Life Cycle Employment and Carbon Footprint Assessment of Automation and Electrification in the US Trucking Sector

Ja'far M. Mandouri
M.Sc. Engineering Management, Mechanical & Industrial Engineering Department
Qatar University
Doha, Qatar
Jm2100053@qu.edu.qa

Nuri C. Onat
Associate Professor, Qatar Transportation and Traffic Safety Center, College of Engineering
Qatar University
Doha, Qatar
onat@qu.edu.qa

Murat Kucukvar
Associate Professor, Department of Business Ethics and Legal Studies, Daniels College of Business
University of Denver
Denver, CO, USA
Murat.kucukvar@du.edu

Abstract

This study investigates the relationship of emissions reduction, technological transition, and employment dynamics within introducing autonomy to the trucking industry. Results highlight the urgency of adopting cleaner technologies and integrating autonomy to curtail greenhouse gas emissions. Despite additional emissions originating from manufacturing autonomous system components and additional maintenance operations, autonomous trucks offer fuel efficiency improvements and emission reductions compared to non-autonomous trucks. Employment implications reveal potential job losses due to automation overwhelming opportunities arising in autonomous system components manufacturing and maintenance, resulting in net losses of jobs within the industry. Transitioning from non-autonomous diesel trucks to autonomous battery electric trucks showcases a 50% reduction in emissions, highlighting the significance of combining autonomy and electrification in reducing emissions. The Green Employment Index is utilized to measure how green employment within the trucking industry is, unveiling a sustainable framework for job creation in tandem with emissions reduction. Based on this, for low penetration levels of less than 50%, transitioning from non-autonomous battery electric trucks to autonomous battery electric trucks offers the "greenest" employment opportunities.

Keywords

Autonomous Electric Trucks; Life Cycle Assessment; Carbon footprint; Autonomy; and Employment

1. Introduction

New technology known as autonomous trucks (AT) has the potential to completely change the logistics and transportation industries. Thanks to sophisticated sensors and machine learning algorithms, ATs can avoid hazards, navigate traffic, increase efficiency, and make decisions without human intervention (Faisal et al. 2019). Autonomous Heavy-duty trucks have the potential to significantly reduce the time and costs associated with long-distance transportation, making them one of the most severe challenges in the logistics sector (Stentz et al. 1999). Furthermore, by eliminating humans from the equation, ATs have the ability to completely solve the driver turnover problem. ATs that use technologically-advanced components might either totally replace drivers or help them with certain tasks, reducing the stress and strain that cause burnout and high turnover rates. However, the adoption of

ATs may have a detrimental influence on the millions of people that work in the transportation industry throughout the world (Leonard et al. 2020). Truck drivers, dispatchers, and other professionals who make a living from the trucking industry may lose their jobs or have their career possibilities reduced if some processes are automated. Understanding how ATs may affect work is critical for minimizing negative repercussions while enhancing positive ones. One of the main variables that may affect how ATs affect employment is the adoption rate, often known as the pace and extent of AT deployment (Simpson et al. 2019a). Some believe that technological, financial, and regulatory limitations may prevent or delay the adoption of ATs, despite predictions that they would eventually displace traditional modes of transportation (Fritschy and Spinler 2019a). For instance, it could take longer than expected to create reliable and affordable autonomous trucking technology, and its advantages might be limited to certain commodities and routes. The type of job that can be automated is a significant problem that might affect how ATs affect employment. While certain processes, such as driving on the highway, may be relatively straightforward to automate, others, such as loading and unloading freight or navigating cities, may be more challenging and require human help (Visser and Obi 2021). As a result, the influence of ATs on employment may vary depending on the specific professions that they automate, and the skills and knowledge required to do them.

The adoption of ATs has the potential to revolutionize the logistics industry. For instance, integrating autonomy might significantly reduce transportation costs while increasing safety and supply chain efficiency (Milakis et al. 2017). Cost-savings are made possible by the fact that ATs may work around the clock without needing set driving or rest periods. As a result, commodities may be provided more quickly and efficiently, perhaps enhancing the overall efficacy of the supply chain. Furthermore, ATs may be programmed to take the best routes and avoid congested areas of the road, enabling deliveries to be made more quickly and affordably. Additionally, businesses may reduce labor costs while boosting profitability by substituting human drivers for autonomous technology. ATs are less likely to malfunction or result in accidents (94% of automobile accidents are caused by human mistake (“Automated Vehicle Safety | NHTSA,” n.d.)), leading to lower accident and insurance costs. A large portion of the world's greenhouse gas (GHG) emissions are attributable to the transportation sector, and the number of cars on the road is rising as a result of rising consumer demand for goods and services (“Sources of Greenhouse Gas Emissions | US EPA,” n.d.). By increasing fuel efficiency and enhancing routes, they can lower fuel use and emissions (Chen et al. 2019). Lower emissions of greenhouse gases and other air pollutants might come from this, which would be good for the environment and the general public's health. Studying the effects of truck autonomy on employment and greenhouse gas emissions is required to evaluate the technology's potential sustainability advantages while taking into account its social ramifications. The goal of this study is to significantly advance the current debate over how ATs will affect jobs in the trucking industry. This study investigates the economic and environmental consequences of widespread AT adoption utilizing cutting-edge analytical methodologies like multi-regional input-output modeling, life cycle assessment, and uncertainty analysis. The major emphasis of this study is the relationship between ATs and unemployment, as well as any potential environmental implications of this unique technology.

1.1 Objectives

1. To evaluate the potential reduction in GWP that might arise from the usage of autonomous vehicles rather than traditional trucks.
2. To identify possible new job opportunities and sectors that may emerge as a result of the autonomous truck ecosystem.
3. To give guidelines and policy recommendations that promote the deployment of self-driving trucks in a sustainable and socially responsible way, while taking employment and GWP reduction problems into mind.

