World	MSP Onions	Lineage	Verbrugge	van Keulen
Maintenance costs (€/y)	3.868,21	1.670,76	6.972,84	159.312,23	83.754,68	7.975,08
Total material costs (€/y)	40.093,21	37.895,76	115.647,84	1.318.512,23	735.804,68	80.425,08
Total	2.328.378,79					

Table 13: Yearly material costs in Scenario B.

Material Costs: Scenario C	Third party
Maintenance costs (€/y)	263.553,79
Total material costs (€/y)	2.255.928,79

Table 14: Yearly material costs in Scenario C.

We compare the total yearly material costs over all three scenarios in Table 15.

Material costs: All Scenarios	Scenario A	Scenario B	Scenario C
Vopak	21.805,59	40.093,21	0,00
Access World	18.992,57	37.895,76	0,00
MSP Onions	59.602,64	115.647,84	0,00
Lineage	748.752,83	1.318.512,23	0,00
Verbrugge	413.353,44	735.804,68	0,00
van Keulen	44.526,33	80.425,08	0,00
Third Party	0,00	0,00	2.255.928,79
Total	1.307.033,39	2.328.378,79	2.255.928,79

Table 15: Overview of yearly material costs in all scenarios.

In terms of material costs, scenario A has minimum costs followed by scenarios C and B. Scenario A has minimum material costs as the number of required TTs is close to number of required ATT for scenarios B and C, and the purchase prices and insurance prices of TTs are considerably lower. Here, scenario C is more economic than scenario B as the required ATT in lower while the purchase price, insurance costs and maintenance costs are the same.

4.2.2 Personnel Costs

The personnel required to perform truck activities are different in TT and ATT scenarios. For TTs, drivers are required to perform activities and for ATTs control room operators are required. For scenario C, it is assumed that control room operators hired by the third party will control ATTs rented by companies.

Each driver can be assigned to one TT but each control room operator can control four ATTs simultaneously (r=0.25). It is also assumed that one full-time driver/operator works 235 days (shifts) per year. The salary of control room operator is assumed to be 50% higher than salary of drivers due to higher skills required for their activities. An overview of the parameters used to calculate personnel costs can be found in Table 16.

Personnel analysis parameters	TT		ATT	
	Weekdays	**Weekends**	**Weekdays**	**Weekends**
r=operator-to-vehicle ratio (person/vehicle)	1		0.25	
number of operational days per year (d/y)	260	104	260	104
work amount per working day (person.shift/d)	1		1	
number of working days per 1fte per year (d/fte/y)	235		235	
Yearly Driver/Operator expenses for 1 fte (€/fte/y)	47034		70551	

Table 16: Overview of parameters used for personnel costs.

Given the personnel parameters above, it is the number of trucks per shift which determines how much FTE personnel is required to that certain shift type per year. Accordingly, the required personnel and their costs detail are for each scenario are provided in Table 17,Table 18, and Table 19.

Yearly required drivers (FTE): Scenario A	Vopak	Access World	MSP Onions	Lineage	Verbrugge	van Keulen
Weekdays - Shift 1	1,11	1,11	3,32	35,40	19,91	2,21
Weekdays - Shift 2	1,11	1,11	1,11	14,38	6,64	1,11
Weekdays - Shift 3	1,11	0,00	0,00	1,11	3,32	1,11
Weekends - Shift 1	0,44	0,00	0,00	0,89	0,00	0,44
Weekends - Shift 2	0,44	0,00	0,00	0,44	0,00	0,44
Weekends - Shift 3	0,44	0,00	0,00	0,00	0,00	0,44
Total Required FTE	4,65	2,21	4,43	52,22	29,87	5,75
Yearly personnel costs (€/y)	218.557,99	104.075,23	208.150,47	2.456.175,52	1.405.015,66	270.595,61

Table 17: Required personnel in Scenario A.

Yearly required operators (FTE): Scenario B	Vopak	Access World	MSP Onions	Lineage	Verbrugge	van Keulen
Weekdays - Shift 1	0,28	0,28	0,83	8,85	4,98	0,55
Weekdays - Shift 2	0,28	0,28	0,28	3,60	1,66	0,28
Weekdays - Shift 3	0,28	0,00	0,00	0,28	0,83	0,28
Weekends - Shift 1	0,11	0,00	0,00	0,22	0,00	0,11
Weekends - Shift 2	0,11	0,00	0,00	0,11	0,00	0,11
Weekends - Shift 3	0,11	0,00	0,00	0,00	0,00	0,11
Total Required FTE	1,16	0,55	1,11	13,06	7,47	1,44
Yearly personnel costs (€/y)	81.959,25	39.028,21	78.056,43	921.065,82	526.880,87	101.473,35

Table 18: Required personnel in Scenario B.

Yearly required operators (FTE): Scenario C	Required FTE	Yearly Personnel costs (€/y)
Weekdays - Shift 1	15,21	1.073.275,85
Weekdays - Shift 2	5,53	390.282,13
Weekdays - Shift 3	0,55	39.028,21
Weekends - Shift 1	0,22	15.611,29
Weekends - Shift 2	0,11	7.805,64
Weekends - Shift 3	0,11	7.805,64
Total	21,74	1.533.808,76

Table 19: Required personnel in Scenario C.

Table 20 gives an overall comparison of personnel costs in all three scenarios. Despite higher salaries for control room operators, adoption of ATTs results in significant decrease in personnel costs which can be seen by comparing scenarios B and C with scenario A. Among scenarios B and C, ATT pool has lower personnel costs because less vehicles are required to be controlled and therefore less staff is needed.

Personnel costs (€): All Scenarios	Scenario A	Scenario B	Scenario C
Vopak	218.557,99	81.959,25	0,00
Access World	104.075,23	39.028,21	0,00
MSP Onions	208.150,47	78.056,43	0,00
Lineage	2.456.175,52	921.065,82	0,00
Verbrugge	1.405.015,66	526.880,87	0,00
van Keulen	270.595,61	101.473,35	0,00
Third Party	0,00	0,00	1.533.808,76
Total	4.662.570,49	1.748.463,93	1.533.808,76

Table 20: Overview of yearly personnel costs in all scenarios.

4.2.3 Energy Costs

Energy is the third main cost type that we consider in this analysis. For scenario A (TT) the energy costs depend on engine-on time of vehicles and average diesel price by external parties. For scenarios B and C, the costs of building charging stations and charging vehicles at the station is included in the scope of the analysis. For scenario B (own ATT) each company has to build its own charging station(s) and recharge the vehicles there, and in scenario C the charging stations are built by the third party at the location of central gate and companies only pay for recharging the vehicles at the same price as scenario B. In addition, it is assumed that no extra trip is required for refueling/recharging of vehicles.

In this report, we assume that companies use a HPC150 high-capacity charging station (Top Sector Logistics, 2019). The cost of installing a HPC150 charging station is €66000 and its expected lifetime is 10 years. In addition, it is assumed that each charging station has operational costs equal to €6546 per year. The capacity of each station is 150 kWh, and we assume that it is available only 30% of times. Details of energy costs parameters are provided in **Table 21**.

Parameter	Value
Average TT fuel consumption per hour (liter/h)	8
Diesel price by external party (€/liter)	1,84
Average ATT electricity consumption (kWh/h)	25
Charging station capacity (kW)	150
availability of charging station (%)	0.3
Installation cost for a private HPC150 charging station (€)	66.000
Charging station lifespan (y)	10
Charging station operational costs (€/y)	6.546
Average cost of electricity from own charging station (€/kWh)	0,08

Table 21: Overview of parameters used for energy costs.

4.2.3.1 Engine-on times

The engine-on times of vehicles during a year in different shift types for all scenarios are provided in Table 22 and Table 23. Generally, in ATT scenarios longer engine-on times are observed because ATTs complete the same task as TTs with lower speed and there is no resting time per shift as there is no driver in an autonomous vehicle.

