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Long-Term Transportation Fuel Consumption in Annex I Countries: A Mixed-Method Multi-Sector Analysis (1990–2020)

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ABSTRACT: The transportation sector is one of the largest consumers of global energy and a major contributor to greenhouse gas (GHG) emissions. This study examines long-term transportation fuel consumption trends in Annex I, countries which are the industrialized nations and economies in transition with legally binding GHG mitigation obligations under the United Nations Framework Convention on Climate Change (UNFCCC). The study utilizes the data reported to the UNFCCC from 1990 to 2020 by these countries. A multi-method analytical framework was applied, combining time series analysis, Pearson correlation, k-means clustering, Kruskal-Wallis statistical grouping, and ANOVA to both aggregate and per capita fuel consumption values. The analysis shows the dominance of road transportation and liquid fuels in transportation fuel consumption, having 10 times higher values than other sectors and fuel types, respectively. The time series data for these variables, as well as total transportation fuel consumption, were found to be non-stationary, highlighting the potentially significant influence of external events and socioeconomic factors on transportation demand and consumption behavior. The existing efforts of decarbonization and promoting renewable energy seem to result in a reduction in solid fuels and a boost in biomass. However, these efforts are still outweighed by growth in consumption of liquid fuel and in road transportation. The study identifies priority areas for transportation decarbonization and highlights limitations in the current UNFCCC data reporting framework.

KEYWORDS: Transportation energy consumption; Annex I countries; time series analysis; clustering techniques; fuel types; transportation sectors

1 Introduction

The transportation sector accounts for a substantial share of global energy consumption and greenhouse gas (GHG) emissions, making it a central focus to international climate policy. Despite commitments made under successive climate frameworks, transport-related fuel consumption has continued to increase across most industrialized nations, driven by expanding vehicle fleets, urbanization, and growing freight demand [1,2]. Without substantial structural changes, transport-related carbon emissions are projected to double by 2050 [2]. Evaluating long-term trends in transportation fuel consumption is therefore essential for assessing the effectiveness of past policies and informing future mitigation strategies.

Annex I countries under the United Nations Framework Convention on Climate Change (UNFCCC) include both established industrialized nations and economies in transition. These countries have historically been among the largest contributors to global transportation emissions and, therefore, carry legally binding

obligations to report and reduce GHG emissions. Their consistently reported data from 1990 to 2020 provides a unique opportunity for longitudinal comparative analysis across diverse economic and geographic contexts [3,4].

While the literature on transportation energy and emissions is extensive, most existing studies remain limited in scope, focusing on individual countries, single transportation modes, or specific fuel categories [5,6]. Consequently, long-term multi-sector and multi-fuel analyses encompassing a broad group of industrialized nations remain relatively uncommon. Established decomposition frameworks such as Index Decomposition Analysis (IDA) and the Impact = Population $\times$ Affluence $\times$ Technology (IPAT) identity has been widely applied; however, they often overlook the persistent divergence between efficiency gains and total demand growth, with efficiency improvements frequently being offset by rising Gross Domestic Product (GDP) and motorization rates [6].

Building on this body of work, three specific research gaps motivate the present study: (1) the absence of long-term comparative analyses examining multiple transportation sectors and fuel types across all Annex I countries simultaneously; (2) the limited use of per-capita alongside aggregate metrics for meaningful cross-national comparison; and (3) the scarcity of studies employing multiple complementary statistical techniques to validate consumption patterns from both temporal and spatial perspectives.

The study is guided by the following research questions:

RQ1: *What are the long-term trends in transportation fuel consumption among Annex I countries between 1990 and 2020?*

RQ2: *Which fuel types and transportation sectors dominate consumption across these countries?*

RQ3: *Are there significant correlations between the temporal trends of different fuel types and transportation sectors?*

RQ4: *Which Annex I countries exhibit similar per capita consumption levels and temporal trends?*

RQ5: *What policy implications can be derived from the observed consumption patterns?*

Prior work has examined transportation emissions through various lenses. Sector-specific analyses have investigated road transport CO₂ in individual countries [7], GHG indicators in North African road transport [8], and carbon-neutral pathways in Gulf Cooperation Council countries [9]. City-level and country-specific studies have evaluated the impact of supply- and demand-side policies on urban passenger transport [10] and tested the Environmental Kuznets Curve hypothesis for Organisation for Economic Co-operation and Development (OECD) transport sectors [11]. On the global scale, recent work has mapped spatial and temporal drivers of transportation carbon emissions across 140 countries [12], developed comprehensive global transport emission inventories [13], and reviewed modeling frameworks for transport demand and decarbonization [14,15]. Collectively, these studies demonstrate the diversity of analytical approaches and geographic scopes applied to transportation energy research. However, several important gaps remain in existing literature. Firstly, the coverage of multisectoral fuel consumption of different types of fuels has not been found. Secondly, the Annex-I countries, despite their crucial role in energy consumption vis-à-vis economic activity, have not been given due consideration. Lastly, the studies generally rely on a particular analysis methodology rather than benefiting from various approaches in different aspects. Considering these limitations, the present study makes a novel contribution by applying a mixed-method analytical framework to examine multi-sectoral transportation energy consumption across different fuel types for Annex-I countries over a 31-year period.

This study makes five key contributions to existing literature. First, it presents a 31-year multi-sector and multi-fuel analysis across all Annex I countries. Second, it integrates both aggregate and per capita analyses to facilitate more meaningful comparisons among countries of different population sizes. Third,

it applies a multi-method validation approach combining descriptive statistics, Augmented Dickey-Fuller (ADF) stationarity testing, Pearson correlation, k-means clustering, Kruskal-Wallis statistical grouping, and ANOVA. Finally, it highlights systematic limitations in the UNFCCC reporting framework, particularly for navigation and cross-border freight activities, with implications for environmental data governance.

2 Methodology

2.1 Data Structure

The secondary data for this study were acquired from the open-access platform of the UNFCCC. The available data comprised 31 years of observation from 1990 to 2020 for Annex I countries, as shown in Fig. 1. The range and features of the data were selected based on their availability and consistency. The Annex I countries included in this study are legally bound under the Kyoto Protocol to provide their emissions data in common reporting formats. Hence, the available data was expected to be reliable and consistent. This, in addition to the historically significant emission contributions and the current economic importance of Annex I countries, was another major reason for focusing on these countries. After reviewing the data, it was found that the aggregate values for fuel consumption were consistent, while there were missing values and inconsistencies found in the reported values for each fuel type within each sector. Hence, the analysis was restricted to aggregate values for each fuel type and sector, and interactions between fuel types and transportation sectors were not considered in this study. Table 1 presents descriptive statistics for the dataset used in the analysis.

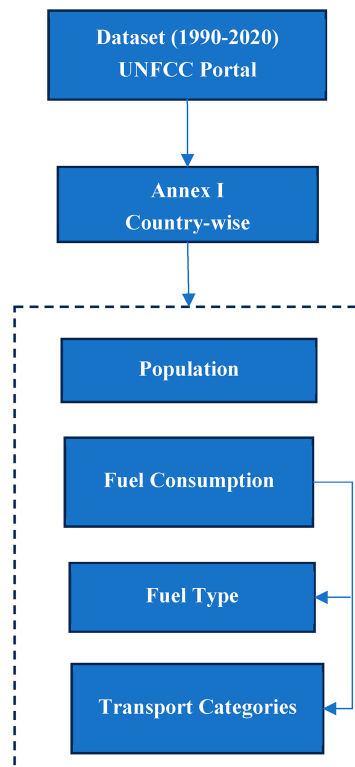


Figure 1: Available data structure.

Table 1: Descriptive statistics of the available data.

Category	Mean_TJ	Std_TJ	Min_TJ	Max_TJ
Population	39,852,679	80,654,667	29,032	448,072,946
Total Fuel (TJ)	122,170,084	8,483,611	106,523,155	134,154,806
Fuel: Biomass (TJ)	1,210,295	1,135,649	62,769	2,971,392
Fuel: Gaseous Fuels (TJ)	2,700,979	188,468	2,436,750	3,200,076
Fuel: Liquid Fuels (TJ)	57,134,675	3,555,313	50,026,646	61,888,606
Fuel: Other Fossil Fuels (TJ)	34,735	23,104	3575	66,043
Fuel: Solid Fuels (TJ)	4358	4258	1216	16,766
Sector: Aviation	3,259,638	285,686	2,306,699	3,607,717
Sector: Road	52,389,133	4,464,183	43,686,060	58,234,133
Sector: Railways	1,060,485	105,715	850,554	1,375,192
Sector: Navigation	1,498,821	222,553	1,062,777	1,860,208
Sector: Other	2,876,960	245,584	2,574,016	3,686,260

Note: TJ refers to Terajoules. Population values represent annual national population estimates corresponding to the transportation fuel consumption dataset.

2.2 Data Cleaning and Processing

Prior to the analysis, data cleaning was done to account for missing data and inconsistencies in the dataset. Inconsistencies in fuel types based on sector-wise analysis for several countries in certain years were identified at the outset of the analysis. To maintain consistency through the period covered by the study, the focus was on aggregate consumption of fuels as well as the transport sector. The annual transportation fuel consumption per country was divided by the country's population to determine the per capita consumption figures.

The basic statistics presented in [Table 1](#) highlight some important trends for the data. The large differences in ranges of data and their high values of standard deviation point to the large variations in transportation fuel consumption in the Annex I countries regarding almost all the available features. Since these countries are industrialized nations, this variation could be an indication that industrial growth is not always directly related to the population (size) or absolute values of fuel consumption. This would also explain per capita values and temporal analysis in this study. Liquid fuels have the highest contribution as the energy source of transportation field which is dominated by the road transportation sector. The subsequent analysis describes the consumption patterns for each fuel source and sector and how they are similar to each other.

2.3 Analysis Methodology

The available data were analyzed from multiple perspectives as illustrated in [Fig. 2](#), including both group-wise and country-wise analysis. For the group analysis, pooled data from all countries were subjected to time series analysis, correlation, and clustering. Univariate time series analysis was performed for the total fuel consumption in the transportation sector as well as for the dominant fuel type and transport sector. This analysis provided year-on-year comparisons, overall growth rate, and the number of years exhibiting positive or negative changes. Furthermore, the ADF test was used to determine whether the time series were stationary [16]. This analysis is particularly important for the Annex I countries, as it helps assess whether long-term commitments to emission reduction have contributed to changes in transportation fuel consumption patterns.

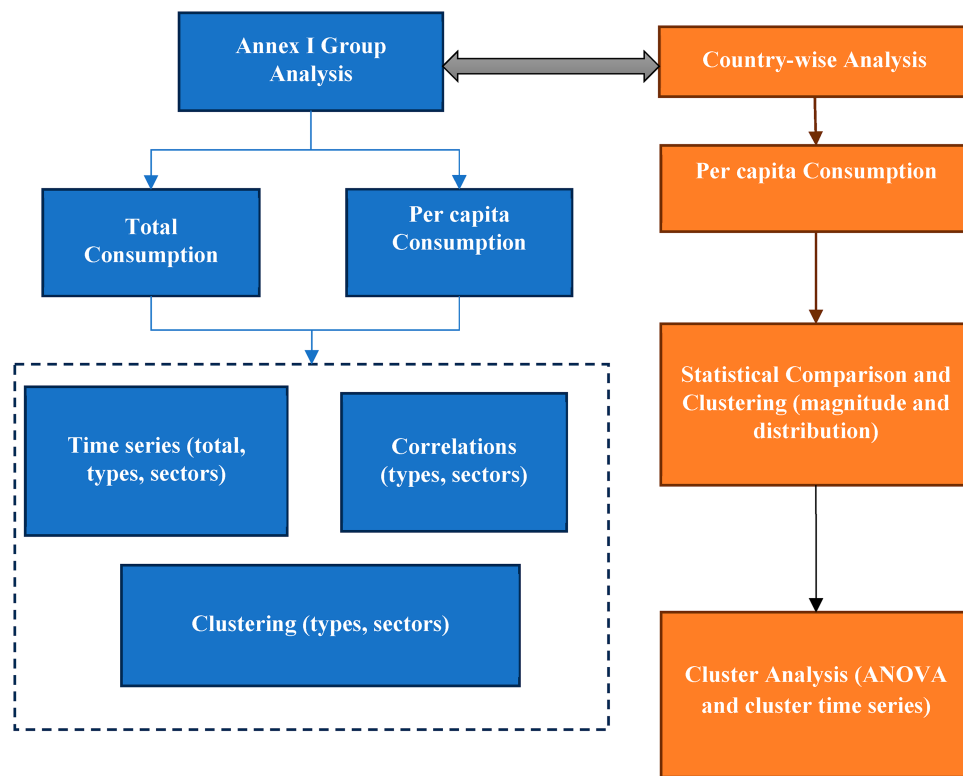


Figure 2: Research analysis methodology.

The Pearson correlation analysis was done within fuel types and transportation sectors to determine which of them were similar to each other in terms of temporal trends. K-means clustering analysis was also done for the same categories, but the focus was on clustering based on magnitude rather than trends [17]. For each of these analyses, raw as well as per capita fuel consumption was used. The optimum number of clusters was determined by two independent methods, namely the Elbow and Silhouette score methods [18].

