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Analysis of Transport-Related Carbon Emissions

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Abstract: The transport industry is still among the most expanding contributors of greenhouse gases in the world with about 23 percent of the total anthropogenic carbon dioxide being emitted by the transport sector with close to 8Gt of CO 2 being emitted each year. The paper will give an extensive discussion of carbon emissions due to transport, modal contribution, and methodology of estimating the emission as well as mitigation methods. As it can be seen, road transport is the leading source of emission, and heavy-duty vehicles make the greatest contribution, despite comprising a small share of the world fleet. More recent innovations in methodology, such as machine learning applications and spatial econometric models have increased the accuracy of emissions estimation and made it possible to implement more specific policy interventions. The paper compares strategies of technological improvement and structural avoid and shift and concludes that the existing complex decarbonisation efforts need to entail vehicle electrification, mode shifting, and demand management as sequential efforts. Results suggest that although electrification has a high potential in emissions reductions, to reach the net-zero transport systems by the middle of the century, combined methods involving technological development and systemic organisational shifts are required.

Keywords: *Transport Emissions, Carbon Intensity, Modal Shift, Decarbonization, Sustainable Freight.*

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I. INTRODUCTION

The transport sector also holds a central role in the global climate change mitigation processes as a major contributor to emissions, as well as an area where the emission rates are constantly increasing despite the technological progress. The Transition Pathway Initiative reported that the transport sector emitted almost 810 GtCO 2 in 2022, or about 22 of all energy-related CO 2 emissions worldwide. This trend means that transport is incompatible with the goals of the Paris Agreement since emissions of the sector have been growing on average by about 2 per cent each year since 1990, a rate outpacing that of any other end-use sector.

The ongoing rise in transport emissions is attributed to various factors which are not independent of each other; rising demand in passenger and freight transport, rising travel distances, infrastructure lock-in towards systems that depend on roads, and the ongoing reliance on fossil fuels. In the wider transport industry, freight transport poses decarbonisation problems. The direct CO 2 emissions produced by global freight transport are estimated to be around 3.2Gt each year or over 40 percent of the total transport emissions as well as approximately 10 percent of all the global CO 2 emissions. Such numbers become even more important when one considers the long-term projections, with the world freight demand being predicted to grow by about two times by 2050.

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The allocation of emissions by the transport modes introduces significant discrepancies that have significant degrees of policy implications. The sectoral emissions are dominated by road transport, which is the greatest contributor with the heavy-duty vehicles contributing disproportionately. Across the world, heavy-duty vehicles make up a small percentage of the vehicles but consume a significant portion of fuel consumption and greenhouse gas emissions because of their energy-intensive activities. The heavy-duty vehicles in the European Union represent more than 25 percent of the road transport related greenhouse gas emissions and over 6 percent of the total GHG output in the EU. Likewise, in the United States, heavy-duty trucks contribute about 20 percent to the overall fuel consumption, indicating their inordinate use of energy in freight transportation.

In this paper, the systematic discussion of transport-related carbon emissions is attempted, focusing especially on how the methods of emissions estimation can be used, the characteristics of emission intensity by modes and regions, and the set of strategies that can be used to decarbonise. The analysis summarises some of the more recent empirical studies and policy initiatives to find successful avenues to low-carbon transport systems.

II. TRENDS & PATTERNS IN TRANSPORT EMISSIONS

➢ *Global and Regional Emission Trajectories*

The transport emissions have significant geographical variation, which is seen in terms of economic development, infrastructure endowment, modal structure and policy regimes. Greenhouse gas emissions in transport increased in Europe by 18 per cent in the period 1990 to 2023 excluding international transport, with the increase mainly because of increased road traffic. Road transport emissions grew by 22 percent between this period, and air transport emissions grew by 16 percent. In contrast, other modes showed a significant decrease in the emissions, including a reduction of 74 per cent in the emissions of rail transport and 28 per cent in the emissions of maritime transport.

