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REGULATING CARBON EMISSIONS IN THE TRANSPORT SECTOR: POLICY INSTRUMENTS, COMPLIANCE MECHANISMS, AND DECARBONISATION PATHWAYS

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ABSTRACT
The transport sector continues to rely on fossil fuels, and faces increasing demand for passengers and freight, coupled with a reliance on long-lived infrastructure and is still a significant contributor to global carbon emissions. This review looks at the policy instruments, compliance mechanisms and decarbonisation pathways in play for the transition to lower carbon transport in the road transport sector, in aviation, maritime shipping, freight transport and urban transport. It takes into account regulatory and economic policy actions such as carbon pricing, emissions trading, vehicle and fuel standards, incentives for electric vehicles, low carbon fuel standards and infrastructure support. The review also assesses the effectiveness of the monitoring, reporting, verification, lifecycle carbon accounting and enforcement measures in ensuring the credibility, comparability and measurability of emission reductions. There is evidence that electrification is an attractive option for road transport, and that it can be good for passenger vehicles, provided that it can be powered by low carbon electricity and charging infrastructure is in place. More challenging sectors such as aviation, shipping and some freight are more likely to need a mix of efficiency measures, sustainable fuels, hydrogen fuels and other fuels. Effectiveness of policy is different from country to country due to the institutional capacity, energy system, infrastructure, affordability and market readiness. Policy frameworks that are coordinated, flexible and enforceable will be crucial to support deep decarbonisation, ensuring that policy frameworks are aligned with technological change, clean energy and infrastructure investment and transparency of compliance systems.

KEYWORDS: Transport decarbonisation; Carbon emissions; Transport policy; Compliance mechanisms; Low-carbon mobility

1. INTRODUCTION

Transport is at the heart of global climate policy as it has continued to rely on fossil fuels, despite the increasing demand for both passenger and freight transport. The transport sectors of the road, aviation, shipping and urban transport infrastructure are associated with economic growth, technology and energy consumption. It is challenging to reduce these emissions since transport is reliant on long-lived assets like vehicle fleets, roads, air/sea ports, airports, and fuel networks. To achieve deep emission reductions, coordinated technology, energy supply, infrastructure, system, and public policy change is necessary (Bashmakov et al., 2022). The challenge is to develop the regulatory and economic conditions that will rapidly speed up the introduction of clean vehicles and fuels, without compromising the measurability, enforceability and consistency of the emission reductions with the long-term climate goals.

One of the most noticeable roads towards emission reductions from road transport has been electrification. Electric mobility and clean energy technology has come a long way, but has not reached parity in countries (IEA, 2023). The factors that affect the expansion of electric vehicles are affordability, charging infrastructure, market development and policy incentives, as can be seen in Gül et al. (2024). Some of the climate benefits also rely on the carbon intensity of electricity generation, battery manufacturing, conditions of the supply chains and supporting infrastructure. Vehicle electrification can't be an isolated solution. It has to be aligned to cleaner power systems, development of public transport, urban planning and wider mobility policies. Urban transport decarbonisation is relevant in the context of the growth of cities where congestion and mobility inequality co-occur together with increasing car ownership and infrastructure gaps (Alves et al., 2023).