Scenario A: TT Total engine-on time (h/y)	Vopak	Access World	MSP Onions	Lineage	VZT	VST	van Keulen
Weekdays - Shift 1	282,88	241,28	645,62	31.443,83	14.931,26	3.317,89	13.69,84
Weekdays - Shift 2	101,03	8,32	242,11	12.359,68	5.021,66	946,67	272,61
Weekdays - Shift 3	40,41	0,00	0,00	75,79	3.169,60	5,98	221,73
Weekends - Shift 1	16,16	0,00	0,00	412,09	0,00	0,00	29,03
Weekends - Shift 2	16,16	0,00	0,00	1,49	0,00	0,00	380,52
Weekends - Shift 3	16,16	0,00	0,00	0,00	0,00	0,00	63,51

Table 22: Total engine-on time in Scenario A.

Scenarios B,C: ATT Total engine-on time (h/y)	Vopak	Access World	MSP Onions	Lineage	VZT	VST	van Keulen
Weekdays - Shift 1	495,04	422,24	1.129,83	39.832,57	19.130,98	3.874,36	1.666,12
Weekdays - Shift 2	176,80	14,56	423,69	15.656,68	6.434,10	1.105,44	355,44
Weekdays - Shift 3	70,72	0,00	0,00	96,19	3.193,00	6,98	281,09
Weekends - Shift 1	28,29	0,00	0,00	879,45	0,00	0,00	29,03
Weekends - Shift 2	28,29	0,00	0,00	2,98	0,00	0,00	405,25
Weekends - Shift 3	28,29	0,00	0,00	0,00	0,00	0,00	83,85

Table 23: Total engine-on time in Scenario B and C.

4.2.3.2 Required Charging stations

For scenarios B and C, it is assumed that charging stations should be built. The number of charging stations can be calculated by dividing total energy consumption of vehicles per year over total available capacity of a charging station. The former can be calculated as multiplication of total engine-on time of vehicles per year and the average ATT electricity consumptions per hour.

Table 24 illustrates the number of charging stations required per company in scenarios B and C, the expected utilization of the available capacity (30% of total capacity), and the yearly cost of installing and operating charging stations.

For scenario B, building and operating charging stations seems to be efficient only for Lineage and Verbrugge. It is also worth noting that utilization of Verbrugge charging stations are high and it implies that the company cannot combine the charging stations requirements of its two branches. For other companies the utilization of charging stations are too low. In addition, the total cost of building charging stations in scenario C (ATT pool) is significantly lower because four fewer stations should be installed and operated.

Annual costs of charging stations: All scenarios	Company	Required charging stations	Utilization of available capacity (%)	Total costs per company (€/y)	Total costs in port (€/y)
Own ATT	Vopak	1	5%	13.146	157.752
	Access World	1	4%	13.146	
	MSP Onions	1	14%	13.146	
	Lineage	4	90%	52.584	
	Verbrugge VZT	3	85%	39.438	
	Verbrugge VST	1	44%	13.146	
	Van Keulen	1	18%	13.146	
ATT Pool	Third party	7	87%	92.022	92.022

Table 24: Overview of required charging stations, their utilization and costs in Scenario B and C.

4.2.3.3 Energy expenses

Table 25 illustrates the overall view on energy costs of companies per scenario. For TTs, the numbers only include the cost of refueling vehicles, for Own ATT the numbers include the costs of building and operating charging stations plus costs of recharging vehicles at the stations. For ATT-Pool scenario the numbers for the third party show the costs of installing and operating the charging stations whereas the numbers for other companies shows the costs of recharging vehicles.

Generally, the energy expenses when using TTs are significantly higher than in ATT scenarios; and between ATT scenarios the total energy costs of the system is significantly lower for ATT pool as fewer charging stations should be installed and operated and the utilization of assets is higher.

Energy Costs: All scenarios	Scenario A	Scenario B	Scenario C
	TT	Own ATT	ATT- Pool
Vopak	6.959,82	14.800,85	1.654,85
Access World	3.674,11	14.019,60	873,60
MSP Onions	13.067,29	16.253,03	3.107,03
Lineage	651.991,22	165.519,74	112.935,74
Verbrugge	403.225,87	120.073,72	67.489,72
Van Keulen	34.404,13	18.787,57	5.641,57
Third party	0,00	0,00	92.022,00
Total energy costs (€/y)	1.113.322,40	349.454,50	283.724,50

Table 25: Overview of yearly energy costs in all scenarios.

4.2.4 Overall Analysis

In this report, we calculate the total costs of different scenarios, which encompasses material, personnel and energy costs. Although for the scenario of non-autonomous vehicles the material costs are lower than for scenarios of adopting autonomous vehicles, the personnel and energy costs are much higher when using non-autonomous transport. In this section, we provide an overall analysis of total costs in all scenarios. For scenario C, the costs of companies and the third party depends on the rental price per shift. Here we consider two sub-scenarios:

- ATT-Pool-minimum rate: Given the assumptions of the current analysis, the minimum rental fee for an ATT is 200,30 €/shift. Using this rate, third party can cover the costs of material, personnel and charging stations, however it effectively makes no profit. With any rate above the 200,30 €/shift, the third party will make more revenues than its costs.
- ATT-pool-maximum rate: When the rental fee is 218,51 €/shift, the total costs of companies in scenario C (excluding the third party) becomes equal to the total costs of companies in scenario B. This is considered as the maximum acceptable rental rate for the pooling, and the third party will make the highest profit in this condition.

In our analysis, we assume that the rental fee includes all costs except for the used electricity. Hence, companies renting a vehicle for a shift only have to pay for the electricity that this vehicle uses during the shift.

Figure 4 illustrates the total costs of companies in all scenarios. Major share of total costs in all scenarios belong to Lineage and Verbrugge (especially for VZT). It is obvious that the total costs of employing conventional terminal tractors is significantly higher than the scenarios of adopting autonomous trucks. The total costs of companies in Scenario B (own ATT) and Scenario C (ATT pool) with maximum rate are equal, and at this rental rate the third party has significant negative costs which indicates profit. Finally, in Scenario C with minimum rate all costs of the third party is covered by rental revenues (with no profit) and total costs of other companies (rent + recharging) is lower than in Scenario B. Therefore, it can be concluded that with any rental value greater than 200,30 €/shift and less than 218,51 €/shift the scenario of implementing ATT pool is more economic than other scenarios for the current companies in the port.

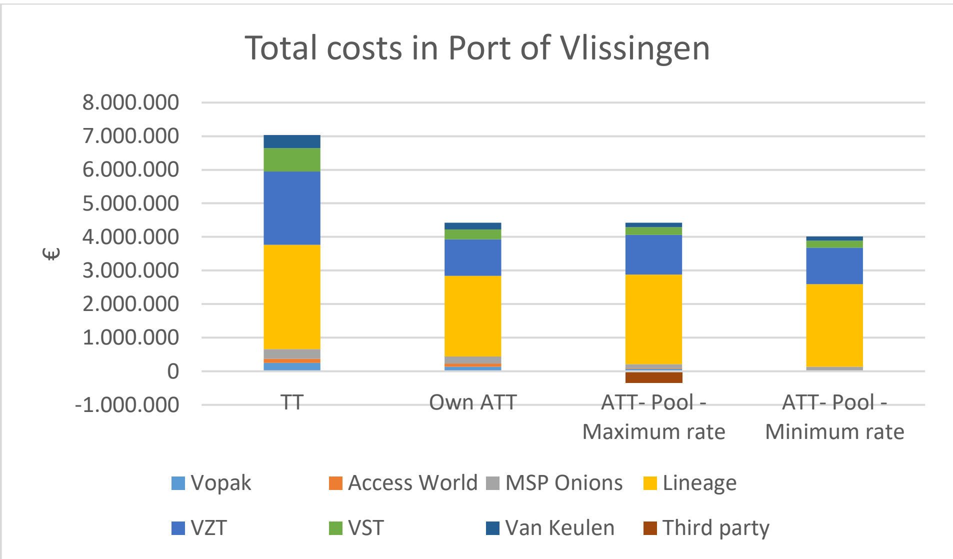

Figure 4: Overview of total costs in all scenarios.