The country-wise disaggregated data was used only with per capita fuel consumption values to provide a fair comparison. In this case, two types of clustering analysis were used, including k-means clustering which focuses on the magnitude of values. The second grouping approach was iterative and based on statistical similarity of country-level fuel consumption distributions using pairwise Kruskal-Wallis tests. Countries with statistically similar distributions were grouped together to identify comparable transportation fuel consumption profiles [19]. This was done because the correlation between 44 countries may not have provided a clear picture. It was found that both types of clustering provided a different perspective of similarities between countries' fuel consumption, justifying their use. Once the clusters were determined from each method, Analysis of Variance (ANOVA) was done between clusters to determine which of the available characteristics of the clusters were unique in addition to the total fuel consumption. Furthermore, time series analysis within each cluster was performed using all types of per capita fuel consumption. The insights from the clusters regarding unique countries were further rechecked using outlier analysis, which was also reinforced by a multi-method approach.

3 Results

3.1 Annex I Group Analysis

3.1.1 Total Consumption

The long-term trends presented in Figs. 3 and 4 demonstrate the overwhelming dominance of liquid fuels and road transportation in the transportation energy sector. The correlation between these findings is reported in other studies, which mentioned that approximately the entire traffic fleet depends upon the liquid fuels consumed by their internal combustion engines [20]. The consumption of gaseous fuels is the next highest contributory in the transportation sector energy demand. These gaseous fuels include Liquefied Petroleum Gas (LPG), Natural Gas, Methane, etc., which are made up of carbon and hydrocarbons and considered more sustainable because of lower emissions compared to liquid fuels [21]. The next type of fuel, which has started contributing significantly to the transportation sector, is biomass, showing a sharp increase in usage around 2008. Biomass is a promising renewable energy source that can be prepared with organic waste from forests, agriculture, etc. [22]. The increase in its consumption is a result of mandates developed and implemented in various regions, most importantly the EU and the USA, to enhance the use of renewable fuels as a mechanism to reduce GHG emissions [23]. Despite the above-mentioned sustainability advantages of gaseous and biomass fuels, their consumption in the transportation sector is still 10 times lower than liquid fuels. Hence, the increase in the consumption of these alternative fuel sources seems to be offset by the increase in vehicular population, most of which still relies on liquid fossil fuels.

Within the transportation sectors, domestic aviation and other transportation sectors are the major contributors after road transportation, as shown in Fig. 4. The aviation industry is one of the major regulators of the global market and has been continually increasing in terms of frequency and capacity [24]. The other transportation sector includes pipelines; industrial and other commercial vehicles used in construction and maintenance operations. This sector is the backbone of the energy system on land for oil and gas. The trends of industrialization and economic growth have been complemented with the expansion of energy supply and distribution systems, with an increase of more than 5×10^4 km in the last decade (2011–2020) [25]. However, consumption of fuels in the road transportation sector is still 10 times higher than in any other sector.

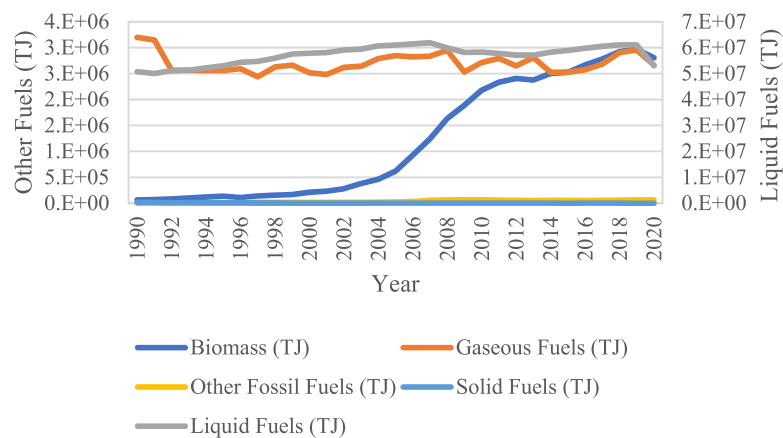


Figure 3: Comparison of temporal trends for different fuel type consumption in Annex I countries.

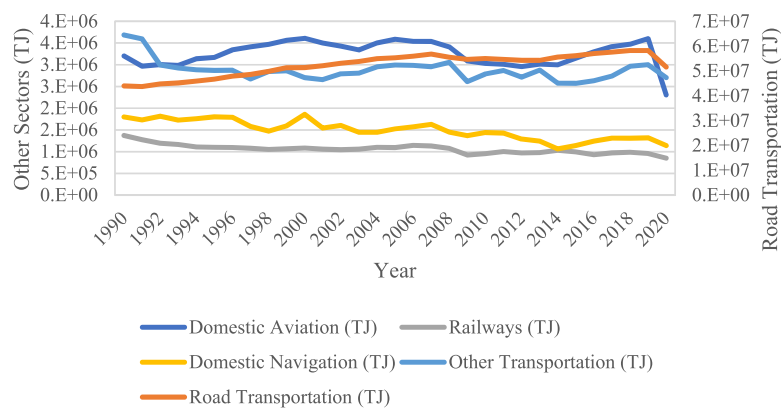


Figure 4: Comparison of temporal trends for different transportation sector consumption in Annex I countries.

Both the consumption of liquid fuel and energy consumption in road transportation show a peak at the start of the century, followed by a slight dip, which seems to recover till 2019. This change in trend around 2005 was a result of dramatic increases in oil prices in that period which is referred to as the “Super-spike”. In that crisis, the International Energy Agency (IEA) advised its member states to implement several fuel-saving strategies [26]. This period also coincided with the development and implementation of renewable energy policies that accelerated the adoption of biomass fuels. All major transportation sectors and energy sources showed another sharp dip near 2020, corresponding with the outbreak of COVID-19 resulting in global and local travel restrictions [27,28]. Owing to the short period after the pandemic, there are no studies that provide definite proof of recovery of fuel consumption trends in the transportation sector. However, there have been studies that indicated some of the impacts of shifts in trends after the pandemic in certain sectors using short-term data. For example, studies have indicated an upward trend in the post-pandemic era in the tourism sector [29]. Another critical change is the increase in work-from-home scenarios which are supposed to decrease the overall transportation energy needs especially in the road transportation sector [30]. But the realization of these trends is still to be analyzed and determined.

The correlation matrix presented in Fig. 5 reveals important relationships between transportation fuel types and their role in replacing the others. Biomass fuel consumption is strongly associated with fossil fuels in transportation. The production of biomass is often carried out within the same processing units where fossil fuels are processed [31] indicating that efficient industrial processes may influence production and use of certain fuel types. The use of solid fuels, such as coal, has been mainly associated with production of electricity which is then used in electric vehicles. This is the reason that it is negatively associated with other types of fuels which are not used in these vehicles [32]. The lower correlations for other types of fuel could indicate that they are being used in different sectors and do not compete or complement each other.

The competing nature of various transportation sectors is more clearly highlighted in the correlation analysis presented in Fig. 6. It clearly shows that road transportation is strongly negatively correlated with railways and navigation. Road transportation is the primary mode for regional and local passenger and freight transport [33] while navigation also serves a major part in international and regional freight transport [34]. However, Fig. 4 has shown that the growth in road transportation exceeds the other modes in all cases. There are also strong correlations between rail transportation with navigation and other modes, which show the integrated support system provided for these modes by the railway systems in the case of freight and energy supply system as the in-land last-mile link [35].

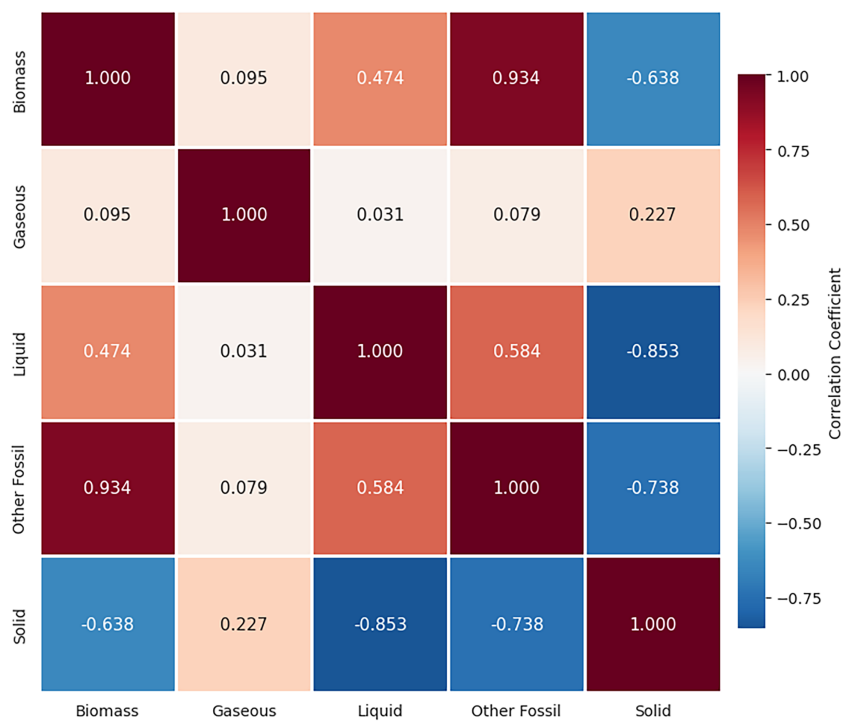


Figure 5: Correlation heatmap for fuel consumption of different types for Annex I countries.

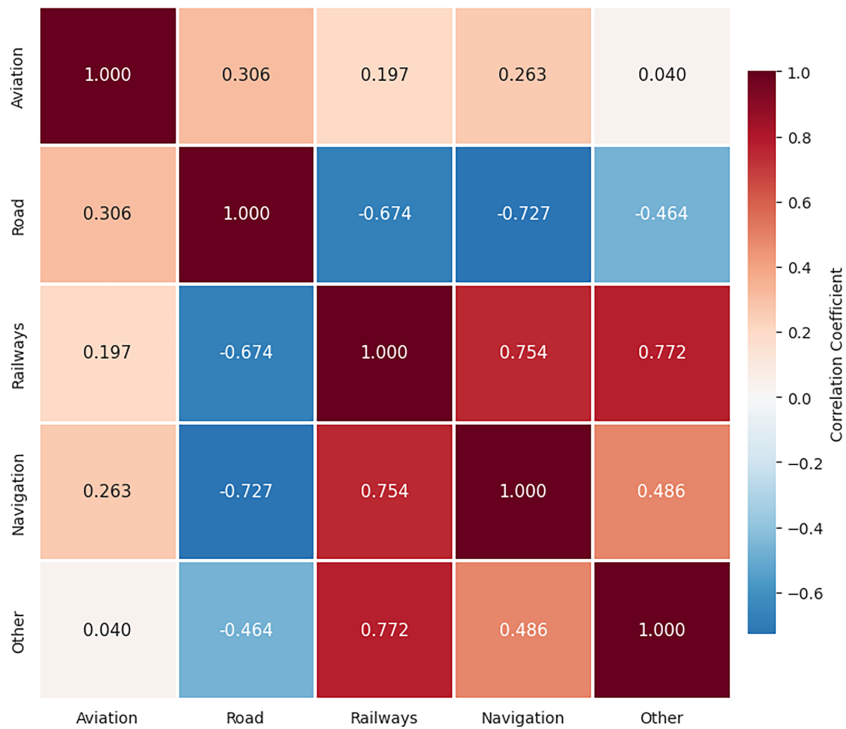


Figure 6: Correlation heatmap for fuel consumption in different transportation sectors for Annex I countries.

The time series analysis of total fuel consumption, liquid fuels, and road transportation shows similar trends with overall upward trends, as shown in Figs. 7–9. In all cases, the variations are also found to be exactly in the same years, providing further evidence of the dominant role of road transportation and its consistent reliance on liquid fuels. The negative growth, shown for some specific years, in this time series has already been explained earlier, including the oil crisis in the mid-2000s and COVID in 2020. The dip in consumption in 1994 can be explained as a lag effect of the Gulf War of 1990–1991 [36].

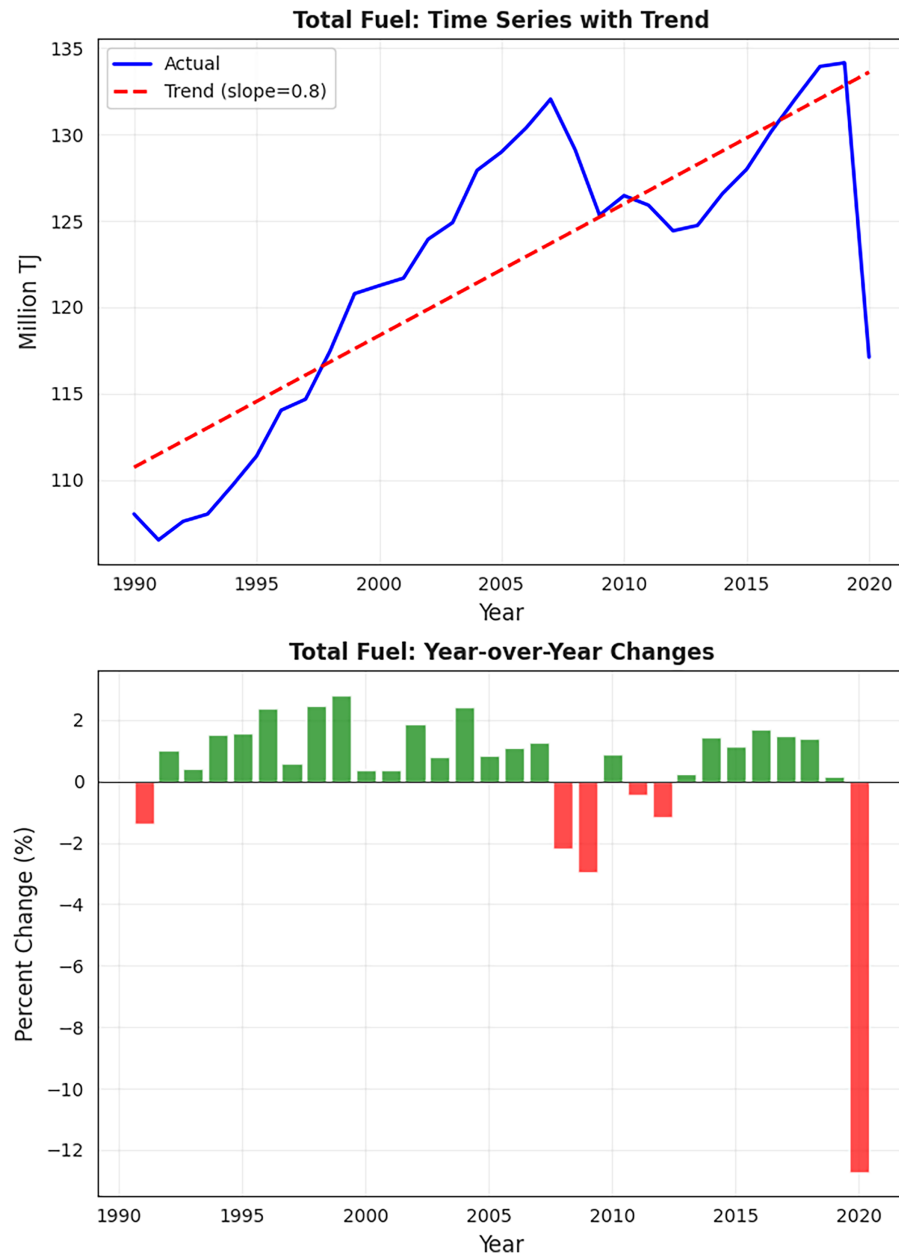


Figure 7: Time series for total fuel consumption in Annex I countries.