However, unlike the other sectors, aviation is subject to other restrictions, since in many medium and long-distance flights it is hard to imagine direct electrification. A wide range of factors is needed for decarbonisation in this sector, including more aircraft efficiency, operational measures, low-carbon fuels, market-based measures, and international regulation (Sabatini & Gardi, 2023). One of the most well-known world-wide approaches to tackle emissions from international aviation is the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). It's based on monitoring, reporting, verification and the allocation of eligible carbon offsets. However, there is uncertainty about the quality of implementation, the integrity of offsets, the accountability of regulation and the potential for market-based solutions to provide long-term emission reductions from aviation (Oginni, 2023).
For non-electric transport activities, it is also gaining greater significance to regulate fuel. Renewable fuels (not of biological origin) have been receiving attention due to the potential for replacing conventional fossil fuels in certain applications. Their contribution is driven by the maturity of technology, availability of renewable electricity, production capacity, development of value chain, infrastructure and regulatory support (Buffi et al., 2022). The ReFuelEU Aviation regulation is an essential step towards greater use of sustainable aviation fuels by putting obligations on the industry.The aviation regulation ReFuelEU is a key step towards promoting the use of sustainable aviation fuels by introducing obligations. It can impact the fuel supply, operating costs, investments, and ability of national aviation industries to evolve and meet the increasingly tight climate regulations (Reijonen, 2025).
Another potential pathway to transport decarbonisation is hydrogen and fuel-cells technology, as battery electric technology can be challenging to deal with in terms of range, weight of the vehicle, charging time or intensity. Yet, there has been some progress in the development of fuel-cell technologies, supply chains, and applications in market (Weidner et al., 2025). However, their environmental values are a strong function of the hydrogen production method. Emissions reduction can be facilitated by hydrogen produced with renewable or other low-carbon energy sources, while those produced with carbon intensive energy sources can lower the expected climate benefits. The long-term potential of hydrogen in transport will also be influenced by factors such as the cost and storage, distribution, refuelling infrastructure and market size.
Another key element of transport climate policy will continue to be carbon pricing. The EU Emissions Trading System is an example of how a market-based approach to regulation can be developed to meet the wider decarbonisation goals (Sabeva, 2025). Carbon-pricing can drive companies and transport companies to reduce the amount of fuel that they use, increase their efficiency, and invest in lower-carbon technologies. They work well when carbon prices are high, regulatory coverage is adequate, they are effectively monitored, they are well enforced, and there are viable alternatives to fossil-fuel based transport.
Transport decarbonisation is not just about changing fuels or vehicle types, but means regulating, technically, economically and institutionally toward a transition. The policy mix for different transport modes is different because of the technological immaturity, infrastructure dependency, energy consumption and regulatory system of the road, aviation and maritime transport and public mobility system. These standards, incentives, carbon pricing, clean technology, alternative fuel sources, investment infrastructure and credible compliance mechanisms all have to be combined and work together to achieve effective emission reduction. This review focuses on the key policy instruments employed to control carbon emissions from transport, the methods for monitoring and enforcing compliance and the key pathways that are currently being followed to aid long-term decarbonisation. There is specific focus on the role of regulatory action and technology changes to provide long-term and credible reductions in transport sector carbon emissions.

2. **Carbon Emissions and Environmental Impacts of the Transport Sector**

The carbon emissions from transport are influenced by the carbon intensity of the energy system, the level of mobility demand, the carbon emissions characteristics of the vehicles and energy use, the infrastructure, and the level of car ownership. This is particularly the case with road transport as it relies heavily on fossil fuels in many countries, and passenger cars and light-duty vehicles are used on a very large scale. The environmental impact of transport is not limited to emissions from transport; the carbon footprint of vehicles includes the environmental impacts of the production of vehicles, electricity, fuels, construction of the infrastructure and the treatment at the end of life. To meet the goals of effective decarbonisation, both operational emissions and wider lifecycle impacts of transport technologies and energy systems need to be considered.
While electrification is considered an important pathway for lowering emission levels in passenger transport, not changing the vehicle fleet to electric vehicles is not sufficient to meet climate goals. Evidence indicates that electrifying light-duty vehicle fleets alone may not be enough considering the anticipated growth in both vehicle numbers and usage, as well as fleet size (Milovanoff et al., 2020). This discovery took the focus away from the mere replacement of technology and put it on broader transport activity changes. While EVs can make significant reductions in direct emissions when in use, continued growth of vehicle kilometres travelled and

mobility overall can diminish the benefits of electrification. Such policies for cleaner vehicles should be coupled with measures to enhance public transport and to minimise unnecessary travel, maximise vehicle utilisation, and promote lower carbon consumption patterns.

The environmental impact of EVs is also highly related to the power grid that power them. In the case of electricity generation from carbon intensive resources, some emissions are transferred from vehicle emissions to electricity generation, but not removed. The economic attractiveness of various vehicle technologies may shift when prices are applied to these indirect emissions, and the cost of these emissions can promote the transition towards lower carbon mobility. EU research on the light-duty vehicle sector also suggests that indirect emissions can be integrated into pricing systems to help the transition to a low-carbon economy roll out more quickly (Wolfram et al., 2021). This is a reminder that tailpipe pollution is not the only source to consider in creating climate policies. This should therefore be considered as a cross-sectoral policy process between vehicle regulation and electricity-sector decarbonisation, instead of separating these two processes.

Another key context where design of technology and policy affect carbon emissions in transportation systems is urban transportation. The large cities tend to experience an increase in the number of vehicles, congestion, air pollution and energy use. Along with the carbon-emissions reduction, other measures that will help reduce vehicles on the road and promote new energy vehicles can bring about environmental benefits as well. A comprehensive analysis of the policies that are implemented for the transition of the car market in Beijing shows that car purchase quota limitations can yield significant environmental co-benefits if they are complemented by policies that favour new energy vehicles (Yang et al., 2021). These results indicate that urban transport decarbonisation is more likely to be successful if both the number of vehicles getting on the road and the technology they use are taken into consideration. Transitioning from conventional to electric cars alone will likely not solve the congestion problem, road space issues, energy consumption or other environmental issues of high private vehicle dependency.