With international transport included in the model, the emissions curve would change significantly, and overall transport-induced GHG emissions would rise by a quarter of 2023 relative to 1990 when international aviation and maritime transportation are both considered. The air and sea traffic in the international transport has been increasing much faster than domestic transport by 125 and 21 percent respectively.The internal differentiation in Europe is very strong. Whereas certain member states have recorded emission cuts such as Germany with a cut in emissions of 11 per cent and Sweden with a cut of 30 per cent, others have registered drastic increases. The increase in emissions of transport in Poland was the highest with a growth of 229 percent in 1990 to 2023, followed by Ireland and Spain with 129 and 50 percent respectively. These inequalities are indicators of divergent economic paths, investments in infrastructures and policies.

The transportation system of China being one of the largest emitters of carbon in the world has a significant influence on the trends in the world. In the Chinese setting, freight industry contributes a portion of 75-percent of the total transport carbon emissions making it central to transport carbon cuts. Between the year 2005 and the year 2023, the carbon intensity of transport declined substantially across certain Chinese provinces as Beijing and Tianjin experienced lessening of 22.94 and 75.49 respectively. Nevertheless, the freight carbon intensity in other provinces like Hebei and Gansu had spiked over 65-percent within the same period. Nevertheless, the general freight carbon intensity in China declined by an estimated 25.69% in the last fifteen years due to improvement in mode and technology of freight transportation.

➢ *Modal Contributions and Intensity of Emission*

The share of various forms of transport in total emissions is quite different according to the factors of emissions, the intensity of activities, and energy sources. Table 1 shows a comparison of freight modes of transport emission intensities in relation to the amount of energy used in a unit activity.

Table 1 Comparative Efficiency of Freight Transport Modes

Mode	Distance per Gallon (ton-miles)	Cost per ton-km (USD)	Relative CO2 Intensity
Barge	576	0.01	Lowest
Rail	413	0.04	Low
Truck (Diesel)	155	0.12	High

The efficiency differentials in Table 1 imply a lot of implications regarding emissions. It will take one ton of freight, in one gallon of fuel to move 576 miles by barge, 413 miles by rail, but only 155 miles by truck. Barge transportation to cover a distance that is more than 1000 kilometres is at a cost of about 0.01 per ton-kilometre, rail transportation has a cost of 0.04 and a diesel truck transportation cost 0.12 per ton-kilometre. Road freight therefore has not only contributed to a disproportionate emission of CO 2 worldwide freight, but also low-cost efficiency as compared to rail and waterborne freight.

The above-mentioned benefits of efficiency notwithstanding, road freight has been recording a growing market share within the major economies. The proportion of the total ton - kilometre distance served by road freight increased in China (by 110 per cent) and in the United States (by 16 per cent) and in the European Union (by 24 per cent) between 2008 and 2023, and thus represents a modal shift to more carbon-intensive means of transport at the expense of rail and inland waterway means of transport.

The express logistics sector, driven by rapid expansion in online retailing, exemplifies emerging emission sources. In China's Yangtze River Delta region, a study utilizing over 1.2

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million origin-destination road express logistics records estimated total carbon emissions from road express logistics at 44,268.1 tons annually. Nationally, China's express delivery sector emitted over 55 million tons of carbon equivalent in 2022. The logistics industry contributes approximately 9% to China's overall carbon emissions, with transportation and distribution activities accounting for about 85% of these emissions.

III. METHODOLOGICAL APPROACHES TO EMISSIONS ANALYSIS

➢ *Estimation Techniques: Bottom-Up and Top-Down Approaches*

The estimation of carbon emissions in the transport sector is based on two major methodological classes; top-down and bottom- top. Top-down solutions are based on macro-level information, involving aggregate energy use rates in transportation, warehousing and other similar areas as a proxy of transport energy use as a way of estimating carbon emissions. The methodology has become much popular due to the availability of national energy statistics and provides benefits in making the same cross-national comparisons and analysing trends over time.

In contrast, bottom-up methods, have emission estimates based on disaggregated activities data, and they combine data on vehicle activity, fuel consumption rates, and emission factors. The improved bottom-up methodology can be formulated as follows:

- *Equation 1: Bottom-up Carbon Emissions Calculation*

$$CE_{ij} = \sum_i \sum_j (FC_{ij} \times EF_j)$$

In which CEij is a value that describes carbon emissions of vehicles of type i using energy source j, FCij is a value that describes the fuel consumption, and EFj is the figure that is attributed to the energy source j. In more detailed specifications fuel properties are included:

$$EF_j = NCV_j \times CC_j \times O_j$$

The net calorific value of energy source, the carbon content per unit calorific value, and the oxidation rate are denoted as NCV j, CC j and O j respectively in this equation.