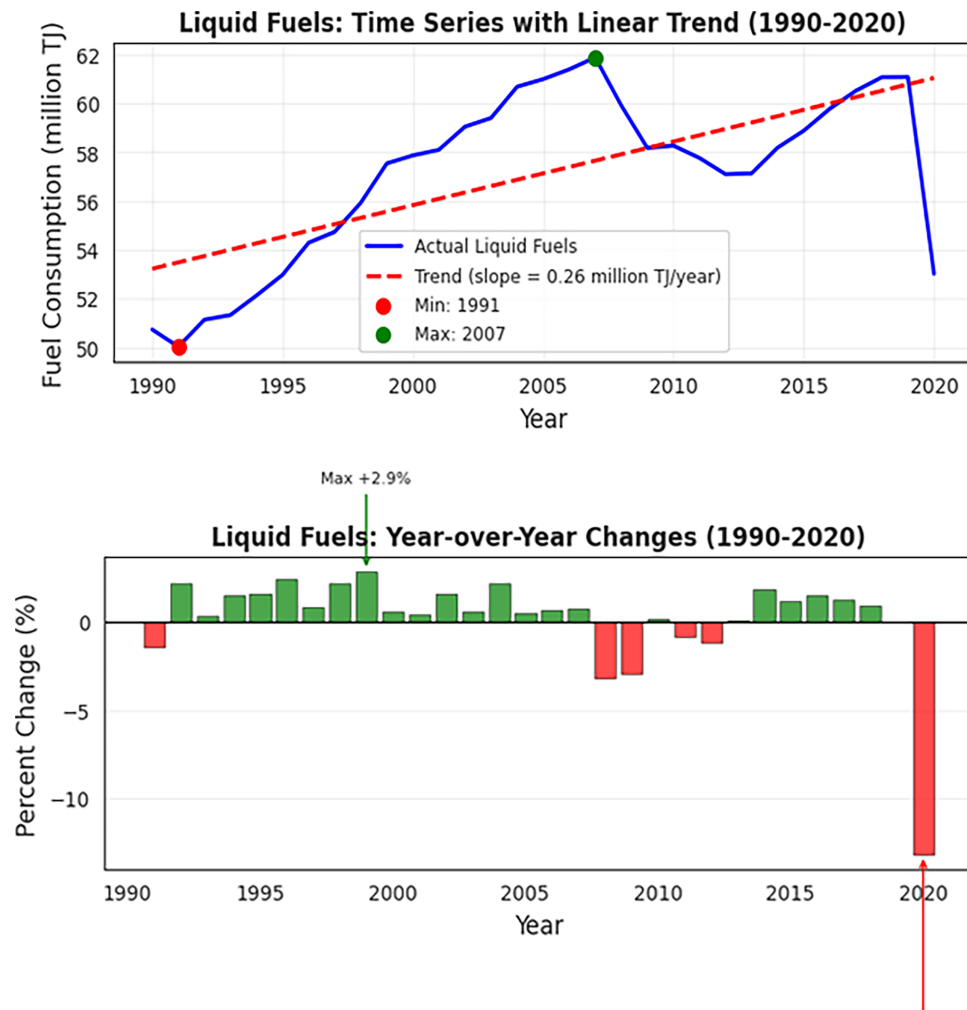


Figure 8: Time series for liquid fuel consumption in Annex I countries.

Table 2 shows that the annual growth in the road transportation sector outperformed the trend for the entire transportation sector. However, the growth in liquid fuel consumption is lower than the overall rate, which shows a positive trend of shifting to alternative fuels in this sector. All these items had non-stationary time series, according to the Augmented Dickey–Fuller (ADF) tests indicate that the behavior and trends of the transportation sector do not exhibit the same nature throughout the study period (1990–2020). This is linked to the many external factors that impact travel demand and its fuel consumption. Some of them are population, economic activities and events, technological changes and shock events, such as COVID and the Gulf War [37,38]. This highlights the importance of continuous long-term monitoring for effects of geopolitical instability and energy market disruptions, making the current study more relevant and pressing in terms of time.

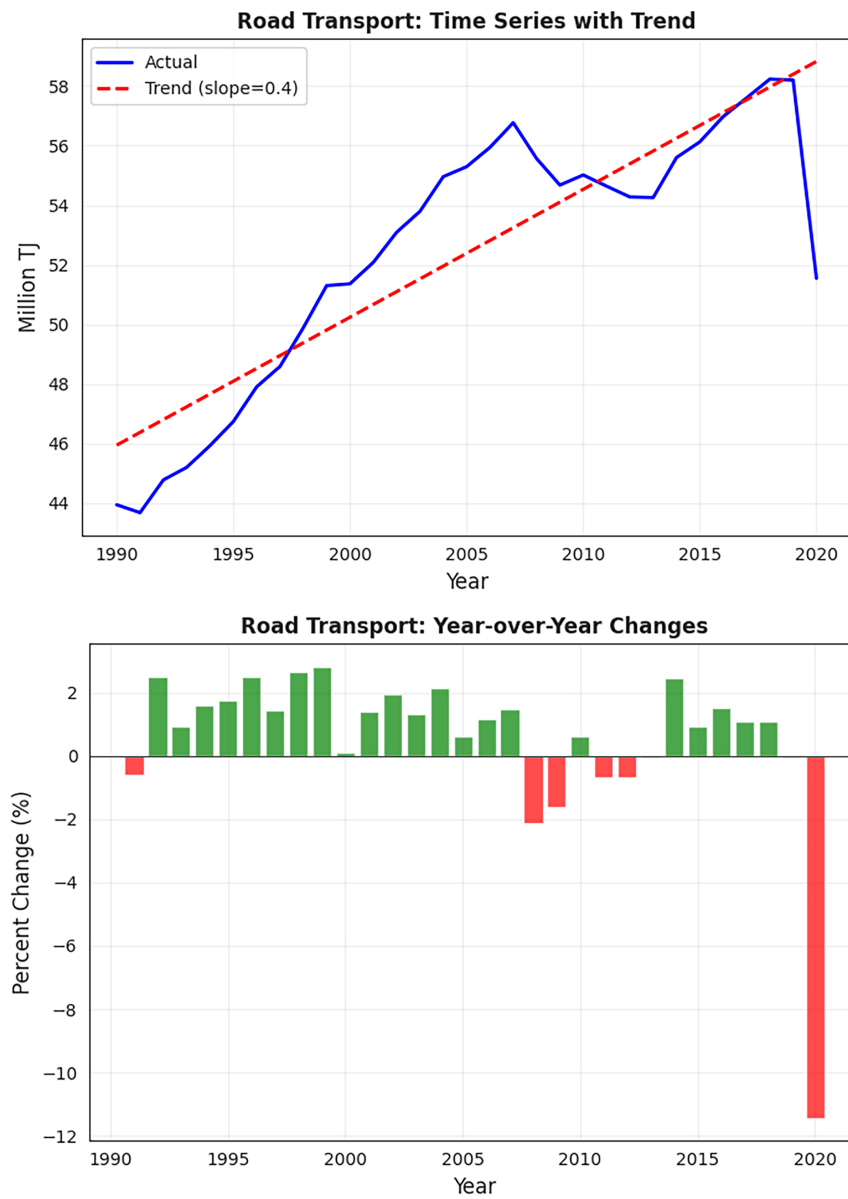


Figure 9: Time series for road transportation sector in Annex I countries.

Table 2: Summary of analysis performed on aggregate fuel consumption patterns in transportation sector in Annex I countries.

Metric	Value
Analysis Period	1990–2020
Number of Countries	44
Number of Years	31
Total Fuel Types	5
Total Transport Sectors	5
Fuel Types Clusters (optimal k)	2 (Liquid fuel and other types)

(Continued)

Table 2 (continued)

Metric	Value
Transport Sectors Clusters (optimal k)	2 (Road transportation and other sectors)
Total Fuel—Annual Growth Rate	0.27%
Road Transport—Annual Growth Rate	0.53%
Liquid Fuels—Annual Growth Rate	0.15%
Total Fuel—Is Stationary?	False
Road Transport—Is Stationary?	False
Liquid Fuels—Is Stationary?	False

3.1.2 Per Capita Consumption

The per capita consumption for Annex I countries within the transportation sector confirmed some of the trends derived from aggregate consumption analysis while providing additional unique insights. The confirmatory trends, as summarized in [Table 3](#), include domination of liquid fuels followed by gaseous and biomass fuels, and heavy consumption in the road transportation sector followed by aviation and navigation. The graphical representation of time series in [Fig. 10](#) also confirms the similarity of trends between aggregate and per capita consumption values. Like aggregate fuel, the time series for total per capita consumption was also found to be non-stationary as per ADF tests, suggesting the impact of external factors. However, several less dominant fuel types—biomass, gaseous fuels, and solid fuels—exhibit stationary behavior. Apart from biomass, other fuel types are being reduced as part of regional and international decarbonization mandates, thus showing a negative growth rate. On the other hand, biomass fuel is promoted by these mandates as a renewable energy source. Therefore, it seems that these policies are maintaining steady progress towards sustainable energy resources.

Table 3: Summary statistics for Per Capita fuel consumption and time series trends in transportation sector of Annex I countries.

Variable	Mean (GJ/Person)	Std. Dev.	Trend Slope	Annual Growth (%)	Total Change (%)	Is Stationary
Total	35.59	1.66	0.093	−0.1	−3.1	FALSE
Biomass	0.69	0.63	0.066	125.8	3895.9	TRUE
Gaseous	1.58	0.13	−0.006	−0.98	−25.6	TRUE
Liquid	33.31	1.58	0.031	−0.23	−6.6	FALSE
Other Fossil	0.02	0.01	0.001	9.66	1488.7	FALSE
Solid	0.003	0.003	−0.0002	−8.72	−93.5	TRUE
Aviation	1.9	0.18	−0.009	−1.45	−35.6	FALSE
Road	30.51	1.81	0.139	0.16	4.9	FALSE
Railways	0.62	0.08	−0.008	−1.96	−44.7	FALSE
Navigation	0.88	0.16	−0.016	−1.88	−43.4	FALSE
Other	0.02	0.01	0.001	9.66	1488.7	FALSE

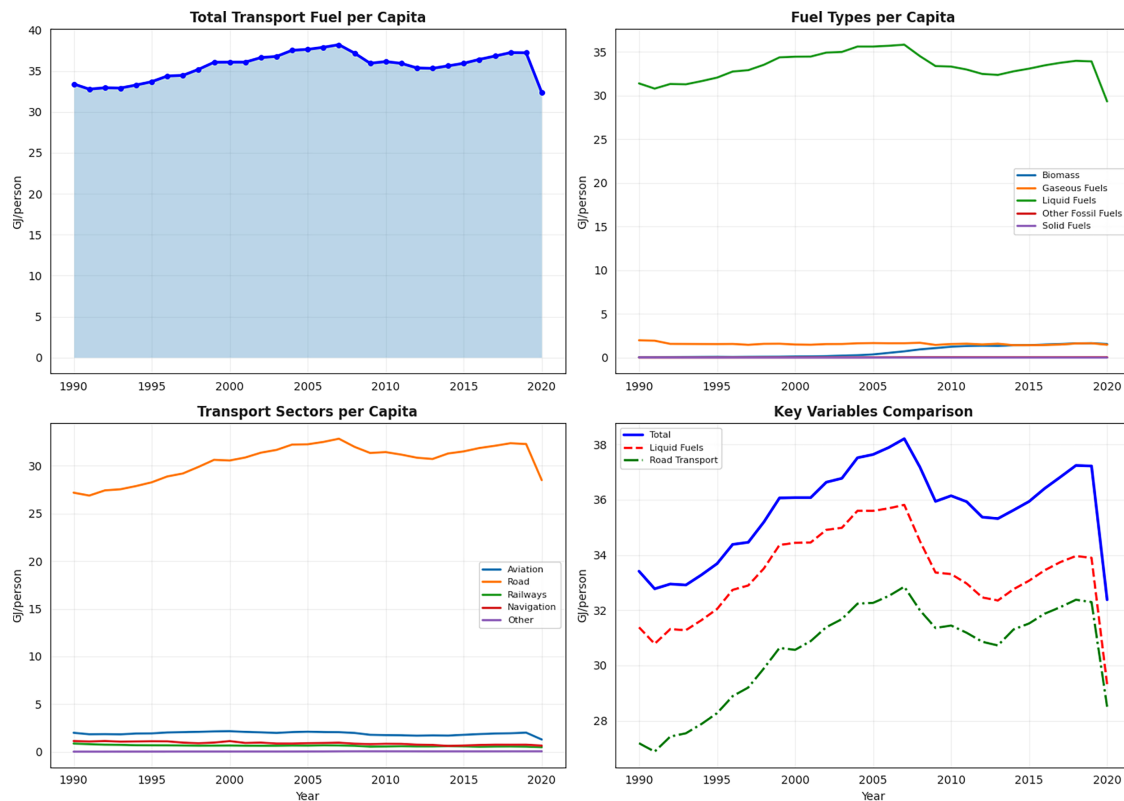


Figure 10: Time series comparison of total fuel, different fuel types and transportation sectors and major Per Capita contributors in Annex I countries. Biomass and other fossil fuel production also appear to be correlated with the normalized per capita values as well, as shown in Fig. 11. The figure also confirms the competing nature of solid fuels with this set of alternative fuels showing strong negative correlations. Unlike aggregate consumption values, the per capita of liquid fuel did not have any strong correlation with other fuel types showing a more robust consumption pattern at the individual level.

