Circulariteit en duurzaamheid

Analysing the business case of autonomous vehicles in logistics

The implementation of autonomous vehicles in logistics can offer a significant solution to the growing driver shortage

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Abstract

The implementation of autonomous vehicles in logistics can offer a significant solution to the growing driver shortage. However, an important barrier to implementation is the financial investment needed to adopt autonomous vehicles. In this article we present a methodology to calculate the business case of autonomous vehicles and demonstrate this methodology in two case studies. Despite the initial increase in equipment costs, our results show substantial benefits in terms of personnel costs, CO_2 emissions and required amount of personnel. By analyzing the two case studies, we identify which factors influence the business case and provide valuable insights for other companies interested in the business potential of autonomous vehicles.

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.

To determine the return on the required investment, companies need a clear overview of the financial benefits of autonomous vehicles. But because this technology is still novel, there is limited data available on the required investment as well as on the economic effects of implementing autonomous transport into your logistical operations. As a result, companies cannot easily assess the economic potential of this new technology and might hesitate to adopt it, potentially hindering their competitiveness in the future.

In this article we present a simple methodology to assess the business case of autonomous vehicles. We demonstrate this methodology in case studies of two separate companies. Company A is a production company which transports raw material from the warehouse to the factory and finished product from the factory back to the warehouse. Company B is a container terminal which uses terminal tractors to transport containers to the warehouse after they are unloaded from barges. By analyzing these cases we evaluate the business potential of autonomous vehicles for these companies. In addition, we identify which factors influence the business case.

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. These benefits are most prominent in settings where drivers' main responsibility is to drive the vehicle and other tasks, such as assisting with (un)loading, are not performed by drivers. In addition, we see that autonomous vehicles can bring a substantial reduction in fuel costs, particularly when charging facilities can be used efficiently. 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. With these results we provide valuable insights into the benefits of using autonomous vehicles and derive which factors influence the business case. Other companies can benefit from these insights in determining the business potential of autonomous vehicles in their context.

The remainder of this article is structured as follows. We start with a brief overview of the theory on autonomous vehicles and their economic effects. Next, we introduce the two case studies for which will determine the business case. We explain the methods used to calculate the business case and present our results. The article closes with a conclusion and discussion.

Theory

Automation of vehicles focuses on replacing some or all human labor related to driving the vehicle. In regular transport, a driver manually drives from A to B based on given instructions. In autonomous transport, this task is partly or completely taken over by an automated system. 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 article 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 actions that a driver performs in addition to driving, such as assistance with loading and unloading, are not taken over by the autonomous vehicle.

Many studies on autonomous vehicles focus on their technological development. However, the changes that these vehicles potentially bring to companies, also require the analysis of the business effects. (Leminen, Rajahonka, Wendelin, Westerlund, & Nyström, 2022) investigate four possible business models for autonomous vehicle solutions, each describing a way in which a firm can create value using autonomous vehicles. They structure these four business models along two dimensions: complexity and autonomy. In terms of complexity two options are considered: a single vehicle or a fleet. Autonomy is also classified into two categories: semiautonomous and fully autonomous solutions. In this paper we look at fully autonomous solutions. This relates to the business model of capacity-as-a-service (a fully autonomous single vehicle) or flexibility-as-a-service (a fully autonomous fleet). (Leminen, Rajahonka, Wendelin, Westerlund, & Nyström, 2022) explain that the business model of capacity-as-a-service is based on better use of capacity, resulting from more hours per vehicle as well as more efficient use of personnel. Flexibility-as-a-service can take many forms, including participating in an external pool of autonomous vehicles instead of self-owning vehicles. (Langebeeke & Westerink-Duijzer, 2023) propose a business model for a third party that owns such an external pool. They show for a particular case study that renting autonomous vehicles from an external pool can be preferred by the participants. This option can be financially attractive for the individual companies and allows for a more efficient deployment of the vehicles.