More recent efforts have used bottom-up estimation techniques to incorporate lower levels of operational data; a study of port-based heavy-duty vehicles in India found that the real levels of CO_2 emissions in the dynamic operation conditions were significantly higher than estimates done in the lab, highlighting the need to bring the issue of operational heterogeneity to the point of emissions inventories.

Table 2 Comparison of Emission Estimation Methodologies

Method	Data Requirements	Advantages	Limitations
Top-Down	Aggregate fuel consumption	Data availability, comparability	Limited spatial/tempo-ral resolution
Bottom-Up	Activity data, emission factors	Higher precision, process understanding	Data intensive, coverage gaps
Machine Learning	Multiple predictor variables	Captures non-linear relationships, high accuracy	Black-box nature, interpretability challenges
Spatial Econometric	Geocoded flow data	Accounts for spatial autocorrelation	Complex implement-ation

➢ *Advanced Methods of Analytics*

The modern studies of transport emissions are also characterized using modern analytical methods to overcome the shortcomings of the traditional methods. The predictive power of machine learning techniques has shown higher accuracy in carbon emission forecasting due to the ability to capture such complex and non-linear predictive relationships between emission determinants. Comparative literature suggests that eXtreme Gradient Boosting (XGBoost) has greater predictive power than the traditional regression model and other assemblies and offers up to a 46 per cent increase in R2, and a greater than 80 per cent decrease in estimation error.

Researchers have embraced explainable artificial intelligence (XAI) frameworks to address the interpretability issues brought by machine learning black-box models. SHapley Additive exPlanations (SHAP) provides the ability to quantify the contribution of a feature to making predictions by a model, which leads to increased interpretability without sacrificing predictive accuracy. This will enable the researchers to determine the effect of input variables on the accuracy of prediction and the most significant determinant of emission intensity under the operating conditions of the real world.

The other methodological development is spatial econometric methods, which would be useful in analysis of the emissions that are spatially dependent and heterogeneous. Geographically and temporally weighted regression (GTWR) model has been used to find applicability in studying spatial and temporal heterogeneity in the impacts of freight structure on changes in carbon intensity. The spatial autocorrelation of carbon emission intensity has been studied using spatial econometric interaction models (SEIM) to establish the spatial patterns and factors that influence carbon emission intensity in the outflow cities, inflow cities, and the origin-destination city pairs.

One of the recent developments, the ELK global emission inventory, is the most consistent bottom-up modelling of land transport, shipping, and aviation, offerings

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of emissions. This inventory has several strengths compared to the current datasets, such as direct determination of the subsector-level of the emissions, the use of transport-specific amounts and emission species, and determination of transport-related emissions of the energy sectors. The data is supplemented with quantitative uncertainty scores based on a comprehensive analysis of the expert-judgment along the modelling chain, starting with the activity data to emission factors.

IV. DETERMINANTS OF TRANSPORT CARBON INTENSITY

➢ *Structural Factors*

Freight structure the distribution of freight activity among transport modes is a key determinant of the carbon intensity. Extended STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) models of carbon emission intensity are empirically analysed with significant findings that freight structure is a significant influence on carbon emission intensity with significant spatial and temporal variation in these effects. The pattern of modal shares and the intensity of emissions itself is non-linear, implying that small shifts in freight structure generate differentiation in emissions effects based on a baseline of the situation and the local nature.

In China, a study has shown that a 1 per cent increase in the share of rail freight as compared to road freight is associated with a decrease in freight carbon intensity of about 0.3-0.5 per cent though this percentage differs significantly across the provinces depending on the economic structure, topography and the available infrastructure. This result can be corroborated by the physical efficiency differentials reported in Table 1 and policy to encourage modal shift.

Industrial structure has an indirect, yet large impact on transport emissions via its impact on freight demand characteristics. Those regions that have more of secondary industry value/added to Gross Domestic Product are more likely to have high freight carbon intensity, implying the intensity of material and transport necessities of manufacturing compared to services. The structure of the industrial output such type of goods as bulk commodities, intermediate goods, and finished products affects the magnitude of freight movement and the appropriateness of various means of transport.