Vehicle electrification also impacts the environmental impacts through financial incentives. Electric vehicle adoption can be promoted through subsidies, tax reductions and procurement incentives, but they have to be designed in specific ways to ensure that public money helps to reduce emissions most effectively. Current evidence indicates that EV incentive programs would need to be rethought to be effective for achieving a net zero target (Nunes et al., 2022). Vehicle-specific, usage-specific, and/or actual emission displacement factors are missing from incentives, which can result in less climate benefit from incentives than anticipated. Policy design should therefore shift away from just promoting EV sales, and consider maximising the benefit of emissions avoided by each supported vehicle.

The broader regulatory landscape is also a key issue. The way in which climate policy is implemented is becoming more and more comprehensive and includes emissions targets, market measures, technical regulations, and specific measures for the transport sector in order to influence transport behaviour and investment. A good example of embedding transport decarbonisation in the broader context of energy transition and emission reduction is the situation of European climate governance (Delreux & Crellin, 2025). This is important since it is not possible to distinguish transport emissions from emissions in the generation of electricity, production of industry, planning of infrastructure, or consumer behaviour.

If CO_2 emissions from transport are to be reduced it is necessary to go beyond the simple replacement of internal combustion vehicles by electric vehicles. While electrification is still relevant, the success and efficiency of its development will rely on the use of cleaner electricity, well-designed incentives, travel demand management and regulatory coordination. Substantial and lasting reductions in the environmental impact of transport can only be achieved through a wider perspective which takes into account lifecycle emissions, urban mobility patterns, interactions between the energy system and transport, and policy design.

3. Policies and Regulatory Measures for Reducing Transport Carbon Emissions

The need to create policy frameworks that can have an impact on vehicle technologies, energy supply, infrastructure, mobility behavior, resource consumption, and sectoral governance is evident when looking at the challenge of reducing carbon emissions from transport. Transport systems rely on investment in long-lived assets and investment patterns, and therefore cannot be transformed at the rate necessary for climate mitigation, without the support of market forces. The transition to lower carbon transport can be aided by the timely implementation of regulatory frameworks, fiscal incentives, clean energy policies, infrastructure support and sector-specific regulations, but their success will rely on their synergy. This policy can make a minimal difference if the electricity for charging electric vehicles continues to be highly carbon intensive, or if battery manufacturing and disposal also result in significant environmental impacts.

The example of electric-vehicle regulation is a good example of this lack of comprehensive policy thinking. With the growing number of electric vehicles on the roads, there has been growing focus on the environmental implications of battery making, critical material requirements, remanufacturing, and end-of-life management.

These pressures can be mitigated through a circular-economy approach, which includes extending battery life, promoting reuse, recovery of valuable materials and decrease in reliance on virgin resource extraction (Richter, 2022). This could result in policies targeting only vehicle sales potentially missing a crucial aspect of the environmental impact of electrification. Regulatory frameworks need to increasingly take into account battery durability, traceability, recycling requirements, second-life use and producer responsibility in order to ensure more sustainable material flows over the transition to EV.

The success of the electric-vehicle policy also depends on the electricity industry. The overall climate benefit of electrification depends on the production of electricity for charging, that is, on the generation mix, whereas direct tailpipe emission reductions are present regardless of the generation mix. This is an especially relevant problem in nations where fossil fuels continue to be the primary source of energy. Studies in India suggest that decarbonising the electricity grid needs to come before electrifying the passenger road mobility sector, on a large scale, to make emission reductions more effective in the short term (Abdul-Manan et al., 2022). This underscores the importance of further integration between transport and energy policies. Expansion of renewable energy combined with lower carbon power generation is likely to be more beneficial for the climate when paired with EV subsidies, charging infrastructure, fleet targets or purchase incentives. The transport decarbonisation requires coordinated approaches in several areas: vehicle electrification, cleaner electricity, shared mobility, maritime standards and integrated governance (as presented in Table 1).