2. Literature Review

It is crucial to gain a comprehensive understanding of how ATs might affect the labor market and the potential risks of rising unemployment rates. This section aims to explore the literature's development in examining the connection between autonomy and the trucking sector while also analyzing its potential influence on employment prospects. Fritschy and Spinler (2019b) investigate the considerable influence of ATs on logistics business models. They conducted cutting-edge scenario analysis, anticipating the base case for 2040 with the Delphi technique. They have determined that the establishment of links between logistics service providers, original equipment manufacturers, and tier 1 suppliers would be a driving factor behind cutting-edge business models. One significant conclusion is that the introduction of ATs will alter the transportation business, worsening the present driver shortage and imposing a social toll on the process. Simpson et al. (2019b) examine the complicated and different market penetration patterns of ATs within the freight transportation industry when predicting future adoption rates of ATs.

They stress the value of attempting to provide manufacturers and policymakers with an accurate prediction of AT adoption rates because doing so enables them to adequately prepare for and manage the innovative technologies and infrastructure changes that will unavoidably accompany the introduction of such technologies. Their research offers a model framework for calculating the market saturation rate of ATs by freight companies. Furthermore, their research suggests that the adoption rate is anticipated to be excruciatingly slow, indicating that businesses will struggle to implement this innovation in the absence of any fundamental modifications to autonomous technology beyond the first introduction of ATs.

Kassai et al. (2020) shed light on the crucial topic of how professionals interpret the advancement of self-driving trucks. The balance between the benefits and drawbacks of ATs is not yet known because these vehicles are currently in the development stage. They conclude that deploying ATs for package deliveries in urban areas is perceived adversely because of a lack of technological and legal infrastructure, the difficulty of last-mile delivery procedures, and customer expectations after consulting with industry specialists. In terms of significance, Talebian and Mishra (2022) study the variables that influence the decision to adopt various levels of ATs, as well as the number and size of AT adopter groups. They contact freight companies in the United States and collect data from them using choice modeling and latent-class cluster analysis. They found that firms consider Level 2 automation to be similar to non-autonomous trucks. Furthermore, it is expected that the distribution of AT adopters will be right-skewed rather than bell-shaped. This is related to the obvious financial benefits of ATs, which may push enterprises to adopt the technology early. Simpson and Mishra (2021) use peer effects to predict the adoption rate of ATs. One of their most insightful findings is that, while the number of organizations choosing to partially implement ATs is rising, the number of enterprises that completely refuse the adoption of ATs is steadily falling. Additionally, organizations that fully implement ATs expand at a slower rate than those that select partial adoption. This demonstrates the significant ambiguity that businesses have when deciding whether or not to employ such technologies owing to their lack of present proof.

Trösterer et al. (2017) provide the results of a contextual inquiry investigation conducted at six different transportation enterprises. It focuses on understanding how truck drivers are incorporated into the business, current procedures, and the potential advantages and downsides of semi-autonomous driving from the transportation industry's perspective. Because of concerns about potential system failures, they demonstrate widespread skepticism of semi-autonomous heavy trucks from both the corporate and truck driver perspectives. Huang and Kockelman (2020) indicate that the widespread adoption of ATs will result in a fundamental shift in how products travel along American streets and railroads. They achieve it by employing a multiregional input-output model based on random utility and being driven by external export demand. ATs, they anticipate, will enhance truck flow values while decreasing rail flow values, lowering transportation costs by up to 25%. This highlights how, by cutting transportation costs, ATs have the potential to drastically disrupt the present logistics sector. Gomes et al. (2018) promote the use of multiple attribute decision-making and fuzzy sets to assist ATs in selecting safe navigation routes. To achieve consistent outcomes, the technique depends on the integration of perceptual systems and diagnostic data from an AT, even if a more comprehensive safety study is required. A dynamic approach to alternative and attribute sets, such as using decision analyzer combinations, may be utilized, for example, to better capture the availability of diagnostic and perceptual information. Kim et al. (2022) call for the use of cutting-edge, secure technology that benefits both customers and businesses, as well as the integration of ATs to modernize transportation. They can challenge the entrenched notion of gender roles in the traditionally male-dominated trucking industry. However, according to current regulations, ATs may only travel on public roads with permission, posing challenges for ATs. Additionally, there might be technological glitches and security problems, such as the potential for hacking. Last but not least, autonomous trucks are viewed as a conventional creation that does not need human interaction, which might be detrimental to employment prospects.

The literature lacks a precise estimate of employment displacement caused by the widespread use of self-driving trucks, which could replace truck drivers. Further research is needed to determine the number of jobs lost in the trucking industry and the geographic dispersion of these effects across the supply chains of activities involved in a truck's life cycle. Additionally, there is a lack of study on potential job creation caused by the introduction of self-driving trucks, such as engineering, data processing, and infrastructure building. To fully understand the employment effects of autonomous trucks, it is essential to evaluate the entire impact of these potential job generation channels. A significant research gap remains in the comprehensive adoption of a full life cycle assessment (LCA) approach. This approach helps researchers and policymakers gain a deeper understanding of the diverse impacts of autonomous trucks on employment, enabling them to make well-informed decisions and formulate efficient strategies to address the opportunities and challenges arising from this technological advancement. The paper aims to quantify the extent of employment elimination in the trucking sector and assess how this detrimental impact spreads within the US and worldwide supply chains. It also aims to analyze the creation and maintenance of autonomous truck technology, data analysis, and infrastructure establishment, and identify potential knowledge gaps to help policymakers and educational institutions better prepare the workforce for the industry's evolving needs. By incorporating a full life cycle assessment (LCA) into the analysis, this research aims to facilitate informed decisions and effective strategies in tackling the challenges and opportunities associated with this technological advancement.