Moreover, the breakdown of costs for each scenario provides additional insights (see Figure 5). For non-autonomous trucks, cost of drivers constitute two third of the total costs. The share drops considerably in autonomous trucking scenarios. In addition, share of energy costs in total costs of non-autonomous trucking becomes about half as large in autonomous driving scenarios.

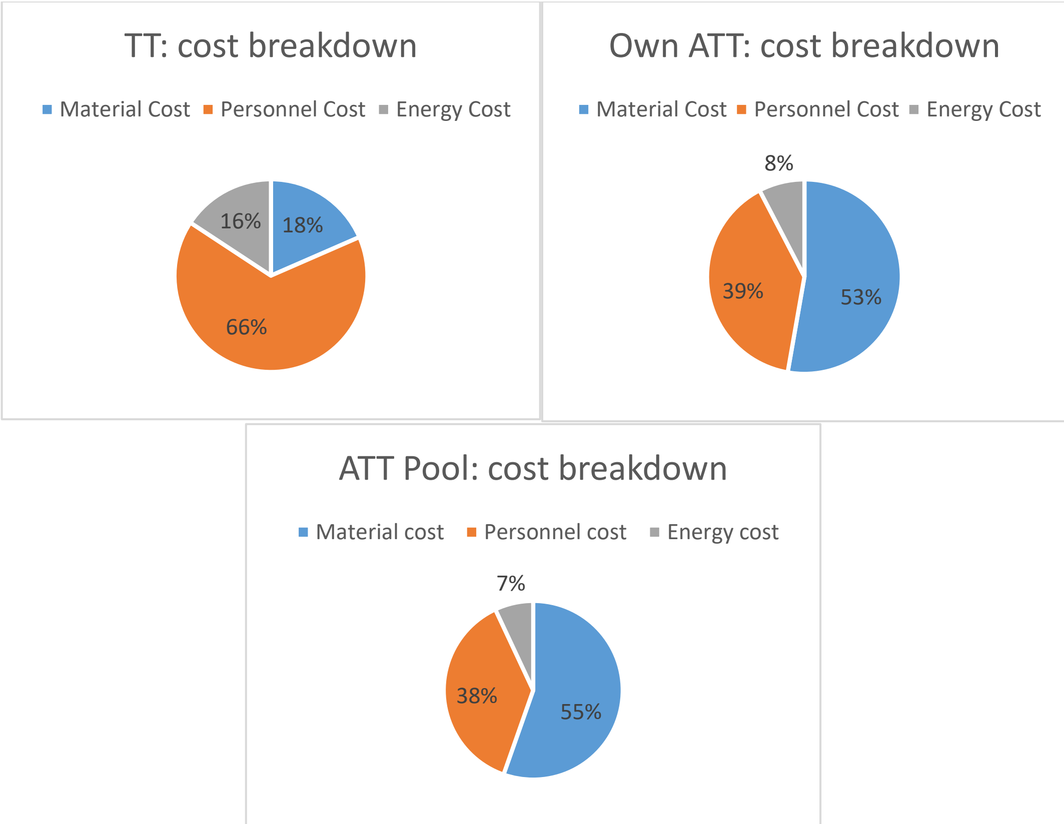

Figure 5: The percentual cost breakdown in all three scenarios.

It is also interesting to see that despite the fact that pooling has reduced the material costs by reducing number of vehicles and increasing their utilization, the share of material costs Scenario C is slightly higher that in scenario B. This indicates that the drops in personnel costs and energy costs in Scenario C are also significant and play even more important role in reducing the total costs.

4.3 Sensitivity Analysis

It is important to evaluate how sensitive the previous results are to the model parameters. Here, we evaluate sensitivity to diesel price, electricity price, and ATT rental price.

First, we check the effects of changes in diesel price on the total costs of the system in all scenarios. The main question here is whether any decrease in diesel price can make TTs more attractive than any ATT scenario. This turns out to be not the case.

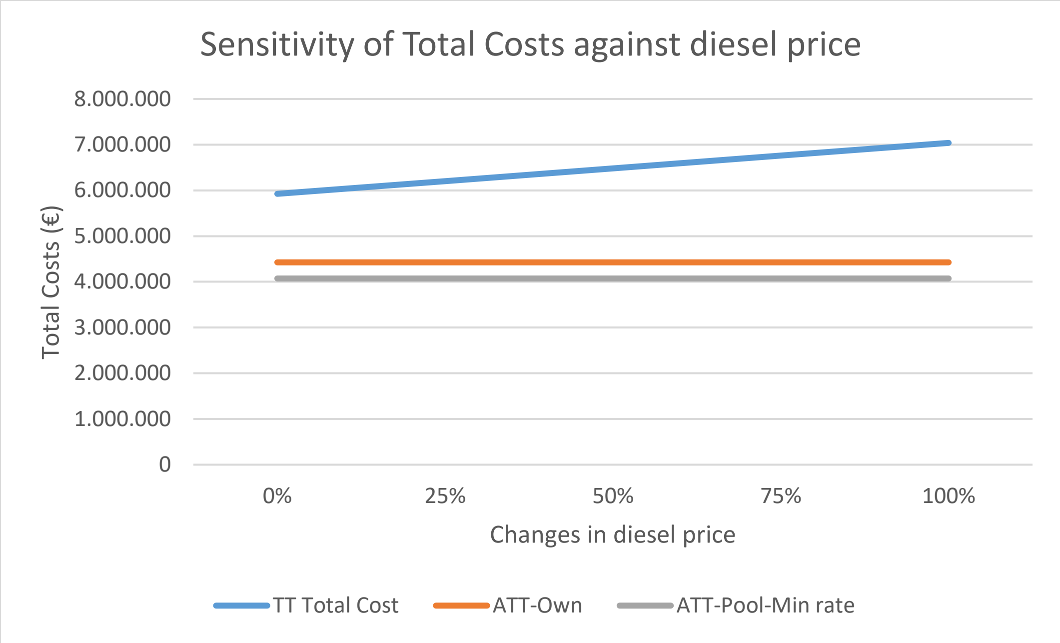

Figure 6 shows that even with 100% reduction in diesel price (free diesel) the material and personnel costs in Scenario A are that high that the total costs of this scenario will stay higher than the total costs of scenarios B and C for ATT adoption.

Regarding changes in electricity price (price of recharging at own or third party's charging station), we can draw the same conclusion. Figure 7 illustrates that the changes in electricity price do not change the ranking of total yearly costs of different scenarios. Implementing ATTs becomes more expensive when electricity prices rise, but even with an increase of 50% the total costs of ATTs are still much lower than those of TTs.