Besides investigating the changes in business models, there are also some studies that analyze the economic effects of autonomous vehicles. (Clements & Kockelman, 2017) discuss these economic effects for various industries. They argue that the transport sector might be the first to adopt autonomous vehicles, in order increase efficiency. For the trucking industry they identify reduction of personnel costs as the main economic benefit, but also mention fuel reduction and increased safety. (Schmidt, Meyer-Barlag, Eisel, Kolbe, & Appelrath, 2015) also demonstrate the positive effects of battery-powered autonomous vehicles in container terminals. They analyze the economic viability of electric autonomous vehicles compared to autonomous vehicles with a diesel engine. Their results show that energy costs can decrease by more than 10% when using electric vehicles. (Varma, 2022) analyzes the business case for autonomous vehicles that transport goods within cities on the last mile. The study shows the importance of the purchasing price of the autonomous vehicle which heavily impacts the business case. They argue that in the future, when acquisition costs of autonomous vehicles are expected to decrease, these vehicles can become a viable alternative for delivering good to certain customer segments.

From the literature we can thus conclude that there is economic potential for autonomous vehicles with an electric driveline. In the remainder of this article we will analyze two case studies of specific companies to see whether using autonomous vehicles indeed results in cost savings.

Data

We calculate the business case of autonomous vehicles in two case studies of anonymized companies, referred to as company A and company B. This section discusses these two companies and presents the data of the trips for which autonomous vehicles could be used. We particularly focus on the implementation of autonomous terminal tractors. In this section we explain the characteristics of the regular and autonomous terminal tractors that are considered in our analysis.

Company A

Company A is an international production company located in the south of the Netherlands. In their production process they use several raw materials of which their main input is stored in a warehouse close to the production factory. This raw material is transported to the production factory by terminal tractors. After production, part of the end product is transported back to the warehouse where it is stored until further handling can take place. Company A is interested in the possibility of replacing their regular terminal tractors with autonomous terminal tractors on these two routes between the warehouse and the production factory.

In Table 1 we present the characteristics of these two routes. Route 1 relates to transporting raw materials from the warehouse to the production factory and Route 2 is the transport of the end product back to the warehouse. Terminal tractors are located at the warehouse and trips are considered to be round trips: from the warehouse to the factory and back to the warehouse.

Table 1 Characteristics of the routes at company A

	Route 1	Route 2
Number of trips per day	13	10
Average distance per trip	0.2 km	0.4 km
Average total time per trip	30 min	30 min
Average (un)loading time per trip	0 min	0 min
Average waiting time per trip	29 min	28 min
Operational time	06:00-22:00 (Mon-Sun)	08:00-18:00 (Mon-Fri)
Number of shifts per day	2	1.25
Duration of a shift	8 hours	8 hours
Average rest time per shift	0.5 hours	0.5 hours

As can be seen from Table 1 there is no time allocated to (un)loading. This is because the vehicle does not stay with the load and the driver is not involved in (un)loading. Driving is the only responsibility of the driver and by moving to autonomy, no modifications will take place in this respect.

The majority of the trip duration is labeled as waiting time, which we consider to be time for everything else but driving and (un)loading. Since the trip distance is very short, the driving time is also very small. Remaining trip time, labelled as waiting time, includes coupling and decoupling, maneuvering and actual waiting. We assume that the engine is on during this waiting time.

Company B

The second case study is from company B, a container terminal in the south of the Netherlands. The terminal has two yards and multiple warehouses located at distances ranging from 0.5 km to 10 kilometer from the terminal. After being unloaded off the barges, the containers are either transferred to their final clients or are moved to one of the warehouses or the second yard. This transport takes place with terminal tractors. The company expects that particularly the transport between the terminal and one of the warehouses, as well as the transport between the terminal and the second yard could be suitable for autonomous transport. We refer to these routes with Route 1 and Route 2 respectively. Table 2 presents the characteristics of these two routes.

Table 2 Characteristics of the routes at company B

	Route 1	Route 2
Number of trips per day	20	50
Average distance per trip	1 km	2 km
Average total time per trip	23 minutes	25 minutes
Average (un)loading time per trip	20 minutes	20 minutes
Average waiting time per trip	1 minute	1 minute
Operational time	07:00-23:00 (Mon-Fri)	07:00-23:00 (Mon-Fri)
Number of shifts per day	2	2
Duration of a shift	8 hours	8 hours
Average rest time per shift	1 hour	1 hour

Compared to company A, the trips of company B have a longer distance. In company B the vehicle waits until the container is loaded or unloaded, which results in a substantial time for (un)loading. We assume the engine of the vehicle is off during (un)loading. Drivers do not assist in the (un)loading process: their only tasks it to drive the terminal tractor.

