Climate Risks and Economic Consequences of Rising Global CO_2 Emissions in Aviation, Shipping, and Heavy-Duty Transport

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This study examines methods to lessen the environmental consequences of global CO_2 emissions from the hard-to-abate transport sector. The paper analyzed historical and projected trends in global CO_2 emissions from the hard-to-abate transport industry under two scenarios: the stated policy scenario (STEPS) and the announced pledged scenario (APS). The study covered the historical period from 2010 to 2022 and projected emissions up to 2050. The analysis revealed that the compound annual growth rate (CAAGR) of STEP exceeded that of APS in 2030 and 2050 for challenging emissions from heavy- duty vehicles, aircraft, and shipping when compared to the baseline year of 2022. The aviation industry has a higher CAAGR of 5.3% and 2.5% for 2030 and 2050, respectively, compared to heavy-duty vehicles at 1.6% and 0.9% for 2030 and 2050, respectively, and shipping at 0.7% and 0.9% for 2030 and 2050, respectively, under STEPS. Under the APS scenario, shipping showed a negative CAAGR of -0.8% and -2.8% for 2030 and 2050, respectively, and 0.4% and -1.8% for 2030 and 2050, respectively, for heavy-duty trucks. In comparison, the aviation industry had CAAGRs of 4.5% and 0.8% for 2030 and 2050, respectively. The data shows that the aviation industry is expected to see a far greater CAAGR in emissions than heavy-duty vehicles and shipping in both STEPS and APS scenarios. Targeted efforts are necessary to mitigate the environmental effects of air travel in the upcoming decades. The paper also examined 56 publicly traded international transportation companies and their corresponding carbon emission targets. Only seven companies, or 12.5%, have established goals for reducing emissions from 2023 to 2050; 10 companies, accounting for 17.9%, have committed to achieving carbon neutrality by 2040 to 2060; five corporations, representing 8.9%, have set targets for reducing emission intensity from 2025 to 2034; and 34 global corporations, making up 60.7%, have committed to achieving net zero emissions between 2040 and 2050. Despite some progress in setting emission reduction targets in the air travel industry, many companies still need to set carbon footprint reduction goals.

Keywords: *Heavy-duty trucks; Aviation industry; Shipping industry; Transport infrastructure; CO_2 emission; Net zero targets*

1. Introduction

The worldwide transportation industry is responsible for roughly 25% of energy-related carbon dioxide (CO_2) emissions, making it one of the most significant contributors to climate change [1]. Within this sector, "hard-to-abate" businesses such as

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aviation, shipping, and long-haul transportation face substantial challenges in decreasing CO_2 emissions due to their reliance on energy-dense fuels and the inherent difficulties of shifting to low-carbon alternatives [2]. As the world transitions to a low-carbon future, reducing emissions from these businesses is important to meeting global climate goals [3]. Hard-to-abate businesses are distinguished by their reliance on fossil fuels [4], significant capital investment in long-lived assets [5], and a scarcity of commercially viable alternatives [6]. For instance, kerosene-based jet fuels, which provide a high energy density necessary for long-haul flights, are significantly utilized in the aviation industry [7]. In a similar vein, heavy fuel oils are necessary for the propulsion of huge vessels over long distances in marine commerce [8], which accounts for 90% of all global commodities transit [9]. Long-haul transportation encounters difficulties implementing electrification because of battery weight and range constraints [10], particularly in areas with wide geographic landscapes [11]. It will become more urgent to discover scalable solutions since these sectors are predicted to increase over the next few decades [12].

Recent technological improvements and policy developments provide a glimmer of hope for decarbonizing these industries [13]. Sustainable aviation fuels (SAFs), for example, offer a promising future for the aviation sector. SAFs can be produced from biomass, waste, or synthetic processes such as power-to-liquid technology [14]. Airlines like United Airlines and British Airways began implementing SAFs into commercial flights in 2022 [15, 16], but expanding manufacturing and lowering prices remain difficult problems [16].

Innovative technologies that promise to drastically cut emissions, such as ammonia and hydrogen-based fuels [17, 18], are also being investigated by the shipping sector [17]. A bridge to zero-emission marine transportation may be provided by the investments made in ammonia-powered ships by companies like Maersk and NYK Line [19]. Furthermore, as complementary options, the electrification of short-sea ships [20] and the development of wind-assisted propulsion technologies are being tested [21]. Technological advances in hydrogen fuel cells and batteries are opening up new possibilities for heavy-duty road transport [22]. Diesel trucks may eventually be replaced with zero-emission vehicles thanks to the development of high-performance [23], long-range hydrogen-powered vehicles like the Nikola One and the Hyundai Xcient Fuel Cell [24]. Even though it is still in its infancy, Tesla's semi-electric truck heralds a paradigm shift in the direction of electrifying freight transportation [25].

Advancements in these sectors are also being fuelled by creative policies [26]. By 2050, the "Fit for 55" program from the European Union intends to cut transportation emissions by 90% via a combination of fuel requirements [27], carbon price, and infrastructure improvements [28]. While the International Civil Aviation Organization (ICAO) approved the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to stabilize aviation emissions at 2020 levels, the International Maritime Organization (IMO) has set aims to halve shipping emissions by 2050 [29]. Scaling solutions is still a major difficulty despite these efforts, mostly because of their high prices [30], poor acceptance rates [31], and gaps in technological maturity [32]. Governments, businesses, and academic institutions must work together to speed innovation and large-scale implementation [33].

The initial part of this article discusses the many variables influencing CO_2 emissions in the transportation sector, including developments in vehicle design and alternative fuel sources, government regulations supporting sustainable mobility, and consumer preferences for environmentally friendly forms of transport. It is essential to take all these factors into account when creating thorough strategies to reduce carbon emissions in the transportation sector. To achieve a more sustainable and eco-friendly transportation system, we might address technical, regulatory, and behavioral elements. Obstacles to reducing CO_2 emissions in the transport sector include limitations in infrastructure for electric vehicles [34] and public transit, economic barriers to implementing sustainable transport solutions [35], globalization [35], and increasing demand for freight transportation [36]. Recognizing the interdependence of these challenges is crucial, requiring comprehensive solutions that consider many stakeholders and their interests [37]. Collaboration between governments, businesses, and communities is essential for overcoming obstacles and achieving substantial advancements in developing an eco-friendlier transportation sector [38].

The section includes case studies on successful CO_2 emission reduction measures, such as the European Union's emission reduction targets for the transport industry. The case studies provide valuable insights into potential approaches and solutions for reducing CO_2 emissions in the transportation sector. Stakeholders may learn how to manage the complexities of transitioning to a more sustainable transportation system by examining these successful examples [39]. The section also includes an analysis of historical and projected trends in global transportation CO_2 emissions. It examines the assessment of the necessity for further measures considering the challenging trends in worldwide transportation-related CO_2 emissions. In this part, the author examined publicly listed global transportation businesses and their associated carbon emissions goals. This analysis provides valuable insights into the progress being made towards reducing carbon emissions in the transportation sector. By studying these examples, stakeholders can gain a better understanding of effective strategies for achieving sustainability goals in this industry.

2. Critical Elements Impacting the Global Landscape's CO_2 Emissions from Transport Sector

2.1 Factors Influencing CO_2 Emissions in the Transport Sector

2.1.1 Technological Advancements in Vehicle Design and Alternative Fuel Sources

Technological advancements in vehicle design, such as the development of electric and hybrid vehicles, have the potential to significantly reduce CO_2 emissions in the transport sector [40]. For example, the use of lightweight materials and aerodynamic designs can improve fuel efficiency and decrease carbon emissions [41]. The adoption of alternative fuel sources like biofuels and hydrogen can further contribute to lowering greenhouse gas emissions and promoting sustainability in transportation [42]. These advancements are crucial in addressing the environmental impact of the transport sector [43] and moving towards a more eco-friendly future. The shift towards alternative fuel sources like biofuels, hydrogen, and electricity can further reduce the environmental impact of transportation on a global scale [44]. These alternative fuel sources offer a cleaner and more sustainable option for powering vehicles [45, 46], ultimately leading to lower CO_2 emissions [47]. The development of infrastructure to support these alternative fuel sources is essential for their widespread adoption. Ultimately, these efforts will play a significant role in reducing our dependence on fossil fuels and mitigating the effects of climate change.

According to a study by the International Energy Agency [48], the adoption of EVs alone could lead to a 30% reduction in CO_2 emissions from road transport by 2030 globally. The IEA also stated that these advancements have the potential to cut CO_2 emissions from road transport by up to 70% by 2050 [48]. This highlights the importance of transitioning to alternative fuel sources and embracing technological innovations in the transportation industry to combat climate change. It is crucial for governments and industries to continue investing in sustainable transportation solutions to achieve significant reductions in CO_2 emissions. The development of alternative fuel sources like biofuels and hydrogen fuel cells is also playing a crucial role in decarbonizing the transportation sector and mitigating its environmental impact [49]. According to a study by the International Energy Agency [28], transitioning to alternative fuel sources could reduce global CO_2 emissions from transportation by up to 30% by 2050 globally. This highlights the urgent need for widespread adoption of sustainable transportation technologies to address the growing threat of climate change.