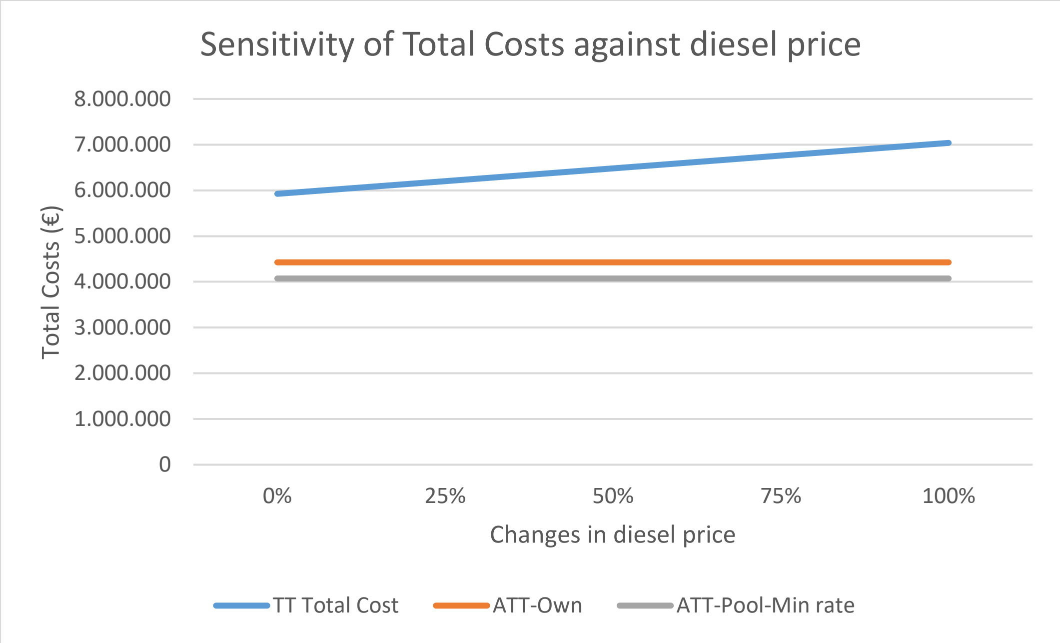

Figure 6: Sensitivity analysis with varying diesel price

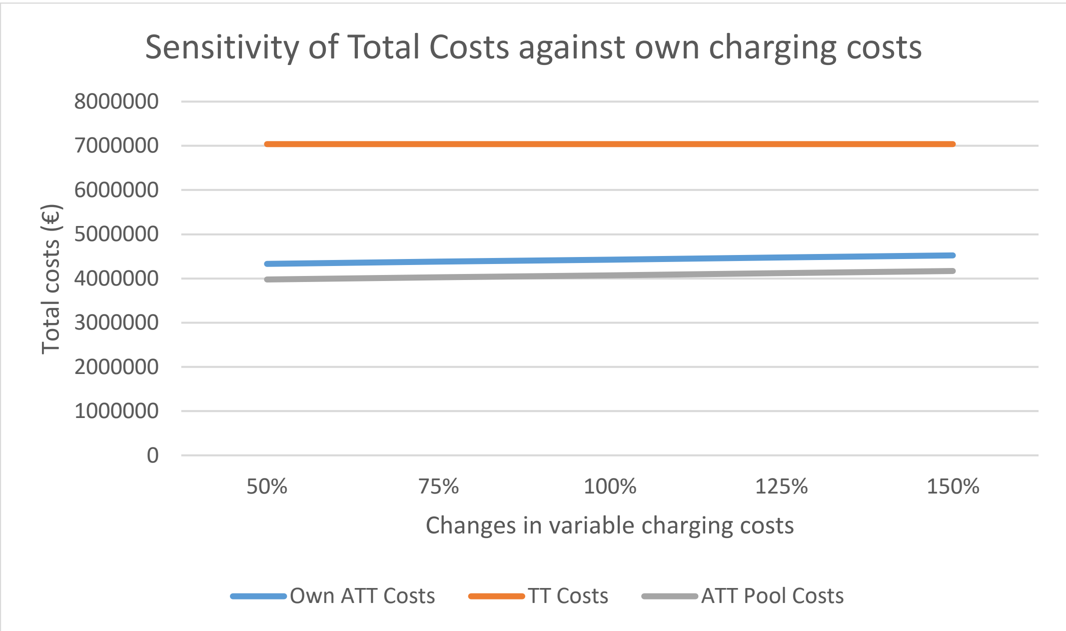

Figure 7: Sensitivity analysis with varying electricity price.

Changes in the rental fee in Scenario C influence the business case. As it is already mentioned, for rental fees above 218,51 €/shift, Scenario B will be more attractive than Scenario C, and for rental fees below 200,30 €/shift Scenario C will not be economically viable for the third party. In addition, in this analysis it is assumed that ATT rental fees in weekends are the same as other weekdays. Figure 8 illustrates the indifference map of changes in Weekend fee and weekday fee such that the total costs of companies (except the third party) stays the same as at the minimum acceptable rate of below 200.30 €/shift. It is obvious that because of the low workload in weekends, any reduction in weekend fees can be compensated by slight increase in weekday fees. With the fixed trip pattern, even with 100% reduction in weekend fee, the incurred costs for the third party can be compensated by increasing weekday fees for with only two percent. Therefore, in the case of inelastic trip pattern, there is sufficient space for the third party to offer great discounts for the weekends by the third party without tangible increase in weekday fees.

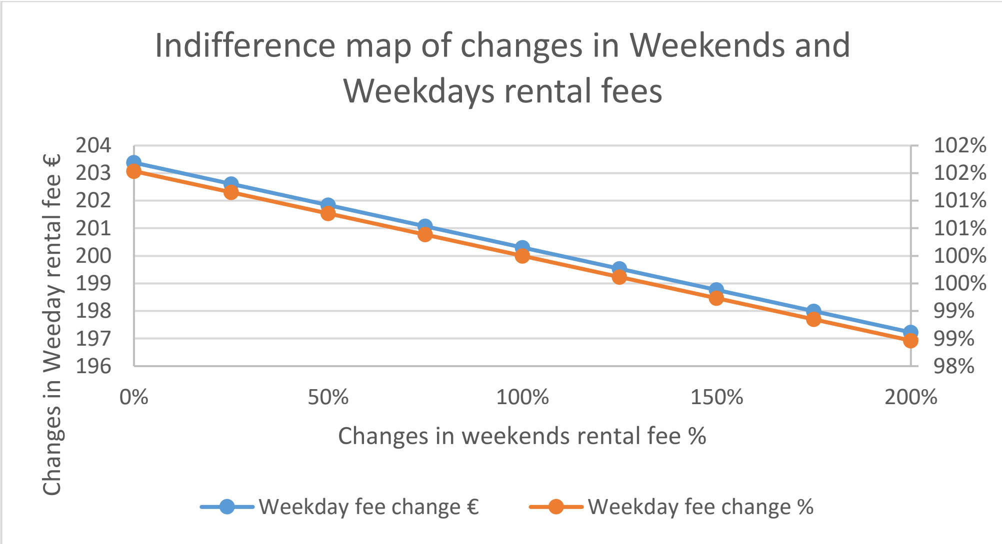

Figure 8: Sensitivity of minimum weekday rental fee to changes in current weekend fees.

To achieve cost reduction in ATT scenarios, personnel costs play a crucial role. In this analysis, we examine how changing the operator-to-vehicle ratio impacts the situation. Currently, the ratio is set at 0.25, meaning each operator can handle four autonomous vehicles simultaneously. Figure 9 illustrates that the break-even point for the operator-to-vehicle ratio is 0.625. Beyond this value, Scenario A becomes more economically favorable than Scenario B. This implies that autonomous vehicles remain economically attractive even with just one operator for every two vehicles.

However, we cannot include Scenario C in the comparison directly. In this case, total costs depend not only on the operator-to-vehicle ratio but also on a variable rental fee. To evaluate Scenario C, we would need to find a new rental fee value for each ratio to maintain costs at an acceptable minimum level. Despite this complication, Figure 9 still shows how total costs for companies in Scenario C vary with changes in the operator-to-vehicle ratio, assuming a fixed rental fee of €200.30 per shift. Under these conditions, Scenario A becomes more attractive than Scenario C at higher operator-to-vehicle ratio values.