3. Methods

This paper incorporates several approaches including Life cycle inventory, life cycle assessment, data processing, drawing policy recommendations, and multi-regional input-output modeling. The first step in the life cycle inventory process is to collect and measure data on the inputs and outputs of a product or process. It improves decision-making by giving a complete-picture view of resource use and emissions. The multi-regional input-output modeling covers regional flows of goods and services as well as interdependence between them. By compiling indirect environmental consequences, displaying effects on the global supply chain, and evaluating the environmental implications of economic activity on a larger scale, it offers a full life cycle study. Then, to extract pertinent insights, data processing is utilized to organize, clean, and analyze the data acquired during the life cycle inventory stage. Through the use of statistical techniques, modeling, and visualization, it encourages the examination of complex data sets and supports the use of evidence in decision-making. Using such evidence, we undertake a thorough input-output-based LCA analysis to examine the environmental consequences of a product, process, or service from extraction through disposal. LCA may assist firms and politicians in identifying problem areas, weighing trade-offs, and developing plans for long-term growth. This study’s scope limits are determined by three distinct phases: manufacturing, operation, and end-of-life. The construction of charging stations and the manufacture of the baseline truck, battery, trailer, and parts of the autonomous system are all included in the manufacturing process. The maintenance of trucks, the manufacturing of battery-electric truck replacement batteries, and a thorough analysis of the energy sources for both diesel and battery electric trucks from a well-to-tank (WTT) and tank-to-wheel (TTW) perspective are all included in the operational phase. The well-to-tank methods examine the environmental effects of producing fuel for automobiles at each stage of the supply chain, from crude oil extraction through diesel truck filling. Regarding battery electric trucks, the refinement process precedes electricity generation and charging. Subsequently, during the end-of-life phase, the baseline truck body, trailer, battery, and autonomous system components undergo recycling. The functional unit considered in this research is per truck during its life cycle. The trucks' assumed service life is 15 years, with an annual mileage of 63,000 miles (Alternative Fuels Data Center: Maps and Data - Average Annual Vehicle Miles Traveled by Major Vehicle Category, Burke et al. 2020). In this study, the investigation delves into four distinct scenarios aimed at comprehending the implications of autonomy on employment opportunities and environmental impacts related to autonomous trucks. The initial scenario (S1) serves as the baseline and simulates the current state of the trucking industry, featuring non-autonomous diesel trucks. On the other hand, scenario two (S2) portrays the shift towards autonomy, where trucks are assumed to be autonomous and powered by diesel. The third (S3) and fourth (S4) scenarios explore the introduction of electrification into the trucking industry. Scenario three entails non-autonomous battery electric trucks, while the fourth scenario involves autonomous battery electric trucks.

3.1 Life Cycle Assessment

LCA is a strong approach for investigating environmental consequences since it encompasses the extraction of raw materials, production, distribution, use, and disposal of goods and processes (Consoli et al. 1993) As society strives to meet the pressing need to address environmental sustainability, LCA has gained significant traction, providing a detailed assessment that takes into account a wide range of repercussions (Klöpffer 2006). LCA analyzes the environmental effect of a process or product, supporting in decision-making, identifying possible issue areas, and advocating sustainable alternatives (Pryshlakivsky and Searcy 2021). LCA considers resource depletion, energy consumption, greenhouse gas emissions, water use, waste generation, and potential repercussions on ecosystems and human health. Aim and scope definition, inventory analysis, impact assessment, and interpretation are the four steps of the LCA process (Xia and Li 2022). During the objective and scope definition phase, the research's purpose and boundaries, including its boundaries for functional units and systems, are established (Uddin and Wright 2022). The inventory analysis process entails collecting information on the inputs and outputs of every stage of the life cycle, such as energy and material flows, emissions, and waste production, and putting it into an inventory that enables the measurement of environmental burdens (Xia and Li 2022). The impact assessment process compares the supplied data to environmental effect categories using a variety of impact assessment methodologies. Stakeholders review and communicate the impact assessment findings during the interpretation phase, which also identifies hotspots or locations with a high environmental impact, looks into chances for improvement, and supports decision-making (Loiseau et al. 2018). To promote sustainable alternatives and help decision-makers pinpoint areas for improvement, LCA is important because it can give a thorough and scientifically supported analysis of products and processes (Vandenbroucke et al. 2015).

3.2 Multi-Regional Input-Output Modeling

The capability of multi-regional input-output modeling (MRIO) to analyze the economic interconnections and interdependencies between different regions within a larger system is tremendous. To describe the intricacies of global economic relationships, it blends input-output analysis with an examination of several domains (Miernyk 1965). Policymakers, scholars, and analysts may study the economic, environmental, and social repercussions of various policy changes thanks to MRIO's comprehensive understanding of the interdependence of regional economies (Zhao et al. 2021). Input-output tables are created for each region under consideration as the foundation of MRIO modeling (Miernyk 1965). The development of a set of input-output tables for each region under consideration is a critical component of MRIO modeling (Miernyk 1965) Supply and usage tables, as well as the input-output framework, are studied in Chapter 9, which provides an in-depth cost study of an economy's production and consumption patterns. These tables list the goods and services produced by different industries, as well as the inputs required by other industries. MRIO enables the measuring of interregional trade and interdependence, as well as the tracing of economic movements, by combining multiple input-output tables from various places.

The capacity of MRIO modeling to account for the induced and indirect effects of economic activity is one of its primary advantages (Miller and Blair 2009). In addition to the direct flow of goods and services between regions, MRIO also addresses the ripple effects brought on by backward linkages (inputs needed by a sector) and forward linkages (demand produced by a sector) (Hallegatte 2008). As a result, one has a deeper understanding of regional interconnectedness and is better able to identify potential policy changes or economic shocks' spillover effects. MRIO models are commonly employed to evaluate the effects of modifications to consumption, production, or trade patterns. For instance, MRIO modeling may be used by decision-makers to assess how a new trade deal would affect employment, economic inequality, and environmental issues. By analyzing the whole production chain, MRIO models shed light on the distributional effects of such changes across various regions and sectors. A crucial use of MRIO modeling is to evaluate the effects on the environment (Wiedmann et al. 2007) Analysts can ascertain the environmental footprints connected to certain economic activities and geographic regions by combining input-output tables with environmental data such as energy use, emissions, or resource consumption (Wiedmann et al. 2007).