According to a study by the International Energy Agency, these advancements have led to a 23% decrease in CO_2 emissions from light-duty vehicles in the United States between 2005 and 2018 [28]. They also predicted that the adoption of EVs alone could reduce CO_2 emissions by up to 50% by 2050 in the United States of America [50, 51]. The adoption of alternative fuel sources like biofuels and hydrogen fuel cells has further helped in lowering carbon emissions from transportation [52]. These advancements have not only reduced emissions but have also improved air quality and public health [53]. As the world continues to shift towards sustainable transportation options, further reductions in CO_2 emissions are expected in the coming years [54]. Overall, the ongoing efforts to promote sustainable transportation are crucial to combating climate change [55] and creating a healthier environment for future generations [56, 57]. It is important for governments, industries, and individuals to continue investing in and adopting these cleaner technologies to achieve long-term environmental benefits.

According to a study by the International Energy Agency, these advancements have led to a 33% decrease in CO_2 emissions from new vehicles between 2005 and 2015 in China [58]. The adoption of alternative fuel sources like biodiesel and natural gas has further helped reduce emissions by providing cleaner energy options for transportation in China [59]. These alternative fuel sources have also played a role in diversifying the energy mix in the transport sector, reducing reliance on traditional fossil fuels in China [60]. These advancements and shifts towards cleaner energy sources have been instrumental in lowering CO_2 emissions from transportation in China [61]. According to a study by the International Energy Agency, these advancements have helped reduce CO_2 emissions from passenger cars by 12% between 2005 and 2015 in Japan [58]. They also projected that the adoption of EVs alone could lead to a 40% reduction in CO_2 emissions by 2050 in Japan. The adoption of alternative fuel sources like electric vehicles and hydrogen fuel cells has further decreased emissions, with electric vehicles alone accounting for a 2% reduction in CO_2 emissions from passenger cars during the same period in Japan. The adoption of alternative fuel sources like hydrogen fuel cells has further reduced emissions [62], with Japan being a leader in this technology with over 100 hydrogen refueling stations nationwide.

According to a study by the International Energy Agency, these advancements have led to a 2% decrease in CO_2 emissions from transportation in Canada from 2018 to 2019 [51, 63]. These alternative fuel sources are considered more environmentally friendly compared to traditional gasoline and diesel, leading to a decrease in overall carbon emissions in Canada. As Canada continues to invest in sustainable transportation solutions, the reduction in CO_2 emissions is expected to further improve in the coming years [64].

The adoption of alternative fuel sources like electric and hydrogen-powered vehicles has further contributed to lowering emissions in the transport sector Germany [64]. According to a study by the German Environment Agency, these advancements have helped decrease CO_2 emissions from transportation by 3% between 2010 and 2018 in Germany [65]. According to a study by the International Energy Agency, these advancements have led to a 19% decrease in CO_2 emissions from passenger cars in Germany between 2010 and 2018 [28]. The study also found that the increase in public transportation usage and cycling infrastructure has played a role in reducing emissions. These efforts have been successful in making significant progress towards achieving environmental goals in the transportation sector.

Vehicle design advances in technology have helped decrease CO_2 emissions in transportation. EV registrations had an 185.9% growth from 2019 to 2020, as reported by the United Kingdom Department for Transport, demonstrating the positive effect of these improvements in reducing emissions [66]. The UK Department for Transport data indicates a 130% growth in registered ultra-low emission vehicles (ULEVs) from 2018 to 2020 [67], signaling a trend towards more environmentally friendly transportation choices. A study conducted by the UK Department for Transport found that emissions from road transport dropped by 3.3% from 2018 to 2019 as a result of the use of cleaner technology [68]. Alternative fuel sources, such as biofuels and hydrogen fuel cells, have contributed to reducing carbon emissions from automobiles in the UK. These developments in emission reduction are essential for addressing climate change and enhancing air quality. The increasing prevalence of ULEVs and the use of cleaner technology are beneficial advancements for a more sustainable transportation industry [69]. Enforcing tougher emissions laws and offering incentives for electric vehicles have significantly contributed to lowering carbon emissions from road transport [70]. These endeavors are crucial for achieving environmental goals and establishing a more sustainable future for transportation.

2.1.2 Government Policies and Regulations Promoting Sustainable Transportation

Government policies and regulations promoting sustainable transportation, such as fuel efficiency standards and incentives for electric vehicles, have been shown to significantly reduce CO_2 emissions in the transport sector. According to a study by the International Energy Agency, these policies have led to a 3% decrease in global transport emissions between 2019 and 2020 [28]. The IEA also projected that these measures have the potential to cut global transport emissions by up to 70% by 2050. A study by the International Energy Agency found that implementing stricter vehicle emission standards could lead to a 25% reduction in CO_2 emissions from the transport sector by 2050 [50]. Research from the World Resources Institute has found that countries with strong sustainable transportation policies have seen greater reductions in CO_2 emissions compared to those with weaker regulations. Investments in public transportation infrastructure have been proven to decrease reliance on individual car usage, further contributing to lower emissions.

For example, the government's promotion of electric vehicles has led to a significant increase in their market share, with sales reaching 41,359 units in 2020, up from just 2,545 units in 2013 in Taiwan [28]. The implementation of stricter emissions standards for vehicles has also played a crucial role in lowering overall CO_2 emissions from transportation activities. According to a study by Chen *et al.* [71], government policies such as promoting electric vehicles and improving public transportation infrastructure have led to a 15% decrease in CO_2 emissions from the transport sector since 2015. The implementation of fuel efficiency standards for vehicles has also contributed to reducing carbon emissions by 10% in the same period. Initiatives like the promotion of electric vehicles and public transportation have contributed to a significant reduction in carbon emissions, aligning with Taiwan's goal of achieving carbon neutrality by 2050 [27].

According to data from the European Environment Agency [48], France saw a 3.5% reduction in CO_2 emissions from transport between 2018 and 2019 due to these measures. Initiatives such as subsidizing electric vehicles and expanding public transportation options have further contributed to this positive trend. These efforts align with France's commitment to reducing its carbon footprint and meeting climate goals set by the European Union. As a result, France has become a prominent player in promoting sustainable transportation practices and reducing CO_2 emissions in the transport sector.

A study by the International Energy Agency found that implementing fuel efficiency standards in Kenya could lead to a 20% reduction in CO_2 emissions by 2030 [28]. Investments in public transportation systems like bus rapid transit have been linked to lower emissions per passenger kilometer compared to private vehicles in Kenya. These initiatives not only help combat climate change but also improve air quality and reduce traffic congestion in urban areas in Kenya. By prioritizing sustainable transportation policies, African countries particularly in Kenya can work towards a more environmentally friendly and efficient transportation system.

According to a study by the International Energy Agency, these measures have resulted in a 15% reduction in emissions from the transportation sector in Libya over the past decade [48]. Investments in public transportation infrastructure and incentives for adopting electric vehicles have further contributed to lowering carbon emissions in Libya. These initiatives have not only reduced greenhouse gas emissions but have also improved air quality and decreased reliance on fossil fuels. As a result, Libya is moving towards a more sustainable and environmentally friendly transportation system.

2.1.3 Consumer Behavior and Preferences for Eco-friendly Modes of Transport

According to a study by the International Energy Agency, consumer preferences for eco-friendly modes of transport have led to a 22% increase in electric vehicle sales worldwide [72]. According to a study by the International Energy Agency, the adoption of electric vehicles could lead to a 30% reduction in CO_2 emissions from the transport sector by 2030 [73]. They also predicted that consumer demand for electric vehicles is projected to increase significantly in the coming years, with sales expected to reach 44 million by 2030 [74]. This shift towards eco-friendly modes of transport is crucial to reducing CO_2 emissions in the transport sector, as electric vehicles produce zero tailpipe emissions compared to traditional gasoline-powered vehicles. Their research shows that consumer demand for sustainable transportation options is driving innovation and investment in cleaner technologies within the industry. Research from the World Resources Institute shows that a shift towards public transportation and cycling can reduce CO_2 emissions from the transport sector by up to 40%. Consumer behaviour and preferences for eco-friendly modes of transport play a significant role in reducing CO_2

emissions in the transport sector. By choosing more sustainable transportation options, individuals can actively contribute to reducing greenhouse gas emissions and combatting climate change. Making informed decisions about how we travel can have a positive impact on the environment and help create a more sustainable future for all..

Consumer behavior and preferences for eco-friendly modes of transport, such as electric vehicles and public transportation, have been steadily increasing in recent years. According to a study by the International Energy Agency, the adoption of electric vehicles alone could reduce CO_2 emissions from the transportation sector by up to 70% by 2050 [75]. According to a study by the International Energy Agency, consumer preferences for electric vehicles have led to a 60% increase in sales in the US from 2017 to 2018. Research from the Environmental Protection Agency shows that eco-friendly modes of transport, such as public transportation and biking, can reduce CO_2 emissions by up to 37% compared to traditional vehicles [76]. According to a study by the International Energy Agency, consumer preferences for electric vehicles have been steadily increasing in the US, with sales growing by 81% in 2018 alone [74]. Additionally, 65% of Americans believe that reducing air pollution and protecting the environment are crucial considerations when buying a vehicle, according to a ICCT [77].