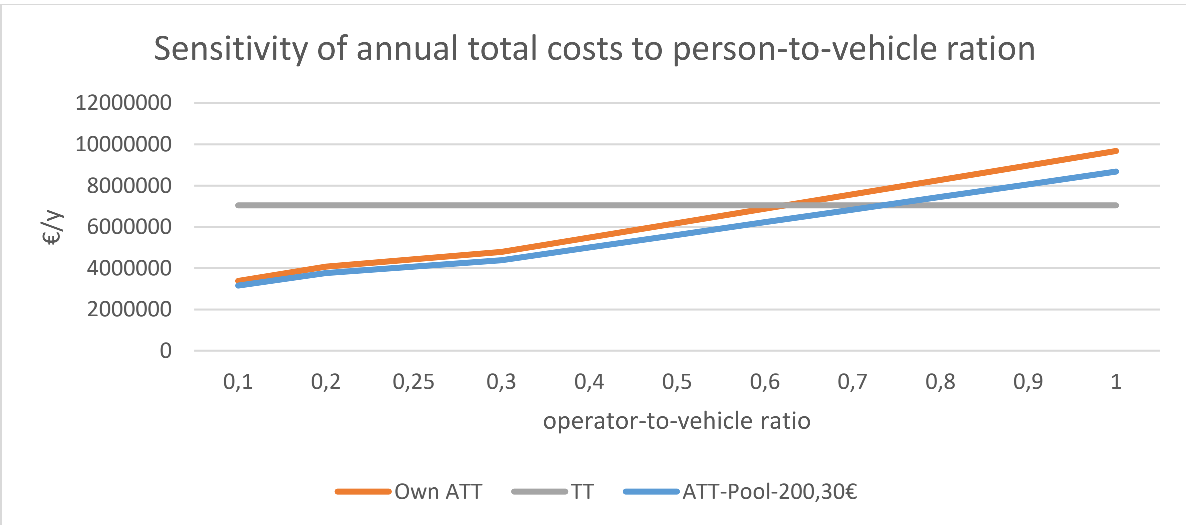

Figure 9: Sensitivity analysis with varying operator-to-vehicle ratio.

4.4 Environmental Analysis

In addition to economic analysis, this report investigates the environmental impacts of the three scenarios. CO_2 emissions are the main indicator for environmental impact in this report. The emission mainly depends on the total energy consumed in each scenario. The CO_2 emission is equal to 2.657 kg per liter of diesel in regular transport and equal to 0.454 kg per kWh in autonomous transport Figure 10 illustrates that the level of CO_2 emission per year for non-autonomous transport scenario (A) is substantially higher than for autonomous transport scenarios (B and C). There is no different between scenarios B and C as the total engine-on time of vehicles in the scenarios is the same.

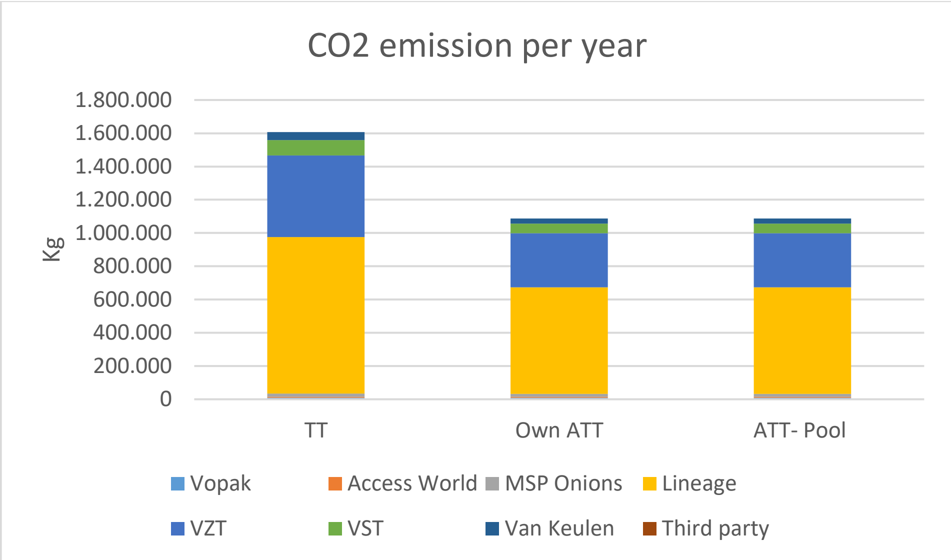

Figure 10: Overview of annual CO2 emissions in all scenarios.

Chapter 5. Conclusion

Based on our in-depth comparison of autonomous terminal tractors with regular terminal tractors in the port of Vlissingen, we can conclude that the deployment of autonomous vehicles is preferred, both from a cost perspective and a sustainability perspective. Although equipment costs will initially increase with the implementation of autonomous vehicles, our analysis shows substantial benefits in terms of energy costs, personnel costs, CO_2 emissions and required amount of personnel. The analysis in this report therefore provides valuable insights into the benefits of using autonomous terminal tractors and their potential for the port of Vlissingen.

Although the purchasing costs of autonomous vehicles are higher than those of regular vehicles, fuel costs are decreasing because of the electric driveline. The use of electricity makes autonomous vehicles financially attractive in the longer term and reduces the dependency on fossil fuels. Our results also show that the business case for autonomous transport remains positive when the price of electricity increases.

Personnel costs will also decrease with the implementation of autonomous vehicles. In contrast to regular vehicles, which each need their own driver, multiple autonomous vehicles can be controlled by a single control room employee. This reduction in the required amount of personnel results in substantial cost savings. Our analysis shows that the operator-to-vehicle ratio is an important parameter that affects the economic attractiveness of autonomous vehicles. A higher ratio results in higher personnel costs for control room operators. If the ratio exceeds 0.625, the business case will be negative for company-owned autonomous transport. This implies that with even a ratio of 0.5, meaning one operator per two vehicles, autonomous transport is still more economically attractive than regular transport.

In addition to cost savings, the use of autonomous vehicles results in a reduction in CO_2 emissions. Autonomous vehicles can thus contribute to reducing the port's emissions and working towards a greener future.

In our analysis we compare two scenarios for implementing autonomous vehicles. In one scenario, each company owns and operates its own autonomous terminal truck and charging stations, and in the other scenario a third party owns and operates charging stations and a pool of vehicles and the companies are only paying rent and recharging expenses. It is concluded that pooling reduces the number of required vehicles in the port, and reduces total material costs, personnel costs and energy costs.

In conclusion, we can say that the implementation of autonomous vehicles is a recommended strategy for the port of Vlissingen. Although equipment costs may initially be challenging, they do not outweigh the savings in fuel costs, personnel costs and CO_2 emissions. In addition to the transition from conventional terminal trucks to autonomous electric terminal trucks, the transition from ownership to pooling adds economic and environmental value. By using autonomous transport, costs are saved, the participating companies reduce their dependency on scarce personnel and fossil fuels and at the same time they contribute to a greener and more sustainable future.

Disclaimer

This business case analysis is based on the information available at the time of writing and should not be considered binding in any way. The results are intended to give a rough estimate of the economic benefits. Actual implementation requires further research and more accurate calculations.

Bibliography

CBS. (2021). *Welke zeehavens zijn er in Nederland?* Retrieved from https://www.cbs.nl/nl-nl/visualisaties/verkeer-en-vervoer/vervoermiddelen-en-infrastructuur/zeehavens

Distribute. (2021). *Simulation Study Central Gate North Sea Port.* Part of CATALYST.

Dries, C. v., Hekke, J. v., & Vermeulen, Y. (2021). *Autonomous Transport - Advice Report.* Minor report. HZ University of Applied Sciences.

North Sea Port. (2023, 5). Modal split data (confidential).

PWC. (2021). *Electric vehicles and the charging infrastructure: a new mindset?* Retrieved 2023, from https://www.pwc.com/us/en/industries/industrial-products/library/electric-vehicles-charging-infrastructure.html

SAE International. (2021, 04 30). *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles* . Retrieved from https://www.sae.org/standards/content/j3016_202104/

TNO. (2020). *CATALYST Living Lab*. Retrieved from https://dutchmobilityinnovations.com/spaces/1182/catalyst-living-lab/about

Top Sector Logistics. (2019). *Charging infrastructure for electric vehicles in city logistics.*

Van den Dries, C., Van Hekke, J., & Vermeulen, Y. (2021). *Autonomous Transport - Advice Report.* Student Minor Report, HZ University of Applied Sciences.