4. Data Collection

Starting with the manufacturing stage, the baseline assumption for the truck's body manufacturing cost is $97500, with a 20% profit margin. The fundamental goal of this hypothesis is to ensure that the investment value used to construct the truck's body is fully utilized in manufacturing activities instead of being taken into account across certain margins of profit. The anticipated 1062 kWh lithium-ion battery manufacturing cost was determined using the 2022 average battery pack cost of $151/kWh (Sharpe and Basma 2022, Worldwide - lithium-ion battery pack costs | Statista). The truck's trailer, which is used to haul freight, was estimated to cost $300,000 to manufacture. The autonomous system is expected to include Radar, V2V Communications, Camera, Dedicated Short-Range Communications (DSRC) modules, Blind Spot Detection System, Adaptive Cruise Control, Automated Manual Transmission, Predictive Cruise Control, LIDAR, and Mobile Eye Advanced Driver Assistance. The autonomous system's components manufacturing has a total cost of $13,000. The software that would manage and coordinate these components costs $724 per truck, based on the size of the global automotive software industry, the anticipated number of automobiles with level 1 or higher autonomy levels by 2030, and the total number of vehicles in the United States by 2030. Finally, the total cost of the building for the charging station is $55000 ("EV Charging Station Cost - Installation and Equipment Cost Breakdown | OhmHome," n.d.). The operating phase maintenance operations are taken into account at $0.175/mile (Leslie, n.d.). Throughout the truck's life cycle, it is anticipated that one battery will need to be replaced due to the original battery's deterioration. since the replacement battery is expected to cost the same as the old one. The WTT operations for diesel vehicles are based on an expected fuel efficiency of 0.18 G/mile, but they equal 2 kWh/mile for battery electric trucks, according to the BETBE (Battery Electric Truck and Bus Energy Efficiency). In contrast, 1.24 KgCO2-Eq/Mile GWP emission estimations from the literature are utilized in the TTW processes for diesel trucks (Nylund and Wenstedt 2019) During the end-of-life phase, the truck body, trailer, battery, and autonomous system are all expected to be recycled.

5. Results and Discussion

5.1 Numerical Results

As shown in Figure 1 a); Scenario 1 has the highest GWP throughout the truck's usable life. This result highlights the critical need to reduce these considerable emissions by transitioning to cleaner, more efficient technologies that promote sustainability goals and reduce the impact of transportation on climate change. One strategy is to integrate autonomy, which has been linked to improved fuel economy. In comparison to Scenario 1, the estimated reduction in emissions during this transition (from Scenario 1 to Scenario 2) is 45 tCO2-Eq./Truck, or roughly 3%. However, activities unique to autonomous cars, such as the creation of autonomous system components and software development, counteract this reduction in emissions as 1.48 tCO2-Eq./Truck emissions are caused by these processes. Additionally, autonomous trucks require more maintenance than non-autonomous trucks due to the presence of autonomous systems, adding 1.44 tCO2-Eq./Truck to the original maintenance emissions estimated at 3.61 tCO2-Eq./Truck for non-autonomous trucks. On the other hand, autonomy improves fuel efficiency and lowers Well-to-Tank emissions by roughly 48 tCO2-Eq./Truck. Despite the possibility that autonomous cars might reduce their life cycle GWP when contrasted with the substantial volume of emissions stemming from the processes of WTT and TTW, this decrement assumes relatively negligible importance. This assertion finds empirical substantiation in the allocation of 80% and 83% of GWP correspondingly, to TTW processes in Scenario 1 and Scenario 2, about the cumulative emissions over the entire life cycle. The prospective feasibility of ATs is essentially tangled with the pivotal role of recycling in mitigating waste and the thoughtful utilization of resources through recovery, as opposed to a dependence on finite terrestrial resources derived from extractive methodologies during the terminal phase of the life cycle. The recycling of components such as batteries, metals, and electronics stands balanced to set up this paradigm shift by yielding a substantial saving in the life cycle emissions. It is noteworthy, however, that the recycling undertaking is anticipated to entail diesel truck emissions at a magnitude of 5.6 tCO2-Eq./Truck, irrespective of the automated or non-automated nature of the vehicle.

In both cases when electric batteries are used to power the truck's engine rather than diesel, Scenarios 3 and 4 attempt to depict the impact of autonomy on the life cycle GWP of the vehicle. According to this hypothetical comparison, moving from non-autonomous diesel trucks to non-autonomous battery electric trucks might result in a 40% decrease in life cycle GWP per truck, however moving from autonomous diesel trucks to autonomous battery electric trucks results in a 48% reduction. This is made feasible by the absence of TTW emissions from battery electric trucks' exhaust pipes. The trucking industry's emissions may be significantly impacted if the life cycle GWP of diesel cars can be reduced by this enormous amount. Alternative solutions, such as electric trucks, which have been examined, might greatly lessen the industry's environmental effects. This would assist in cutting total greenhouse gas emissions and create a more sustainable transportation future. Battery electric trucks can reduce life cycle emissions by 12 tCO2-Eq./Truck due to battery recycling, which is connected to considerable mining emissions. When compared to our current situation (non-automated diesel trucks as in Situation 1) and the groundbreaking case (autonomous battery electric vehicles as in Scenario 4), life cycle emissions might be reduced by up to 50%. The significant reduction in GWP demonstrates the enormous potential of self-driving battery-powered vehicles to tackle climate change and achieve sustainable mobility.

5.2 Graphical Results

Figure 1 shows the employment related to each scenario by geographic location, whether it is inside or outside of the regional boundaries of the United States. Starting, with the four possibilities, Scenario 1 (the current state of the trucking industry) offers the greatest job opportunities, with 73% of them being created in the United States. While 12% of total employment chances are created inside the TTW process, which is akin to the occupations offered for truck drivers, 76% of all employment opportunities are created across the supply chain of WTT operations, starting with crude oil petroleum extraction and ending with fueling. This shows that just around 25% of job opportunities in the trucking business are related to the manufacturing phase and its processes. In contrast, the end-of-life phase is expected to have fewer job opportunities since the number of jobs linked to recycling activities is substantially smaller than that of professions associated with the mining process. When examining employment possibilities in the US, all occupations associated with the TTW process are assumed to be accessible only within US borders, accounting for 17% of all employment chances there. WTT procedures generate the highest employment opportunities in this context, accounting for 63% of new jobs. When autonomous cars are adopted, the trucking sector in the United States is predicted to lose 27% of its jobs. As a result of autonomy, trucks will use less fuel to go the same distance, which will be bolstered further by driver job losses. This decrease in employment is linked to increased fuel economy. Manufacturing of autonomous system components, software development, and new maintenance chores suggested by the presence of the autonomous system all result in a significant rise in employment. In this hypothetical scenario of switching diesel vehicles from non-autonomous to autonomous trucks, the number of jobs lost surpasses the number generated by 27%. When autonomy is established, 17% of employment openings outside of the United States are lost. Similar to this, the conversion of non-autonomous diesel vehicles to autonomous trucks obliterates employment opportunities in the United States, with more jobs destroyed than created once autonomy is implemented.