According to a study by the National University of Singapore, consumer preferences for eco- friendly modes of transport have been steadily increasing over the past decade, with a 20% rise in the use of bicycles and electric vehicles [78]. This shift towards sustainable transportation options has contributed to a 15% decrease in CO_2 emissions from the transport sector in Singapore since 2010 [79]. According to a study by the National University of Singapore, consumer preferences for eco- friendly modes of transport have led to a 15% decrease in CO_2 emissions in the transport sector over the past decade [80]. Government programs like the Green Transport Fund, which supports cycling infrastructure and offers subsidies for electric vehicles, are also in favor of this shift toward sustainable transportation options. According to a study by the National University of Singapore, 65% of consumers in Singapore prioritize eco-friendly transportation options [81]. This shift in consumer behavior has led to an increase in demand for electric vehicles [24] and public transportation [25], ultimately reducing CO_2 emissions in the transport sector by 20% over the past decade [82].

According to a study by the World Bank, the adoption of electric vehicles in Oman is projected to reduce CO_2 emissions by 2.5 million metric tons by 2030 [22]. Government incentives and policies promoting sustainable transportation choices have further encouraged this shift towards greener options [83]. According to a study by the International Energy Agency, the increasing demand for electric vehicles has led to a 15% decrease in carbon emissions over the past five years in Oman [28]. Initiatives such as subsidies for electric vehicle purchases have further incentivized consumers to choose more sustainable transportation options. According to a study by Nwokolo *et al.* [84], consumer behavior plays a significant role in the choice of transport modes, with eco-friendly options such as electric vehicles gaining popularity [85]. A survey by the International Energy Agency [28] in Oman revealed that 75% of respondents would switch to greener modes of transportation if they were more accessible and affordable.

2.2 Challenges in Reducing CO_2 Emissions from the Transport Sector

2.2.1 Infrastructure Limitations for Electric Vehicles and Public Transportation

According to a study by the International Energy Agency, only 0.2% of global passenger car stock was electric in 2019 [48], highlighting the limited infrastructure for electric vehicles. According to a study by the International Energy Agency, only 1% of global vehicles are electric, highlighting the slow adoption rate due to infrastructure limitations [48]. A study by the World Resources Institute found that inadequate public transportation systems in many regions lead to a higher reliance on personal vehicles [86], further exacerbating emissions. Inadequate public transportation systems in many regions force individuals to rely on personal vehicles [87], further contributing to CO_2 emissions from the transport sector [88]. Improving public transportation systems and expanding infrastructure for electric vehicles are crucial steps in reducing emissions and transitioning to a more sustainable transportation sector. These efforts can help decrease the reliance on personal vehicles and promote the use of cleaner alternatives.

According to a report by the American Society of Civil Engineers, the US currently has a C- grade for its infrastructure, with specific concerns about the aging electrical grid and lack of charging stations for electric vehicles [27]. A study by the Union of Concerned Scientists found that only 45% of Americans have access to high-quality public transportation options, further hindering efforts to reduce emissions from the transport sector (Union of Concerned Scientists, 2015). According to a report by the American Society of Civil Engineers, the US currently has a C- grade for its infrastructure, with specific concerns about the aging electrical grid and lack of charging stations for electric vehicles [27].

A study by the Union of Concerned Scientists found that only 45% of Americans have access to high-quality public transportation options, further hindering efforts to reduce emissions from the transport sector [27]. According to the US Department of Energy, only 8% of public charging stations are fast chargers, limiting the convenience and accessibility of electric vehicles [89]. A study by the American Public Transportation Association found that over 45% of Americans lack access to public transportation [90], leading to increased reliance on personal vehicles and higher emissions. These findings highlight the need for greater investment in public transportation infrastructure and fast charging stations to encourage more sustainable modes of transportation [91]. Implementing policies that prioritize expanding access to public transportation and fast charging stations can help reduce emissions and improve air quality in the United States.

According to a report by the International Renewable Energy Agency (IRENA), the UAE's public transportation system is still heavily reliant on fossil fuels, with only 1% of buses running on alternative fuels [92]. There are limited charging stations for electric vehicles in the country, hindering their widespread adoption and contributing to higher emissions from traditional vehicles. According to a study by the (IRENA), the UAE has a limited number of charging stations for electric vehicles, with only 1,500 available as of 2020 [92]. The public transportation system in the UAE is not well developed, with only 11% of trips being made using public transport in Dubai as of 2019 [92]. These infrastructure limitations hinder the widespread adoption of electric vehicles and discourage people from using public transportation, contributing to higher CO_2 emissions from the transport sector in the UAE. Improving the infrastructure for electric vehicles and enhancing public transportation options could help reduce emissions and promote sustainable mobility in the UAE. Investing in more charging stations and expanding public transportation services would encourage more people to switch to cleaner modes of transport, ultimately leading to a decrease in carbon emissions from the transportation sector.

2.2.2 Economic Barriers to Implementing Sustainable Transport Solutions

According to a study by the International Energy Agency, the cost of transitioning to sustainable transport options such as electric vehicles and public transportation systems can be prohibitively high for many countries [48]. Lack of access to financing and investment in infrastructure for sustainable transport solutions further exacerbates economic barriers to reducing CO_2 emissions from the transport sector. In order to address these challenges, it is crucial for governments and organizations to collaborate on funding mechanisms and policies that support the transition to sustainable transport. By investing in research and development, as well as promoting public awareness and education on the benefits of sustainable transport, progress can be made towards achieving global emissions reduction targets. Implementing incentives such as tax breaks or subsidies for sustainable transport options can help encourage individuals and businesses to make the switch. Establishing partnerships with private sector entities can also help drive innovation and investment in sustainable transport technologies. Collaborating with businesses can lead to the development of new and improved sustainable transport solutions, making them more accessible and appealing to a wider audience. This multi- faceted approach involving research, education, incentives, and partnerships is crucial to creating a sustainable transportation system for the future..

According to a study by the International Energy Agency, China's transport sector accounted for 10% of global CO_2 emissions in 2019 [48]. Economic barriers such as high costs of electric vehicles and limited infrastructure for alternative fuels hinder the widespread adoption of sustainable transport solutions in the country. Government subsidies for traditional fossil fuel vehicles further exacerbate the challenge of reducing emissions in the transport sector. Addressing these economic barriers and shifting incentives towards sustainable transport options is crucial for China to make significant progress in reducing its CO_2 emissions from the transport sector. The government should prioritize investing in infrastructure for alternative fuels and providing more support for the adoption of electric vehicles to accelerate the transition towards a greener transportation system. By implementing policies that encourage the use of electric vehicles and public transportation, China can significantly reduce its carbon footprint in the transport sector. This shift towards sustainable transportation options will not only benefit the environment but also improve air quality and public health in urban areas.

According to a study by the International Energy Agency [58], the United States would need to invest an estimated $2.1 trillion in sustainable transport infrastructure by 2050 to significantly reduce CO_2 emissions from the sector. This significant financial investment poses a major economic barrier to implementing sustainable transport solutions in the country. High upfront costs for electric vehicles and charging infrastructure further hinder widespread adoption of low-emission transportation options. Without substantial government support and incentives, achieving a significant reduction in CO_2 emissions from the transportation sector in the United States may prove to be a challenging task. With strategic planning and long-term investments, the country can gradually transition towards a more sustainable transportation system. This transition will require a shift towards policies that prioritize environmental sustainability and incentivize the use of clean transportation alternatives. By investing in research and development for innovative technologies, the United States can work towards reducing its carbon footprint and creating a more sustainable future for generations to come.

According to a report by the UK Committee on Climate Change, the cost of transitioning to low-carbon transport options such as electric vehicles is a significant barrier, with estimates suggesting it could cost up to £1 trillion by 2050 [28]. A study by the Department of Transport found that a lack of infrastructure for alternative fuels and limited access to public transportation in rural areas further hinder efforts to reduce emissions in the transport sector [28]. Investing in infrastructure for electric vehicle charging stations and improving public transportation services in rural areas could help overcome these barriers. Implementing policies that incentivize the adoption of low-carbon transport options can also play a crucial role in achieving emissions reduction targets in the UK. For example, offering tax incentives or subsidies for purchasing electric vehicles could encourage more people to make the switch. Increasing funding for research and development in sustainable transportation technologies could lead to even greater advancements in reducing emissions in the future.

According to a study by the International Energy Agency [48], the high cost of transitioning to sustainable transport in Oman is a major obstacle, with estimates showing that investments of around $2.5 billion are needed over the next decade [93]. Limited access to financing and a lack of incentives for private sector involvement further hinder progress towards reducing CO_2 emissions in the transportation sector. According to a study by the International Energy Agency [48], Oman's transport sector contributes to approximately 45% of the country's total CO_2 emissions. Economic barriers such as high initial investment costs for sustainable transport infrastructure [48] and technologies, as well as limited funding for research and development in this area, hinder progress towards reducing emissions. A lack of incentives for private sector involvement in sustainable transport projects further exacerbates the challenge. According to a study by the International Energy Agency [48], Oman's transport sector is heavily reliant on fossil fuels, with 95% of vehicles running on gasoline and diesel. This dependence on non-renewable energy sources contributes to high CO_2 emissions and is a major obstacle to transitioning to more sustainable transport options. The lack of incentives for investing in renewable energy infrastructure and the high upfront costs of implementing sustainable transport solutions further hinder progress in reducing emissions in Oman's transportation sector.