➢ *Technological and Operational Factors*

Technology of vehicles is a key factor of the intensity of emissions as large differences exist among vehicles of various types, fuels and age categories. Freight transportation which involves the use of heavy diesel-powered trucks releases around 2.6kg of CO_2 per litre of fuel consumed. The European Council and Parliament have proposed required standards of CO_2 emission performance of new heavy-duty vehicles, with an obligation of a 15 percent average fleet emissions reduction as of 2025 at a 2019 benchmark, and more ambitious targets of 2030 and 2035.

Operational determinants which include driver behaviour, road topography and load characteristics have an appreciable effect on emissions which are seen in actual transport operations. Research that uses explainable artificial intelligence (XAI) methods have proven that micro-operational patterns that exist under conditions of realistic operation have gone through a relatively small amount of examination, and thus substantive gaps in the accuracy of the emissions estimation.

The operational environments are dynamic in nature and include congestion, gradient changes, and acceleration regimes that produce the emission levels that are significantly higher compared to the emission levels predicted by standardized laboratory test cycles. Empirical studies support the fact that such dynamic variables are having a disproportional contribution to total emissions compared to their contribution in traditional testing procedures.

Digitalisation has become a increasingly topical aspect of the impact on transport emissions, but its influence is also complex and situation specific. A review of the priority logistic activities in China indicates that a 1 per cent rise in digitalisation level does correlate with a 2.326 per cent rise in carbon emission intensity. This correlation implies that the development of e-commerce and digitally facilitated logistics could increase emissions through a higher volume of freight and higher service expectations. There is spatial heterogeneity to the correlation between digitalisation and emissions, and different effects of the outbound and inbound city are of divergent impacts depending on the local conditions.

➢ *Economic and Policy Factors*

The desired level of economic development and its effects on transport emissions are numerous due to the presence of various mechanisms such as aggregate freight demand, modal allocation, and technological innovations diffusion. Freight carbon intensity is positively related to per capita gross domestic product (GDP) to some extent; it may also lead to a decline in the interactions beyond these levels, as economies move to service-intensive and higher-value, lower-bulk products. This non-linear quality of this relationship carries significant consequences regarding the emission trends in the developing economies.

The intensity of emissions is affected significantly by infrastructure development because it determines the relative utility of alternative forms of transportation. Greater infrastructure development in outbound and inbound cities is associated with reduced carbon emission intensity, which can be explained by the fact that it regulates more efficient routing, congestion reduction, and modal shifts. The investments in rail and waterways infrastructure increases the number of modal alternatives within which freight can be moved.

Consumer influences are determined by the income levels of the residents on emission patterns. Comparative studies have suggested that a higher level of resident income in cities where outbound traffic is related to lower carbon

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emission intensity, which may represent a shift towards lower-material intensity consumption patterns or high-value goods able to absorb increased transport cost per unit. This correlation is important and provides the importance of consumption-based solutions to emissions accounts and mitigation.

V. MITIGATION STRATEGIES AND POLICY PATHWAY

➢ *Improve Strategies: Technological Solutions*

Fig 1 Electric Vehicle Charging Point Supporting Transport Electrification

The objective of technological improvement strategies is to reduce the intensity of the emission in the transport activities without necessarily changing either the demand structures or modal split. The most important enhancement strategy is vehicle electrification, and there is an almost unanimous agreement that passenger on-road vehicles will be predominantly electrified to operate on electric propulsion in net-zero emissions conditions. In the case of heavier transport modes, the range of solutions decarbonisation can take is wider and includes greater use of liquid biofuels and hydrogen.

A study conducted by the European Commission concerning the application of the Emissions Trading System (ETS) Phase 2 determines several best-practice actions to decarbonise the road freight. Financial incentives on charging infrastructure, which are imposed in Germany, Spain, France and Italy, help lessen the high capital cost of installing depot and public charging stations which in turn increase the viability of an electric fleet shift to operators. Reduced administrative processes to connect to a grid as exhibited in the Netherlands and the United Kingdom will greatly decrease the time delays in the installation of charging infrastructure.

Changes in Germany have been introduced to the Euro vignette tolls and exemptions on zero-emission trucks: kilometre-based tolls imposed on these trucks are reduced, which makes the ownership of zero-emission trucks cheaper and the business case of owning zero-emission trucks more favourable. Public charging price transparency, based on the Alternative Fuels Infrastructure Regulation (AFIR) will not only guarantee a level of fair competition but will also provide consumers with more confidence in the charging market.

