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Cost-Effectiveness of Introducing Autonomous Trucks: From the Perspective of the Total Cost of Operation in Logistics

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Abstract: This study explored the economic influence of introducing fully autonomous trucks (ATs) on the total cost of operation (TCO) from the viewpoint of freight transport operators. We utilized the cost–benefit analysis and scenario planning frameworks using a case study of a middle-mile route between a port and a large logistics distribution center in South Korea, where an autonomous truck pilot project has been running for several years. We employed a data source obtained from Hanjin Transportation Co., LTD., which enables us to reflect the actual expenses of operating freight transportation in the context of the study route. The findings of this study indicate that ATs would attain substantial operation cost savings for freight transport operators across all five scenarios, ranging from the most pessimistic to the most optimistic. Specifically, results of the base scenario reveal that monthly TCO decreases by 56.25, 47.04, 42.97, and 41.73 percent for 1-, 5-, 12-, and 25-ton trucks, respectively. The cost reduction per month was USD 2399 for a 1-ton truck, USD 2891 for a 5-ton truck, and USD 3438 for a 12-ton truck. Even in the most pessimistic scenario, the operation cost savings for operating with ATs in the route are USD 1415, USD 1642, USD 1985, and USD 2222 per month for 1-, 5-, 12-, and 25-ton trucks, respectively. When factoring in changes in cost, the wage reduction for vehicle drivers was substantial (USD 2430, USD 2835, USD 3240, and USD 3645 for 1-, 5-, 12-, and 25-ton trucks, respectively). However, remote operation was a new cost factor that increased TCO, which increased by USD 243,384,357 in the base case. This study's findings have multiple implications, including (1) informing economic efficiency and productivity of operating autonomous vehicles (AVs), (2) providing insights on indicative cost estimates for AV operations, (3) providing valuable information for making informed investment decisions, and (4) supporting the notion that freight transport is an especially attractive market for AVs.

Keywords: logistics; autonomous trucks; operation costs of operation; cost–benefit analysis

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Citation: Lee, S.; Cho, K.; Park, H.; Cho, D. Cost-Effectiveness of Introducing Autonomous Trucks: From the Perspective of the Total Cost of Operation in Logistics. *Appl. Sci.* **2023**, *13*, 10467. https://doi.org/10.3390/app131810467

Academic Editor: Tingsong Wang

Received: 4 September 2023
Revised: 18 September 2023
Accepted: 18 September 2023
Published: 19 September 2023

1. Introduction

Automation, usually referred to as automatic control, has developed into a significant component of our modern civilization [1]. Many different supply chains have become more streamlined and efficient during the last decades thanks to automation. These adjustments have frequently led to a decrease in the total cost of operation (TCO) [2]. One of the real-world applications of automation is a fully autonomous truck (AT) in the logistics industry, which refers to light- or heavy-duty commercial trucks that are fully automated (i.e., level 5). The auto industry has been developing new technologies for ATs, which are anticipated to be deployed gradually and earn market shares [3]. This shift will not only provide risks for the involved companies, but it will also present opportunities for them to pursue in the logistics businesses [4]. Accordingly, the past few years have seen significant advancements in the research on the effects of introducing ATs. The economic advantages and costs of ATs are frequently discussed in the gray literature; specifically, in comparison to human-driven trucks (HDTs), it is anticipated that ATs will be able to facilitate significant cost reductions [5]. The availability of data and the unpredictability of costs are two of the primary research challenges associated with calculating TCO. To be more specific, autonomous trucks are still a comparatively new technology, and as a result, there is a paucity of information regarding the costs associated with their operation and maintenance. In addition, the costs associated with operating an autonomous truck can differ greatly depending on a variety of variables including the kind of cargo being transported, the distance traveled, and the terrain.

This study attempts to overcome the issues and quantify the change in TCO when introducing ATs, from the viewpoint of freight transport operators. This study employs the cost–benefit analysis framework with scenario planning ranging between the most pessimistic and the most optimistic. This study further focuses on the following points in the analysis: first, it developed assumptions of each scenario based on previous literature; second, it used diverse operation cost factors collected from a logistics firm; third, it utilized a case study area of a middle-mile route in South Korea; and fourth, it explored TCO of different types of ATs, such as 1-ton, 5-ton, 12-ton, and 25-ton ATs. The following research questions were posed to investigate: (1) what are the anticipated operating costs involved in putting 1-ton, 5-ton, 12-ton, and 25-ton ATs into operation?; (2) how will the adoption of the ATs influence the costs associated with logistics operations?; and (3) how significant would the impact be on cost estimation when considering various scenarios?

This study has several areas of significance and many implications. First, the results of this study have the potential to have a substantial economic impact, as they may not only result in substantial cost reductions for logistics firms but may also increase economic productivity if ATs prove cost-effective. Second, it may cast light on the readiness of the logistics industry to adopt ATs, given that the study provides information on the cost-effectiveness of ATs and may help firms overcome potential obstacles and difficulties. Thirdly, investors in the logistics and technology sectors can make informed investment decisions based on the findings of such a study. Fourth, the findings of this study can assist freight transport operators in reallocating resources to operations that are both more vital and performance-enhancing by investigating and analyzing procedures from an operation cost-reduction perspective.

2. Background

2.1. Total Cost of Operation of Autonomous Trucks

A small body of literature has examined the economic impact of ATs on TCO, although a multitude of research studies have been conducted to investigate the effects of ATs in the context of heavy-duty and long-haul truck transportation [6]. Overall, previous literature has confirmed overall TCO reduction from the perspective of freight transport operators. Specifically, the grey literature of Nowak et al. [7] argued that costs associated with trucking logistics will decrease by 47%, primarily due to a reduction in labor. Wadud [8] analyzed TCO for three different types of ATs and found that TCO will reduce by 15–20% overall. A study by Engholm et al. [9] revealed significant cost reductions for freight transport operators; for instance, the operation costs for 16-ton trucks, 24-ton trucks, 40-ton trucks, and 60-ton trucks will reduce by 45%, 37%, 33%, and 29%, respectively. Heutger and Kückelhaus [10] suggested that ATs will be able to travel 24/7 without requiring driver rest time, and in comparison to driving as it is conducted today, they could achieve overall cost reductions of 40% per kilometer. Clements and Kockelman [11] estimated the economic impact of ATs in the United States to be USD 1.2 trillion, as they will reduce the demand for auto maintenance, traffic police, medical, insurance, and legal services.