Terminal tractors

We analyze the business case for autonomous terminal tractors (ATTs) in comparison to regular terminal tractors (TTs). We consider ATTs on SAE-level 4 or 5, meaning that the vehicles can drive without a driver. Based on discussions with a vehicle manufacturer we were able to derive estimates of the 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. The purchasing price of the ATT also includes the costs for a battery pack of 220 kW and the hardware together with the software from the autonomous kit supplier. The annual insurance cost is taken as 3.5% of the purchasing price of the vehicle (Top Sector Logistics, 2019).

In addition to the buying price and insurance costs, we also include maintenance costs. We note that the time needed for maintenance is neglected, since it is spent in both modes. We work with maintenance costs of €2.50 per hour for a regular TT. Based on the literature we assume that maintenance costs for a vehicle with a diesel engine is 1.5 times as high as the maintenance costs for vehicles with an electric driveline. The resulting maintenance costs for both vehicle types are presented in Table 3.

TTs and ATTs also differ in terms of their engine. We assume that TTs run on diesel and ATTs have an electric driveline. Discussions with a vehicle manufacture about the fuel consumption resulted in estimates of 8 liters per hour as the average diesel consumption of a TT. The ATT consumes an average of 25 kW per hour. Table 3 presents an overview of the used parameters for TTs and ATTs.

Table 3 Overview of the parameters related to both vehicle types used in the business case

	TT	ATT
Purchasing price	Confidential	Confidential
Lifespan	7 years	10 years
Maintenance costs	€2,50/h	€1,70/h
Annual insurance costs	3.5% of purchasing price	3.5% of purchasing price
Driveline	Diesel	Electric
Average fuel consumption	8 l/h	25 kW/h
Average speed at company A	21 km/h	12 km/h
Average speed at company B	35 km/h	20 km/h

The vehicle manufacturer estimated the speed of a TT to be 35 km/h and of an ATT to be 20 km/h. We use these speeds for the routes at company B. The routes at company A have such a short distance, that it seems unlikely for a vehicle to reach the same average speed. We therefore use lower speeds for the routes at company A, keeping the relative difference in speed between the TT and ATT the same.

Methods

This section gives an explanation of the methodology we use. We start with a clarification of the scope of the business case analysis. Next, we explain the methods applied to calculate the required number of vehicles and the actual business case. We close with a brief discussion on how we determine the environmental impact of the different vehicle types.

Scope

To successfully implement autonomous transport, there are a number of preconditions that must be met. A small portion of the routes in both case studies is within public roads. Accordingly, rules and regulations for the application of autonomous vehicles should be clarified. In addition, the technical infrastructure required for the ATT to communicate with the ERP system of the company through an API should be provided. Finally, the infrastructure at the location and the layout of the facility must be adapted to the autonomous vehicle. The infrastructure for the vehicle-to-vehicle, vehicle-to-infrastructure, and vehicle-to-everything communications should be provided. We consider these preconditions to be outside of the scope of the article and we assume that are met are such that driving autonomously is possible.

Our business case analysis is made based on the comparison of costs between the operation of conventional and autonomous transport. That is to say, we explicitly focus on operational costs in the calculation method and therefore do not provide a complete overview of all costs required for the implementation of autonomous transport. Accordingly, the business case does not contain the costs of necessary infrastructural changes both physical or digital to enable safe autonomous vehicle maneuvers over the intended route. Any other costs that may arise from the implementation of autonomous vehicles, such as integrating IT systems or automating or digitizing certain processes.

In our calculations we compare annual costs. Purchasing costs for vehicles and charging infrastructure are translated into annual costs using their lifetime.

Required number of vehicles

A crucial factor in calculating the business case for autonomous vehicles is the number of vehicles that a company would need for completing the trips. We base our required number of vehicles on the duration of a trip, which consists of driving time, time for (un)loading, waiting and resting. Driving time is determined based on average trip distance and speed.

Time for (un)loading and waiting is assumed to be the same for TTs and ATTs. For the resting time, however, it is important to distinguish between the two vehicle types. We assume that TTs stand still during the breaks in a shift and that this resting time is part of the trip duration. To calculate the resting time per trip, the total resting time per shift is divided evenly over the number of trips made per shift. ATTs can continue their operation during staff breaks, so no time is needed for rest during a trip of an ATT.

When we know time required to complete a trip, we can calculate the total workload in hours for all trips made on an annual basis.