The model intercomparison literature on the net-zero emissions futures suggests that transport sector will have the biggest role to play in the demand-side emission reduction, mainly through the technology substitution. There is however a limited role of modal shifting and decreases in the utilisation of personal cars as it can be modelled within the context of the United States, with technological solutions being of the key issue in which structural changes are more impeded.

➢ *Avoid and Shift Strategies: Structural Approaches*

Prevention and diversion strategies aim to achieve the reduction of transport demand and promote the use of lower-carbon modes, and thus reduce the structural causes of emissions, but not only its technological intensity. Such plans include reduction of unneeded freight demand with the help of circular economy plans, reduction of supply chains, and the repositioning of the freight flows to rail and water transportation. Such structural changes have not gotten as much policy attention as technological improvements despite their potential.

The Deep Decarbonisation Pathways network research determines four principal organisational changes in the freight decarbonisation: (1) circular production and consumption patterns development to reduce unnecessary freight demand; (2) localisation of goods production to lower the number of kilometres travelled; (3) the creation of inland waterway, coastal shipping, rail freight, and related infrastructure integrated with an industrial organisation; and (4) the modification of consumption, production, and logistic patterns to make the non-road logistics services more appealing.

The potential reduction of emissions of modal shift is high. An experiment that estimated the effect of the replacement of a quarter of long-haul truck freight with rail in the United States estimated the reduction of 13.1 million tonnes of greenhouse gases per year. CO 2 emitted by road-rail or road-waterway intermodal routes can be up to 30-60 percent lower than the amount emitted by truck-only transport, and in certain cases cost reductions of 20-40 have also been achieved.

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Table 3 Emissions Reduction Potential of Mitigation Strategies

Category	Measure	Reduction Potential	Timeline
Improve	Vehicle electrification	80%	Medium-long
Improve	Fuel efficiency	15-30%/vehicle	Near-medium
Shift	Mode shift	30-60%/shipment	Medium
Shift	Intermodal opt.	30-60% + cost↓	Near-medium
Avoid	Supply chains	Variable	Long
Avoid	Circular economy	25% demand↓	Long

China has set targets of 25% and 9% of ton km craters in rail and inland waterways respectively in 2035, as opposed to 16% and 9% in 2022. The European Union Transport 2050 Strategy targets to move 30 per cent of road freight longer than 300 km to rail or waterborne transport by 2030 (50 per cent by 2050) and cut emissions by 290 million tonnes of CO 2 by 2050. Other areas developing modal shift policies are India, with the National Rail Plan, Japan, with its Eco Rail Mark programme and Brazil with its National Logistics Plan 2035.

➢ *Integrated Policy Frameworks*

A thorough transport decarbonisation strategy needs to involve the co-ordinated policy frameworks to balance between the improvement, avoid and shift strategies considering regional situations and co-benefits. Historically, the international collaboration on freight decarbonisation has been focusing on the improvement strategies, on the deployment of zero-emission vehicles and fuelling infrastructure. Programs like the Road Transport Breakthrough bring governments, corporations and researchers together to fasten the electrification process, including batteries, charging infrastructure and trade conditions.

However, the successful achievement of the avoid and shift transformations relies on the national efforts and is capable of being triggered by the increased international collaboration. The main areas of cooperation involve sharing experience about the national policies, international technical assistance programmes, international financing conditions, and international legal instruments, as regards production, trade, and transport.

The SCF process in the European Union distributes funds to Member States in a way that enables them to develop policies that can ease decarbonisation on the one hand and at the same time mitigate the social consequences of the same. With the partial realization of ETS2 in 2027, the lesson of stakeholder consultations is that policy makers need to bring operational realities on board when designing the policies. Inclusion of logistics industry in policy formulation helps in making sure that the act is not only feasible but also effective and that the economic competitiveness is not compromised.

Future research priorities in the development of transport decarbonisation include continued research on the development of on-road electrification, the use of biofuels and hydrogen in heavier travel modes, and the possibility to shift towards modal and travel-behaviour change to facilitate decarbonisation on national and regional levels. These dynamics are vital in understanding on how to temper the fast-growing clean-fuel and electricity demand and attain the emissions-reduction goals.