In detail, ATs would be of enormous advantage to freight transportation and trucking business by eliminating or reducing the wages of truck drivers and allowing the firms to address the scarcity of truck drivers; yet, the employment opportunities available to millions of truck drivers will decline as a result [11]. Fritschy and Spinler [4] also argued that ATs will result in lower costs for drivers. Moreover, Andersson and Ivehammar [3] found that improvements in fuel efficiency will result in lower TCO for truck owners over the long term. Merfeld et al. [12] suggested that since ATs will be designed to have a lower fuel consumption, they will reduce fuel expenses. In addition, vehicles have the potential to improve their hours of service because they can travel around the clock without requiring drivers to take breaks. Mauler et al. [6] found that ATs will be cost-competitive since they will eliminate mandatory break and rest times and reduce energy consumption.

2.2. Methodological Approaches

Regarding the methodological approaches, previous literature has used several ways to examine and predict TCO, the most prominent of which are surveys and literature reviews. For instance, Fritschy and Spinler [4] adopted the Delphi method by surveying 30 experts to provide a multistakeholder perspective including academics, consultants, practitioners, and government representatives. Clements and Kockelman [11] conducted a literature review to determine the effect that ATs would have on the logistics industry and the economy as a whole. Izadi et al. [13] also reviewed previous literature to determine cost factors (e.g., operational costs, the value of time, and external costs) and analytical models (e.g., statistical models and surveys, and meta-analyses). Only a few studies employed cost–benefit analysis, including Kang et al. [14], who used case study areas in Illinois with varying levels of AT market penetration to estimate cost savings for the freight sector. However, this study considered a few cost factors, such as fuel efficiency, pollutant emissions, and safety.

2.3. Research Gaps and Contributions of This Study

Several research gaps exist in the body of prior publications. First, although a large body of literature has explored the TCO of HDTs with diverse geographical scopes and methods [13], few studies have attempted to explore the operation cost estimation of introducing ATs due to their uncertain nature. Second, previous literature has observed the potential to offer widespread gains in safety as well as time savings; nonetheless, few studies have explored the economic side effects of ATs. Third, previous literature has not compiled and integrated a wide range of factors of operation costs of freight transport operators into the analysis framework. Fourth, only two prior studies, to our best knowledge, have employed the cost–benefit analysis framework using actual cost data from a freight transport operator. Fifth, previous studies have not analyzed TCO savings by focusing on a middle-mile route; specifically, they have not attempted to separate middle-mile travel from first- and last-mile travel as part of the analysis. We aim to fill these gaps in this study.

3. Materials and Methods

3.1. Problem Statement

ATs have the potential to completely transform the transportation and logistics industry by reducing the expense of labor, boosting productivity, and making the roads safer for everyone. However, there is a lack of understanding regarding its TCO. This cost does not just include the cost of purchasing and maintaining the vehicles; it also includes the cost of infrastructure, software, and regulatory compliance. Due to this gap in understanding, it is challenging for businesses and policymakers to make decisions that are based on accurate information regarding the use of autonomous trucks. Therefore, this study aims to find a solution to this issue since it is necessary to devise a comprehensive framework for determining how much it will cost to run ATs as a whole. Quantifying TCO is a difficult problem that calls for a strategy that draws from multiple disciplines as well as collaboration between researchers, policymakers, and industry stakeholders.

3.2. Case Study Area of the Middle-Mile Route in South Korea

This study uses a middle-mile route between the Bieungdo port and the Hanjin Jeonju logistics distribution center in South Korea, in Figure 1, as a case study area, where a series of autonomous truck pilot projects has been running. The route is 57 km long with a speed limit of 90 km per hour. It includes both interrupted and continuous flow intersections. It passes through two municipalities, including Gunsan and Jeonju; specifically, it connects Jeonju, a major city in North Jeolla Province, and the Saemangeum National Industrial Complex, Gunsan National Industrial Complex, and domestic commercial vehicle production base in Gunsan.