Interestingly, several alternative fuel categories, including biomass, gaseous fuels, and solid fuels, display stationary time-series characteristics. A possible reason for this decline could be the use of more efficient engines in the vehicles used for freight transportation, including trucking fleets [39], as well as non-road transportation modes [40]. However, the trends in the road sector, which is mainly operating on liquid fuels, are still showing an increase. So, it can be said that while the efficiency of vehicle technology has its impacts, the increase in vehicle fleet, expansion of road networks, and recurring congestion patterns have overcome any potential advantages of the technology changes related to local passenger travel. In fact, energy-efficient and safer vehicles have been reported to encourage vehicle ownership in some cases, such as in Great Britain [41]. The same has been speculated with autonomous vehicles [42].

The correlations among different transportation sectors (Fig. 11) highlight patterns linked to competing freight transportation systems. On one hand, there is the complementary relationship between navigation and rail, both of which are strongly positively correlated to each other. On the other hand, they are negatively correlated to roads and others which are positively correlated with each other. The first system with shipping and rail combination provides efficient services at a higher cost, consequently higher fuel consumption and emissions. On the other hand, the navigation (shipping) based system is characterized by low financial and environmental costs at the expense of time [43]. Based on these observations, it seems that the system with

road transportation has been gaining popularity among freight transport operators in the last 3 decades. This indicates that business competitiveness is driving the progress of freight transportation instead of sustainability mandates and policies.

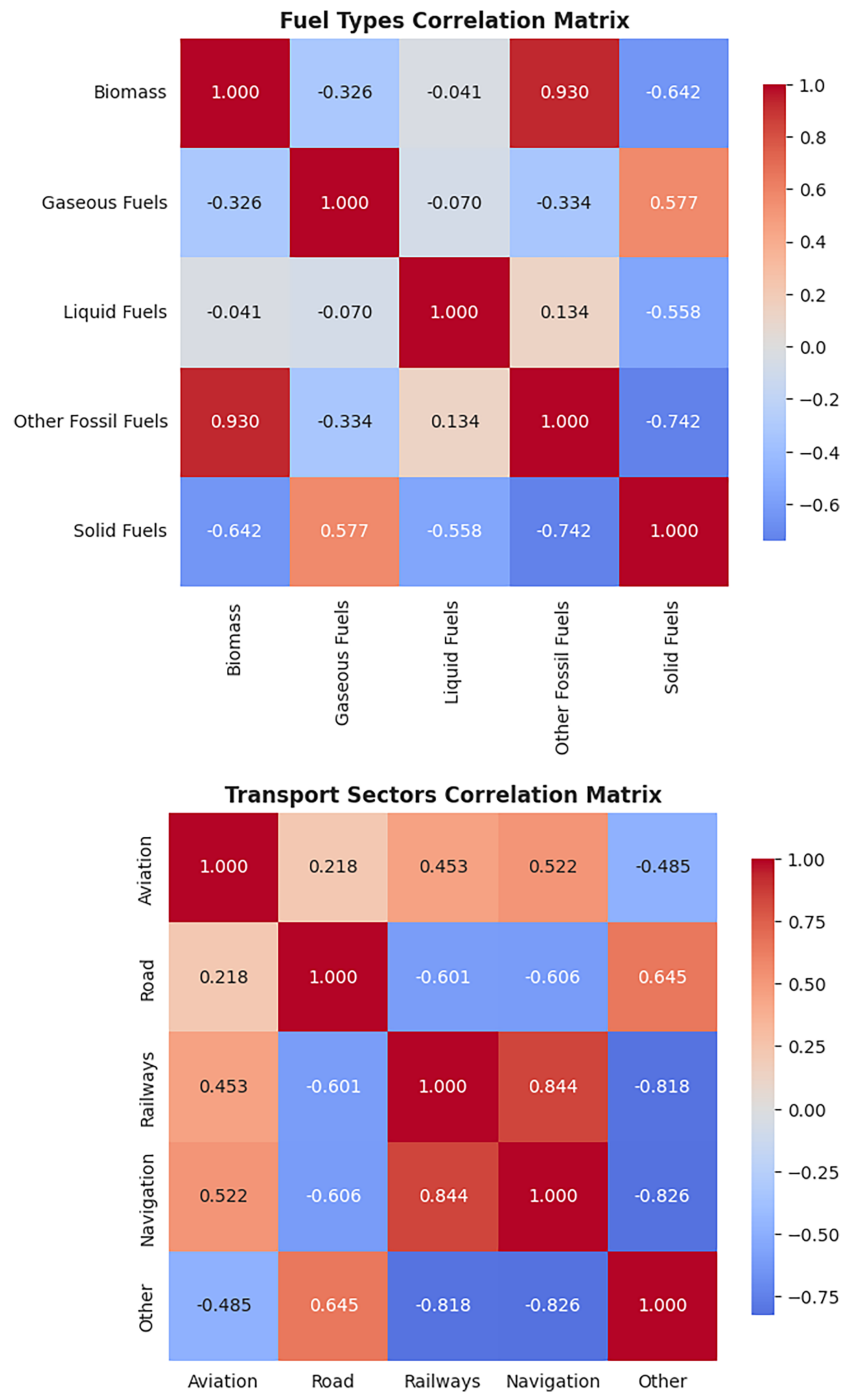


Figure 11: Correlation analysis with Per Capita fuel consumption parameters for Annex I countries.

3.2 Country-Wise Analysis

3.2.1 Clustering with K-Means

The k-means clustering analysis of per capita transportation fuel consumption identified two optimal clusters among the Annex I countries. As mentioned above, the optimal clusters were determined using Elbow and Silhouette score methods, which were applied for a range of 2 to 10 clusters. The Elbow method shows the largest drop in inertia when changing the number of clusters from 2 to 3, making the former the clearest Elbow point. 2 clusters also received the highest Silhouette score of 0.5828, verifying the results of the Elbow method. Among these clusters, one cluster incorporated most of the countries (40) while the other one included only three countries. The latter included Luxembourg, Canada, and the United States of America. Once the clustering was done based on total fuel consumption, ANOVA tests were applied to these clusters to determine the significance of differences in the consumption of different fuel types and transportation sectors between these clusters. Hence, this test highlighted the nuanced parameters that are causing the differences among these clusters.

Table 4 presents the ANOVA test results showing a significant difference in the overall per capita consumption of fuel, indicative of the validity of the clusters. It was found that the clusters were only similar in terms of per capita consumption of other fossil fuels and solid fuels and in the navigation sector. These fuel types have a negligible share in the overall fuel consumption in both clusters, which is shown by their mean values. This observation shows that the decarbonization efforts have been more successful in the reduction of minor fuel types as compared to major fuels. The lack of differences in the navigation sector is due to the reporting mechanism adopted by UNFCCC in which fuel consumption for shipping trips is divided equally among the origin-destination countries. Hence, a country or clusters' characteristics do not directly impact on the fuel consumption in this sector [44]. This issue of reporting results in equal emissions and consumption reporting for a land-locked country (Luxembourg) and countries that have direct sea access.

Despite being in the same cluster, US and Canada have different causes for their over-consumption as compared to Luxembourg. For the US and Canada, these reasons include post-World War II urban sprawl resulting in car dependency [45], historical pattern of low fuel prices without carbon tax [46,47], and weak intercity railway networks despite large land areas [48]. However, the reasons in case of Luxembourg could include cross-border freight traffic which come to refuel due to comparatively lower fuel prices [49], and job attractions [50]. These observations suggest that Luxembourg represents a unique case in which cross-border transportation activity and refueling by non-resident drivers may substantially influence national per capita fuel consumption estimates. Furthermore, biomass industry in the North American context is quite popular due to the national mandates requiring use of renewable fuels and use of Ethanol in gasoline [51]. Similarly, Luxembourg's transportation sector relies extensively on E10 gasoline and B7/B10 diesel, both of which contribute to higher per capita renewable fuel consumption despite the country's relatively small population [52,53].

In case of gaseous fuels, the North American countries of cluster 2 have large reservoirs of natural gas which makes it a locally available cheap source of energy for transportation [54]. The per capita consumption of this fuel is also boosted by the heavy volumes of transit buses, operational vehicles and long-haul trucks [55]. Its use is also encouraged by national policies of tax credits [56]. The same aspect also explains the high per capita consumption of "other" sector which mainly deals with pipelines. US and Canada rely on these pipelines to utilize their natural gas reservoirs [57] while Luxembourg carries important interconnectors and compressor stations for the EU gas pipelines network [58].

Table 4: Inter-cluster ANOVA analysis for Per Capita fuel consumption.

Variable	Cluster 1 Mean	Cluster 1 SD	Cluster 1 Min	Cluster 1 Max	Cluster 2 Mean	Cluster 2 SD	Cluster 2 Min	Cluster 2 Max	Effect Size (η^2)	Significant ($p < 0.05$)
Per_Capita_ Total_GJ	25.2	9.56	8.76	55.78	99.98	35.58	65.75	149.04	0.67	TRUE
Per_Capita_ Biomass_GJ	0.37	0.33	0	1.7	1.77	0.67	0.86	2.44	0.49	TRUE
Per_Capita_Gaseous Fuels_GJ	0.62	1.49	0	8.96	2.7	2.24	0	5.5	0.1	TRUE
Per_Capita_Liquid Fuels_GJ	24.19	9.74	8.5	54.88	95.48	37.09	59.4	146.49	0.64	TRUE
Per_Capita_Other Fossil Fuels_GJ	0.02	0.04	0	0.17	0.04	0.06	0	0.12	0.02	FALSE
Per_Capita_Solid Fuels_GJ	0	0.01	0	0.07	0	0	0	0	0.01	FALSE
Per_Capita_ Aviation_GJ	0.6	0.92	0.01	4.08	3.59	3.12	0.02	7.63	0.28	TRUE
Per_Capita_ Road_GJ	22.81	9.03	7.38	48.27	90.09	42.18	50.54	148.53	0.59	TRUE
Per_Capita_ Railways_GJ	0.38	0.4	0	1.5	1.69	0.93	0.45	2.69	0.34	TRUE
Per_Capita_ Navigation_GJ	0.72	1.17	0	7.03	1.03	0.75	0.04	1.85	0.004	FALSE
Per_Capita_ Other_GJ	0.7	1.64	0	8.96	3.59	3.43	0	8.21	0.14	TRUE

The absence of intercity railway line and a large area increase the aviation fuel consumption dramatically in North American countries. On the other hand, Luxembourg houses Cargolux cargo airline which contributes to its high per capita consumption in aviation sector. However, the freight in the north American countries is carried by non-electrified trains, which is not the case in the countries of cluster 1 [59].

Similar to previous observations, the time series analysis of each of these clusters, presented in Fig. 12, shows that all the per capita fuel consumption patterns are non-stationary. The only exception to this observation is the solid fuels which were found to be consumed in negligible amounts in the transportation sector due to the global decarbonization efforts which also explains the increase in consumption of biomass in both the clusters. The increase in gaseous fuel in case of cluster 1 could be linked to some of the countries in the cluster promoting the use of LPG and propane for vehicles. These countries include Poland, Italy, Turkey, and Japan which adopted this fuel due to the government tax policies resulting in substantial savings for commercial vehicles [60]. Overall, both clusters demonstrate declining compound annual growth rates in transportation fuel consumption, suggesting that improvements in vehicle efficiency and increasing adoption of sustainable transportation modes are beginning to moderate long-term growth [61,62].

In this clustering approach, countries with completely different nature of fuel consumption patterns ended up in the same cluster. Especially, the case of Luxembourg was overly exaggerated due to its small population and influence of incoming drivers. These aspects warranted another trial of clustering through statistical approach which is presented in the following section.