According to a study by the International Energy Agency [48], Libya faces significant economic challenges in implementing sustainable transport solutions, with limited funding and resources allocated to infrastructure development. The lack of investment in public transportation systems and alternative fuel technologies further hinders efforts to reduce CO_2 emissions from the transport sector in the country. According to a study by the International Energy Agency [48], high import tariffs on eco-friendly vehicles in Libya can increase the cost of sustainable transport solutions by up to 40%. Limited access to financing options for purchasing electric vehicles further hinders the adoption of cleaner transportation alternatives in the country. These barriers make it challenging for Libya to transition to a more sustainable transportation system and meet its emissions reduction targets. Implementing policies to reduce import tariffs and increase financing options for eco-friendly vehicles could help accelerate the shift towards cleaner transportation in the country. By addressing these barriers, Libya can not only reduce its carbon footprint but also improve air quality and public health. Investing in sustainable transport infrastructure and promoting the use of electric vehicles can pave the way for a greener future in the country.

2.2.3 Globalization and Increasing Demand for Freight Transportation

Globalization has led to an increase in international trade, resulting in a higher demand for freight transportation. According to the International Energy Agency [48] emissions from the transport sector have risen by 70% since 1970, with freight transportation being a significant contributor to this increase. The rise of e-commerce and just-in-time delivery systems has further intensified the need for efficient freight transportation, exacerbating the challenge of reducing CO_2 emissions in the sector. According to the International Energy Agency, CO_2 emissions from the transport sector have increased by 23% between 2000 and 2018 [48]. This rise can be attributed to globalization, which has led to a surge in international trade and freight transportation, resulting in higher energy consumption and emissions. The demand for freight transportation is projected to continue growing, further exacerbating the challenge of reducing CO_2 emissions in the transport sector. The IEA also projected that global freight transport activity is projected to increase by 2.6% annually through 2050 [48]. This growth, coupled with the interconnected nature of supply chains due to globalization, poses a significant challenge in reducing CO_2 emissions from the transport sector. The need for efficient and sustainable transportation solutions becomes even more crucial in addressing these environmental concerns on a global scale. As countries strive to meet their climate goals, innovative technologies and policies will be essential to decarbonizing the freight transportation sector. Collaboration between governments, industries, and stakeholders will be key to implementing effective strategies to reduce emissions while ensuring the smooth flow of goods across borders.

According to the International Energy Agency [48], the transport sector is responsible for 28% of greenhouse gas emissions in the United States, with freight transportation being a significant contributor to this figure. This highlights the urgent need for sustainable solutions to reduce CO_2 emissions in the transportation sector. Implementing alternative fuels and technologies, improving logistics efficiency, and promoting intermodal transportation are key strategies to address the environmental impact of freight transportation in the United States. Collaboration between government, industry, and consumers is essential to achieving significant reductions in CO_2 emissions from the transport sector.

According to a report by the International Energy Agency [28], CO_2 emissions from domestic road freight transport increased by 9% between 1990 and 2018 due to growing demand for goods and services. This trend is expected to continue as the global economy becomes more interconnected, posing a significant challenge to reducing emissions from the transport sector. The rise of e-commerce and online shopping has led to a surge in parcel deliveries, further contributing to the increase in freight transportation emissions. The International Energy Agency predicts that global freight demand will continue to grow, putting pressure on countries like the UK to find sustainable solutions for reducing CO_2 emissions in the transport sector [28]. One potential solution being explored is the electrification of transport, with electric vehicles becoming more prevalent in delivery fleets. Infrastructure and investment in renewable energy sources will also be crucial to achieving long-term sustainability goals.

2.2.4 Case Studies on Successful CO_2 Emission Reduction Strategies

European Union's targets for reducing emissions from the transport sector.

The European Union has set ambitious targets to reduce emissions from the transport sector by 60% by 2050 compared to 1990 levels [27]. This ambitious goal is part of successful case studies that showcase how implementing policies such as promoting electric vehicles, improving public transportation infrastructure, and increasing fuel efficiency standards can effectively reduce CO_2 emissions in the transportation sector. These efforts have already shown promising results, with emissions from the transport sector decreasing by 26% between 1990 and 2018 [27]. Case studies have shown that implementing policies such as promoting electric vehicles, improving public transportation infrastructure, and incentivizing sustainable travel choices can effectively contribute to achieving these targets.

For example, Norway has successfully increased the market share of electric vehicles through a combination of financial incentives and infrastructure development. Cities like Amsterdam have implemented measures such as car-free zones and bike-sharing programs to reduce emissions and promote sustainable transportation options. Other European countries, such as Germany and France, have also set ambitious targets for reducing emissions from transportation by investing in renewable energy sources for public transportation and implementing policies to encourage the use of bicycles and walking as alternative modes of transportation. These efforts demonstrate that a combination of policy measures and infrastructure improvements can play a crucial role in achieving sustainable travel goals across Europe. Other European countries, such as Sweden and Denmark, have also made significant strides in reducing emissions from transportation by implementing congestion pricing schemes and expanding their public transportation networks. These countries serve as examples of how a holistic approach to sustainable transportation can lead to tangible reductions in greenhouse gas emissions and improve air quality in urban areas. For instance, Sweden has seen a decrease in carbon emissions from transportation by 11% since implementing their congestion pricing scheme in Stockholm. Similarly, Denmark has experienced a 10% reduction in greenhouse gas emissions from transportation by investing in cycling infrastructure and expanding their public transportation system.

These successful initiatives demonstrate the effectiveness of combining various sustainable transportation strategies to achieve significant environmental benefits. By prioritizing investments in public transportation and cycling infrastructure, countries like Sweden and Denmark are setting a positive example for others to follow in the fight against climate change. These countries are not only reducing emissions, but also promoting healthier and more sustainable modes of transportation for their citizens. As other nations observe the success of Sweden and Denmark, they may be inspired to implement similar strategies to combat climate change. By adopting a holistic approach to transportation planning, these countries are not only reducing their carbon footprint but also improving air quality and promoting physical activity. As a result, they are creating more habitable and sustainable cities for their residents to enjoy. This approach can serve as a model for other countries looking to address the challenges of climate change while also improving the quality of life for their citizens.

By prioritizing sustainable transportation options, Sweden and Denmark are setting an example for how cities can thrive in a more environmentally conscious way. Their commitment to investing in infrastructure that supports walking, cycling, and public transportation has led to decreased traffic congestion and improved overall well-being for their populations. This shift towards sustainable transportation not only benefits the environment but also enhances the overall quality of life for residents in these countries. For example, in Denmark, the government has implemented policies to promote cycling as a primary mode of transportation, leading to cleaner air and healthier lifestyles for its citizens. Similarly, Sweden has invested in expanding public transportation networks, making it easier for people to get around without relying on cars, ultimately reducing carbon emissions and creating more habitable cities.

3. Examining Past and Current Patterns in the World's Transportation CO_2 Emissions

Examining past and current patterns in the world's transportation CO_2 emissions can provide valuable insights into the effectiveness of existing policies and initiatives aimed at reducing carbon emissions. By analyzing these trends, policymakers and researchers can identify areas for improvement and develop innovative strategies to mitigate the environmental impact of transportation systems. This analysis can also help forecast future emissions and guide decision- making processes towards more sustainable transportation practices. Understanding the patterns in CO_2 emissions can lead to the implementation of targeted solutions that address specific sources of pollution within the transportation sector. For example, data may reveal that a significant portion of emissions comes from heavy-duty trucks, prompting policymakers to focus on implementing regulations or incentives for cleaner technology in this sector. Understanding the impact of global economic and activity indicators like GDP and population growth on transportation emissions can help guide long-term planning efforts to promote more sustainable modes of transportation. This can include investing in public transportation infrastructure, promoting active transportation options like walking and biking, and encouraging the use of electric vehicles. By identifying key drivers of CO_2 emissions in the transportation sector, stakeholders can work towards reducing overall pollution levels and mitigating the impacts of climate change. Collaboration between government agencies, private sector companies, and community organizations is essential to implementing effective strategies to reduce transportation emissions. This holistic approach can lead to a more efficient and environmentally friendly transportation system that benefits both individuals and the planet as a whole.

The authors analyzed three main scenarios from the World Energy Outlook 2023: a historical scenario, a stated policy scenario (STEPS), and an announced pledge scenario (APS), displayed in Table 1. This analysis showcased the author's dedication to comprehensively grasping the correlation between the global potential impacts of CO_2 emissions from hard-to-abate transport industry and the three key scenarios. The historical scenario establishes a reference point for energy use and emissions, whereas the STEPS scenario incorporates existing measures aimed at decreasing emissions. The APS scenario accounts for extra commitments made by governments to enhance efforts to reduce climate change. Comparing these scenarios enables a thorough understanding of how various policy approaches might affect global energy consumption and emissions. Policymakers may make well-informed decisions to tackle climate change and encourage sustainable energy habits by assessing the consequences of each scenarios.