We represent the total workload with the variable W:

$$W = \textit{trip duration} * \textit{number of trips per day} * \textit{number of operational days per year}$$

In the same way we can calculate the operational time of one vehicle on an annual basis. We can see this as the number of hours a vehicle can make per year. We define the variable O for this.

$$O = \textit{shift duration} * \textit{number of shifs per day} * \textit{number of operational days per year}$$

We represent the number of vehicles required with V. This number can now be calculated by dividing O the total annual workload by total operational time per vehicle per year, W. We round this number upwards, to guarantee an integer number of vehicles. Hence, $V = \left\lceil \frac{O}{W} \right\rceil$.

Business case

As mentioned in Section 4.1, we calculate the business case using operational costs. We distinguish between three types of cost: equipment costs, personnel costs and fuel costs. We discuss these types of costs below.

Equipment costs

Equipment costs include all costs related to the vehicle itself: purchase costs, maintenance costs, and insurance costs. The purchase price is translated into annual cost by dividing its value over the life span of the vehicle. Maintenance costs are given per hour. We translate these to annual costs accounting only for the hours that the engine is on. We assume that the engine is on when the vehicle is either driving or waiting. During loading, unloading or resting, the engine is assumed to be off. Insurance costs are already on a yearly basis, as can be seen in Table 3.

Personnel costs

A second category of costs are personnel costs. In the case of regular transport, these are the costs for the drivers. Two types of personnel costs can be distinguished in autonomous transport: costs for a control operator and costs for a local operator. The control operator can monitor several autonomous vehicles from a distance and intervene when necessary. The local operator is available to assist in loading and unloading the vehicle. We note that in both case studies in this article, the driver does not perform additional tasks on top of driving, so support from a local operator will not be needed.

When determining personnel costs, we assume that the salary of a control operator is 50% higher than that of a driver, due to the increased complexity and the extra responsibility for handling dangerous situations properly. The salary of a control operator can therefore be compared to that of a planner. When it is decided to outsource the control operator, we assume that the wage costs are 20% lower than for internal control personnel. We do not charge fixed annual costs when outsourcing the control operator. The assumptions regarding the costs of control operators are therefore in line with previous studies into the salary costs of control operators for tele-operated transport (HZ University of Applied Sciences, 2021). This results in the following wage costs:

Table 4 The wage costs per month for the various positions, based on the average salary for the professions truck driver (driver) and logistics employee (local operator), as stated on www.nationaleberoepgids.nl/salaris in November 20

	Driver	Control operator (in-house)	Control operator (outsourced)	Local operator
Labour costs gross	2490 € / month	3735 € / month	2988 € / month	1775 € / month

In the remainder of this article we work only with outsourced control operators. We calculate the personnel costs as follows, assuming that full-time employees have 25 days off per year, which corresponds to 235 working days per year. We first determine the required amount of personnel in FTE based on the vehicles that the company needs.

$$Personnel\ in\ FTE = r * \frac{V * number\ of\ shifts * number\ of\ operational\ days\ per\ year}{number\ of\ working\ days\ per\ year}$$

where r equals the operator-to-vehicle ratio. This ratio is equal to 1 in case of regular terminal tractors, since every terminal tractor needs one driver. With autonomous transport there are no drivers needed, but there are control operators monitoring the autonomous vehicles from a distance. Based on conversations with project partners, we assume that one control operator can monitor four autonomous vehicles simultaneously, which corresponds to an operator-to-vehicle ratio of 0.25. The total annual personnel costs are determined by multiplying the number of employees in FTEs with their corresponding salaries.

Fuel costs

The final type of costs included are the fuel costs. We calculate these costs based on the number of kilometers driven, the average consumption and the prices for energy. We introduce the variable for the total distance driven per year:

$$D = distance\ per\ trip * number\ of\ trips\ per\ day * number\ of\ operational\ days\ per\ year$$

The total fuel costs are then equal to the product of the total distance driven, , the average fuel consumption and the fuel price per liter or kWh. The fuel prices are as follows when fuel is purchased from an external party: diesel costs €1,782 per liter and electricity costs €0,360 per kWh (Global Petrol Prices, 2023). If a company has its own charging station, electricity costs only €0.08 per kWh, assuming an HPC150 private charging station (Top Sector Logistics, 2019).

Both companies in our analyses do not have private charging stations, so we include the required investments costs. We assume an HPC150 high-capacity charging station, with installation costs of €66,000, a lifetime of 10 years and annual operation costs of €6,546 (Top Sector Logistics, 2019). We assume that this charging station has one charger with a capacity of 150 kW and 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). We assume that the usage percentage is higher for industrial use than for passenger cars and therefore assume the upper limit of 30%. Based on this capacity and the required amount of electricity, we determine how many charging stations are needed. We do not include the time required for charging.