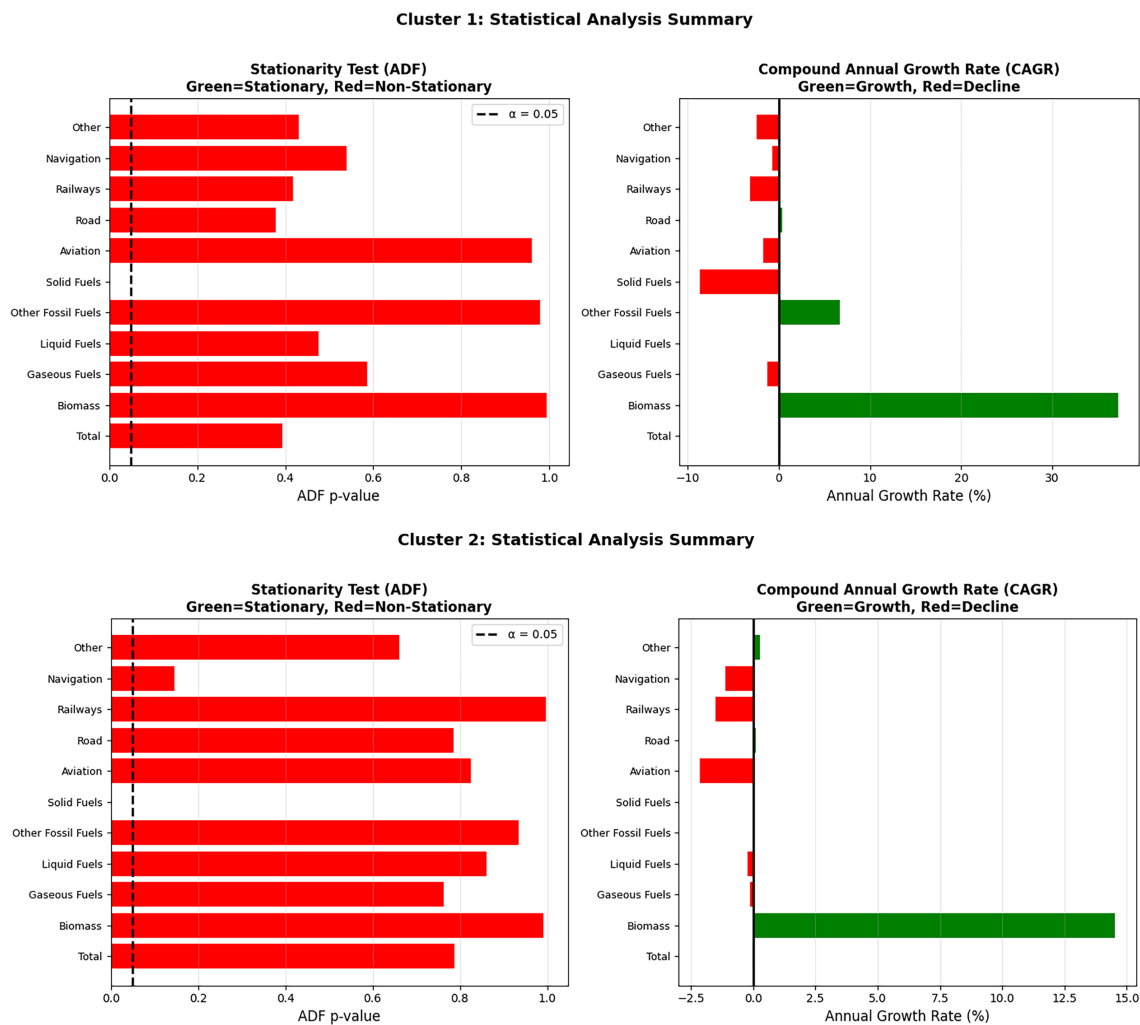


Figure 12: Time series analysis of clusters with k-means clustering for Annex I countries.

3.2.2 Clustering with Kruskal-Wallis Tests

To complement the magnitude-based k-means clustering, distribution-based clustering was performed using pairwise Kruskal–Wallis statistical tests. In this method, the distributions between each pair of Annex-I of countries were statistically compared using Kruskal-Wallis tests and the pairs satisfying the null hypothesis of insignificant differences were put in the same cluster. The optimum number of clusters was left to the natural grouping observed with the pair-wise comparisons.

The statistical clustering approach provided more nuanced insights, than the previous approach, into the different transportation fuel patterns of Annex I countries by dividing them into 9 unique clusters (shown in Fig. 13). The first major difference was the identification of Luxembourg as an outlier which was in its cluster (6) alone with extremely high per capita consumption as shown in Table 5. Considering the above discussion, this is the most plausible scenario for this country. Similarly, this approach also identified other outliers fitted as solitary members of other clusters including the USA (9), Canada (4), Australia (1) and New Zealand (7). Among them, the USA has the highest consumption of per capita fuel after Luxembourg which

could be linked to its large area, high car dependency, lower fuel rates and absence of high-speed rail systems. The lowest per capita consumption is found to be for Türkiye and Romania in cluster 8 which are developing economies and have lower car ownerships than other countries [63].

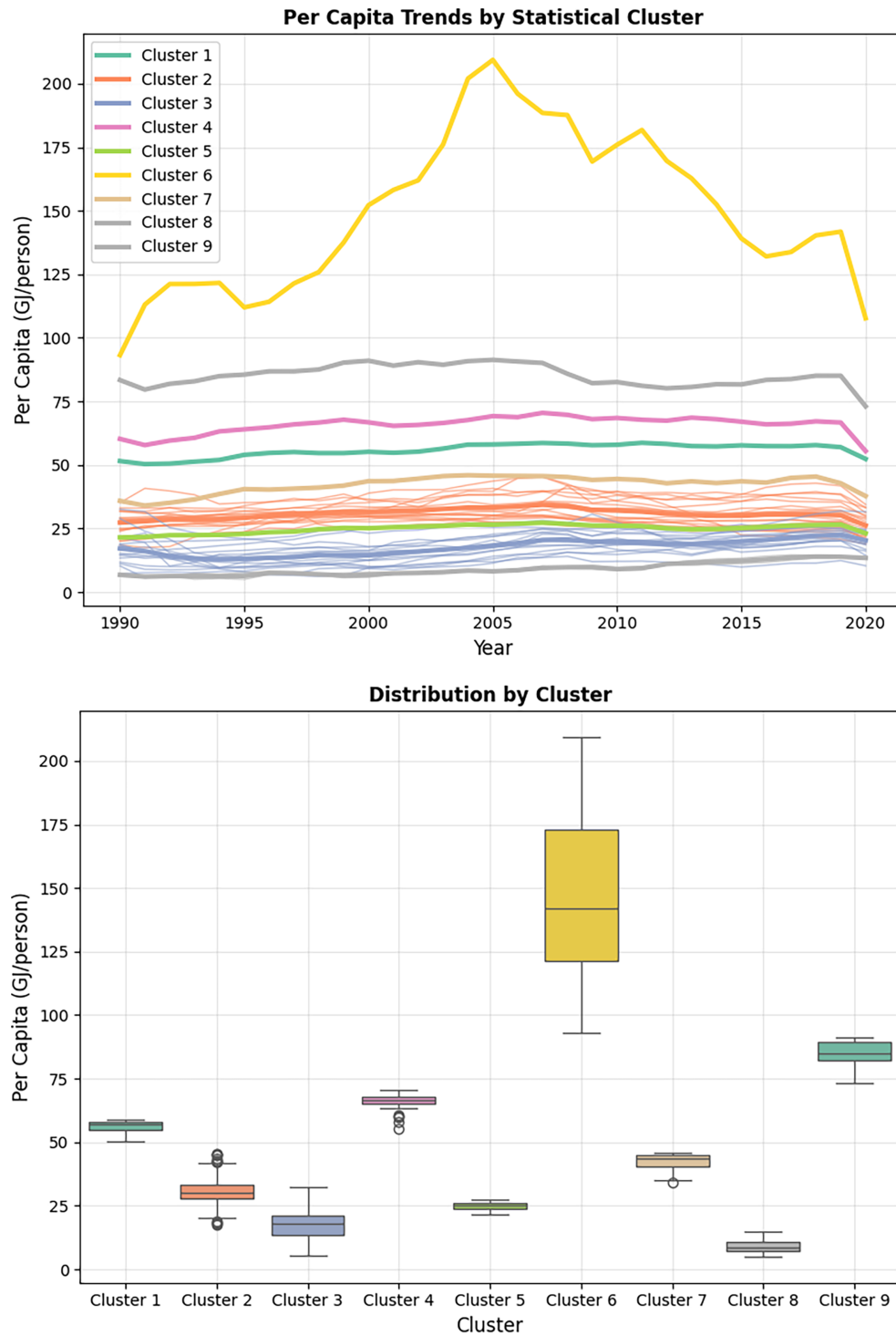


Figure 13: Time series comparison and distribution comparisons of clusters with Kruskal-Wallis tests for Per Capita total fuel consumption among Annex I countries (Details in [Appendix A](#)).

Table 5: Statistical clusters summary.

Cluster	Number_of_Countries	Mean_Per_Capita	Min_Per_Capita	Max_Per_Capita	Countries
1	1	55.77	55.77	55.77	Australia
2	19	30.79	26.55	36.97	Italy, Liechtenstein, Belgium, Slovenia, Finland, Austria, Spain, Switzerland, Denmark, Iceland, Sweden, France, Cyprus, United Kingdom of Great Britain and Northern Ireland, Japan, Ireland, Norway, The Netherlands, Germany
3	16	17.58	12.85	23.25	Lithuania, Ukraine, Latvia, Bulgaria, Malta, Hungary, Estonia, Russian Federation, Greece, Kazakhstan, Belarus, Croatia, Portugal, Slovakia, Czechia, Poland
4	1	65.75	65.75	65.75	Canada
5	1	24.92	24.92	24.92	European Union (Convention)
6	1	149.04	149.04	149.04	Luxembourg
7	1	42.25	42.25	42.25	New Zealand
8	2	9.13	8.75	9.50	Türkiye, Romania
9	1	85.15	85.15	85.15	United States of America

As with the earlier clustering, post-hoc ANOVA tests were performed for these clusters to determine the aspects causing the difference in overall consumption. These are shown in [Table 6](#) which indicate a high effect size (0.98) for the total fuel per capita consumption which is higher than the previous approach (0.67). This indicates that the current approach of clustering can capture the variation in the data at a much higher level. Among the other results, gaseous and solid fuels and navigation sector have negligible differences between clusters. In the consumption of liquid fuels and road transportation, the patterns are similar to total per capita fuel consumption. The US dominates the aviation sector while European countries (EU and Luxembourg) are among those having the lowest contribution in this sector. This can be linked to the large area of the US without high-speed rail connections, while the European countries have a well-established high speed railway network. Countries with higher non-electrified rail freight transportation (the USA and Canada) dominate the railway sector per capita fuel consumption. On the other hand, European countries have largely electrified their railway networks resulting in lower per capita fuel consumption patterns, especially for Western Europe and Japan [64].

Canada dominates the “Other Transportation” sector owing to its role as a major natural gas supplier operating extensive long-distance pipelines [65]. In the case of biofuels, Luxembourg has the highest consumption with its production and use in refueling transit freight transportation. On the other hand, New Zealand has the lowest biofuel consumption due to the absence of any mandate in this regard.

Based on these observations, Western Europe and Japan cluster represents a low consumption benchmark case among Annex I countries, showing favorable trends of declining per capita consumption with higher use of public transportation systems running on electrified systems. The cluster of Türkiye & Romania are also amongst the lowest consuming countries, but it is mainly attributed to their developing economies. Another important point from [Fig. 13](#) is that most of the clusters do not show distinct departure from each

other. However, Kruskal-Wallis tests were still able to differentiate them based on slight differences which further justify their use for insightful objective analysis. The only exception to this point was Luxembourg which shows a sharp increase around 2005. Referring to the fuel crisis around that period, the other European countries adopted higher fuel rates making the refueling options in Luxembourg much more appealing [66]. These results must be interpreted carefully, considering aspects of size of the nation, location, and transit function.

Table 6: ANOVA tests results for comparison between statistical clusters.

Variable	Significant_ $p < 0.05$	Effect_ Size_ EtaSq	Cluster_1 _Mean	Cluster_2 _Mean	Cluster_3 _Mean	Cluster_4 _Mean	Cluster_5 _Mean	Cluster_6 _Mean	Cluster_7 _Mean	Cluster_8 _Mean	Cluster_9 _Mean
Total	TRUE	0.98	55.77	30.79	17.58	65.75	24.92	149.04	42.25	9.13	85.15
Biomass	TRUE	0.72	0.09	0.53	0.22	0.85	0.57	2.43	0.01	0.11	2.01
Gaseous Fuels	FALSE	0.31	0.63	0.22	1.19	5.49	0.29	0	0.27	0.06	2.59
Liquid Fuels	TRUE	0.98	54.88	30.01	16.15	59.39	24.01	146.48	41.94	8.94	80.54
Other Fossil Fuels	TRUE	0.58	0.16	0.02	0.005	0	0.03	0.11	0.01	0	0
Solid Fuels	FALSE	0.09	0.0002	0.001	0.008	0	0.002	0	0	0.002	0
Aviation	TRUE	0.88	4.07	0.61	0.19	3.11	0.45	0.01	3.65	0.36	7.62
Road	TRUE	0.98	48.27	28.65	15.17	50.53	23.43	148.53	36.90	8.26	71.18
Railways	TRUE	0.72	1.49	0.18	0.55	2.688	0.21	0.45	0.52	0.23	1.91
Navigation	FALSE	0.14	1.35	1.07	0.30	1.20	0.57	0.03	1.04	0.21	1.85
Other	TRUE	0.42	0.57	0.27	1.36	8.20	0.25	0	0.13	0.05	2.57

3.2.3 Outlier Analysis

The above analysis points out certain countries as outliers with a vast difference in their per-capita fuel consumption patterns. This observation regarding the outliers was further validated with analysis conducted using Cook's Distance, Mahalanobis Distance, Isolation Forest, and Local Outlier Factor (LOF) methods. The results of this analysis are summarized in Table 7 showing that Australia, North American countries, along with three other countries, are influential at the cluster level with Cook's distance only.