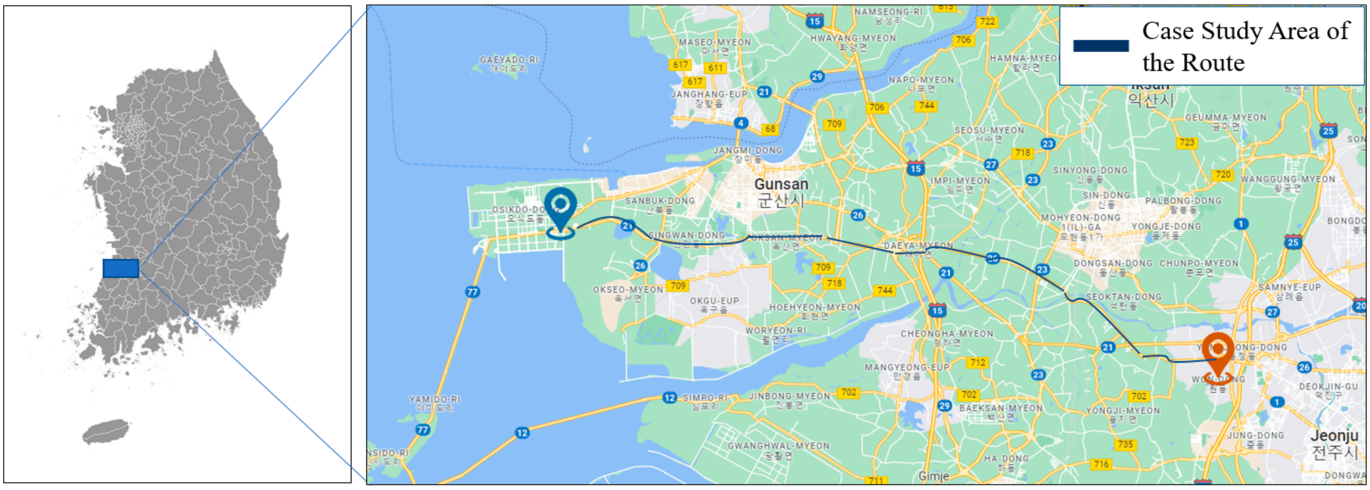

Figure 1. The case study area of the middle-mile route in South Korea.

We selected this route for the following reasons. First, a case study area in South Korea is an appropriate candidate to explore the impact of ATs on TCO given the readiness of driving automation. Specifically, KPMG International [15] released the autonomous vehicle readiness index in 2020 to evaluate the readiness of AVs by considering policy and regulation, technological advancement, infrastructures, and consumer acceptance. According to this report, the most significant growth was seen in South Korea. This was partly attributable to the massive government-funded AV pilot programs and the accessible infrastructures, including 4G coverage and mobile connection speed. More importantly, significant research efforts have been made on the route for ATs by collaborating with federal and local governments, research institutions, universities, and freight transport operators. Thus, the route in South Korea has the potential to become a focal point of AT operation in the proximate future.

Second, since the route connects a port to one of the largest distribution centers for logistics in the region, it is a suitable study area for middle-mile travel for the logistics industry. This feature is important in this study, given its emphasis was placed on the use of ATs on highways or freeways for long-distance and regional freight movements rather than on their use for local transportation or transportation over the first and last mile within metropolitan areas. We focused on middle-mile travel because ATs are assumed to be feasible in long-distance settings well before urban areas [7]. Also, the operations of first-mile transport and last-mile transport encounter serious challenges that need to be analyzed separately.

Third, the proportion of trucks along the route follows a pattern that is comparable to that of South Korea as a whole. Specifically, annual averaged daily traffic of trucks on the route was approximately 2328 (24.5%), while that of freeways in South Korea was roughly 4,846,000 (21.8%). Therefore, the choice of this location as a study area could exclude the possibility of selection bias given the travel patterns of trucks.

3.3. Analysis of Autonomous Trucks

This study focuses on the economic impact of introducing ATs on TCO since the AT market could potentially have a significant impact on the road freight transportation industry [1]. First, there is an anticipated shortage of truck drivers, with an estimated shortfall of 800,000 drivers in the United States and the European Union by the year 2030 [16]. Labor costs have also been on the rise. In this regard, ATs can help mitigate these challenges in the labor market. Second, industry experts anticipated gains in areas that are targeted, such as traffic safety and truck productivity, and they believe that these benefits will be realized due to ATs [11]. Third, many logistics companies operate in intense competition, which compels them to look for innovative ways to reduce costs to stay competitive. One strategy for dealing with this issue could involve developing brand-new, groundbreaking solutions using the assistance of modern technology, such as ATs. Fourth, one of the primary motivating factors for the use of innovative technology is the possibility of operating cost savings [17]. For instance, ATs have the potential to significantly cut driver costs, which account for a significant portion of road freight transportation costs, which is approximately forty percent of total costs [9].

3.4. Truck Cost Model

TCO of a vehicle is essentially the total of all costs incurred by the vehicle's owner while the vehicle is in their possession [8]. It is noted that externalities, such as prospective infrastructure costs that have not been internalized by taxes or other fees, are not considered in this calculation [9]. This study focused on the perspective of freight transport operators, although the cost of freight transport can be broken down into three distinct groups of parties, including the freight transport operators, the freight owners, and governments. Despite the recent fluctuation in the exchange rate, all values were converted to US dollars for the global readers of this paper by using the exchange rate of 26 January 2023, which is 1230.87 South Korean won per US dollar.

This study explores four different types of ATs, and they are classified according to the total maximum weight of the truck. The AT types are 1-, 5-, 12-, and 25-ton trucks, which are used most frequently in the logistics industry in South Korea. Also, this analysis was based on TCO per month instead of lifetime TCO since different truck types have varying TCO estimations due to diverse factors, such as different investment durations and utilization rates. Therefore, the cost factors were not considered time-dependent, but they were averaged out throughout a truck's lifetime to yield a cost per month.

Table 1 shows operating cost factors, including both fixed and variable expenditures, employed in this study. The fixed costs, such as acquisition costs, are those that are associated with keeping a vehicle parked and available for use in the freight system. These costs do not fluctuate frequently and are not typically impacted by the amount of time that the vehicle is used. The variable costs, such as fuel consumption, are those whose total amount is determined by the way the vehicle is operated. Since all cost factors converted all factor units (for instance, liters per 100 km for fuel consumption) into monthly US dollars by Hanjin Logistics Corporation, we used US dollars per month as the unit of analysis.

The data in Table 1 were obtained from Hanjin Logistics Corporation. The firm is one of the leading companies in the logistics industry in South Korea. Also, the world-class logistics network that Hanjin Shipping maintains around the globe is supported by its approximately 5800 global staff members, its four regional headquarters located in the United States, Europe, Asia, and Southeast and West Asia, and its twelve container terminals located in the world's major ports. The cost model was based on regulations in South Korea, such as the hours of service and minimum wage protection. The truck cost model was finalized after being cross-checked with individuals working in the logistics industry in South Korea. The primary advantage of using these data was that we could employ real-world data that accurately reflect the actual expenses of operating freight transportation in the context of the case study of the route.