VI. PRACTICAL STRATEGIES FOR TRANSPORT POLLUTION REDUCTION

➢ *Personal and Group Level Interventions*

Individual transportation decision making helps to create a path of emission, and the personal behavioral adjustments can also be important to curb pollution. When the short-distance movement is made to be active in nature i.e. walking and cycling, the emissions are completely removed and co-benefits given to the society in terms of their physical health by the virtue of being physically active. In medium-range commuting, the use of public transport leads to much smaller per-capita emission levels than the use of single-occupancy vehicles; buses generate about 0.6 kg CO2/km/cap in a passenger-km, versus 1.2 kg of a single vehicle.

Ride-sharing and carpooling will maximize the vehicle usage rate, sharing fixed emissions among the occupants and lowering the carbon intensity per person. The emergence of online services that provide ride-matching has increased the possibility of dynamic carpooling, specifically when it comes to commuting and long-distance transportation. The trip chaining, which is the process of combining a series of errands into one trip, will decrease the number of kilometers that the vehicle travels and will eliminate cold-start emissions with a combination of multiple short trips.

The maintenance practices in vehicles affect the level of emissions. Inflation of tires to accurate levels decreases the rolling resistance leading to a 3-5 percent increase in fuel economy. Periodic engine care guarantees maximum efficiency in combustion, and the elimination of the unnecessary weight in vehicles lowers the use of fuel. Among the households deciding to buy cars, the choice of fuel-efficient vehicles, hybrid vehicles, or electric vehicles can be viewed as a long-term investment in reduced emission.

➢ *Business and Corporate Sector Strategies*

Logistics and transportation companies, especially the business sector, can have a significant load of freight emissions, and it has a much more significant potential to reduce the level of pollution. Updating a fleet by replacing older units with newer more efficient ones can achieve a reduction in per-vehicle emissions of 20-40 with an accelerated payoff in the case of electric or hybrid powertrains. Some of the companies such as DHL, UPS and FedEx already have pledged to electrify their fleets, with

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some companies aiming at 50-60 percent electric vehicles by 2030.

The route optimization software reduces the distance covered, the idle time, and prevent congestion and the emission can be reduced by 10-30% based on the operational situation. The real time traffic data integration provides the capability of dynamically rerouting to avoid delays as well as the maximization of vehicle utilization in return trips, which would otherwise be empty, by use of an algorithmic load matching. Location optimization of warehouses places distribution centers nearer to customer concentrations which minimizes the last-mile delivery distances.

The use of joint logistics facilities such as common warehousing and combined deliveries minimizes the number of vehicle kilometers through the elimination of the duplication. Cities with freight consolidation centers where the freight is received by many suppliers and final deliveries are dictated using single vehicles have produced 40-70% of a reduction in emissions in European pilot projects. The integration of reverse logistics eliminates value in empty trips, enhancing the economic performance and environmental performance.

Green procurement policies that span supply chains promote the reduction of emissions that are not directly related to operations. Companies that develop emissions standards when choosing suppliers and contracting carriers develop market opportunities to encourage cleaner transportation. The carbon in setting programs, which require businesses to invest in emissions reduction initiatives in their respective supply chains, mitigate scope 3 emissions and enable them to develop the partnership capacity required to continue improving their performance.

- *Urban Planning and Infrastructure Solutions*

Fig 2 Urban Green Logistics Delivery Vehicle

City-based initiatives influence the transportation infrastructure in which individual and corporate decisions are made. Transit-oriented development puts population and employment together at the nodes of a transport system and minimizes the average length of trips and enhances the viability of transit. Mixed-use zoning that collocates housing, work and service areas minimises travel needs in general and the vehicle kilometers travelled reduction may be 20-40% when compared to traditional segregated land use.

Complete streets policies make the road infrastructure user-friendly to all users, such as pedestrians, cyclists, and public transit cars in addition to the personal vehicles. Specific bus rapid transit lanes enhance the speed and reliability of the services and get ridership at the expense of the personal vehicles. Guaranteed cycling infrastructure enhances mode share in bicycle transportation, especially among the people discouraged due to safety issues.