Environmental impact

In addition to the difference in costs between regular and autonomous transport, we also calculate the consequences for the environment and employment. With regard to the impact on the environment, we focus on CO_2 emissions. We calculate with the tank-to-wheel emissions, so that only the emissions of the actual transport are included. We assume that regular vehicles run on fossil diesel and that autonomous vehicles run on gray electricity. When using electricity based on wind or solar energy, we can assume that there are no CO_2 emissions (CO_2 emissiefactoren, 2022).

We assume that 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 (CO2 emissiefactoren, 2022).

Results

We present our results in this section. We first present the total business case for both companies, followed by a validation of certain assumptions and a sensitivity analysis.

The business case

We calculate the business case for company A and B, for which both two routes are included in our analysis. Quick calculations seem to indicate that the workload generated by most of the routes is insufficient to keep a terminal tractor busy the entire day. For example, consider route 2 of company A. There are 10 trips of 30 minutes each per day, resulting in a workload of 5 hours. These trips can be performed between 08:00-18:00h. As a result, the terminal tractor would be idle for roughly half of the time. We therefore propose to allow a single vehicle to perform both route types within the same company, which potentially results in the need of less vehicles.

Table 5 presents the required number of vehicles and the resulting costs for both companies, comparing regular transport (TTs) with autonomous transport (ATTs).

Table 5 Total business case for company A and B

	COMPANY A TTs	COMPANY A ATTs	COMPANY B TTs	COMPANY B ATTs
Required number of vehicles	1	1	2	2
Required personnel (FTE)	2.07	0.497	4.35	1.05
CO_2 emissions (kg)	77962	42435	25396	21149
Total equipment cost	29623	53606	43894	97668
Total personnel cost	165851	47732	347639	101239
Total fuel cost	44189	20624	14394	16873
Total annual costs	239663	121961	405927	215779

Let us first consider the required number of vehicles in Table 5, which does not differ if we move from regular transport to autonomous transport. We can thus conclude that the slightly lower speed of an ATT is compensated by the fact that it can continue its operation during breaks. Company A needs only a single vehicle to perform both routes, whereas there are two vehicles needed for the routes of company B.

- **People:** Since autonomous vehicles drive independently, requiring only a control operator from a distance who can monitor multiple vehicles simultaneously, the personnel requirement drops substantially with 75% for both companies.
- **Planet:** Table 5 shows a positive environmental impact of using autonomous vehicles, because of their electric driveline. CO_2 emissions are reduced by respectively 46% and 17% for company A and B. The reduction for company A is substantially larger, because in their operation the shift to autonomous transport has less impact on the fuel consumption. In company B, driving accounts for most of the engine-on-time, whereas in company A most engine-on-time is spend while waiting. We assume that the waiting time is the same for regular and autonomous transport, but driving takes longer with autonomous vehicles because of their lower driving speed. As a result, the engine-on-time in company B is more impacted by the lower driving speed of autonomous vehicles, resulting in a lower reduction of CO_2 emissions.
- **Profit:** The total annual costs for autonomous transport are lower then for regular transport, resulting in a positive business case in both companies. Equipment costs are higher when using ATTs, but this increase is outweighed by the decreased personnel costs (both companies) and fuel costs (only company A).

Besides a reduction in costs, we also see that the total costs of autonomous transport have a different composition. Figure 1 shows the percentual cost structure for company A. With regular transport the largest part consist of personnel costs, being 69% of the total costs. With autonomous transport the picture is different: then equipment costs and personnel costs have comparable shares. Similar results can be found for company B.