Table 1. Operation cost data for the manually driven trucks in the case study of the route.

Variables	1-Ton Truck	5-Ton Truck	12-Ton Truck	25-Ton Truck
vehicle driver	2430.00	2835.00	3240.00	3645.00
vehicle acquisition	611.43	993.57	1222.86	1528.57
vehicle depreciation	86.39	292.77	490.38	663.80
fuel consumption	191.47	340.44	437.64	547.05
driver insurance	159.22	247.81	407.18	472.79
car insurance	150.79	239.90	275.27	299.08
commercial driver license fee	1.65	56.98	202.27	232.66
taxes	25.39	86.57	211.60	250.10
environment improvement payment	171.06	491.76	881.85	990.95
tax filing fee	28.00	27.14	24.85	24.90
regular inspection fee	242.21	325.91	360.59	379.75
maintenance	30.21	43.26	52.92	59.30
tire	8.46	17.53	23.19	33.48
other car components	1.55	1.61	2.05	2.64
car wash	10.76	7.38	7.84	7.83
logistics association registration fee	15.66	16.11	24.85	24.59
parking	36.82	60.54	61.87	92.14
accommodation	0.00	0.00	0.00	0.00
telecommunication	64.46	62.37	74.26	72.30
toll	0.00	0.00	0.00	0.00
Total	4265.53	6146.65	8001.45	9326.92

Unit: since the data source converted all factor units to US dollars per month, we used US dollars per month as the unit of analysis. Note: this study categorized trucks into 1-, 5-, 12-, and 25-ton trucks since they are used most frequently in the logistics industry in South Korea. Note: this study used the factors in this table since they are utilized by Hanjin Logistics Corporation, which provided the data. Note: all values have been converted to US dollars using the exchange rate of 26 January 2023, which is 1230.87 South Korean won per US dollar.

3.5. Literature-Based Scenario Planning

3.5.1. The Five Scenarios

In the 1950s, Kahn pioneered the application of the scenario planning approach, which combined in-depth assessments with so-called scenarios on emerging types of technology [18]. This study adopted the definition of scenario planning offered by Schoemaker [19], who refers to it as a methodical approach to the imaginative recreation of potential futures as they relate to the implementation of organizational decisions, although there are numerous definitions of scenario planning [4].

Thus, this study uses this approach to examine future development with uncertain outcomes. Specifically, this study creates five alternative scenarios ranging between pessimistic and optimistic in the long-term horizons instead of regarding it as fixed (see Table 2). The findings of earlier research are used in this study to define the five possible outcomes as follows: (1) the most pessimistic, (2) pessimistic, (3) the base, (4) optimistic, and (5) the most optimistic (see Table 2). Since the basic scenario would correspond to a real-world situation, we concentrated on the interpretation of the scenario's results. In this imagined version of the future, all the scenarios take place when AT technology has advanced to a point where it is commonly available. The literature utilized in the development of the scenarios encompassed a range of research, including both outdated and recent studies.

We make several assumptions for this analysis. First, because of the inherent unpredictability of changes to real costs, it has been assumed that the connection between the various cost components connected with AT operations will remain the same. Second, there will be no disruption to the transport or logistics processes, such as transport routes, the average share of cargo, and loading capacity, due to the introduction of ATs. Third, it is assumed that the economic impacts of ATs across all the scenarios will have the same relative impacts on all different types of ATs.

Table 2. Assumptions on operation cost factors relative to the manually driven trucks for the five scenarios.

Variables	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
	The Most Pessimistic	**The Pessimistic**	**The Base**	**The Optimistic**	**The Most Optimistic**
vehicle driver	−100%	−100%	−100%	−100%	−100%
vehicle acquisition	25%	10%	0%	−10%	−25%
fuel consumption	−10%	−15%	−20%	−25%	−40%
driver insurance	−100%	−100%	−100%	−100%	−100%
car insurance	0%	−5%	−10%	−15%	−20%
regular inspection fee	25%	10%	0%	−10%	−25%
maintenance	25%	10%	0%	−10%	−25%
other car components	25%	20%	15%	10%	5%
remote operation	40% of vehicle driver	20% of vehicle driver	10% of vehicle driver	7% of vehicle driver	5% of vehicle driver

Note: Assumptions on other operation factors that were not presented in this table were unchanged since previous literature did not show a concrete indication.

3.5.2. Assumptions on the Factors

This study defines the five scenarios based on previous literature (see Table 2). First, regarding the driver and remote operation costs, the driver cost was eliminated in all scenarios, since this study considered ATs with level 5, which is that ATs can make decisions without any human intervention or control [20,21]. However, since ATs will require costs for new technologies, networks, and skilled operators, this study considered the cost estimate; for instance, the most pessimistic scenario assumed 40% of driver costs [9].

Second, a change in the acquisition cost of the vehicle was included in the cost estimation due to the distinction made between the components and design standards for ATs and trucks. On the one hand, the driver’s cabin is one of the most difficult components to manufacture, and it normally accounts for approximately one-third of the total cost of a vehicle [7]. On the other hand, since the necessity for safety features will be much reduced, it will lower costs associated with the production of ATs [22]. That is, this study assumed that the cost of acquisition will remain the same in the basic scenario, while it will increase by 25% in the most pessimistic and decrease by 25% in the most optimistic scenario.