It is anticipated that jobs will be lost in both the autonomous and non-autonomous vehicle scenarios when electrification is widely deployed in the trucking industry, as indicated in Scenarios 3 and 4. The number of employment generated by diesel trucks is predicted to drop by 48% when non-autonomous vehicles move from diesel to electric power. The removal of 87% of jobs in the WTT process supply chain is mostly to blame for this decline. Jobs created by truck electrification, such as those in battery production, charging station building, and replacement battery manufacturing, much exceed those lost in the WTT supply chain. New jobs were generated in the United States as a result of the change from 6.27 P/Truck to 6.28 P/Truck. Furthermore, 3.15 P/Truck employment openings are projected in the United States for techniques to create both the main battery and the replacement battery. In the case of autonomous vehicles, switching from diesel to electric trucks is predicted to result in a 14% increase in overall employment in the United States. For the sake of this example, 83% of all the jobs in the WTT supply chain were lost. On the other side, it is anticipated that the construction of charging stations and the production of primary & replacement batteries would result in the creation of 3.23 P/Truck worth of jobs.

a) Global warming potential

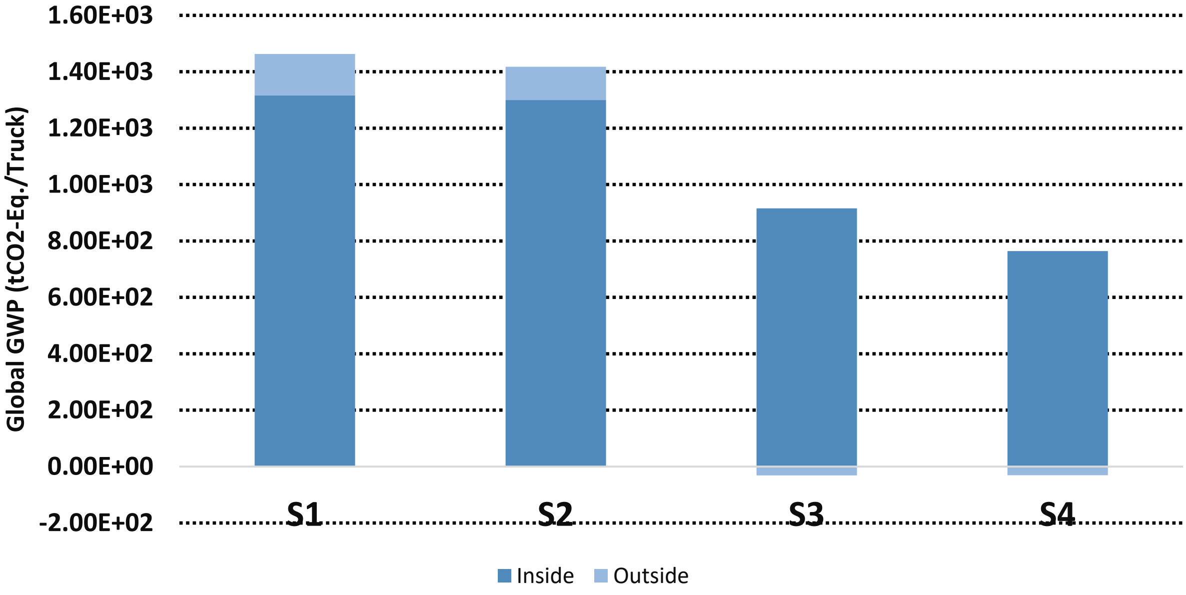

Figure 1. Employment related to each scenario by geographic location

b) Employment

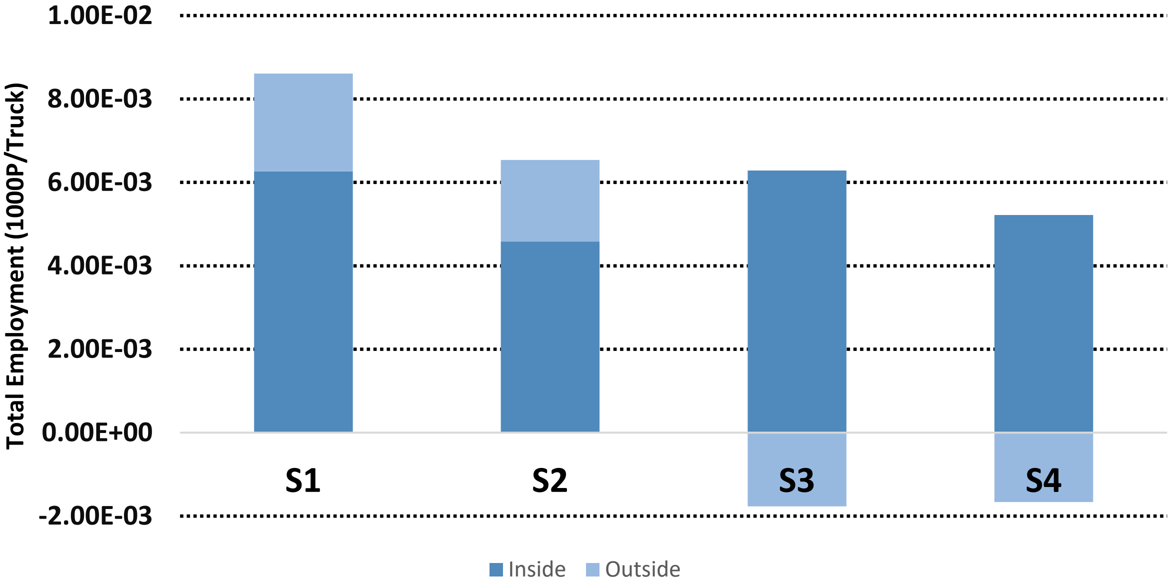

Figure 2. Life cycle impacts results

It is crucial to analyze the impact of different autonomous truck penetration rates since they have a direct impact on two important variables: employment and GWP. The Green Employment Index (GEI), which measures the "greenness" of employment through the division of employment by GWP and is expressed in (P/KtCO2-Eq.), representing emissions associated with employing one person, is a new variable that is introduced to allow for a thorough evaluation of the sustainability of the trucking industry. To get important insights into the complex interaction between automation, job creation, and environmental sustainability, Figure 3 shows the influence of various penetration rates on GEI. This study enables the formulation of policies that support a greener, more inclusive future for everyone as well as better-informed decision-making. Three different scenarios for the current state's transition to the adoption of new transportation technologies are shown in the graph. To start, navy blue is used to represent the integration of autonomy into diesel vehicles, while cobalt blue is used to represent the integration of autonomy into battery-powered trucks. Last but not least, sky blue symbolizes the quick transition from our current situation to widespread acceptance of autonomous battery electric cars by embracing both electrification and autonomy. Contrarily, the final example shows a gradual transition from our current state of manually operated diesel trucks to autonomous battery electric cars, which might take some time to complete and would be considered a very unlikely alteration to occur rapidly. The transition from non-autonomous battery electric trucks to autonomous battery electric trucks has the highest GEI value, as seen by low penetration