Table 7: Results of outlier analysis.

Category	Countries	Characteristics	Method(s) Flagging
Persistent Consensus Outliers	Australia, Austria, Belarus	Flagged in all years (1990–2020)	LOF + Isolation Forest
Persistent with Influential Status	Australia	Flagged in all years + cluster influence	LOF + Isolation Forest + Cook's Distance
Time-Varying Outliers	Belgium	Outlier 1990–2013; normal 2014–2020	LOF + Isolation Forest (until 2013)
Point-Level Only (Non-Consensus)	Bulgaria, Canada (2007–2020)	Flagged by 1 method only	Isolation Forest (Bulgaria, Canada 2007–2012)
Cluster-Level Influential Only	Canada (1990–2006), Kazakhstan, Norway, Russian Federation, Ukraine, USA	Influential at cluster level; no point-level flags	Cook's Distance only

4 Discussion

This study targets specific research questions about energy consumption trends in the Annex I countries. The subsequent paragraphs provide the answers to these questions with the insights gained from the analysis of the study.

RQ1: What are the long-term trends in transportation fuel consumption among Annex I countries between 1990 and 2020?

Transportation fuel consumption exhibited an overall increasing trend between 1990–2020 has been mostly positive upward trends with few years in between and towards the end showing decline. The first decline was due to the fuel crisis between 2005–2010 while the second one was due to COVID-19. The time series data remains non-stationary for the overall consumption as well as consumption of the main contributory types and sectors showing the impact of external factors on these growth trends. The trends for per capita consumption also follow the same patterns showing that these factors also impact travel behavior and choices whenever a major change happens. It highlights the fact that travelers and traders respond to the changes in situations in more than one way, including reducing or increasing the trips, and changes of mode choice [67].

RQ2: Which fuel types and transportation sectors dominate consumption across these countries?

Road transportation remains the dominant contributor to transportation energy consumption, largely because of its continued dependence on liquid fuels. Consequently, the time series data for the aggregate as well as per capita consumption of total fuel closely resembles the trends of these contributors. The next major contributing sector is aviation. In terms of fuel types, gaseous and biomass are the second and third highest types being consumed in transportation sector. Biomass has gained higher contribution in the industry within the study period which corresponds to local and national mandates of renewable energy consumption, and convenience in its industrial processes coinciding with other fuel types.

RQ3: Are there significant correlations between the temporal trends of different fuel types and transportation sectors?

The correlations between different sectors clearly highlight the competition between two different integrated modes of freight transportation. Wherein, the faster and more environmentally expensive modes of road-driven transportation compete with railway and navigation with the former being opted for more commonly by businesses for better efficiency for their product deliveries. The correlation analysis between fuel types shows the strong correlation between biomass and other fossil fuels which are operationally produced together. On the other hand, it also shows the high substitution relationship of liquid fuels with competing fuel types used in the road sector mainly including biomass. Solid fuels, used in the electrification of vehicles in some countries, also show a negative correlation with other major fuel types.

RQ4: Which Annex I countries exhibit similar per capita consumption levels and temporal trends?

The clustering analysis clearly shows the similarity in trends in the North American region than other parts of the world. Luxembourg represents a unique statistical case because cross-border commuting and international freight activity substantially influence its per capita transportation fuel consumption. The European and some of the industrialized Asian countries showed positive trends with various transportation fuel related parameters attributed to their electrification of high-speed public transportation options. The North American countries, along with Australia and New Zealand, are far behind in this regard and thus having major shares in overall fuel consumption, road transportation, aviation, and liquid and gaseous fuels.

RQ5: What policy implications can be derived from the observed consumption patterns?

The analysis highlighted several key elements which can be used to develop and implement sustainable environmental protocols in Annex I countries. It highlighted the need to focus attention on the dominant liquid fuels and road transportation. It showed that vehicle efficiency is not enough to curtail the growth of these major sectors until travel behavior is changed. The growth trends in the major contributing nations are characterized by urban sprawl, the lack of sustainable high-speed options along with historical trends of lower fuel prices. On the other hand, positive impacts of environmental mandates are shown with continuous growth of biomass and reduction of solid fuels. However, these mandates still do not curtail the major contributors of road transportation and liquid fuels. Hence, greater efforts are required to establish high-speed intercity public transportation networks in addition to those mandates. Future transportation policies should also combine land-use planning, public transportation expansion, travel demand management, and renewable energy transition strategies.

The choices of traders in improving their efficiency using faster modes at the expense of non-renewable energy and emissions is another major issue. Businesses need stricter penalties and greater encouragement to shift to sustainable mode choices as they seem willing to pay the extra financial costs of adopting faster modes. The analysis also highlighted certain reporting issues in the form of fuel used for shipping and by transit modes. The current study was able to detect some of the underlying factors behind the fuel consumption patterns, but a more accurate reporting system would further benefit in this regard.

While the analysis clearly pointed out the dominance of liquid fuels and road transportation, the available UNFCCC database did not provide a continuous time series of the emerging low-carbon transportation fuel pathways. Therefore, the insights remain speculative, and a comparative discussion on the sustainable pathways is being made using the previously studied literature. Firstly, the different pathways and correlations highlight the fact that no single strategy could be sufficient to transform fuel consumption into low-carbon solutions, and a synergistic multi-fuel strategy will be required to tackle the existing issues. In terms of decarbonizing passenger transport, the role of EVs has been greatly emphasized due to their high energy efficiency reported up to 18–20 kWh/100 km [68]. They have also been found to provide economic viability for the public transportation systems making them attractive for governmental interventions [69]. However, their use is associated with other environmental aspects, including the carbon efficiency of the grid system [69,70]. Another issue is the energy density limitation when EVs are used for long-haul heavy-duty transportation tasks [69].

These issues could be covered using hydrogen fuel cells for applications in heavy-duty road, rail, shipping, and aviation [71]. Their economic viability is dependent on infrastructure maturity and can be reduced to a competitive level with the traditional fuel options [69,72]. However, in the current conditions, their cost and energy efficiency are lower than other EVs, and emissions also depend on the green hydrogen production pathways [69]. Apart from alternative fuel technologies, behavioral and policy changes are also important aspects of sustainable transportation pathways, especially in urban areas, with possibilities of micromobility, shared mobility and avoiding travel. The efficiency of these demand management solutions can be further enhanced with the establishment of mobility hubs subject to the balance between substitutions and logistics [73]. In any case, large-scale behavioral and policy changes remain the vital driving force behind the successful adoption of these solutions [74].

The above discussion clearly supports the need for a multi-fuel strategy in which EVs take center stage for the dominant cases of road transportation by replacing liquid fuels. However, the policy interventions to invest in infrastructure to support sustainable pathways with alternative fuels and smart mobility options remain vital for increasing system efficiency and maturity and instigating the required behavioral changes.

5 Limitations of the Study

Despite these contributions, several limitations should be acknowledged. To begin with, the analysis of data was conducted within the range from 1990 to 2020 due to data availability restrictions imposed by the UNFCCC database. As a result, the recent trends in transportation energy post-COVID could not be analyzed properly. This restriction reduces confidence in future expectations and recommendations driven by the conclusions of this study. In addition, there was no socioeconomic data, including GDP, urbanization, prices, and numbers of vehicles included in the analysis. Hence, the causality of the trends had to be approximated by secondary sources which could have been enhanced in the presence of above-mentioned data.

Moreover, the reported fuel consumption data cannot be regarded as representative in some cases, including that for shipping and transit and refueling activities, which may have an impact on the results obtained. This issue is especially pertinent to transit states like Luxembourg. Therefore, further validation with a more accurate data report system would provide better insights for shipping sector and small nations. Another lack in the available data set was regarding the reporting of different types of fuel within the emerging categories which were not available due to their recent adoption. This hampered a more detailed comparison of traditional and sustainable fuel regimes on quantitative basis.

6 Practical Implications

Several practical implications can be derived from the results of this study. First, the prevalence of road transportation and liquid fuel consumption makes it clear that any future efforts aimed at decarbonizing the transportation sector should focus on creating sustainable modes, alternative fuels, and modal switching to rail transportation and public transportation systems. This recommendation is strongly supported by the network optimization models in literature which have demonstrated that such investments in inter-city electrified railway networks can significantly reduce road transportation demand while minimizing overall system costs [75]. Similarly, multi-modal transportation optimization frameworks have also shown energy savings up to 30%–40%, compared to road-only networks, when combined with route optimization algorithms for efficient logistics planning [76]. With the use of these optimization models, rail-based freight transport becomes an optimal solution for medium-to-long distances, while electric road transport shows up as an efficient option for short-haul distribution.

In this respect, the countries in the high-consumption clusters should be urged by the international environmental organizations to adopt greater sustainability measures in transportation sector. These would include inter-city electrified railway networks and promotion of non-motorized modes through planning measures; which have been proven fruitful for other countries as indicated by the clusters. It is further backed up by energy efficiency studies showing a reduction of up to 25% in consumption of transportation fuels with the increase in non-motorized modes and that up to 60% with the use of electric buses [77,78]. These planning measures are expected to be equally viable for high-consumption countries in the North American region with large land areas and current trends of reliance on car. The efficiency could be further increased with the spatial optimization of charging infrastructure and public transport networks. Second, the revealed regional disparities in transportation energy consumption make it necessary to develop differentiated transportation energy policies considering geographical and economic specifics of each country. These policies could focus on fuel efficiency standards, EV adoption targets, and public transit investments tailored to local infrastructure, income levels, and geography rather than a one-size-fits-all approach. In this context, optimization algorithms have proven to be beneficial in balancing competing policy goals and identifying region-specific pathways [79].

Furthermore, the study calls for more precise and accurate international fuel reporting systems concerning cross-border transportation of goods and navigation sectors. In this regard, it is recommended that, for Annex-I countries, the fuel consumption for the shipping sector be divided vis-à-vis the contribution of the countries. Moreover, the fuel consumption for the transit freight trips should also be reported separately. This is crucial for the application of optimization strategies to attain higher accuracies and efficiencies, especially those which have been specifically identified in freight planning studies [80].

7 Conclusions

This study examined transportation fuel consumption trends in Annex I countries from 1990 to 2020 using a multi-method analytical framework. To identify transportation fuel consumption trends for both aggregate and per-capita consumption, diverse statistical methods including descriptive statistics, correlation, time-series, clustering, and ANOVA, were employed.

The analysis highlighted the importance of prioritizing fuel consumption reduction strategies in the road transportation sector, especially for the consumption of liquid fuels. It shows the positive impacts of mandates in the case of biomass and solid fuels, which are outperformed by the growth of the above contributors. The findings provide a detailed evidence base for future transportation energy policies and serve as a reference point for preparedness planning in the context of ongoing geopolitical and economic uncertainty.

This study has several limitations that should be noted. These include the lack of post-pandemic data beyond 2020 and the exclusion of other economic and demographic variables that may influence transportation fuel consumption. Future research should incorporate more recent data and examine additional variables influencing fuel consumption patterns.

Future studies should also incorporate post-2020 transportation data to evaluate long-term impacts of the COVID-19 pandemic, energy market fluctuations, and emerging transportation technologies such as EVs and AVs. In addition, integrating socioeconomic indicators, transportation infrastructure variables, and environmental policy measures could provide a more comprehensive understanding of transportation energy transitions in industrialized economies. The current study uses only K-Means and Kruskal-Wallis based grouping hence future studies may therefore compare these results with other appropriate methods including hierarchical clustering, DBSCAN, Gaussian Mixture Models, or spectral clustering. The study makes use of other time-series methodologies such as ARIMA, SARIMA, Prophet, LSTM, or Temporal Fusion Transformer models that could lead to future projections. Hence, it is recommended that future studies should venture into these aspects, with a larger dataset if possible.

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Availability of Data and Materials: The data used in this study are publicly available from the UNFCCC GHG Data Interface (<https://unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/how-to-find-your-data>).

Ethics Approval: Not applicable. This study used publicly available secondary data and did not involve human participants, animals, or sensitive personal information.

Conflicts of Interest: Given their role as Guest Editors of this journal, Md Kamrul Islam and Uneb Gazder had no involvement in the peer review of this article and had no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to another journal editor. The authors declare there are no other conflicts of interest.