Third, fuel consumption will decrease in all the scenarios, based on the previous literature. For instance, Andersson and Ivehammar [3] quantified and valued the effects of ATs and found that ATs will reduce fuel consumption by approximately 10%. Kang et al. [14] found that fuel economy improvement in ATs was around 15%. Zhang et al. [23] revealed that the fuel consumption saving would be around 5 to 15%. Chen et al. [24] suggested that the effect size of autonomous vehicles on fuel consumption would be between −45% and 30%. Relatively outdated studies have also indicated the potential cost savings of ATs associated with reduced fuel consumption. For example, McKinsey Global Institute [25] anticipated that ATs will have an increased fuel efficiency of between 10 and 40 percent compared to the trucks that are available today. Heutger and Kückelhaus [10] suggested that ATs will reduce fuel consumption by 15%. In sum, since the previous studies suggested that the fuel consumption saving will range between 10% and 40%, this study used this range to define the scenarios. That is, ATs can operate without mandatory breaks, with greater traffic performance per month, and consequently, the gasoline costs can be significantly higher than those of HDTs.

Fourth, ATs will eliminate driver insurance due to the absence of drivers in the vehicle. Also, ATs will lower the cost of auto insurance to some extent, mainly due to their potential to improve road safety [16]. For instance, Engholm et al. [9] estimated a reduction in insurance costs ranging between 10% and 20%. Thus, this study followed the findings of the previous literature.

Fifth, there is no consensus among experts on the change in maintenance costs of ATs, because smoother driving for DL trucks may lower the cost of maintenance that is required, but it is also possible that the new and complex technology could cause an increase in the cost. For instance, Clements and Kockelman [11] estimated around a 25% reduction in maintenance costs. Bosch et al. [26] maintained that the costs will be unchanged. According to Engholm et al. [9], it is anticipated that the expenses would reduce by 20%; however, it is possible that the costs could increase by 20%. As a result, the most pessimistic scenario in this study was defined as a 25% decrease in the regular check fee and maintenance cost, while the most optimistic scenario was characterized as a 25% increase in those costs.

Sixth, the price of car components will increase since it is necessary to have several highly integrated functions, such as sensors and video cameras, vehicle-to-everything (V2X) communication, as well as prediction and decision-making algorithms, and the car acquisition cost will increase. Clements and Kockelman [11] found that expenses of electronic and software technologies will increase by around 15%. Therefore, this study utilized the percentage increase as the base situation.

Lastly, the previous research does not provide any definite clues as to how other expenditures, such as the cost of depreciation, the charge for a commercial driver's license, taxes, tires, the fee for a logistics association, and tolls, will alter because of driving automation. It is assumed that other costs will remain the same for all the scenarios because there is a lot of uncertainty and very little information in the relevant literature [9].

4. Results

4.1. Change in Total Costs of Operation

Table 3 presents TCO savings for ATs compared with HDTs in the logistics industry. Overall, the cost structure of operating a truck has been significantly impacted by the introduction of driving automation. The findings in Table 3 confirmed the overall TCO reductions when replacing HDTs with ATs, although the magnitude of the savings varies depending on which of the five scenarios is considered. Thus, this study concludes that ATs will likely enable a net decrease in TCO from the perspective of freight transport operators; however, the degree of the potential reduction will be uncertain.

Table 3. The results of the overall total cost of operation reduction due to autonomous trucks in the case study of the route.

Scenario		1-Ton Truck	5-Ton Truck	12-Ton Truck	25-Ton Truck
		TCO Savings in US dollars			
1	the most pessimistic	1415	1642	1985	2222
2	the pessimistic	2051	2442	2915	3289
3	the base	2399	2891	3438	3892
4	the optimistic	2578	3142	3735	4241
5	the most optimistic	2795	3466	4124	4706
		TCO Savings in Percent (%)			
1	the most pessimistic	33.17	26.71	24.81	23.82
2	the pessimistic	48.08	39.73	36.43	35.26
3	the base	56.25	47.04	42.97	41.73
4	the optimistic	60.43	51.11	46.67	45.47
5	the most optimistic	65.53	56.39	51.54	50.46

Specifically, the results of the base scenario (scenario 3) indicate that the cost reduction per month was USD 2399 for a 1-ton truck, USD 2891 for a 5-ton truck, USD 3438 for a 12-ton truck, and USD 3892 for a 25-ton truck. Expressed as percent change in TCO for ATs, the monthly savings were 33.17, 26.71, 24.81, and 23.82 percent for 1-, 5-, 12-, and 25-ton trucks, respectively, in the most pessimistic scenario. As shown in Figure 2, the percent change in TCO compared to the most pessimistic scenario increased by approximately 30% for the various types of trucks in the most optimistic scenario.