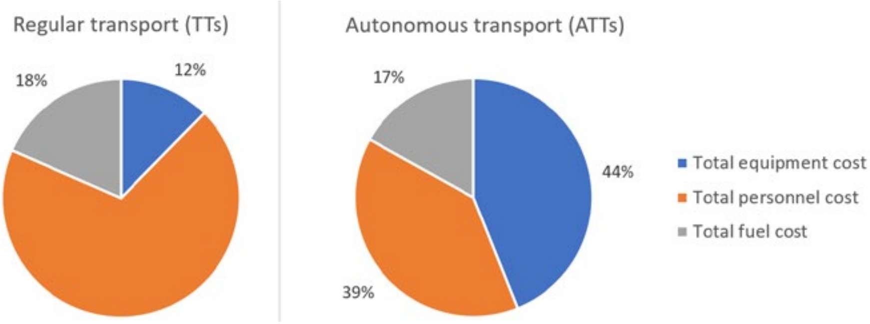

Figure 1 The percentual cost structure for regular and autonomous transport in company A

Validating assumptions

We will now validate our assumption that charging time for autonomous vehicles is not included. We assumed sufficient slack time in the operation to charge the vehicles. The autonomous terminal tractors have a battery pack of 220 kW, of which approximately 80% capacity can be used before recharging is required. So a fully charged ATT can consume about 176 kW. With a consumption of 25 kWh/h, this implies that the engine of the vehicle can be on for 7 hours after which recharging is needed.

For company A, the vehicle has its engine on during the entire trip. With a trip duration of 30 minutes and in total 23 trips per day, the daily engine-on-time equals 11.5 hours. This implies that recharging during the day is necessary. The operational time to complete these trips equals 16 hours (from 06:00-22:00) and is thereby sufficiently large that it is valid to assume that there is time to recharge the vehicle once during the day and once during the night.

For company B, a substantial portion of the trip time is dedicated to (un)loading during which the engine is assumed to be off. For both routes the engine is on for maximum 5 minutes per trip. With 70 trips per day this results in a daily engine-on-time of less than 6 hours. This implies that recharging during the day is not needed and the vehicle can recharge overnight.

Sensitivity analysis

Our results in Table 5 show that the business case for autonomous transport is positive, because of a reduction in personnel costs and fuel costs. In this section, we analyse how sensitive this outcome is to variations in certain crucial parameters.

In Figure 2 we analyse the effect of the electricity price, considering a private charging station and varying prices per kWh. The figure shows that for company A fuel costs of autonomous transport are structurally lower than fuel costs for regular transport. This results turns out to be robust to substantial increases in the electricity price. For company B we see a different picture with fuel costs of autonomous transport being slightly higher than fuel costs for regular transport. The difference between the two companies is caused by the relatively low fuel consumption in company B which leads to fuel costs being mainly driven by the costs of the charging facility. Despite this, the business case for autonomous transport remains positive for company B, indicated by the large difference in total costs.

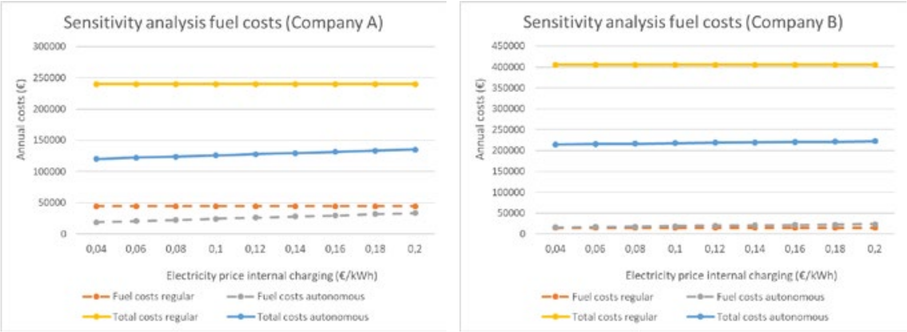

Figure 2 Sensitivity analysis with varying electricity price

In Figure 3 we perform a similar analysis, now changing the operator-to-vehicle ratio of autonomous transport. The figure shows that personnel costs of autonomous transport are lower than those of regular transport when the operator-to-vehicle ratio is smaller than 0.6 for both company A and B. Total costs of autonomous transport exceed those of regular transport with operator-to-vehicle ratios of more than 0.6 or 0.5 for company A and B respectively. We thus conclude that the operator-to-vehicle ratio is an important parameter influencing the business case. However, our assumption of 1 operator per 4 vehicles does not turn out to be very limiting. Even with a ratio of 0.4, implying 1 operator per 2.5 vehicles, the business case is positive for both companies.