rates of less than 50%, enabling maximum employment formations while emitting the fewest emissions. The first two possibilities are connected to comparable green job prospects in such low-scale adoption due to their beginnings in non-autonomous diesel automobiles. As the penetration rate of non-autonomous diesel trucks increases, more green employment is generated since the environmental impact is smaller than when transitioning to autonomous diesel vehicles. In WTT processes, fossil fuel-dependent vehicles offer more employment chances than battery-powered trucks, but the significant environmental advantages of electrification considerably exceed the fewer employment prospects that threaten the livelihoods of those employed in the fossil fuel supply chain. The contrast between the first two situations is even wider as the penetration rate increases since this pattern also occurs at higher penetration rates. The quantity of green employment created during the switch from non-autonomous battery electric trucks to autonomous battery electric trucks is comparable to that created during the switch from non-autonomous battery electric trucks to autonomous battery electric trucks at relatively high penetration rates.

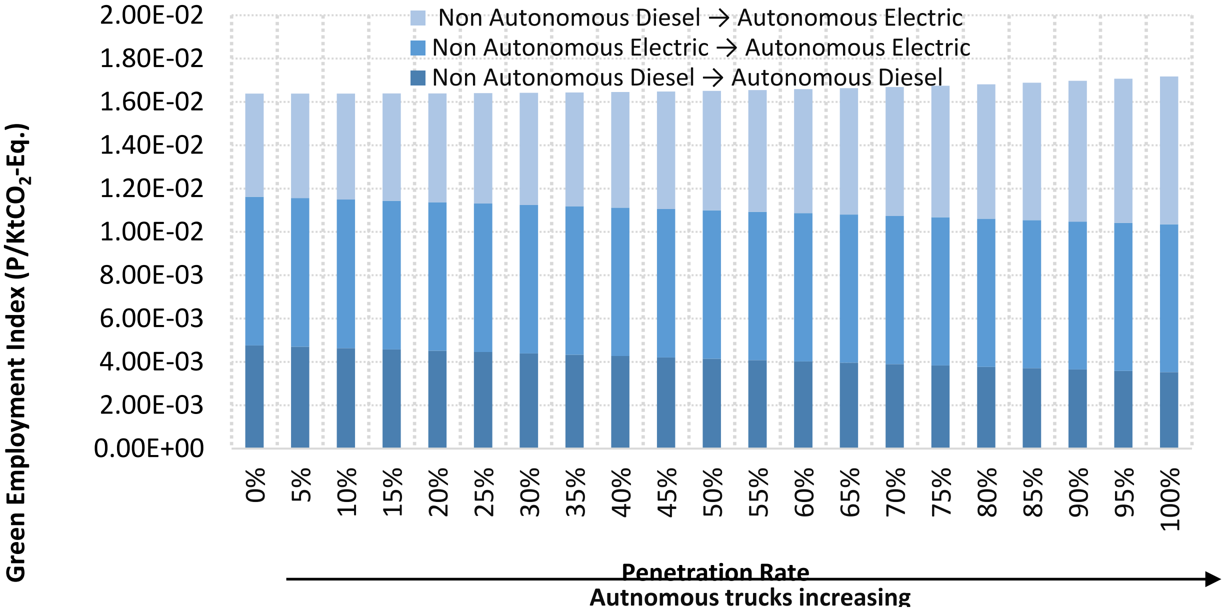

Figure 3. Green employment index at varying penetration rates

5.3 Proposed Improvements

According to the findings of the study, there is an urgent need for comprehensive solutions that address both the preservation of trucking job opportunities and the reduction of greenhouse gas emissions. To achieve sustainable mobility and decrease the sector's contribution to climate change, the proposed solution employs a multifaceted approach that combines technological advancements and legal adjustments. The increasing usage of autonomous battery-powered trucks is a significant area for development. Combining autonomy and electrification is an efficient strategy to reduce the industry's environmental impact and encourage sustainable practices. Scenario 4's 48% decrease demonstrates that they can significantly reduce life cycle greenhouse gas emissions. The absence of tailpipe emissions and the large decline in Well-to-Tank emissions associated with battery-powered cars are the main contributors to this reduction. Additionally, to ensure a smooth transition to autonomous battery electric trucks and a skilled workforce, preventive measures must be put in place to offer new employment prospects in emerging areas while addressing possible job losses. Government programs, industry partnerships, and educational initiatives can help truck drivers and other impacted people retrain and upskill so they can contribute to the growth of the electric vehicle ecosystem in fields like battery production, charging infrastructure, and vehicle maintenance. Lastly, to implement the proposed improvement, strong recycling and circular economy practices must be implemented. In addition to decreasing the environmental impact of raw material extraction, investment in cutting-edge recycling technologies for batteries, metals, and electronics will create new green jobs in waste management and recycling facilities. Effective recycling procedures may significantly reduce life cycle emissions, as demonstrated by the reduction of 12 tCO2-Eq./Truck in Scenario 3.