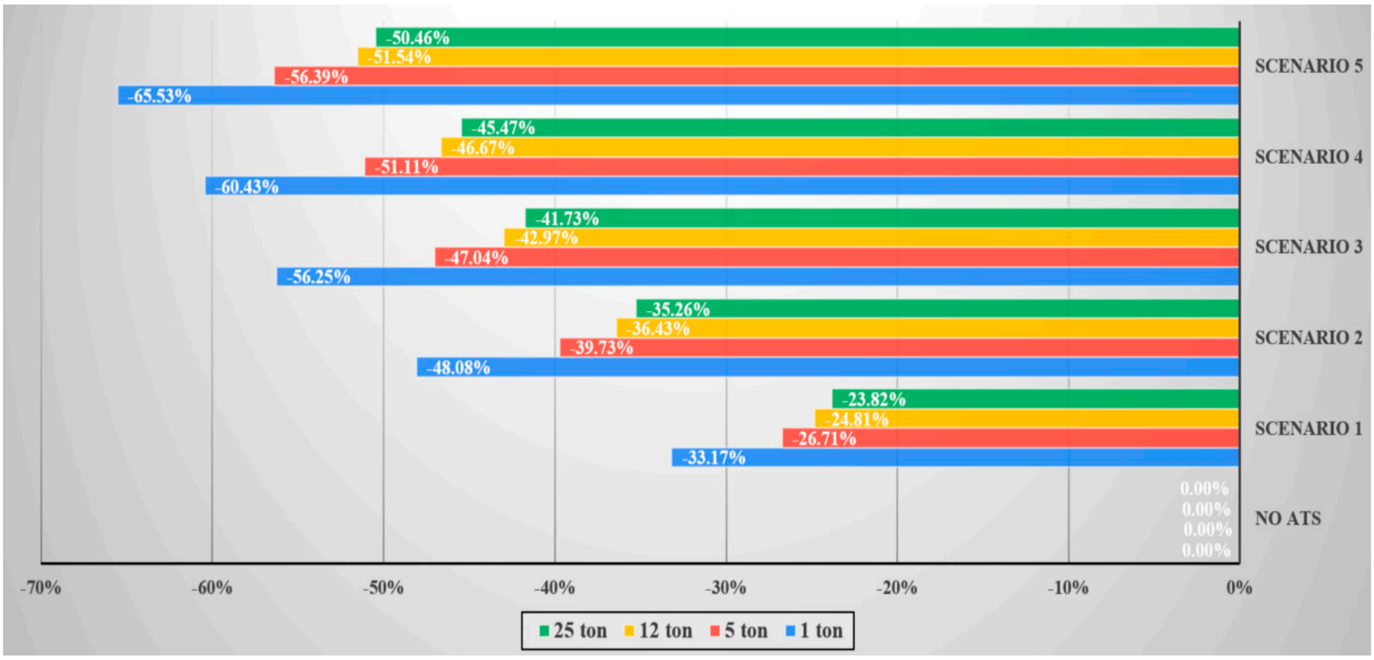

Figure 2. Percent change in the total cost of operation for autonomous trucks under the five scenarios (unit: percent).

4.2. Breakdown of Change in Cost Factors

Figures 3–6 each provide a breakdown of the change in each cost factor for a 1-ton, 5-ton, 12-ton, and 25-ton truck, respectively, under the current status (i.e., no ATs) and five scenarios. In general, the patterns for the four different types of trucks are quite comparable to one another. The reduction of driver costs, which accounted for around half of TCO for an operational truck in the current logistics business, was the primary factor behind the cost savings that will be realized. Additionally, the new cost component for the remote operation turned out to be the most significant contributor to the overall cost rise across all five scenarios. TCO for ATs increased due to rising acquisition expenses, and the acquisition costs increased the proportion of TCO for ATs.

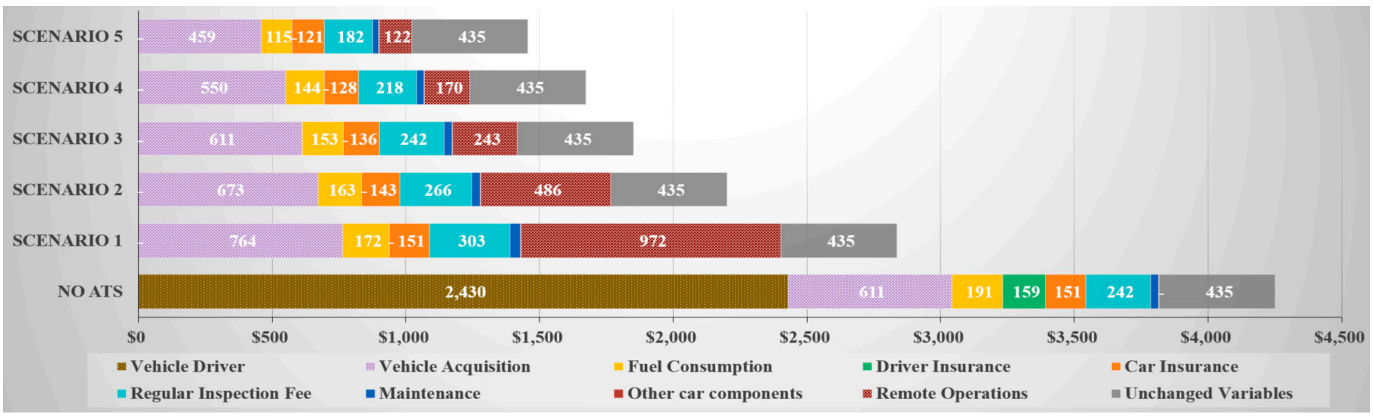

Figure 3. Breakdown of the cost structures for a 1-ton truck under the current status (i.e., no ATs) and five scenarios in the case study of the route (unit: USD per month).

In Figure 3, while the monthly wage for a driver of a 1-ton HDT was USD 2430, the driver cost was eliminated in all five scenarios. The acquisition cost of a 1-ton HDT was USD 611 per month, and the cost increased by USD 153 in scenario 1 (the most pessimistic scenario) and USD 61 in scenario 2 (the pessimistic scenario). Scenario 5 (the most optimistic scenario) results in a monthly TCO saving of USD 53 due to lower fuel consumption.

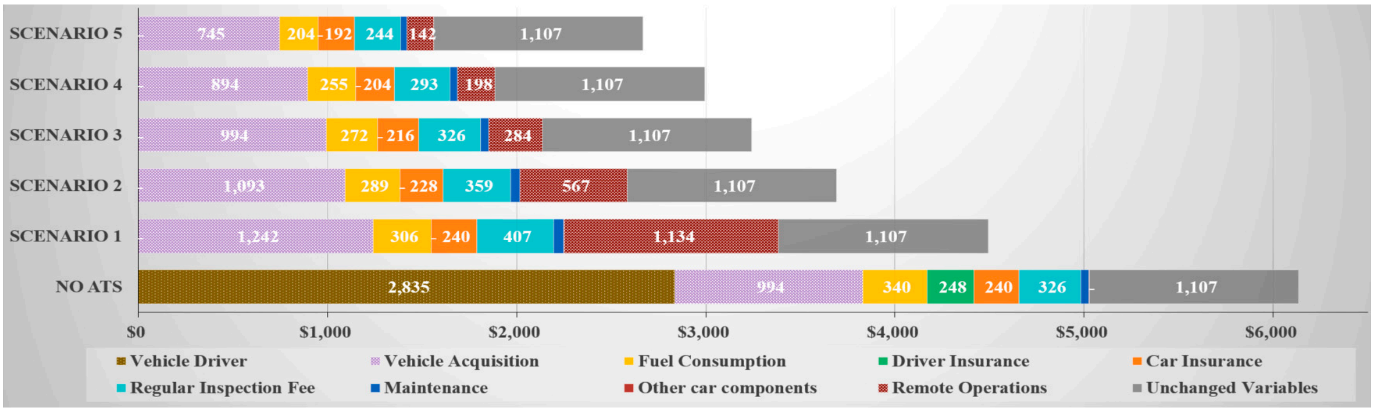

Figure 4. Breakdown of the cost structures for a 5-ton truck under the current status (i.e., no ATs) and five scenarios in the case study of the route (unit: USD per month).