Appendix A Details of Statistical Clusters Time Series Analysis

Variable	Mean_GJ_per_person	Std_Dev	Trend_Slope	Annual_Growth_Percent	Total_Change_Percent	Is_Stationary
Cluster 1						
Total	55.78	2.58	0.20	0.05	1.6	FALSE
Biomass	0.1	12	0.01	N/A	N/A	FALSE
Gaseous Fuels	0.63	0.18	0.01	3.57	186.3	FALSE
Liquid Fuels	54.88	2.41	0.18	0.02	0.5	FALSE
Other Fossil Fuels	0.17	0.12	−0.01	−100	−100	FALSE
Solid Fuels	0	0	0	N/A	N/A	TRUE
Aviation	4.08	0.8	0.07	1.74	67.8	FALSE
Road	48.27	2	0.12	−0.05	−1.4	FALSE
Railways	1.5	0.3	0.02	0.98	33.8	FALSE
Navigation	1.35	0.31	−0.03	−2.05	−46.4	FALSE
Other	0.58	0.16	0.01	2.75	125.5	FALSE
Cluster 2						
Total	30.8	1.94	0.04	−0.14	−4	FALSE
Biomass	0.54	61	0.06	35.44	896,963.7	FALSE
Gaseous Fuels	0.22	0.07	0.007	2.32	98.9	FALSE
Liquid Fuels	30.02	2.09	−0.02	−0.39	−11	FALSE
Other Fossil Fuels	0.02	0.02	0.002	15.58	7595.3	FALSE
Solid Fuels	0	0	0	N/A	N/A	TRUE
Aviation	0.62	0.09	0.006	−2.47	−52.7	FALSE
Road	28.66	1.87	0.06	−0.05	−1.6	FALSE
Railways	0.18	0.04	−0.004	−2.87	−58.3	FALSE
Navigation	1.07	0.09	−0.005	−0.4	−11.4	FALSE
Other	0.27	0.03	−0.002	−1.15	−29.2	FALSE
Cluster 3						
Total	17.59	2.95	0.29	0.56	18.1	FALSE
Biomass	0.22	0.26	0.02	0	inf	FALSE
Gaseous Fuels	1.2	0.23	−0.006	−2.1	−47.1	FALSE
Liquid Fuels	16.16	73	0.27	0.58	19	FALSE
Other Fossil Fuels	0.01	0.01	0.0008	0	inf	FALSE
Solid Fuels	0.01	0.01	−0.0008	−9.12	−94.3	TRUE
Aviation	0.2	0.03	−0.0008	−2.42	−52.1	FALSE
Road	15.17	3.12	0.32	1.15	40.8	FALSE
Railways	0.56	0.18	−0.01	−4.15	−72	FALSE
Navigation	0.3	0.04	−0.0005	−1.22	−30.8	TRUE
Other	1.36	0.27	−0.01	−2.83	−57.7	FALSE
Cluster 4						
Total	65.75	3.51	0.15	−0.28	−7.9	FALSE
Biomass	0.86	0.9	0.09	21.53	34,621	FALSE
Gaseous Fuels	5.5	1.64	−0.13	−0.7	−18.9	TRUE
Liquid Fuels	59.4	3.76	0.19	−0.36	−10.4	FALSE
Other Fossil Fuels	0	0	0	0	0	FALSE
Solid Fuels	0	0	0	0	0	FALSE

(Continued)

(continued)						
Variable	Mean_GJ_per_person	Std_Dev	Trend_Slope	Annual_Growth_Percent	Total_Change_Percent	Is_Stationary
Aviation	3.11	0.35	−0.01	−2.49	−53.1	FALSE
Road	50.54	3.85	0.27	−0.18	−5.4	FALSE
Railways	2.69	0.21	−0.01	−0.97	−25.3	FALSE
Navigation	1.2	0.09	0.005	0.77	26	FALSE
Other	8.21	1.63	−0.10	0.09	2.6	FALSE
Cluster 5						
Total	24.93	1.64	0.11	0.24	7.6	FALSE
Biomass	0.57	0.55	0.05	39.05	1,974,923	FALSE
Gaseous Fuels	0.3	0.06	0.005	1.25	45.3	FALSE
Liquid Fuels	24.02	1.43	0.04	0	0.1	FALSE
Other Fossil Fuels	0.04	0.03	0.002	31.71	387,494.5	FALSE
Solid Fuels	0	0	−0.0003	−10.1	−95.9	TRUE
Aviation	0.46	0.07	−0.0008	−1.53	−37.1	FALSE
Road	23.44	1.68	0.13	0.37	11.6	FALSE
Railways	0.21	0.07	−0.008	−4.14	−71.9	TRUE
Navigation	0.57	0.08	−0.008	−1.12	−28.6	FALSE
Other	0.25	0.04	−0.0005	−0.96	−25.2	FALSE
Cluster 6						
Total	149.04	30.43	1.17	0.48	15.6	FALSE
Biomass	2.44	2.99	0.30	0	inf	FALSE
Gaseous Fuels	0	0	0	0	0	FALSE
Liquid Fuels	146.49	30.64	0.85	0.18	5.5	FALSE
Other Fossil Fuels	0.12	0.14	0.01	0	inf	FALSE
Solid Fuels	0	0	0	0	0	FALSE
Aviation	0.02	0	0.0003	1.13	40.2	FALSE
Road	148.53	30.57	1.20	0.51	16.5	FALSE
Railways	0.45	0.26	−0.02	−5.49	−81.6	FALSE
Navigation	0.04	0.01	−0.0008	−5.28	−80.3	FALSE
Other	0	0	0	0	0	FALSE
Cluster 7						
Total	42.26	3.37	0.22	0.17	5.3	FALSE
Biomass	0.02	0.02	0.001	0	inf	FALSE
Gaseous Fuels	0.28	0.2	−0.01	−5.41	−81.2	TRUE
Liquid Fuels	41.95	3.54	0.23	0.23	7.2	FALSE
Other Fossil Fuels	0.01	0.01	−0.0009	−10.12	−95.9	FALSE
Solid Fuels	0	0	0	0	0	FALSE
Aviation	3.65	0.69	−0.05	−2.37	−51.3	FALSE
Road	36.91	3.37	0.28	0.44	14	FALSE
Railways	0.52	0.12	−0.006	−0.21	−6.1	FALSE
Navigation	1.05	0.23	−0.008	−1.17	−29.7	FALSE
Other	0.13	0.06	0.004	5.51	399.2	FALSE
Cluster 8						
Total	9.13	2.58	0.27	2.3	98	FALSE
Biomass	0.12	0.16	0.01	0	inf	FALSE
Gaseous Fuels	0.06	0.03	0.003	7.4	752.3	TRUE
Liquid Fuels	8.95	2.41	0.25	2.16	89.9	FALSE
Other Fossil Fuels	0	0	0	0	0	FALSE
Solid Fuels	0	0.01	−0.0005	−100	−100	TRUE

(Continued)

(continued)						
Variable	Mean_GJ_per_person	Std_Dev	Trend_Slope	Annual_Growth_Percent	Total_Change_Percent	Is_Stationary
Aviation	0.37	0.13	0.006	1.98	80.1	FALSE
Road	8.26	2.62	0.27	2.55	112.9	FALSE
Railways	0.23	0.08	−0.006	−1.27	−31.9	FALSE
Navigation	0.21	0.08	−0.006	−3.03	−60.2	FALSE
Other	0.06	0.03	0.002	1.95	78.6	FALSE
Cluster 9						
Total	85.15	4.25	−0.14	−0.44	−12.4	FALSE
Biomass	2.01	1.68	0.17	9.62	1474	FALSE
Gaseous Fuels	2.6	0.33	0.007	0.7	23.4	FALSE
Liquid Fuels	80.54	5.47	−0.33	−0.67	−18.2	FALSE
Other Fossil Fuels	0	0	0	0	0	FALSE
Solid Fuels	0	0	0	0	0	FALSE
Aviation	7.63	1.04	−0.09	−2.02	−45.8	FALSE
Road	71.19	3.48	0.002	−0.26	−7.4	FALSE
Railways	1.91	0.23	−0.01	−1.38	−34.1	FALSE
Navigation	1.85	0.52	0.04	−2.55	−54	FALSE
Other	2.57	0.33	0.006	0.66	22	FALSE

Note: N/A indicates that the percent-change metric (Annual_Growth_Percent or Total_Change_Percent) is mathematically undefined because the baseline value (Mean_GJ_per_person) is zero or near-zero for that variable/cluster.

References

1. Song MJ, Seo YJ, Lee HY. The dynamic relationship between industrialization, urbanization, CO₂ emissions, and transportation modes in Korea: empirical evidence from maritime and air transport. *Transportation*. 2023;50(6):2111–37. doi:10.1007/s11116-022-10303-x.
2. Pietzcker RC, Longden T, Chen W, Fu S, Kriegl E, Kyle P, et al. Long-term transport energy demand and climate policy: alternative visions on transport decarbonization in energy-economy models. *Energy*. 2014;64:95–108. doi:10.1016/j.energy.2013.08.059.
3. Schipper L, Ting M, Khrushch M, Golove W. The evolution of carbon dioxide emissions from energy use in industrialized countries: an end-use analysis. *Energy Policy*. 1997;25(7–9):651–72. doi:10.1016/S0301-4215(97)00058-X.
4. Wright SJ, Sietsma A, Korswagen S, Athanasiadis IN, Biesbroek R. How do countries frame climate change? A global comparison of adaptation and mitigation in UNFCCC National Communications. *Reg Environ Change*. 2023;23(4):129. doi:10.1007/s10113-023-02113-3.
5. Andrés L, Padilla E. Driving factors of GHG emissions in the EU transport activity. *Transp Policy*. 2018;61:60–74. doi:10.1016/j.tranpol.2017.10.008.
6. Ott J. Input-output based decomposition analysis to evaluate the drivers of resource efficiency in countries with higher and lower levels of development [master's thesis]. Graz, Austria: University of Graz; 2022.
7. De Luca G, Pizzolante F. Time series clustering from road transport CO₂ emission. *Int J Environ Stud*. 2024;81(4):1563–78. doi:10.1080/00207233.2023.2174741.
8. Abdallah K, Belloumi M, De Wolf D. Indicators for sustainable energy development: a multivariate cointegration and causality analysis from Tunisian road transport sector. *Renew Sustain Energy Rev*. 2013;25:34–43. doi:10.1016/j.rser.2013.03.066.
9. Alsabbagh M. Toward carbon-neutral road transportation in the GCC countries: an analysis of energy consumption and CO₂ emissions. *Manage Environ Qual Int J*. 2025;36(2):446–69. doi:10.1108/meq-07-2024-0269.

10. Batur İ, Bayram IS, Koc M. Impact assessment of supply-side and demand-side policies on energy consumption and CO₂ emissions from urban passenger transportation: the case of Istanbul. *J Clean Prod.* 2019;219:391–410. doi:10.1016/j.jclepro.2019.02.064.
11. Çatik AN, İlhan A, Akdeniz C. Testing the environmental Kuznets curve hypothesis in the transport sector for OECD countries: a dynamic panel threshold approach. *Environ Sci Pollut Res.* 2024;31(4):6372–84. doi:10.1007/s11356-023-31468-7.
12. Lin X, Jiang Z, Pang J, Pi C. Research on the sustainable spatio-temporal evolution and driving factors of global transportation carbon emissions: evidence from a panel of 140 countries, 1971–2018. *Sustainability.* 2025;17(16):1–28. doi:10.3390/su17167175.
13. Righi M, Ehrenberger S, Brinkop S, Hendricks J, Hellekes J, Banyś P, et al. The ELK global emission inventory for the transport sectors. *Earth Syst Sci Data.* 2026;18(2):1619–64. doi:10.5194/essd-18-1619-2026.
14. Thomas H, Carmona Aparicio LG, Creutzig F, Hara T, Hayashi A, Ludovique C, et al. Models and methods for transport demand and decarbonisation: a review. *Environ Res Lett.* 2024;19(9):093005. doi:10.1088/1748-9326/ad6b3a.
15. Yan L, Zhang Q, Zheng B, He K. Modeling fuel-, vehicle-type-, and age-specific CO₂ emissions from global on-road vehicles in 1970–2020. *Earth Syst Sci Data.* 2024;16(10):4497–509. doi:10.5194/essd-16-4497-2024.
16. Dickey DA, Fuller WA. Distribution of the estimators for autoregressive time series with a unit root. *J Am Stat Assoc.* 1979;74(366):427–31. doi:10.1080/01621459.1979.10482531.
17. Thorndike RL. Who belongs in the family? *Psychometrika.* 1953;18(4):267–76. doi:10.1007/bf02289263.
18. Rousseeuw PJ. Silhouettes: a graphical aid to the interpretation and validation of cluster analysis. *J Comput Appl Math.* 1987;20:53–65. doi:10.1016/0377-0427(87)90125-7.
19. Cleophas TJ, Zwinderman AH. Non-parametric tests for three or more samples (Friedman and Kruskal-Wallis). In: *Clinical data analysis on a pocket calculator: understanding the scientific methods of statistical reasoning and hypothesis testing.* Cham, Switzerland: Springer; 2016. p. 193–7. doi:10.1007/978-3-319-27104-0_34.
20. Khan MZA, Ali Khan H, Ravi SS, Turner JW, Aziz M. Potential of clean liquid fuels in decarbonizing transportation: an overlooked net-zero pathway? *Renew Sustain Energy Rev.* 2023;183:113483. doi:10.1016/j.rser.2023.113483.
21. Singh D, Dadhich J, Bhadoriya Y, Taneja S. A review on the prospects of various gaseous fuel as an automotive fuel and for reducing environmental pollution. *Evergreen.* 2023;10(4):2661–74. doi:10.5109/7160925.
22. Ali F, Dawood A, Hussain A, Alnasir MH, Khan MA, Butt TM, et al. Fueling the future: biomass applications for green and sustainable energy. *Discover Sustain.* 2024;5(1):156. doi:10.1007/s43621-024-00309-z.
23. Millinger M, Reichenberg L, Hedenus F, Berndes G, Zeyen E, Brown T. Are biofuel mandates cost-effective? An analysis of transport fuels and biomass usage to achieve emissions targets in the European energy system. *Appl Energy.* 2022;326:120016. doi:10.1016/j.apenergy.2022.120016.
24. Kölker K, Bießlich P, Lütjens K. From passenger growth to aircraft movements. *J Air Transp Manage.* 2016;56:99–106. doi:10.1016/j.jairtraman.2016.04.021.
25. Wang G, Cheng Q, Zhao W, Liao Q, Zhang H. Review on the transport capacity management of oil and gas pipeline network: challenges and opportunities of future pipeline transport. *Energy Strategy Rev.* 2022;43:100933. doi:10.1016/j.esr.2022.100933.
26. International Energy Agency (IEA). Saving oil in a hurry [Internet]. Paris, France: IEA; 2005 [cited 2026 Jul 27]. Available from: <https://www.iea.org/reports/saving-oil-in-a-hurry-2005>.
27. Kikstra JS, Vinca A, Lovat F, Boza-Kiss B, van Ruijven B, Wilson C, et al. Climate mitigation scenarios with persistent COVID-19-related energy demand changes. *Nat Energy.* 2021;6(12):1114–23. doi:10.1038/s41560-021-00904-8.
28. Mogaji E, Adekunle I, Aririguzoh S, Oginni A. Dealing with impact of COVID-19 on transportation in a developing country: insights and policy recommendations. *Transp Policy.* 2022;116:304–14. doi:10.1016/j.tranpol.2021.12.002.
29. Haque MR. From disruption to recovery: a multi-country analysis of tourism and hospitality firms' performance post-COVID-19. *Tour Recreat Res.* 2025;50(5):1062–73. doi:10.1080/02508281.2024.2372969.