The existence of low-emission zones that do not allow high-polluting vehicles to enter urban centers has the effect of increasing the turnover of the fleet and promoting modal shift. The ULEZ in London has decreased the level of nitrogen dioxide in the atmosphere by 44 per cent and the adherence rates to 94 per cent because of natural replacement of the fleet. Congestion pricing internalizes the gains associated with driving, offers a source of sustainable transport investment and deters unwarranted vehicle travel.

Green logistics zones supporting consolidated deliveries, off-hour delivery programs, and electric vehicle charging infrastructure address freight emissions specifically. The urban freight plan of Barcelona is a combination of delivery time windows, loading bay management, and last mile microhubs to halve the freight vehicle kilometers and sustain the service levels.

- *Policy and Regulatory Measures*

The government intervention provides the framework conditions under which the efforts of reducing emissions are carried out by individuals and corporations. Carbon pricing as taxes or emissions trading incorporates costs related to climate in transportation choices and provides financial incentives to reduce all emissions of every mode. Car efficiency regulations are used to guarantee a consistent grouping of performance in the new vehicles and the present EU regulations demand a reduction of 15% by 2025 and 30% by 2030 on the heavy-duty vehicles.

Low-emission vehicles have purchase incentives that enhance the rate at which these vehicles are penetrated in the market by overcoming the initial differentials in costs. Programs such as feebate systems that have a combination of fees on inefficient vehicles with rebates on efficient vehicles are revenue neutral but shift the consumer choice. Scrappage programs that speed up the retirement of older, high-emitting vehicles provide an immediate payoff to the benefits of emissions and promote the markets of new vehicles.

Emission long-term trends are determined by infrastructure investment priorities. Rearranging the funding between the expansion of roads and the transit network, rail, and active transportation infrastructure allows the modal shift by enhancing the quality of the alternative services. The infrastructure of charging and refueling infrastructure solves

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the range anxiety and the operational barrier to the implementation of zero-emission vehicles. Research and development facilitate technology preparedness in application of solutions that are still in their infantile stages.

International collaboration can be used to deal with aviation and shipping emissions, of which national action has a jurisdictional constraint. The Energy Efficiency Design Index and the Carbon Intensity Indicator created by the International Maritime Organization provide the international standards of vessel efficiency. The Carbon Offsetting and Reduction Scheme of International Aviation of the International Civil Aviation Organization is aimed at dealing with the growth of emissions by means of offset requirements, but the notion of the environmental integrity remains under criticism.

VII. CONCLUSION

Carbon emissions in transport are a very complicated and pressing issue of climate-change mitigation. The fact that the sector is still growing with the emissions even with the technological advances indicates that the sector is underpinning by strong structural forces, such as the increasing demand of mobility, the infrastructure lock-in, and the dominant role of road transport. To handle the challenge, most effective approaches entail the integration of a holistic approach to technological enhancement and organisational change.

Various findings are made in the analysis provided in this paper. To start with, transport emissions have a high geographical and modal dispersion, road freight being the most important and difficult. Heavy-duty vehicles are a significant source of emissions in comparison with their share in the fleet, which requires special consideration of the policy. Second, the methodological improvements, such as machine learning, spatial econometrics, and high-resolution emissions inventories, make the analysis of emissions more accurate and allow conducting more effective interventions. Third, transport carbon intensity determinants are multifaceted and include both structural (modal composition, vehicle efficiency, type of fuel, etc.) and economic and policy factors.

Fourth, mitigation measures lie on a spectrum between technological enhancement and structural avoidance and shift measures. Although, electrification has a significant potential of reducing emissions, especially in passenger transportation, the deep decarbonisation of freight involves the use of supplementary measures that involve modal shift, optimisation of supply chains, and demand management. A combination of these strategies into consistent policy frameworks with the help of international collaboration and adaptation to regional conditions is the most effective way to go in the direction of sustainable and low-carbon transport systems.

It is suggested that the future research directions include the evolution of on-road electrification, the contribution of alternative fuels to heavy transport, modal shifting in various geographical and economic conditions, as well as behavioural and organisational adjustments required to facilitate the process of transport decarbonisation. With the timeframe of the accomplishment of the objectives of the Paris Agreement becoming tighter, the pace of low-carbon transport adoption is becoming even more pressing, which demands not only a technological advance but also a radical transformation in the way mobility is delivered and consumed.

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