5.4 Validation

Sen et al. (2020) study was used to validate the results of this study. A significant result from the analysis was the existence of numerous sensitive elements that have an impact on the estimations for the Life Cycle Greenhouse Gas Emissions of autonomous trucks. It was discovered that little changes to the original data inputs had a disproportionately large influence on the outcomes for variables such as WTT. This sensitivity highlighted the critical importance of exact and accurate data values for each variable. The accuracy and importance of the results were quickly revealed to be dependent on the reliability of the data and the inputs used in the research.

6. Conclusion

This research analyzes how autonomy impacts employment in the trucking business using a life cycle approach. It investigates the global warming potential, employment, and various penetration rates of converting to autonomous and electric trucks. The findings indicate that adopting autonomous technology is critical for lowering carbon footprints in the sector. Despite higher maintenance and manufacturing costs, incorporating autonomy provides the opportunity to enhance fuel economy and reduce emissions. The analysis demonstrates a considerable drop in overall GWP over time, except for WTT/TTW processes. By encouraging the use of electric trucks and embracing recycling technology as part of sustainable practices, the trucking industry may significantly reduce the environmental effects caused by transportation operations. However, the adoption of autonomous technology may adversely impact jobs since it reduces fuel costs and eliminates driver responsibilities. However, this development creates new job prospects in fields like producing parts for automated systems, creating software, and carrying out maintenance procedures. Several recommendations must be made for autonomous trucks to be adopted and used effectively. First, contrast human-driven vs. automated vehicle safety criteria, performance efficiency measurements, infrastructure readiness, and environmental impact evaluations. This will make it simpler to identify areas where automated systems excel and regions where they still need to be enhanced to produce more trustworthy automated structures. For the implementation of autonomous trucks, further investigation should be done to assess the present road networks, charging stations, and communication systems. The long-term development of autonomous trucks needs significant environmental impact assessments in addition to the GWP that is often used. The development of autonomous trucking technology and its social integration may be significantly impacted by a range of environmental factors, which academics must address while researching the sustainability implications of autonomous trucking. The anticipated advantages of autonomous freight transportation, such as increased safety, increased fuel efficiency, and less environmental impact, will eventually be realized with the help of these programs.

References

Alternative Fuels Data Center: Maps and Data - Average Annual Vehicle Miles Traveled by Major Vehicle Category [WWW Document], n.d. URL https://afdc.energy.gov/data (accessed 8.2.23).

Automated Vehicle Safety | NHTSA [WWW Document], n.d. URL https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety (accessed 5.1.23).

Burke, A., Sinha, A., Kumar, A., 2020. UC Davis Research Reports Title Technology, Sustainability, and Marketing of Battery Electric and Hydrogen Fuel Cell Medium-Duty and Heavy-Duty Trucks and Buses Permalink https://escholarship.org/uc/item/7s25d8bc Publication Date Data Availability. https://doi.org/10.7922/G2H993FJ

Consoli, F., Allen, D., Boustead, U.S.A.I., Jensen, A.A., Parrish, R., n.d. Guidelines for Life-Cycle Assessment: A "Code of Practice."

Faisal, A., Yigitcanlar, T., Kamruzzaman, M., Currie, G., Understanding autonomous vehicles: A systematic literature review on capability, impact, planning and policy. J Transp Land Use 12, pp. 45–72, 2019. https://doi.org/10.5198/JTLU.2019.1405

Fritschy, C., Spinler, S., The impact of autonomous trucks on business models in the automotive and logistics industry–a Delphi-based scenario study. Technol Forecast Soc Change, vol. 148, pp. 119736, 2019. https://doi.org/10.1016/J.TECHFORE.2019.119736

Fritschy, C., Spinler, S., The impact of autonomous trucks on business models in the automotive and logistics industry–a Delphi-based scenario study. Technol Forecast Soc Change, vol. 148, pp. 119736, 2019. https://doi.org/10.1016/J.TECHFORE.2019.119736

Gomes, I.P., Bruno, D.R., Ośorio, F.S., Wolf, D.F., Diagnostic analysis for an autonomous truck using multiple attribute decision making. Proceedings - 15th Latin American Robotics Symposium, 6th Brazilian Robotics Symposium and 9th Workshop on Robotics in Education, LARS/SBR/WRE, pp. 291–296, 2018. https://doi.org/10.1109/LARS/SBR/WRE.2018.00059

Hallegatte, S., An adaptive regional input-output model and its application to the assessment of the economic cost of Katrina. Risk Analysis, vol. 28, pp. 779–799, 2008. https://doi.org/10.1111/J.1539-6924.2008.01046.X

Huang, Y., Kockelman, K.M., What will autonomous trucking do to U.S. trade flows? Application of the random-utility-based multi-regional input–output model. Transportation (Amst), vol. 47, pp. 2529–2556, 2008. https://doi.org/10.1007/S11116-019-10027-5/TABLES/6

Kassai, E.T., Azmat, M., Kummer, S., Scope of Using Autonomous Trucks and Lorries for Parcel Deliveries in Urban Settings. Logistics, vol. 4, 2020. https://doi.org/10.3390/LOGISTICS4030017

Kim, E ;, Kim, Y ;, Park, J, Evangelista, P., Brlek, P., Brčiˊbrčiˊc, D., Sovreski, Z., Krpan, L., Kim, Eunbin, Kim, Youngrim, Park, Jieun, The Necessity of Introducing Autonomous Trucks in Logistics 4.0. Sustainability, vol. 14, pp. 3978, 2022. https://doi.org/10.3390/SU14073978

Klöpffer, W., The role of SETAC in the development of LCA. International Journal of Life Cycle Assessment, vol. 11, pp. 116–122, 2006. https://doi.org/10.1065/LCA2006.04.019/METRICS

Leonard, J.J., Mindell, D.A., Stayton, E.L., Autonomous Vehicles, Mobility, and Employment Policy: The Roads Ahead, 2020.

Loiseau, E., Aissani, L., Le Féon, S., Laurent, F., Cerceau, J., Sala, S., Roux, P., Territorial Life Cycle Assessment (LCA): What exactly is it about? A proposal towards using a common terminology and a research agenda. J Clean Prod, vol. 176, pp. 474–485, 2018. https://doi.org/10.1016/J.JCLEPRO.2017.12.169

Miernyk, W.H., 1965. The Elements of Input-Output Analysis.