30. Navaratnam S, Jayalath A, Lu A. Effects of working from home on greenhouse gas emissions and the associated energy costs in six Australian Cities. *Buildings*. 2022;12(4):463. doi:10.3390/buildings12040463.
31. de Paula Leite AC, Pimentel LM, de Almeida Monteiro L. Influence of renewable energy trends on fossil fuel refining operations. *Biofuels Bioprod Bioref*. 2026;20(1):201–18. doi:10.1002/bbb.70062.
32. Mittal V, Shah R, Huq N. The future of coal as a transportation fuel. *Energy Environ*. 2022;33(7):1265–78. doi:10.1177/0958305x211037973.
33. Aguilera A, Grébert J. Passenger transport mode share in cities: exploration of actual and future trends with a worldwide survey. *Int J Automot Technol Manage*. 2014;14(3–4):203. doi:10.1504/ijatm.2014.065290.
34. de Souza FLU, Larranaga AM, Palma D, Pitombo CS. Modeling travel mode choice and characterizing freight transport in a Brazilian context. *Transp Lett*. 2022;14(9):983–96. doi:10.1080/19427867.2021.1976011.
35. Paulauskas V, Henesey L, Plačienė B, Jonkus M, Paulauskas D, Barzdžiukas R, et al. Optimizing transportation between sea ports and regions by road transport and rail and inland waterway transport means including “last mile” solutions. *Appl Sci*. 2022;12(20):10652. doi:10.3390/app122010652.
36. Lieber RJ. Oil and power after the 1991 Gulf War. In: *The Iraqi aggression against Kuwait*. London, UK: Routledge; 2019. p. 153–75. doi:10.4324/9780429312007-9.
37. Mwale M, Luke R, Pisa N. Factors that affect travel behaviour in developing cities: a methodological review. *Transp Res Interdiscip Perspect*. 2022;16:100683. doi:10.1016/j.trip.2022.100683.
38. Milesi-Ferretti GM. The travel shock. *IMF Econ Rev*. 2024;72(4):1502–19. doi:10.1057/s41308-023-00224-9.
39. Vyas AD, Patel DM, Bertram KM. Transportation energy futures series: potential for energy efficiency improvement beyond the light-duty-vehicle sector. Argonne, IL, USA: Argonne National Laboratory; 2013 [cited 2026 Jul 27]. Available from: <https://scispace.com/pdf/transportation-energy-futures-series-potential-for-energy-klv7c7xmpr.pdf>.
40. Balazadeh Meresht N, Moghadasi S, Munshi S, Shahbakhti M, McTaggart-Cowan G. Advances in vehicle and powertrain efficiency of long-haul commercial vehicles: a review. *Energies*. 2023;16(19):6809. doi:10.3390/en16196809.
41. Craglia M, Cullen J. Do vehicle efficiency improvements lead to energy savings? The rebound effect in Great Britain. *Energy Econ*. 2020;88:104775. doi:10.1016/j.eneco.2020.104775.
42. Othman K. Exploring the implications of autonomous vehicles: a comprehensive review. *Innov Infrastruct Solut*. 2022;7(2):165. doi:10.1007/s41062-022-00763-6.
43. Bilgili L. Operational greenhouse gas emissions of air, rail, road, and sea transport modes in life cycle perspective. In: *Transportation energy and dynamics*. Singapore, Singapore: Springer; 2023. p. 343–52. doi:10.1007/978-981-99-2150-8_14.
44. Selin H, Zhang Y, Dunn R, Selin NE, Lau AKH. Mitigation of CO₂ emissions from international shipping through national allocation. *Environ Res Lett*. 2021;16(4):045009. doi:10.1088/1748-9326/abec02.
45. Lewyn ME. Sprawl in Canada and the United States. *Urban Lawyer*. 2012;44(1):85–133. doi:10.2139/ssrn.2103999.
46. Metcalf GE. On the economics of a carbon tax for the United States. *Brook Pap Econ Act*. 2019;2019(1):405–84. doi:10.1353/eca.2019.0005.
47. Winter J. Carbon pricing in a federal state: the case of Canada. *ifo DICE Rep*. 2020;18(01):13–9.
48. Powell N. Urban rapid rail transit system intermodality: identifying themes in urban public transit within Canada and the United States [dissertation]. Montreal, QC, Canada: Concordia University; 2023 [cited 2026 Jul 27]. Available from: <https://spectrum.library.concordia.ca/id/eprint/992258/>.
49. ODYSSEE-MURE. Border trade or fuel tourism [Internet]. Paris, France: Odyssee-MURE; [cited 2026 Jul 14]. Available from: <https://www.odyssee-mure.eu/faq/result/40/>.
50. Kudashev R. Cross-border commuting, tax, congestion and job search in the Greater Region of Luxembourg: a perspective from quantitative spatial economics [dissertation]. Luxembourg City, Luxembourg: Université du Luxembourg; 2025 [cited 2026 Jul 27]. Available from: <https://hdl.handle.net/10993/66178>.
51. Johnson C, Moriarty K, Alleman T, Santini D. History of ethanol fuel adoption in the United States: Policy, economics, and logistics. Golden, CO, USA: National Renewable Energy Laboratory; 2021. Report No.: NREL/TP-5400-76260. [cited 2026 Jul 27]. Available from: <https://afdc.energy.gov/files/u/publication/76260.pdf>.

52. Domagała J, Kadłubek M. Economic, energy and environmental efficiency of road freight transportation sector in the EU. *Energies*. 2023;16(1):461. doi:10.3390/en16010461.
53. Cendon OV. Decarbonisation of heavy-duty road transport in Europe [master's thesis]. Delft, The Netherlands: TU Delft; 2024 [cited 2026 Jul 29]. Available from: <https://hal.science/hal-03836284v1/document>.
54. Shirazi M, Ghasemi A, Šimurina J. The impact of the North American shale gas technology on the US' energy security: the case of natural gas. *Int J Sustain Energy*. 2022;41(7):810–31. doi:10.1080/14786451.2021.1979002.
55. Sharafian A, Asaee SR, Herrera OE, Mérida W. Policy implications of liquefied natural gas use in heavy-duty vehicles: examples in Canada and British Columbia. *Transp Res Part D Transp Environ*. 2019;69:123–40. doi:10.1016/j.trd.2019.01.021.
56. Lin N, Xu L. Navigating the implementation of tax credits for natural-gas-based low-carbon-intensity hydrogen projects. *Energies*. 2024;17(7):1604. doi:10.3390/en17071604.
57. INGAA Foundation. 2025 North American midstream infrastructure report. Washington, DC, USA: INGAA Foundation; 2026 [cited 2026 Jul 27]. Available from: <https://ingaa.org/foundation/resources/ingaa-foundation-report-outlines-midstream-buildout-needed-through-2052/>.
58. Liuhto K. Natural gas in the EU in the twenty-first century: a special emphasis on LNG. In: *The future of energy consumption, security and natural gas: LNG in the Baltic Sea Region*. Cham, Switzerland: Springer; 2022. p. 21–60. doi:10.1007/978-3-030-80367-4_2.
59. Mandegari M, Ebadian M, Saddler JJ. Decarbonizing North America's rail sector, international initiatives and local opportunities. *Transp Res Interdiscip Perspect*. 2023;21:100859. doi:10.1016/j.trip.2023.100859.
60. Kivevele T, Raja T, Pirouzfard V, Waluyo B, Setiyo M. LPG-fueled vehicles: an overview of technology and market trend. *Automot Exp*. 2020;3(1):6–19. doi:10.31603/ae.v3i1.3334.
61. Lovins AB. Reframing automotive fuel efficiency. *SAE Int J Sustain Transp Energy Environ Policy*. 2020;1(1):59–84. doi:10.4271/13-01-01-0004.
62. Batool T, Ross V, Van Blerk J, Neven A, Dendale P, Janssens D, et al. Promoting sustainable transportation: a transtheoretical examination of active transport modes. *Sustainability*. 2024;16(2):472. doi:10.3390/su16020472.
63. Ceylan H, Baskan O, Ozan C. Modeling and forecasting car ownership based on socio-economic and demographic indicators in Turkey. *TeMA J Land Use Mobil Environ*. 2018;47–66. doi:10.6092/1970-9870/5452.
64. Montero J, Finger M. Railway regulation: a comparative analysis of a diverging reality. In: *Handbook on railway regulation*. Cheltenham, UK: Edward Elgar Publishing; 2020. p. 1–20. doi:10.4337/9781789901788.00005.
65. Antonanzas J, Quinn JC. Regional greenhouse gas analysis of compressor drivers in natural gas transmission systems in Canada. *J Clean Prod*. 2023;400:136671. doi:10.1016/j.jclepro.2023.136671.
66. Schipper L. Automobile use, fuel economy and CO₂ emissions in industrialized countries: encouraging trends through 2008? *Transp Policy*. 2011;18(2):358–72. doi:10.1016/j.tranpol.2010.10.011.
67. Wang Z, Sun Y, Zeng Y, Wang B. Substitution effect or complementation effect for bicycle travel choice preference and other transportation availability: evidence from US large-scale shared bicycle travel behaviour data. *J Clean Prod*. 2018;194:406–15. doi:10.1016/j.jclepro.2018.04.233.
68. Kochanek A, Załona T, Pietrucha I, Petryk A, Ziemiańczyk U, Basak Z, et al. Renewable energy integration in sustainable transport: a review of emerging propulsion technologies and energy transition mechanisms. *Energies*. 2025;18(24):6610. doi:10.3390/en18246610.
69. Chong JW, Hanafiah MM. Life cycle externalities and abatement costs of public transport electrification using fuel cell and battery electric buses in Putrajaya city. *Sci Rep*. 2026;16(1):15312. doi:10.1038/s41598-026-46665-w.
70. Antczak D, Porta F. Beyond operational emissions: LCA of passenger transport modes for short-distance travel. *J Air Transp Manage*. 2026;135:103008. doi:10.1016/j.jairtraman.2026.103008.
71. Zhou R, Fulton L. Comparative analysis of global transportation/energy models: methodologies, scenarios and policy implications. *UC Davis Res Rep*. 2025:1–48. doi:10.7922/G2KS6PZM.
72. Pukazhselvan D, Sandhya KS, Fagg DP, Blaabjerg F. The future of clean transportation: hydrogen, batteries, ammonia, and green methane in perspective. *Renew Sustain Energy Rev*. 2026;226:116286. doi:10.1016/j.rser.2025.116286.

73. Torabi Kachousangi F, Kreutzberger E, van Oort N, van Binsbergen A, Hoogendoorn S. Emerging transport modes and mobility hubs: a review of their impacts on CO₂ emissions. *Front Sustain Cities*. 2026;8:1685930. doi:10.3389/frsc.2026.1685930.
74. Sang Y, Zhang Z, Liu S, Song C. Decarbonization pathways in the transport sector: a review of integrated assessment models and future directions for model improvement. *Renew Sustain Energy Rev*. 2026;225:116204. doi:10.1016/j.rser.2025.116204.
75. Li C, Feng J, Li X, Chen Z, Zhang Z, Qu D, et al. Progress in transportation electrification in China: perspectives from electric vehicles and electrified railways. *IEEE Electr Mag*. 2025;13(3):17–27. doi:10.1109/MELE.2025.3590670.
76. Truvolo M. Sustainable solutions for freight transport optimization [master's thesis]. Genoa, Italy: University of Genoa; 2025 [cited 2026 Jul 27]. Available from: https://tesidottorato.depositolegale.it/bitstream/20.500.14242/200937/4/phdunige_5388109.pdf.
77. Kenworthy JR, Svensson H. Exploring the energy saving potential in private, public and non-motorized transport for ten Swedish Cities. *Sustainability*. 2022;14(2):954. doi:10.3390/su14020954.
78. Borén S. Electric buses' sustainability effects, noise, energy use, and costs. *Int J Sustain Transp*. 2020;14(12):956–71. doi:10.1080/15568318.2019.1666324.
79. Su J, Dong S. Multi-objective optimization for dynamic logistics scheduling based on hierarchical deep reinforcement learning. *Sci Rep*. 2025;15(1):33544. doi:10.1038/s41598-025-18309-y.
80. Sustainable freight planning: building smarter and greener logistics [Internet]. Linbis Logistics Software; 2025 [cited 2026 Jul 27]. Available from: <https://www.linbis.com/general/sustainable-freight-planning/>.