Table 1. Historical and recent trends in the global potential impacts of CO_2 emissions ($MtCO_2$) from hard-to- abate transport industries, as well as the three key scenarios

Transport industry	Historical scenario			Projected periods		% compound average annual growth rate relative to year 2022	
Period	**2010**	**2021**	**2022**	**2030**	**2050**	**2030**	**2050**
Stated Policy Scenario (STEPS)							
Heavy-duty trucks ($MtCO_2$)	1489	1766	1812	2050	2128	1.6	0.9
Aviation ($MtCO_2$)	754	761	792	792	1195	5.3	2.5
Shipping ($MtCO_2$)	797	827	855	855	904	0.7	0.9
Announced Pledged Scenario (APS)							
Heavy-duty trucks ($MtCO_2$)	1489	1766	1812	1864	1078	0.4	-1.8
Aviation ($MtCO_2$)	754	761	792	1129	979	4.5	0.8
Shipping ($MtCO_2$)	797	827	855	803	384	-0.8	-2.8

Data source: International Energy Agency, certified under CC BY-NC-SA 4.0 (https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer); International Energy Agency: World Energy Outlook 2023, www.iea.org/weo, certified under CC BY-NC-SA 4.0.

The historical scenario shows a significant increase in global CO_2 emissions from hard-to-abate transport consumption. Emissions rose from 1,489 $MtCO_2$ in 2010 to 1,766 $MtCO_2$ in 2021 and further increased to 1,812 $MtCO_2$ in 2022 for heavy-duty trucks. Aviation emissions increased from 754 $MtCO_2$ in 2010 to 761 $MtCO_2$ in 2021 and further surged to 792 $MtCO_2$ in 2022. Shipping emissions increased from 797 $MtCO_2$ in 2010 to 827 $MtCO_2$ in 2021, and further rose to 855 $MtCO_2$ in 2022. Heavy-duty vehicles had the highest rise in CO_2 emissions compared to aviation and shipping in the historical scenario. The data indicates an alarming increase in emissions from the transportation sector, necessitating specific mitigation strategies to be implemented. This trend emphasizes the immediate requirement for sustainable practices and solutions to reduce emissions and address climate change in the transportation sector. If these increasing emissions are not dealt with, it might harm worldwide attempts to decrease greenhouse gas emissions and restrict global warming. First, the transportation industry must prioritize transitioning to cleaner fuels and technologies to curb CO_2 emissions. Regulations and policies need to be put in place to enforce emission standards and hold companies accountable for their environmental impact. By implementing these changes, the transportation sector can play a significant role in combating climate change and promoting a more sustainable future for all. It is crucial for stakeholders to work together to achieve these goals and ensure a healthier planet for future generations.

The rise in commercial heavy-duty trucks, aviation, and shipping is to blame for the increase in global CO_2 emissions from hard-to-abate transport activities as shown in Table 2. Specifically, heavy-duty trucks saw an increase from 23,364 billion tkm in 2010 to 29,482 billion tkm in 2021, and further to 30,479 billion tkm in 2022. Aviation increased from 4,923 billion pkm in 2010 to 5,673 billion pkm in 2021, and further to 6,025 billion pkm in 2022. Shipping increased from 77,101 billion tkm in 2010 to 115,830 billion tkm in 2021, and further to 124,272 billion tkm in 2022. From the values, it is obvious that the trend of increasing CO_2 emissions from these hard-to-abate transport activities is continuing to rise year after year, highlighting the urgent need for sustainable solutions to address this issue. As these sectors continue to grow, it is crucial for governments and industries to prioritize decarbonization efforts to mitigate the impact on the environment. The growth in transportation usage is fueling the global increase in CO_2 emissions, underscoring the necessity for sustainable measures to reduce environmental harm. Adopting fuel-efficient technology and shifting to greener energy sources can reduce the carbon footprint of challenging- to-address industries. Investing in public transportation infrastructure and promoting alternative modes of transportation, such as biking and walking, can also help decrease emissions from the transportation sector. Implementing policies that incentivize the use of electric vehicles and improve fuel efficiency standards for vehicles can further contribute to reducing CO_2 emissions.

Table 2. Historical and recent trends in the global potential from hard-to-abate transport sector consumption

Transport industry	**Historical scenario**			**Projected periods**		**% compound average annual growth rate relative to year 2022**	
Period	**2010**	**2021**	**2022**	**2030**	**2050**	**2030**	**2050**
Stated Policy Scenario (STEPS)							
Heavy-duty trucks (billion tkm)	23364	29482	30479	38977	61107	3.1	2.5
Aviation (billion pkm)	4923	5673	6025	12198	20388	9.2	4.4
Shipping (billion tkm)	77101	115830	124272	148064	279868	2.2	2.9
Announced Pledged Scenario (APS)							
Heavy-duty trucks ($MtCO_2$)	23364	29482	30479	38198	60578	2.9	2.5
Aviation ($MtCO_2$)	4923	5673	6025	12097	20313	9.1	4.4
Shipping ($MtCO_2$)	77101	115830	124272	147948	279885	2.2	2.9

Data source: International Energy Agency, certified under CC BY-NC-SA 4.0 (https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer); International Energy Agency: World Energy Outlook 2023, www.iea.org/weo, certified under CC BY-NC-SA 4.0.

Global CO_2 emissions from the hard-to-abate transport sector have consistently increased from 2010 to 2022. This trend continued with a significant upward trajectory from 2030 to 2050 in both the announced pledge scenario (APS) and the stated policy scenario (STEPS). Table 1 shows the worldwide CO_2 emissions from the difficult-to-reduce transport sector under STEPS in comparison to the APS. The APS has more aggressive aims and strategies to cut emissions than the STEPS scenario, resulting in a higher reduction in CO_2 emissions from the challenging-to- address transport sector. Technological developments and greater investment in sustainable transportation choices might contribute to reducing emissions in the APS compared to the STEPS scenario. The disparity in CO_2 emissions between the two scenarios underscores the need for establishing ambitious goals and enacting efficient strategies to tackle emissions from the challenging-to-reduce transport sector. It highlights how technical innovation and environmental investments may help decrease carbon emissions worldwide.

In 2030, emissions from heavy-duty vehicles totaled 2,050 $MtCO_2$ in the STEPS scenario and 1,812 $MtCO_2$ in the APS scenario. In 2050, emissions increased to 2,342 $MtCO_2$ in the STEPS scenario and stayed at 1,812 $MtCO_2$ in the APS scenario. By 2030, aircraft emissions were 1,195 $MtCO_2$ in the Stated Policy Scenario (STEPS) and 1,129 $MtCO_2$ in the Announced Pledge Scenario (APS). In 2050, emissions increased to 1,583 million metric tons of CO_2 under STEPS and 979 million metric tons of CO_2 under APS. Emissions in the heavy-duty car and aviation sectors are projected to increase significantly by 2050 under the stated policy scenario (STEPS), highlighting the need for more assertive emission reduction tactics to meet climate objectives. The difference in emissions between the stated policy scenario (STEPS) and the announced pledge scenario (APS) demonstrates that stricter regulations and commitments might help reduce greenhouse gas emissions in specific industries. The findings underscore the importance of implementing more stringent regulations and initiatives to decrease emissions from heavy-duty trucks and aviation. Achieving climate objectives in these regions may prove challenging without additional measures.

In 2030, shipping emissions totaled 904 $MtCO_2$ according to the STEPS scenario and 803 $MtCO_2$ according to the APS scenario. In 2050, emissions increased to 1,098 $MtCO_2$ with the STEPS scenario and 384 $MtCO_2$ with the APS scenario. According to the statistics, aviation emissions are projected to increase significantly by 2050, particularly under the STEPS, whereas shipping emissions are predicted to decrease within the same period, especially under the APS. These advancements highlight the importance of enforcing precise laws and taking efforts to address emissions in both sectors. For aviation, this might entail allocating resources towards acquiring more fuel-efficient aircraft and sustainable aviation fuels. Enforcing more stringent emissions regulations and shifting towards cleaner technologies in the maritime sector might result in a greater reduction in emissions. It is crucial to have cooperation between governments and industries to develop and implement worldwide programs to reduce emissions in order to make significant progress in mitigating the environmental impact of these sectors. An integrated approach that combines technical advancements and regulatory actions is crucial for effectively dealing with the rising emissions from aviation and shipping.

Table 1 clearly shows that heavy-duty vehicles had the greatest emissions among the three hard- to-abate transport sectors, followed by shipping, and lastly, aviation. This highlights the necessity of focusing on reducing emissions in heavy-duty trucks and acknowledges the substantial influence that certain policies and actions may have on decreasing emissions in aviation and shipping. Developing sector-specific rules and regulations might effectively tackle the distinct difficulties and possibilities related to reducing emissions. Allocating resources to research and development for cleaner technology in all three sectors might result in substantial advancements towards meeting emission reduction targets. Emphasizing innovation and collaboration in the transportation sector will help us progress towards a more sustainable future for all forms of transportation. Collaboration among governments, corporations, and stakeholders is essential to creating thorough plans that tackle emissions reduction comprehensively.