Williams, A. (2021). *Autonomous Transport Integration in European Logistic Terminals - Feasibility Assessment for Verbrugge International.* Graduation Report, HZ University of Applied Sciences.

Appendix A. Methodology

The business case analysis in this report includes the comparison of total annual costs and CO_2 emissions among three scenarios. In this appendix, the details of our methodology are provided and explained.

In the formulas, we use different indices belonging to the four following sets.

$c \in Companies = \{Vopak, Access\ World, MSP\ Onions, Lineage, VZT, VST, Van\ Keulen\}$

$s \in Shifts = \{shift_1, shift_2, shift_3\}$

$d \in Days = \{Weekday, Weekend\}$

$f \in Flow = \{In \backslash Outbound, Intraportal, Shuttle\}$

Note that we use square brackets in the formulas to indicate the units of the variables considered.

A.1. Calculating Total Costs

The total annual cost comprises material costs, personnel costs, and energy costs which will be elaborated on.

A.1.1. Material Costs

For scenarios A and B, number of vehicles for a company at a day type and shift, denoted as $V_{c,d,s}$, can be calculated by dividing the annual workload of the company at the day type and shift $W_{c,d,s}$ (in hour per year) by the vehicles' annual operational time. This number is usually a decimal number which is rounded to the upper integer by ceiling function ($\lceil\ \ \rceil$) to ensure that sufficient vehicle capacity exist to perform operations.

$$V_{c,d,s} = \left\lceil \frac{W_{c,d,s}\ \left[\frac{h}{y}\right]}{Vehicle\ Annual\ Operational\ time_{c,d,s}\ \left[\frac{h}{y}\right]} \right\rceil$$

Below we will explain how we calculate the workload $W_{c,d,s}$ and the vehicles' annual operational time.

Similarly, for scenario C, number of vehicles for the third party at a day type and shift, denoted as $V_{Pool,d,s}$ can be calculated by dividing the annual workload of all other companies at a day type and shift by the vehicles' annual operational time.

$$V_{Pool\,,d,s} = \left\lceil \sum_{c \in Companies} \frac{W_{c,d,s}\ \left[\frac{h}{y}\right]}{Vehicle\ Annual\ Operational\ time_{c,d,s}\ \left[\frac{h}{y}\right]} \right\rceil$$

The required vehicles for each company can be calculated as the maximum required vehicles of all day types and shift:

For Scenario A,B $\qquad V_c = \max_{\substack{d \in Days \\ s \in Shifts}} V_{c,d,s}$

For Scenario C $\qquad V_{Pool} = \max_{\substack{d \in Days \\ s \in Shifts}} V_{Pool,d,s}$

The workload $W_{c,d,s}$ is the sum of annual workload from all flows of the company c at specific day d and shift s.

$$W_{c,d,s}\left[\frac{h}{y}\right] = \sum_{f \in Flow} W_{f,c,d,s}\left[\frac{h}{y}\right]$$

For some flows, such as the shuttle flows of Lineage and Verbrugge, $W_{f,c,d,s}$ is calculated based on estimates provided by experts, while for the rest, it is determined based on the number of trips, average trip duration, and the number of operational days per year.

$$W_{f,c,d,s} = \, Number\ of\ trips_{f,c,d,s} * Average\ time\ per\ trip\ \left[\frac{h}{trip}\right] * Operational\ days\ per\ year\ _{c,d}\left[\frac{day}{y}\right]$$

The average time per trip is the sum of the times for driving, (un)loading, (de)coupling, and waiting per trip. The driving time can be calculated by dividing the trip's distances by the average speeds of vehicles, which are 35 km/h for TT and 20 km/h for ATT. Any combination of (un)loading and (de)coupling is assumed to take an average of 21 minutes per trip. It's important to note that in this research, no waiting time is assumed to be involved in the trips due to the unavailability of data.

Moreover, the vehicles' annual operational time, necessary for calculating the required number of vehicles, can be determined by multiplying the useful duration of a shift and the operational days for each day type. It is assumed that the duration of each shift is 8 hours. However, for TT (scenario A), it is assumed that 1 hour per shift is spent on personnel resting which makes the useful duration 7 hours, while for ATT (Scenarios B and C), the useful duration of the shift is assumed to be 8 hours as no resting is needed. In addition, the operational days per year are set to 260 for weekdays and 104 for weekends for all companies. It's worth noting that most companies do not have a weekend shift and setting operational weekend days does not affect their business case as they have no trips then.

$$\begin{aligned} &Vehicle\ Annual\ Operational\ time_{c,d,s}\left[\frac{h}{y}\right] \\ &\qquad = Shift\ Useful\ duration\ \left[\frac{h}{day}\right] * Annual\ operational\ days\ _{c,d}\left[\frac{day}{y}\right] \end{aligned}$$

The annual maintenance cost of a company can be obtained by multiplying the annual workload of the company (sum of annual workload of all day types and shifts) by the maintenance rate per hour for the vehicles. The maintenance rate per hour for TT and ATT are 2.5 €/h and 1.7 €/h, respectively.

$$Annual\ maintenance\ cost_c\left[\frac{€}{y}\right] = \left(\sum_{\substack{d \in Days \\ s \in Shifts}} W_{c,d,s}\left[\frac{h}{y}\right]\right) * maintenance\ rate\left[\frac{€}{h}\right]$$

The annual equivalent costs of purchasing vehicles can be obtained by dividing one-time purchase price by the life time of the vehicle. Additionally, the insurance premium per year can be estimated as 3.5% of the annual purchase cost.

$$Annual\ vehicle\ purchase\ cost\ \left[\frac{€}{y}\right] = \frac{Purchase\ price\ [€]}{Lifetime\ [y]}$$

Finally the total material cost for company c can be calculated given the number of required vehicles, annual purchase cost, annual insurance premium, and annual maintenance cost as follows:

$$\begin{aligned} &Material\ cost_c\ \left[\frac{€}{y}\right] = V_c * \left(Annual\ purchase\ cost\ \left[\frac{€}{y}\right] + Annual\ insurance\ premium\ \left[\frac{€}{y}\right]\right) + \\ &Annual\ maintenance\ cost_c\left[\frac{€}{y}\right] \end{aligned}$$

A.1.2. Personnel Costs

The next important cost to calculate is the personnel costs. Here, first, the number of FTEs (Full-Time Equivalent) personnel is calculated for each company, day type, and shift. Then, the personnel costs can be calculated by multiplying the required FTEs by the annual salary of 1 FTE.

The number of drivers or operators (referred to as 'person' here) depends on the number of vehicles, the person-to-vehicle ratio, annual operational days for a day type, and the number of annual working days per 1 FTE. The annual working days for one FTE is assumed to be 235 days, considering 260 operational weekdays and 25 days of holidays. It is worth noting that the number of operational weekend days is 104 days for companies that have weekend shifts.

$$Number\ of\ persons\ per\ year_{c,d,s}\left[\frac{FTE}{y}\right] = V_{c,d,s}[vehicle] * \frac{person/vehicle\ ratio\ \left[\frac{person}{vehicle}\right] * Annual\ operational\ days_{c,d}\left[\frac{day}{y}\right]}{Annual\ working\ days\ for\ one\ person\ per\ FTE\ \left[\frac{day}{y}.\frac{person}{FTE}\right]}$$

$$Personnel\ cost_{c}\left[\frac{€}{y}\right] = Annual\ salary\ of\ 1\ FTE\left[\frac{€}{FTE}\right] * \sum_{\substack{d \in Days \\ s \in Shifts}} V_{c,d,s}\left[\frac{FTE}{y}\right]$$

A.1.3. Energy Costs

Finally, energy costs are the other main cost type for all scenarios. In all scenarios, we estimate the energy consumption of companies and the associated energy costs. For scenarios B and C, it is also assumed that companies build and operate charging stations, which will be elaborated upon as well.