Milakis, D., Van Arem, B., Van Wee, B., Policy and society related implications of automated driving: A review of literature and directions for future research, Vol. 21, pp. 324–348, 2017. https://doi.org/10.1080/15472450.2017.1291351

Miller, R.E., Blair, P.D., Input-Output Analysis Foundations and Extensions Second Edition, 2009.

Nylund, S., Wenstedt, N., WELL-TO-WHEELS ANALYSIS OF HEAVY-DUTY TRUCK FUELS : A comparison between LNG, LBG and Diese, 2019. https://urn.kb.se/resolve?urn=urn:nbn:se:mdh:diva-44032

Pryshlakivsky, J., Searcy, C., Life Cycle Assessment as a decision-making tool: Practitioner and managerial considerations. J Clean Prod, vol. 309, pp. 127344, 2021. https://doi.org/10.1016/J.JCLEPRO.2021.127344

Simpson, J.R., Mishra, S., Developing a methodology to predict the adoption rate of Connected Autonomous Trucks in transportation organizations using peer effects. Research in Transportation Economics, vol. 90, pp. 100866, 2021. https://doi.org/10.1016/J.RETREC.2020.100866

Simpson, J.R., Mishra, S., Talebian, A., Golias, M.M., An estimation of the future adoption rate of autonomous trucks by freight organizations. Research in Transportation Economics, vol. 76, 2019. https://doi.org/10.1016/J.RETREC.2019.100737

Simpson, J.R., Mishra, S., Talebian, A., Golias, M.M., An estimation of the future adoption rate of autonomous trucks by freight organizations. Research in Transportation Economics, vol. 76, pp. 100737, 2019. https://doi.org/10.1016/J.RETREC.2019.100737

Sources of Greenhouse Gas Emissions | US EPA [WWW Document], n.d. URL https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions (accessed 5.1.23).

Stentz, A., Bares, J., Singh, S., Rowe, P., A Robotic Excavator for Autonomous Truck Loading. Auton Robots, vol. 7, pp. 175–186, 2019.

Talebian, A., Mishra, S., Unfolding the state of the adoption of connected autonomous trucks by the commercial fleet owner industry. Transp Res E Logist Transp Rev, vol. 158, pp. 102616, 2022. https://doi.org/10.1016/J.TRE.2022.102616

Trösterer, S., Meneweger, T., Meschtscherjakov, A., Tscheligi, M., Transport companies, truck drivers, and the notion of semi-autonomous trucks: A contextual examination. AutomotiveUI 2017 - 9th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications, Adjunct Proceedings, pp. 201–205, 2017. https://doi.org/10.1145/3131726.3131748

Vandenbroucke, M., Galle, W., De Temmerman, N., Debacker, W., Paduart, A., Using life cycle assessment to inform decision-making for sustainable buildings. Buildings, vol. 5, pp. 536–559, 2015. https://doi.org/10.3390/BUILDINGS5020536

Visser, R., Obi, O.F., Automation and Robotics in Forest Harvesting Operations: Identifying Near-Term Opportunities. Croatian Journal of Forest Engineering : Journal for Theory and Application of Forestry Engineering, vol. 42, pp. 13–24, 2021. https://doi.org/10.5552/CROJFE.2021.739

Wiedmann, T., Lenzen, M., Turner, K., Barrett, J., Examining the global environmental impact of regional consumption activities — Part 2: Review of input–output models for the assessment of environmental impacts embodied in trade. Ecological Economics, vol. 61, pp. 15–26, 2007. https://doi.org/10.1016/J.ECOLECON.2006.12.003

Xia, X., Li, P., 2022. A review of the life cycle assessment of electric vehicles: Considering the influence of batteries. Science of The Total Environment, vol. 814, pp. 152870, 2007. https://doi.org/10.1016/J.SCITOTENV.2021.152870

Zhao, D., Liu, J., Sun, L., Ye, B., Hubacek, K., Feng, K., Varis, O., Quantifying economic-social-environmental trade-offs and synergies of water-supply constraints: An application to the capital region of China. Water Res, vol. 195, pp. 116986, 2021. https://doi.org/10.1016/J.WATRES.2021.116986

Biographies

Ja'far Mohammad Mandouri holds a Bachelor of Science in Industrial Engineering from Jordan University of Science and Technology and is currently pursuing a master's degree in engineering management at Qatar University. As a Graduate Research Assistant at the Qatar Transportation and Traffic Safety Center, Jafar's research interests focus on sustainability and sustainable transportation. With a strong academic background in engineering and management, he is dedicated to finding solutions to improve the environmental impact of transportation systems and reduce their carbon footprint.

Nuri C. Onat is an Associate Professor at the Qatar Transportation and Traffic Safety Center within Qatar University. He is also the co-founder and co-director of the Sustainable Systems Solutions Lab located at Istanbul Sehir University, Turkey. Furthermore, he serves as a Senior Sustainability Fellow at the Global Institute of Sustainability at Arizona University, United States. His research efforts have been recognized through prestigious global competitive fellowship programs, including the Walton Sustainability Fellowship with Arizona State University, Australian Endeavour Research Fellowship with the University of Queensland, Achievement Award from the University of Florida, and Fulbright. Dr. Onat boasts a portfolio of over 60 publications encompassing various subjects such as sustainability assessment, sustainable mobility, system dynamics, and electric vehicles.

Murat Kucukvar is an Assistant Professor in the Department of Business Ethics and Legal Studies in Daniels College of Business, at University of Denver. He specializes in quantitative sustainability assessment, sustainable business practices, industrial sustainability, and business analytics. He previously founded the Sustainable Systems Solutions Lab at City University of Istanbul, where his graduate students undertook comprehensive sustainability assessments of energy, manufacturing, and transportation sectors at regional and global scales. Kucukvar's contributions to research in life cycle sustainability assessment, carbon footprint analysis, and sustainable supply chains were acknowledged in a recent review paper, placing him among the world's most esteemed scientists. He is recently listed among the top 1 % scientists in the world in the fields of Energy, Environmental Earth Sciences, and Sustainability, according to the global ranking published by Stanford University, USA.