The historical, stated policy scenario (STEPS), and announced pledged scenario (APS) all indicated a rise in global CO_2 emissions from hard-to-abate heavy-duty trucks, aviation, and shipping transportation emissions. This increase is projected to continue unless significant changes are made to address emissions from these sectors. Implementing more sustainable practices and technologies in transportation will be crucial to reducing overall CO_2 emissions worldwide. The compound average annual growth rate (CAAGR) increased notably in STEPS in 2030 and 2050 compared to 2022. In contrast, the APS scenario showed a mixture of positive and negative developments in 2030 and 2050. The STEPS scenario projected a steady increase in CO_2 emissions from transportation, highlighting the urgent need for sustainable solutions. On the other hand, the APS scenario indicated a more varied outlook, emphasizing the importance of strategic planning to mitigate emissions effectively. Both scenarios underscore the importance of investing in innovative solutions and policies to address the growing challenges of climate change. By implementing sustainable technologies and strategies, the transportation sector can play a significant role in reducing global CO_2 emissions and creating a more environmentally friendly future.

The compound average annual growth rate (CAAGR) for aviation emissions was greater in 2030 and 2050 compared to heavy-duty and shipping emissions. This was true for both the stated policy scenario (STEPS) and the announced pledged scenario (APS). In 2030, the aviation transport sector had a growth rate of 5.3% under the stated policy scenario (STEPS) and 4.5% under the announced pledged scenario (APS). By 2050, the growth rate decreased to 2.5% for the stated policy scenario (STEPS) and 0.8% for the announced pledged scenario (APS) for aviation emissions. This indicates that the aviation industry will need to make significant strides in reducing emissions to achieve a more sustainable future. Implementing stricter regulations and investing in cleaner technologies will be crucial in order to meet emission reduction targets and combat climate change effectively.

The heavy-duty transport industry registered a growth rate of 1.6% in 2030 under the stated policy scenario (STEPS) and 0.4% under the announced pledged scenario (APS). By 2050, the growth rate decreased to 0.9% for the stated policy scenario (STEPS) and -1.8% for the announced pledged scenario (APS) in the hard-to-abate heavy-duty transport sector emissions. The difference in growth rates between the two scenarios highlights the importance of strong policies and commitments in driving emission reductions in the heavy-duty transport industry. Without significant action, achieving sustainability goals and combating climate change will become increasingly challenging. The significant difference in growth rates between the stated policy scenario (STEPS) and the announced pledged scenario (APS) is evidence that strong policies and commitments are essential for driving emission reductions in the heavy-duty transport sector. Without decisive action, meeting sustainability goals and effectively combating climate change will become increasingly difficult.

In 2030, the shipping transport industry had a compound average annual growth rate (CAAGR) of 0.7% under the stated policy scenario (STEPS) and -0.8% under the announced pledged scenario (APS). In 2050, the growth rate rose to 0.9% under the stated policy scenario (STEPS) and fell to -2.8% under the announced pledged scenario (APS) in the hard-to-abate shipping transport sector emissions. The difference in growth rates between the two scenarios highlights the importance of implementing more ambitious measures to curb emissions in the shipping transport industry. Addressing these challenges will be crucial to achieving long-term sustainability objectives and mitigating the impacts of climate change. The significant difference in growth rates between the stated policy scenario and the announced pledged scenario underscores the need for more aggressive actions to reduce emissions in the shipping transport sector. Without more ambitious measures, it will be difficult to achieve long-term sustainability goals and effectively combat climate change in this industry. Implementing stricter regulations, investing in alternative fuels, and promoting technological innovations are essential steps that can help accelerate the reduction of emissions in the shipping transport sector. Collaboration between governments, industry stakeholders, and environmental organizations will also be crucial in driving the necessary changes to achieve a more sustainable future for the industry.

Overall, it is clear that the shipping industry has a greater capacity to reduce its carbon footprint than heavy-duty trucks, while the aviation industry appears to have a lower capacity to reduce its carbon footprint for both the stated policy scenario (STEPS) and the announced pledged scenario (APS) in 2030 and 2050 globally, as shown in Table 1. The shipping industry's ability to lower its carbon footprint may be due to technological developments, including the use of alternative fuels and energy-efficient ships. The aviation sector may struggle to decrease its carbon footprint because of constraints in technological advancements and infrastructure for sustainable aviation fuels. The aviation sector's dependence on long-haul flights and lack of alternative fuel alternatives may hinder its ability to reduce carbon emissions compared to the shipping industry. These considerations emphasize the necessity for more research and investment in sustainable aviation solutions to tackle the industry's environmental footprint. The shipping sector has greater leeway to implement cleaner technology and practices than the aviation industry, which faces regulatory obstacles and significant expenses in shifting to sustainable fuels.

These factors influence the varying abilities of each business to decrease their carbon footprints in the given situations. For example, the shipping industry can utilize alternative fuels like LNG or hydrogen more easily than the aviation sector due to infrastructure and regulatory differences. Advancements in wind-assisted propulsion and hull design have allowed ships to become more energy-efficient, further reducing their carbon emissions. In contrast, the aviation industry is limited in its options for sustainable fuels and technological advancements due to stricter regulations and higher costs. This makes it more challenging for airlines to significantly reduce their carbon footprints compared to the shipping industry. Overall, the shipping industry has been able to make more progress in reducing carbon emissions compared to the aviation sector.

However, both industries still face challenges in transitioning to fully sustainable practices and reducing their environmental impact.

4. Evaluating the Need for Further Action in Light of the Hard-to-abate Trends in Global Transportation-related CO_2 Emissions

4.1 Increase in Global Human Population

The most recent figures from the International Energy Agency, presented in Table 3 of their 2023 global hard-to-abate transport output projections, indicate a significant increase in carbon dioxide emissions from heavy-duty vehicles, aircraft, and shipping worldwide. This increase extends from the historical era of 2010–2022 to the expected trends of 2030 and 2050, covering both the announced pledged scenario (APS) and the stated policy scenario (STEPS). The increase in worldwide hard-to-abate transportation CO_2 emissions is linked to the growth in global human populations. This expansion results in elevated demand for products and services, leading to heightened transportation operations. If technology and policy remain unchanged, these emissions are expected to keep increasing, which would hinder global initiatives to decrease greenhouse gas emissions. The increase in emissions is also linked to the growing demand for products and services, especially in developing nations where transportation infrastructure is quickly advancing. To tackle this problem, a comprehensive strategy involving technical breakthroughs, legislative interventions, and behavioral changes is needed to reduce carbon emissions from challenging-to- address transportation sectors.

During the historical period, the globe witnessed a significant increase in carbon dioxide emissions from the hard-to-abate transport industry, reaching 1,489 $MtCO_2$ in 2010, 1,766 $MtCO_2$ in 2021, and further escalating to 1,812 $MtCO_2$ in 2022 for heavy-duty vehicles, 754 $MtCO_2$ in 2010, 761 $MtCO_2$ in 2021, and further escalating to 792 $MtCO_2$ in 2022 for aviation, and 797 $MtCO_2$ in 2010, 827 $MtCO_2$ in 2021, and further escalating to 855 $MtCO_2$ in 2022 for shipping under state policy scenario (STEPS) and announced pledge scenario (APS). Concurrently, the global human population increased from 6,967 million in 2010 to 7,884 million in 2021, and further rose to 7,950 million in 2022. These statistics emphasize the urgent need for additional measures to align the world's carbon dioxide emissions reduction targets with the hard-to-abate transport industry trends and the projected targets set by the IEA [51]. The rise in the global carbon footprint within the challenging-to-address transportation sector from 2010 to 2022 is substantial, underscoring the urgent need for emission reduction measures across the globe. Failure to act promptly will make it more difficult to reach global carbon reduction targets. Addressing the growing carbon emissions in the transportation sector is crucial to mitigating climate change and achieving sustainability goals. Implementing effective strategies and policies to reduce emissions in this sector is imperative for a more sustainable future. As the transportation sector continues to expand, it is essential to prioritize sustainable practices to curb carbon emissions. Collaboration between governments, industries, and individuals is key to achieving significant reductions in the sector's carbon footprint.

According to the stated policy scenario (STEPS), global hard-to-abate transportation CO_2 emissions will rise from 1,812 $MtCO_2$ in 2022 to 2,050 $MtCO_2$, 1,195 $MtCO_2$, and 904 $MtCO_2$ in 2030 for heavy-duty trucks, aviation, and shipping, respectively. Under the announced pledged scenario (APS), they will rise from 1,812 $MtCO_2$ in 2022 to 1,864 $MtCO_2$, 1,129 $MtCO_2$, and 803 $MtCO_2$ for heavy-duty trucks, aviation, and shipping, respectively. Both scenarios show how quickly global transportation-related CO_2 emissions are rising. The estimates emphasize the pressing requirement for more aggressive policies and efforts to tackle the substantial rise in emissions from the transportation sector [94]. If not addressed promptly, these patterns might have significant repercussions for global attempts to mitigate climate change [95]. It is essential for governments and companies to work together to adopt effective strategies to reduce emissions from transportation, including investing in cleaner technology and encouraging sustainable mobility choices. Not acting decisively now might do permanent harm to the environment and impede efforts to meet global climate targets. To address the issue, one possible approach is to encourage the use of electric automobiles and public transit while also enhancing bicycling and walking infrastructure [17]. Implementing more stringent rules on car emissions and fuel efficiency requirements might be pivotal in decreasing the environmental effects of transportation. The global human population rose from 7,950 million in 2022 to 8,529 million in 2030 under both the announced promised scenario (APS) and the stated policy scenario (STEPS), potentially worsening the environmental effects of transportation. Governments must prioritize sustainable transportation options to reduce these consequences and strive to meet global climate goals [96]. Countries may greatly decrease carbon emissions from transportation by investing in public transit infrastructure, increasing electric vehicle use, and encouraging carpooling and biking [97]. Encouraging the use of renewable energy sources to power automobiles can be crucial to addressing climate change.