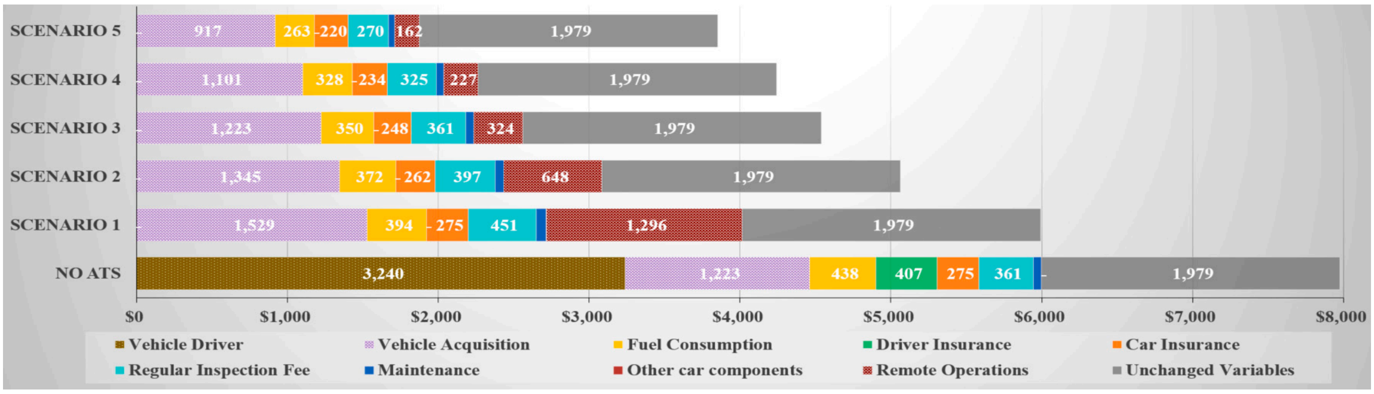

Figure 5. Breakdown of the cost structures for a 12-ton truck under the current status (i.e., no ATs) and five scenarios in the case study of the route (unit: USD per month).

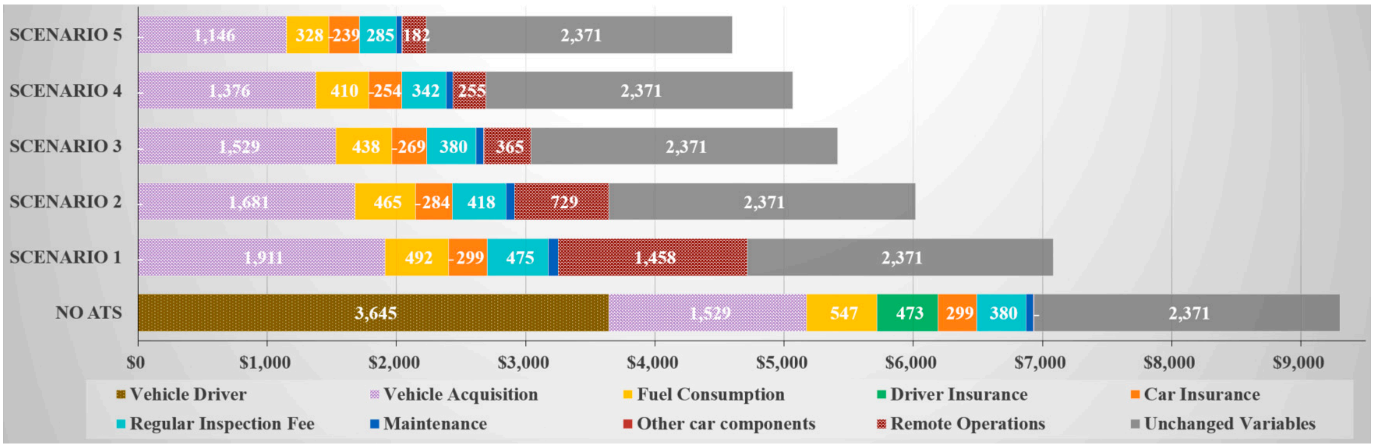

Figure 6. Breakdown of the cost structures for a 25-ton truck under the current status (i.e., no ATs) and five scenarios in the case study of the route (unit: USD per month).

The findings of Figure 4 reveal that the cost of a 5-ton AT will be reduced by USD 2835 per month, while the cost for remote operations of ATs will increase by USD 1134, USD 567, USD 284, USD 198, and USD 142 per month for scenario 1, 2, 3, 4, and 5, respectively. The costs for regular checks and maintenance showed a significant reduction, which amounted to USD 277 per month in scenario 5.

Figure 5 shows that the driver cost of a 12-ton HDT was USD 3240 per month, which was equivalent to around 40.6% of TCO for a 12-ton truck. However, ATs will be able to eliminate this cost and offer considerable operation cost saving for freight transport operators. However, remote operations and acquisition costs significantly increased, by USD 1296 per month in total in scenario 1 (the most pessimistic scenario).