To calculate energy consumption, it is necessary to estimate annual engine-on times of vehicles for all companies, flows, day types, and shifts in terms of hours per year. This estimation is a function of the number of trips and average driving time. As mentioned before, driving time is a function of distance and speed. For companies where distance data is unavailable, the hours are directly estimated based on expert opinions. For in/outbound trips, we assume that the engine is off during (un)loading and (de)coupling. For intraportal and shuttle trips, we assume the engine is always on.

$$Annual\_engine\_on\ \_time_{c,f,d,s}\left[\frac{h}{y}\right] = number\_of\_trips_{c,f,d,s} * average\_driving\_time_{c,f}$$

$$Annual\_engine\_on\ \_time_{c}\left[\frac{h}{y}\right] = \sum_{\substack{f \in Flow, \\ d \in Days, \\ s \in Shifts}} Annual\_engine\_on\ \_time_{c,f,d,s}\left[\frac{h}{y}\right]$$

Diesel costs for TTs

Energy costs for TTs is equal to diesel costs. The annual diesel consumption for each company can be calculated by multiplying annual engine-on times by the average diesel consumption per hour of operation. Then, the annual diesel cost for each company can be obtained by multiplying the consumption by the diesel price.

$$Annual\ diesel\ consumption_{c}\left[\frac{L}{y}\right] = Annual\_engine\_on\ \_time_{c}\left[\frac{h}{y}\right] * Average\ fuel\ consumption\ per\ hour\ \left[\frac{L}{h}\right]$$

$$Annual\ diesel\ cost_{c}\left[\frac{€}{y}\right] = Annual\ diesel\ consumption_{c}\left[\frac{L}{y}\right] * Diesel\ price\ \left[\frac{€}{L}\right]$$

Energy costs for ATTs

Energy costs for ATTs include recharging costs of vehicles and the costs of own charging stations. For scenario B (company-owned ATTs) energy costs for each company are equal to costs of building/operating charging stations plus costs of recharging vehicles. For scenario C, energy costs for the third party includes only costs of building/operating charging stations whereas for other companies energy costs include only costs of recharging vehicles at third-party-owned charging station.

Recharging costs for ATT

Similar to TTs, the costs of recharging electricity for ATTs can be calculated by obtaining the annual electricity consumption and multiplying it by the electricity price.

$$Annual\ electricity\ consumption_c \left[\frac{kWh}{y}\right] = Annual\_engine\_on\ \_time_c \left[\frac{h}{y}\right] * Average\ electricity\ consumption\ per\ hour \left[\frac{L}{h}\right]$$

$$Annual\ recharging\ cost_c \left[\frac{€}{y}\right] = Annual\ electricty\ consumption_c \left[\frac{kWh}{y}\right] * electricty\ price\ from\ own\ station \left[\frac{€}{kWh}\right]$$

Building and operating charging stations

In this analysis, it is assumed that companies (scenario B) or a third party (scenario C) own charging stations. In the first step, we determine how many charging stations (referred to as 'CS') are required. For scenario B, the number of required charging stations for a company CS_c can be calculated by dividing the annual electricity consumption of the company by the available energy from a charging station per year. The available energy depends on the power capacity of the station, availability of the station (assumed to be 30%), and the total hours in a year, which is 8,736 hours. The calculated number for CS_c is usually a decimal number which is rounded to the upper integer.

$$CS_c = \left\lceil \frac{Annual\ electricity\ consumption_c \left[\frac{kWh}{y}\right]}{CS\ capacity\ [kW] * station\ avaiability\ [\%] * total\ hours\ per\ year\ \left[\frac{h}{y}\right]} \right\rceil$$

Utilization of available capacity of charging station of a company η_c can be calculated by dividing the original decimal value of CS_c by integer value of CS_c or as follows:

$$\eta_c = \frac{Annual\ electricity\ consumption_c \left[\frac{kWh}{y}\right]}{CS_c *\ CS\ capacity\ [kW] * station\ avaiability\ [\%] * total\ hours\ per\ year\ \left[\frac{h}{y}\right]}$$

Then, given the CS_c, annual costs for charging stations of companies can be calculated as follows where the values for CS installation costs, CS lifetime and CS annual operation costs are parameters and assumption of the analysis.

$$Annual\ costs\ of\ charging\ station_c \left[\frac{€}{y}\right] = CS_c * \left(\frac{CS\ installation\ costs\ [€]}{CS\ lifetime\ [y]} + CS\ annual\ operational\ costs\ \left[\frac{€}{y}\right]\right)$$

For scenario C, calculating required charging stations and utilization rate are similar to scenario B, and the difference is that we divide the sum of the annual electricity consumption of all other companies by the annual available energy from the charging station.

$$CS_{Pool} = \left\lceil \frac{\sum_c Annual\ electricity\ consumption_c \left[\frac{kWh}{y}\right]}{CS\ capacity\ [kW] * station\ avaiability\ [\%] * total\ hours\ per\ year\ \left[\frac{h}{y}\right]} \right\rceil$$

$$\eta_{Pool} = \frac{\sum_{c \in Companies} Annual\ electricity\ consumption_c \left[\frac{kWh}{y}\right]}{CS_{Pool} *\ CS\ capacity\ [kW] * station\ avaiability\ [\%] * total\ hours\ per\ year\ \left[\frac{h}{y}\right]}$$

A.2. Calculating CO_2 emissions

Calculating CO_2 emissions in all scenarios depend on the volume of fuel consumption in the systems and the CO_2 emission rate per unit of fuel.

For scenario A, the CO_2 emission is calculated as follows:

$$Annual\ CO_2\ emission_c \left[\frac{kg}{y}\right] = Annual\ diesel\ consumption_c \left[\frac{L}{y}\right] * CO\ _2\ emission\ per\ liter\ of\ disel\ \left[\frac{kg}{L}\right]$$

For scenarios B and C, the CO_2 emission is calculated as follows:

$$Annual\ CO_2\ emission_c \left[\frac{kg}{y}\right] = Annual\ electricity\ consumption_{c\ or\ Pool} \left[\frac{kWh}{y}\right] *$$
$$CO_2\ emission\ per\ kWh\ of\ electricitcy\ \left[\frac{kg}{kWh}\right]$$

A.3. Data handling

A.3.1. MSP Onions

The intraportal trips of MSP Onions exhibit different patterns during peak and non-peak months, as detailed in the figure below.

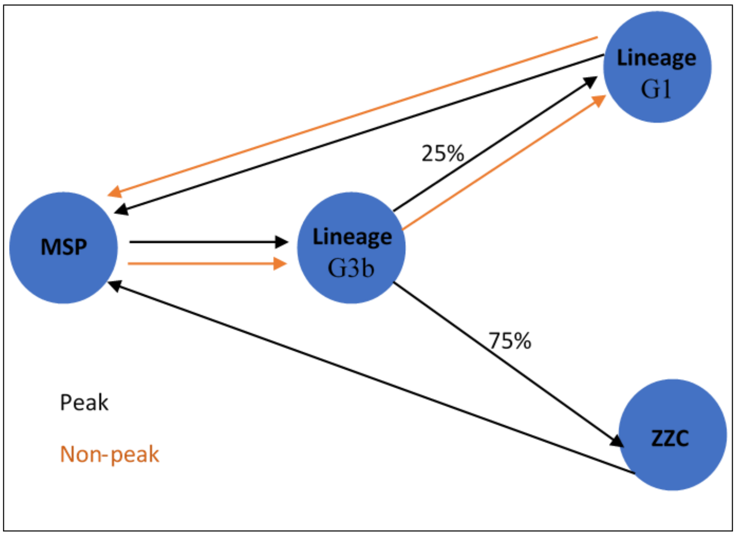

Figure A- 1: The trips between MSP Onions and Lineage in the port of Vlissingen.