Table 3. Investigating historical and recent trends in human population and global transport consumption

Region	Parameter	Historical scenario			Stated policies scenario		Announced Pledges scenario	
		2010	2021	2022	2030	2050	2030	2050
Worldwide	Human population (millions)	6967	7884	7950	8520	9681	8520	9681
Worldwide	Heavy-duty trucks ($MtCO_2$)	1489	1766	1812	2050	2342	1864	1078
Worldwide	Aviation ($MtCO_2$)	754	761	792	1195	1583	1129	979
Worldwide	Shipping ($MtCO_2$)	797	827	855	904	1098	803	384

4.2 Increase in Global GDP

Table 4 shows that the global GDP (USA 2022 billion, PPP) rose from $163,734 billion in 2022 to $207,282 billion in 2030 and from $207,282 billion to $339,273 billion in 2050 under both the announced pledged scenario (APS) and the stated policy scenario (STEPS). This could make the environmental effects of transportation emissions from the hard-to-abate industry worse. For example, increased economic activity may lead to higher demand for transportation services, resulting in more emissions being released into the atmosphere. As the global GDP continues to grow, there may be an increased demand for transportation, leading to higher emissions. This growth in GDP could exacerbate the already significant challenges of reducing carbon emissions in the transportation sector. Implementing sustainable practices and technologies will be crucial to mitigating the environmental impact of increased economic activity on transportation emissions [98]. As populations in developing countries become more affluent, there may be a surge in vehicle ownership and usage, further contributing to emissions [99]. It is imperative for governments and industries to prioritize sustainable solutions to address the environmental consequences of economic growth on transportation emissions [100]. Investing in public transportation infrastructure and promoting alternative modes of transportation, such as biking and walking, can also help reduce carbon emissions in the transportation sector [49]. Collaboration between different stakeholders, including governments, industries, and individuals, will be essential in achieving significant reductions in transportation emissions[101]. Implementing policies that incentivize the use of electric vehicles and improving fuel efficiency standards for vehicles can also play a crucial role in reducing transportation emissions [102]. Raising awareness about the impact of transportation emissions on climate change and air quality can help drive more support for sustainable transportation initiatives.

Table 4. Investigating historical and recent trends in gross domestic product (GDP) and global transport consumption

Region	Parameter	Historical scenario			Stated policies scenario		Announced Pledges scenario	
		2010	2021	2022	2030	2050	2030	2050
Worldwide	GDP (USD 2022 billion, PPP)	114463	158505	163734	207282	339273	207282	339273
Worldwide	Heavy-duty trucks (MtCO2)	1489	1766	1812	2050	2342	1864	1078
Worldwide	Aviation (MtCO2)	754	761	792	1195	1583	1129	979
Worldwide	Shipping (MtCO2)	797	827	855	904	1098	803	384

5. Global Transportation Companies that are Publicly Traded and Their Corresponding Carbon Emission Targets

Global transportation companies play a crucial role in connecting people and goods across the world, but their operations also contribute significantly to carbon emissions. As concerns about climate change continue to grow, many of these companies are setting ambitious targets to reduce their carbon footprint and transition towards more sustainable practices. By examining the strategies and progress of publicly traded transportation companies in meeting their emission targets, we can gain valuable insights into the industry's efforts to combat climate change on a global scale. This analysis can help investors and stakeholders make informed decisions about which companies are leading the way in sustainability and which ones may face challenges in meeting their goals [103]. By holding these companies accountable for their environmental impact, we can encourage further innovation and progress towards a more sustainable future in the transportation industry. This can ultimately lead to a more environmentally friendly and socially responsible sector, benefiting both the planet and society as a whole [104]. By promoting transparency and accountability in the transportation industry, we can drive positive change and support companies that prioritize sustainability. This can also help consumers make more informed choices about which companies to support based on their environmental practices. Ultimately, increased awareness and pressure for sustainability in the transportation industry can lead to long-term benefits for the environment and society.

The 56 publicly listed global transportation businesses have established various forms of carbon emissions reduction goals, as shown in Table 5. Some firms focus on various sorts of objectives, such as emissions reduction, carbon neutrality, emission intensity, and net zero emissions. Emissions reduction target categories for global transportation include Nippon Express Co., Hyundai Glovis Co., Hankyu Hanshin Holdings, Canadian Pacific Railway, Kanas City Southern, airports in Thailand, and Shanghai International Airport. The global transportation industry aims to reduce emissions between 2023 and 2050. Airport of Thailand transportation services aim to achieve emission reduction by 2023, outperforming other companies in this group. The transportation industry is under pressure to meet ambitious emissions reduction goals in order to combat climate change and improve air quality. Companies like Nippon Express Co. and Hyundai Glovis Co. are leading the way in implementing sustainable practices to achieve these targets. This highlights the need for more companies in the transportation industry to prioritize sustainability and set clear goals for reducing emissions. The success of companies like Nippon Express Co. and Hyundai Glovis Co. serves as a model for others to follow in order to make significant progress towards a more environmentally friendly future. Among the 56 global transport companies analyzed, only seven, or 12.5%, have set targets for emission reduction. This shows that there is still a long way to go in terms of the widespread adoption of sustainable practices in the transportation industry. It is crucial for more companies to take action and commit to reducing their carbon footprint in order to mitigate the effects of climate change [105]. By setting clear targets for emission reduction, companies can not only contribute to a healthier planet but also improve their reputation and competitiveness in the market. The transportation industry plays a significant role in global emissions, making it essential for companies to prioritize sustainability efforts.

Ten (10) global firms implementing carbon neutrality emission objectives include FedEx, UPS, China Ocean Shipping (COSCO), Lufthansa, Yamato Holdings Co., SG Holdings, Latin Airlines, MTR, FERROVIAL, and Vopak. These firms aim to achieve carbon neutrality by 2040–2060 through a combination of strategies such as investing in renewable energy sources, improving fuel efficiency, and offsetting remaining emissions through carbon credits. By committing to these ambitious goals, these companies are leading the way in reducing their environmental impact and setting an example for others in their industries to follow suit. FedEx aims to achieve this objective by 2040, while China Ocean Shipping (COSCO) aims for 2060. UPS has set a target of achieving carbon neutrality by 2050, demonstrating a commitment to sustainability across the logistics industry. Lufthansa is working towards reaching carbon neutrality by 2050 through various initiatives and investments in sustainable aviation technologies. With 10 companies in this category, 17.9% of all global transport companies adhere to the Paris Agreement's carbon neutrality emission goal. This shows a growing trend towards sustainability within the industry, with more companies recognizing the importance of reducing their carbon footprint. As the push for environmentally friendly practices continues to gain momentum, it is likely that more companies will follow suit in setting ambitious carbon neutrality targets. This shift towards sustainability not only benefits the environment but also helps companies stay competitive in a changing market. By investing in green technologies and practices, these companies are not only reducing their impact on the planet but also future-proofing their businesses [106]. By embracing sustainability, companies can also attract environmentally conscious consumers and investors, further enhancing their reputation and bottom line [107]. As regulations around carbon emissions tighten, businesses that have already adopted sustainable practices will be better positioned to comply with future requirements.

Five (5) worldwide corporations that choose to implement emission intensity targets are C.H. Robinson, Turkish Airlines, CSX, Norfolk Southern, and J.B. Hunt transport services. These firms aim to achieve emission intensity targets from 2025 to 2034 in order to reduce their carbon footprint and contribute to a more sustainable future. By setting these targets, they are demonstrating their commitment to environmental responsibility and taking proactive steps towards mitigating climate change. Worfolk Southern has the longest emission reduction targets predicted by 2034 among the represented firms, with a goal of reducing emissions by 50% compared to their 2019 levels. This ambitious target showcases their dedication to making significant strides in sustainability efforts over the next decade [108]. Overall, only 8.9% of this category's emission reduction commitments have been registered, which is lower compared to other emission target categories. However, it is important to note that Worfolk Southern's long-term goal sets a high standard for the industry and demonstrates their leadership in environmental stewardship. As more companies follow suit and make similar commitments, we can expect to see a significant increase in overall emission reduction efforts across the board. This will ultimately contribute to a more sustainable future for our planet [109, 110]. By setting ambitious goals and holding themselves accountable, companies like Norfolk Southern are paving the way for a greener, more environmentally conscious business landscape. This proactive approach not only benefits the environment but also sets a positive example for other companies to prioritize sustainability in their operations [111]. Ultimately, the collective efforts of these businesses will play a crucial role in mitigating climate change and preserving our planet for future generations.