In Figure 6, a 25-ton AT will save USD 3645 per month due to the presence of a driver on an HDT. The acquisition cost increased by USD 382 and USD 153 per month in scenarios 1 and 2, respectively. The environmental improvement fee, which accounted for 10.6% of TCO, was an important cost element for a 25-ton truck. Since driving automation will be able to improve pollution emissions [27], the cost factor may be an additional significant cost component that will offer TCO savings for freight transport operators. However, this economic factor was not considered in this study because previous literature has not provided a clear indication of how much of a cost reduction there would be in terms of the improvement fee for the environment.

5. Discussion

5.1. Major Findings

The major findings are as follows. First, introducing ATs has dramatically altered the cost structure of truck operations. This analysis validated the overall TCO reductions for ATs from the standpoint of freight transport operators, albeit the magnitude of the savings varies depending on which of the five scenarios is considered. Second, the decrease in driver costs, which accounted for about half of TCO for an HDT, was the primary element behind the cost savings that will be realized. The new cost component for remote operation was the largest contributor to the overall cost increase across all five scenarios. TCO for introducing ATs increased because of rising acquisition charges, and the proportion of TCO for ATs increased as a result. Third, in terms of comparison with the findings of previous studies, the cost savings of this study across all scenarios were slightly higher than those in the few directly comparable publications. Specifically, previous literature suggested that the reduction in TCO of ATs was between 15% and 50%, depending on the types of ATs and the assumptions of scenarios [7–9]. However, our estimates fell anywhere between 25 and 65 percent. There are several possible explanations for these findings. For example, ATs can be more profitable for middle-mile operations since the first- and last-mile operations will require sophisticated technologies to perform well.

5.2. Implications

The market for logistics services is extremely competitive, and as a result, many businesses are putting a lot of effort into becoming either cost-efficient or innovative to obtain a competitive advantage over their rivals. If logistics organizations place their primary emphasis on cost leadership as their primary source of competitive advantage, then their rivals may discover cheaper labor or lowered prices and be able to surpass other players who place the same emphasis on cost-efficiency. On the other hand, if logistics companies were to concentrate on being innovative and distinguishing themselves from their competitors, they would be using a long-term strategy that has the potential to be successful in the long run. The findings of this study suggested that it is more profitable in the long run to focus on developing new and improved services of higher quality by using ATs rather than cutting costs to unprofitable levels. In other words, the results indicated that TCO will significantly reduce by revolutionizing the way that we carry commodities in the not-too-distant future. As expected, many automakers, such as Volvo Trucks and the Volkswagen Group, are conducting research on cutting-edge technology because of the significant benefit that these advancements will offer to freight transport operators. However, several businesses are looking into developing ATs, but no one has yet been successful in commercializing a fully functional autonomous vehicle. Therefore, the freight transport operators ought to consider investing in the development of ATs to move up launching and enhance the market penetration rates of ATs, which offers significant TCO savings for them.

5.3. Limitations of This Study

We acknowledge several limitations and offer future research directions. First, while diverse stakeholders, including end-users, employees, regulators, and technicians, will be in the AT industry, this study focused merely on the perspective of freight transport operators. Second, the time horizon represents the most significant constraint of this study. Because we were looking ahead, a significant amount of our data was derived from external estimations, which could shift as more time passes. Third, since only the expenses that are directly associated with transportation have been explored, a future study should analyze the entire process of logistics, such as warehousing operations, and loading and unloading the goods. Fourth, although the results may change according to the market penetration rates of ATs, this study did not consider this aspect in the cost estimates. Fifth, in a subsequent study, it should also be an objective to differentiate between the various levels of automation of ATs. Sixth, this study focused solely on one mode of transportation (i.e., trucks), while ruling out other transportation modes in logistics, such as rail, air, and marine vehicles. Seventh, since this study conducted a case study in South Korea, the findings based on this analysis with a limited geographic scope may not be generalizable. Eighth, this research disregarded one of the most significant contributors to the operating expenses of freight transportation companies—namely, investments in AT technology. Also, the potential expenditures for new infrastructure that would be necessary to enable ATs were not included in the cost estimation of this study because it is unclear whether such infrastructure would be required and what precise specifications and costs should be included in the calculations. Even more critically, the rebound effect may very well reverse the gains in cost-efficiency that have been achieved. For instance, major employment losses may result, and in level 4 automation, the drivers' responsibilities are minimized to include just straightforward activities. Nevertheless, we did not consider the impact of these adverse effects on the TCO estimation.

6. Conclusions

This study quantifies the effects that ATs will have on TCO from the perspective of freight transport operators, using a case study of a middle-mile route in South Korea. We combine the usage of the cost–benefit analysis framework with scenario planning. TCO for HDTs is compared to that of ATs for a total of four different truck types (1-, 5-, 12-, and 25-ton trucks) and five different scenarios reflecting between pessimistic and optimistic assumptions based on previous literature. We believe that while there is still some degree of uncertainty regarding the findings, this study contributes to investigating the potential economic effects and providing estimates that are illustrative of the transport costs associated with AT operations.

Author Contributions: Conceptualization, S.L., K.C., H.P. and D.C.; methodology, S.L., K.C., H.P. and D.C.; software, S.L.; validation, K.C., H.P. and D.C.; formal analysis, S.L.; investigation, S.L. and D.C.; resources, K.C. and H.P.; data curation, K.C. and H.P.; writing—original draft preparation, S.L., K.C. and H.P.; writing—review and editing, D.C.; visualization, S.L.; supervision, D.C.; project administration, K.C. and H.P.; funding acquisition, K.C. and H.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Ministry of Trade, Industry, and Energy in the Republic of Korea (Grant Number: P0020670, Research Title: Establishing a Demonstration Infrastructure of Autonomous Cargo Transportation Service for Commercial Vehicles in Saemangeum).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

Conflicts of Interest: The authors declare no conflict of interest.

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