In non-peak months, the route includes a loop from MSP to Gate 3B of Lineage, then to Gate 1 of Lineage, and finally back to MSP, covering a total distance of 6.8 kilometers.

During peak months, 25% of trips follow the same loop as in non-peak months, while 75% of trips take a different path, going from MSP to Gate 3B of Lineage, then to ZZC, and finally back to MSP. We have an aggregated number of trips for each period per shift. To simplify, we assume a hypothetical loop with a length equal to the weighted average of the lengths of the two loops during the peak period, where the length of this hypothetical round-trip loop is 9.73 kilometers.

Additionally, because we have data on the number of one-way trips, we consider half of the total paths for each period as the hypothetical one-way distance for MSP's trips. Using the distance and average speeds of vehicles, we can calculate the costs associated with MSP in a manner similar to other companies.

Month	Path	Distance (km)	Weight	Total path (km)	Hypothetical one-way distance
Non-peak path	MSP to Lineage Gate 3b	3.1	1	6.8	3.4
	Lineage Gate 3b to Lineage Gate 1	0.3	1		
	Lineage Gate 1 to MSP	3.4	1		
Peak Month	MSP to Lineage Gate 3b	3.1	0.25	9.73	4.86
	Lineage Gate 3b to Lineage Gate 1	0.3	0.25		
	Lineage Gate 1 to MSP	3.4	0.25		
	MSP to Lineage Gate 3b	3.1	0.75		
	Lineage Gate 3b to ZZC	2.6	0.75		
	ZZC to MSP	5	0.75		

Table A- 1: Calculation of MSP Onions one-way distances

A.3.2. Van Keulen

Van Keulen is a transporting company and its in/outbound trips vary substantially over time, therefore the average distance per trip cannot easily be calculated with the available data. However, it is possible to calculate travelled distance per shifts of different day types. Therefore, by assuming that in each shift of a day, there is only one in/outbound trip with the total distance of the shift, it is possible to estimate the workload and engine-on time as follows

$$D_{van\ Keulen,Weekday,s}[km] = Average_{\substack{f' \in \{inbound,outbound\} \\ t \in \{Monday,\dots,Friday\}}} \left(D_{f',vanKeulen,t,s}[km] \right)$$

$$D_{van\ Keulen,Weekends,s}[km] = Average_{\substack{f' \in \{inbound,outbound\} \\ t \in \{Saturday,Sunday\}}} \left(D_{f',van\ Keulen,t,s}[km] \right),$$

where $D_{f\prime,c,t,s}[km]$ represents the trip distance of an in/outbound during performed by Van Keulen during a particular shift and day. Given data of travelled distances for all shifts per week, we calculate the average distance per shifts of different day types. In addition, given the distances, the average driving time per trip for vehicles can be obtained by dividing distances over the speeds. The average speed on conventional trucks and autonomous trucks are assumed to be 35 km/h and 20 km/h, respectively. Average time per trip is the average driving time plus 21 minutes average (un)loading and (de)coupling time for all trip.

In addition, for intraportal trips of van Keulen the distances are not known, but the travel times per different types of shifts are obtained from the company and they are directly used as workload and engine-on times. For this specific flow, the 21 minutes of (un)loading + (de)coupling is ignored, because it is assumed to be already included in the total travel times.

A.3.3. Lineage

For Lineage we have information on aggregated trip hours per month plus percentages of a baseline for trips in each day of the week. Given the percentages we calculate the share of shuttle trips in each day for the company as follows:

Lineage shuttle trips	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
% of baseline	90%	132%	140%	111%	115%	11%	0%
% of week	15%	22%	23%	19%	19%	2%	0%

Table A- 2: Distribution of Lineage shuttle trips over days of the week

In addition, we assume that distribution of shuttle trips over different day types and shifts follows the distribution of in/outbound trips of the company. Given that there are 2400 hours of shuttle trips for the company, the annual work load can be calculated as follows:

yearly hours workload per shift (h/y)	Weekdays	Weekends
Shift 1	20258.85	527.66
Shift 2	7963.67	1.22
Shift 3	48.60	0.00

Table A- 3: Annual workload associated to Lineage shuttle trips in different shifts and day types

A.3.4. Verbrugge

We know that the annual shuttle trip times of the company is close to 18924 hours. We assume the the distribution of the shuttle trip over day types and shifts follows the distribution of in/outbound trips of the company at each location. Therefore, the annual work load per shifts and day types can be calculated as follows:

Yearly hours per shift (h/y)	Weekdays	Weekends
VST_ Shift 1	2575.94	0
VST_ Shift 2	734.97	0
VST_ Shift 3	4.64	0
VZT_ Shift 1	9331.64	0
VZT_ Shift 2	3138.40	0
VZT_ Shift 3	3138.40	0

Table A- 4: Annual workload of Verbrugge shuttle trips

A.4. Business case assumptions

Overview all parameters used in this business case analysis is provided in the following tables.

Companies	Average distance to Central Gate (km)	Annual Operational days	
		Weekdays	**Weekends**
Lineage Logistics	5.2	260	104
Verbrugge Zeeland Terminal (VZT)	7.5	260	0
Verbrugge Scaldia Terminal (VST)	3.6	260	0
Vopak	4	260	104
Access World	5.6	260	0
MSP Onions	-[2]	260	0
Van Keulen	variable	260	0

Table A- 5: Distances to central gate and the operational days per year

[2] We assume in our analysis that trips from MSP Onions do not go through the Central Gate.

Shifts and trips	TT	ATT	Source
Shift info			
Duration of a shift (h/shift)	8	8	Self-determined
Average rest time per shift (h/shift)	1	0	Self-determined
Shift 1	7:00-15:00		Self-determined based on opening times of companies and trip patterns
Shift 2	15:00-23:00		
Shift 3	23:00-7:00		
Trips assumptions			
Average (un)loading + (de)coupling time per trip (min/trip)	21	21	(Distribute, 2021)
Average waiting time per trip (min/trip)	0	0	Self-determined

Table A- 6: Shifts and trips assumption per vehicle type

Parameters	Value		Source
Vehicle parameters	**TT**	**ATT**	
Purchase price (€/vehicle)	confidential	confidential	Discussions with project partners
lifetime (y)	7	10	Discussions with project partners
maintenance rate (€/h)	2.5	1.7	Own calculations based on discussions with project partners
Average Speed (km/h)	35	20	Own calculations based on discussions with project partners
Personnel parameters			
Driver per vehicle (person/vehivle)	1		Self-determined
Operators per vehicle (person/vehivle)	0.25		Self-determined
Annual drivers' salary 1 fte (€/fte/y)	47034		Vrachtwagenchauffeur salary (from nationaleberoepengids.nl) + 30% other personnel costs
Yearly control operators' salary 1 fte (€/fte/y)	70551		Own assumption: 50% higher than drivers' costs because of advanced skills
Energy parameters			
Average diesel consumption per hour (liter/h)	8		Discussions with project partners
Diesel price by external party (€/liter)	1.84		Globalpetrolprices.com
Average ATT electricity consumption (kWh/h)	25		Discussions with project partners
Charging station capacity (kW)	150		(Top Sector Logistics, 2019)
availability of charging station (%)	30[3]		Own assumption based on (PWC, 2021)
Installation cost for a private HPC150 charging station (€)	66000		(Top Sector Logistics, 2019)
Charging station lifespan (y)	10		(Top Sector Logistics, 2019)
Charging station operational costs (€/y)	6546		(Top Sector Logistics, 2019)
Average cost of electricity from own station (€/kWh)	0.08		(Top Sector Logistics, 2019)

Table A- 7: Parameters of material, personnel, and energy costs

[3] We assume that the charger can be used 30% of the time. We base this on research into charging stations for passenger cars, where a usage percentage of between 5-30% is considered (PWC, 2021).