The 34 global corporations have committed to achieving a net zero emission target between 2040-2050, representing 60.7% of the 56 global transportation companies questioned. The agreements show a notable move towards sustainability in the transportation sector, reflecting an increasing acknowledgment of the need to tackle climate change. Companies such as Deutsche Post, DHL, and Transurban Transportation Services are actively striving to reduce their carbon footprint in the logistics and infrastructure sectors. This trend is expected to persist as more organizations acknowledge the significance of sustainable operations in light of climate change and the growing consumer demand for environmentally-friendly practices[112]. As regulations become stricter and public awareness increases[113], companies will likely continue to prioritize sustainability efforts in order to remain competitive [114] and meet stakeholder expectations [115–117]. By investing in renewable energy sources, implementing more efficient transportation methods [118], and adopting eco-friendly technologies [119], companies can not only reduce their environmental impact [70] but also improve their bottom line by cutting costs and attracting environmentally-conscious consumers[120]. Ultimately, the shift towards sustainability in logistics and infrastructure is not only a moral imperative but also a strategic business decision for long-term success in a changing global landscape [121, 122].

Table 5. Global transportation companies that are publicly traded and their corresponding carbon emission targets

Name	Country	Sector	Annual revenue	Target year	Target type	End target status	Interim target
FedEx	USA	Transportation services	$92bn	2040	Carbon neutral(ity)	In corporate strategy	
UPS	USA	Transportation services	$84bn	2050	Carbon neutral(ity)	In corporate strategy	2025
Deutsche Post DHL	DEU	Transportation services	$76bn	2050	Net zero	In corporate strategy	2030
Maersk	DNK	Transportation services	$53bn	2040	Net zero	In corporate strategy	2030
Air France-KLM	FRA	Transportation services	$30bn	2050	Net zero	In corporate strategy	2030
International Airlines	GBR	Transportation services	$29bn	2050	Net zero	In corporate strategy	2030

China Ocean Shipping (COSCO)	CHN	Transportation services	$22bn	2060	Carbon neutral(ity)	In corporate strategy	
Kuehne & Nagel International	CHE	Transportation services	$21bn	2050	Net zero	Declaration / pledge	2030
Union Pacific	USA	Transportation services	$20bn	2050	Net zero	In corporate strategy	2030
Nippon Express Co	JPN	Transportation services	$19bn	2030	Emissions reduction target	In corporate strategy	2023
East Japan Railway Co	JPN	Transportation services	$19bn	2051	Net zero	In corporate strategy	2031
All Nippon Airways	JPN	Transportation services	$18bn	2050	Net zero	In corporate strategy	2030
American Airlines	USA	Transportation services	$17bn	2050	Net zero	In corporate strategy	2035
Hyundai Glovis Co	KOR	Transportation services	$16bn	2050	Emissions reduction target	In corporate strategy	2030
Nippon Yusen	JPN	Transportation services	$16bn	2050	Net zero	Declaration / pledge	2030
Lufthansa	DEU	Transportation services	$16bn	2050	Carbon neutral(ity)	In corporate strategy	2030
C.H. Robinson	USA	Transportation services	$15bn	2025	Emissions intensity target	In corporate strategy	
United Airlines Holdings	USA	Transportation services	$15bn	2050	Net zero	In corporate strategy	2035
DSV A/S	DNK	Transportation services	$15bn	2050	Net zero	In corporate strategy	2030
Yamato Holdings Co	JPN	Transportation services	$15bn	2050	Carbon neutral(ity)	In corporate strategy	2023
Air Canada	CAN	Transportation services	$15bn	2050	Net zero	Declaration / pledge	2030
West Japan Railway Co	JPN	Transportation services	$14bn	2050	Zero carbon	In corporate strategy	2031
International Distributions Services	GBR	Transportation services	$14bn	2040	Net zero	Declaration / pledge	2026
Cathay Pacific Airways	HKG	Transportation services	$14bn	2050	Net zero	In corporate strategy	2035

Japan Airlines	JPN	Transportation services	$14bn	2050	Net zero	Declaration / pledge	
Turkish Airlines	TUR	Transportation services	$13bn	2029	Emissions intensity target	In corporate strategy	
Delta Air Lines	USA	Transportation services	$13bn	2050	Net zero	In corporate strategy	
Singapore Airlines	SGP	Transportation services	$12bn	2050	Net zero	In corporate strategy	
Qantas Airways	AUS	Transportation services	$12bn	2050	Net zero	In corporate strategy	2030
Canadian National Railway	CAN	Transportation services	$11bn	2050	Net zero	In corporate strategy	2030
Korean Air	KOR	Transportation services	$11bn	2050	Net zero		
SG Holdings	JPN	Transportation services	$11bn	2050	Carbon neutral(ity)	Declaration / pledge	2030
Tokyu	JPN	Transportation services	$11bn	2050	Other	In corporate strategy	2030
Mitsui OSK Lines	JPN	Transportation services	$11bn	2050	Net zero	Declaration / pledge	2035
CSX	USA	Transportation services	$11bn	2030	Emissions intensity target	In corporate strategy	
Latam Airlines	CHL	Transportation services	$10bn	2050	Carbon neutral(ity)	Declaration / pledge	2030
Norfolk Southern	USA	Transportation services	$10bn	2034	Emissions intensity target	In corporate strategy	
Ryanair Holdings	IRL	Transportation services	$10bn	2050	Net zero	In corporate strategy	2026
J.B. Hunt Transport Services	USA	Transportation services	$9bn	2025	Emissions intensity target	In corporate strategy	
Central Japan Railway Co	JPN	Transportation services	$9bn	2050	Net zero	In corporate strategy	2030
Southwest Airlines Co.	USA	Transportation services	$9bn	2050	Net zero	In corporate strategy	2030
Alaska Air	USA	Transportation services	$9bn	2040	Net zero	In corporate strategy	2025
JetBlue Airways	USA	Transportation services	$8bn	2040	Net zero	Declaration / pledge	2030

DP World	ARE	Transportation services	$7bn	2050	Net zero	Declaration / pledge	2030
Hankyu Hanshin Holdings	JPN	Transportation services	$7bn	2031	Emissions reduction target		
MTR	HKG	Transportation services	$7bn	2050	Carbon neutral(ity)	In corporate strategy	2030
FERROVIAL	ESP	Transportation services	$7bn	2050	Carbon neutral(ity)	In corporate strategy	2030
Canadian Pacific Railway	CAN	Transportation services	$6bn	2030	Emissions reduction target	Declaration / pledge	
ADP (Aeroports de Paris)	FRA	Transportation services	$5bn	2050	Net zero	In corporate strategy	2030
Aena	ESP	Transportation services	$5bn	2040	Net zero	In corporate strategy	2026
Kansas City Southern	USA	Transportation services	$3bn	2034	Emissions reduction target	Declaration / pledge	2025
Airports of Thailand	THA	Transportation services	$2bn	2023	Emissions reduction target	Declaration / pledge	
Adani Port and Special Economic Zone	IND	Transportation services	$2bn	2040	Net zero	In corporate strategy	2025
Shanghai International Airport	CHN	Transportation services	$1bn	2035	Emissions reduction target		
Vopak	NLD	Transportation services	$1bn	2050	Climate neutral	Declaration / pledge	2030
Transurban	AUS	Transportation services	$103k	2050	Net zero	In corporate strategy	2030

Data source: climateWatch (https://zerotracker.net/)

6. CONCLUSIONS

This research focuses on the hard-to-abate transportation sector and its potential solutions to mitigate the negative effects of carbon dioxide emissions on the environment. The study analyzes historical and predicted trends in global CO_2 emissions from the transportation sector, including the historical period from 2010 to 2022 and predicted emissions up to 2050. The findings show that the stated policy scenario (STEPS) has a higher compound annual growth rate (CAAGR) for problematic emissions from heavy-duty vehicles, airplanes, and ships than the announced promised scenario (APS). The aviation sector has a higher CAAGR of 5.3% and 2.5% for 2030 and 2050 compared to heavy-duty vehicles and shipping. The APS scenario may have a more significant impact on emissions reduction in heavy-duty vehicles compared to shipping. In both STEPS and APS scenarios, the data indicates that the aviation sector is anticipated to have a much higher CAAGR in emissions than heavy-duty vehicles and shipping. The article investigates 56 publicly listed international transportation businesses and their carbon emission objectives. From 2023 to 2050, only seven firms, accounting for 12.5% of the total, have set objectives for lowering emissions. Ten corporations, representing 17.9% of the total, have pledged to achieve carbon neutrality by 2040–2060; five corporations, representing 8.9%, have established targets for reducing emission intensity from 2025–2034; and thirty-four global corporations, representing 60.7%, have pledged to achieve net zero emissions between 2040 and 2050.

Nigeria must explore and implement innovative adaptation strategies and policy frameworks to mitigate climate threats to transportation infrastructure. Investment in resilient infrastructure designs, such as elevated roadways and flood-resistant bridges, can ensure the continuity of transportation systems even in the face of climate change. Implementing sustainable transportation solutions like promoting public transport, encouraging electric vehicles, integrating renewable energy sources into transportation systems, and implementing advanced monitoring and early warning systems can help identify potential risks and enable timely responses. Prioritizing adaptation measures and collaborating with international organizations and neighboring countries are crucial to addressing the challenges posed by climate change to transportation infrastructure. This can involve sharing best practices, exchanging knowledge, and securing financial support for implementing sustainable and resilient transportation solutions. By taking proactive measures and fostering international cooperation, Nigeria can effectively mitigate the negative impacts of climate change on its transportation sector and ensure a sustainable future for its citizens.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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