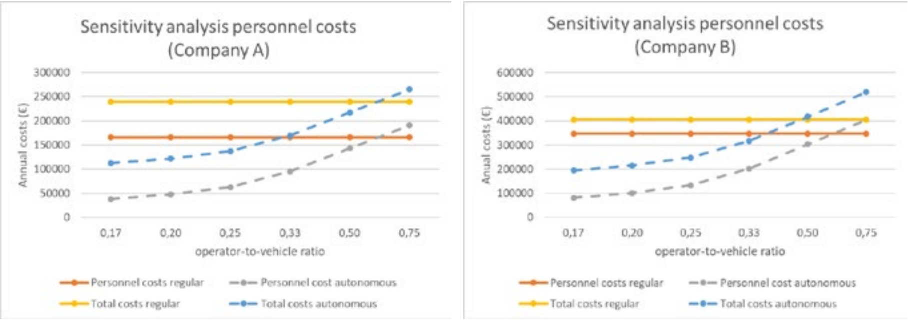

Figure 3 Sensitivity analysis with varying operator-to-vehicle ratio

Non-stop operation

Finally we investigate the possibility of extending the current operation to 24 hours a day. For company A the setting of 24/7 operation could be of interest. Company B indicated that their workload in the weekend is very limited, so they might only consider a non-stop operation during the weekdays. Since autonomous vehicles require less personnel, these vehicles could easily drive during the night. Allowing for night-operation can be a way to use the equipment more efficiently, perhaps even requiring less vehicles for completing the same trips.

When analyzing the required number of vehicles in a non-stop operation, we use the following additional assumption. Without vehicles standing still during night, we must guarantee sufficient time for battery charging during the operation. We assume that autonomous vehicles will have an availability of 85%, implying that they are not available for trips the remaining time. This time can then be used for battery charging or maintenance. We determine this percentage using the energy consumption of an ATT, which his 25 kWh per hour. With the charging station used in this study, it takes 10 minutes to charge 25 kWh. Hence, the vehicle can drive 60 minutes out of every 70 minutes. This roughly corresponds to an availability of 85%.

Table 6 Required number of vehicles for two scenarios of autonomous transport, with fractional value in brackets

	COMPANY A current operation autonomous	COMPANY A 24/7 operation autonomous	COMPANY B current operation autonomous	COMPANY B 24/5 operation autonomous
Required number of vehicles	1 (0.93)	1 (0.56)	2 (1.91)	2 (1.5)

As can be seen in Table 6, the required number of vehicles when extending to 24-hour operation remains the same for both companies. Even though the vehicles are used more efficiently, indicated by the reduction in fractional values, an actual reduction of required vehicles is not possible. For company A this was to be expected, since only a single vehicle is needed in the operation. If no reduction in the number of vehicles is possible, the extension to 24-hour operation is not financially attractive as personnel costs will increase due to irregular working hours. With 24/7 operation of autonomous vehicles, also 24/7 support from the control center will be required. We therefore have to conclude that an implementation of 24-hour operation is not advisable, because of the small scale of the operation in both companies.

Conclusion and discussion

Based on our in-depth comparison of autonomous terminal tractors with regular terminal tractors in two case studies, 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 article therefore provides valuable insights into the benefits of using autonomous terminal tractors.

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. Comparing the two case studies we see that the potential of autonomous transport is larger when charging facilities can be used efficiently in order to pay back the installation costs of a charging station. 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. Roughly, personnel costs are reduced by the same factor as the increase in purchase cost of the vehicle. The potential for autonomous transport is higher when drivers do not perform additional tasks such as assisting in (un)loading, which holds for both case studies in this paper. If drivers do have other tasks on top of driving, alternative solutions are required to compensate the absence of the driver in the case of autonomous transport.

Our analysis shows that the operator-to-vehicle ratio is an important parameter that affects the economic attractiveness of autonomous vehicles. 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.

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

Beside the aforementioned findings, our results show that transitioning to a 24/7 operation setting with autonomous vehicles is not recommended for both case studies considered. The analysis reveals that due to the small-scale trips, the cost of implementing a round-the-clock operation does not outweigh the potential benefits. Using autonomous vehicles to extend to 24/7 operation is only expected to be profitable for companies that operate on a larger scale using a larger fleet of vehicles.

In conclusion, we have presented a method to calculate the business case for autonomous vehicles and derived crucial influencing factors. We studied two case studies for which both the implementation of autonomous vehicles turns out to be a recommended strategy. Although equipment costs may initially be challenging, they do not outweigh the savings in personnel costs and CO_2 emissions. By deploying autonomous transport, companies can save costs, reduce their dependency on scarce personnel and fossil fuels, while contributing to a greener and more sustainable future.

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