Table 1. Key Regulatory Measures Supporting Low-Carbon Transport Transitions

Policy and Regulatory Area	Core Policy Focus	Role in Transport Decarbonisation
Electric vehicle regulation	Vehicle electrification and battery sustainability	Reduces dependence on fossil-fuel vehicles
Grid decarbonisation	Cleaner electricity for transport	Improves the climate benefits of EVs
Shared mobility policy	Efficient vehicle use and reduced private ownership	Supports lower-carbon urban mobility
Global South transport policy	Affordable and context-specific interventions	Enables equitable decarbonisation pathways
Maritime regulation	Fuel standards, efficiency, and carbon-intensity control	Reduces emissions from shipping
Integrated transport governance	Coordination across energy, infrastructure, and mobility	Strengthens overall policy effectiveness

Another important aspect of transport policy is that of usage; it is indeed the most significant of all strategic sections in designing a transport policy. The environmental impacts of shared mobility are not necessarily good, and are frequently marketed as a way to cut down on private car usage and enhance the effectiveness of urban mobility. Vehicle lifespan and life cycle carbon footprint of EVs (Morfeldt & Johansson, 2022) can be impacted by increased vehicle use. Shared mobility could also lead to a higher overall vehicle kilometre travelled when it replaces public transport, walking or cycling instead of private car use. This should be based on real emission and resource reductions and not on policy targets. High occupancy, the integration with public transport, efficient fleet management and an increased vehicle service life can enhance the environmental profile of shared mobility systems.

Different regions also have widely varying designs for their transport regulation. The Global South context of rapid urbanisation, growing mobility demand, infrastructure deficits, fiscal constraints and significant institutional capacity gaps are all part of the picture of decarbonisation policies.The Global South context of rapid urbanisation, rising level of mobility demand, uneven infrastructure, limited fiscal resources and significant institutional capacity gaps all form part of the picture of decarbonisation policies. The results of a systematic review of transport decarbonisation in the Global South indicate that the effectiveness of policies is greatly influenced by local economic, social and technological conditions (Emodi et al., 2022). Solutions designed in high income countries are not necessarily applicable in low and middle income countries. In many instances, improved public transport, cheap clean transport, transport efficiency and equipment, finance and basic infrastructure investments can be more relevant than policies focused on private EV adoption. Equity should also be taken into account; inadequate pricing or technology policies would disproportionately affect the lower-income households.

However, maritime transport is another area of regulation that has a challenge because of the international nature of maritime transport. The decarbonisation of it relies on coordinated legal and policy actions that focus on energy saving, carbon intensity, alternative fuel and long-term targets to reduce GHGs (Dong et al., 2022).

A lack of a clear national set of rules can lead to uncertainty and competitive imbalances, whereas a set of rules that is internationally aligned can give more clarity on investment signals to shipowners, ports, and fuel suppliers. Consistent monitoring, transparency and reporting, clear standards and long-term certainty on policies are thus essential for effective maritime regulation, enabling investment in cleaner technologies and fuels.

The evidence suggests that transport regulation should not be based on isolated measures, but should take a holistic approach to the transport system of which mobility is a component. Electric-vehicle policies must be based on cleaner electricity generation and better management of EV batteries, shared mobility on more nuanced regulation of its usage, developing economies on more context-appropriate positioning of policy, and international shipping on coordinated governance. Regulatory coherence, both within and between the technology, energy, infrastructure and institutional systems, is central to effective transport decarbonisation policy, that increases real, durable and deep carbon emission cuts and does not simply transfer emissions from one component of the transport system to another.

4. Compliance, Monitoring, and Enforcement of Transport Emission Regulations

Crucial to transport decarbonisation is to go beyond the introduction of targets, standards and cleaner technologies. It also demands credible emission measurement systems, reporting systems, verifiable emission claims and compliance verification systems to implement regulatory commitments. In the transport sector, these functions are especially relevant as emissions are generated in various supply chains of fuels, electricity, vehicles and infrastructure. This approach to a compliance system could miss significant upstream and life-cycle effects. Transparency and clarity in the rules of accounting, the reliability of information, its independent recording and assessment, as well as the consequences of failing to comply with the requirements, are prerequisites for effective regulation.

Aviation is a good example of the trend towards lifecycle compliance. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was launched by the International Civil Aviation Organisation (ICAO) as a new, global scheme for calculating lifecycle GHG emissions of aviation fuels. This is an approach that goes beyond the combustion of fuel, and the emissions caused by the production, processing and transport of fuels and feedstocks, and other steps in the pathway of the fuel (Prussi et al., 2021). When sustainable aviation fuels are deployed to fulfil regulatory requirements, such accounting is required as fuels with the same operational performance might have significantly different overall climate impact. Reliable monitoring and verification is thus required to allow for monitoring of reported emission reductions, rather than merely replacement of one fuel category for another.

The general transport literature also illustrates a greater multidimensionality of emission monitoring. With the development of the study on carbon emissions and vehicle technology, energy consumption, urbanisation, transport demand, infrastructure and policy intervention, the linkage of each factor with carbon emission has gradually increased (Liu & Qiu, 2023). This broader view is relevant for designing regulators. Fuel consumption and tailpipe emissions must be measured with compliance systems. Additionally, they need to consider the energy used, use rates of vehicles used, emissions from production processes, transport intensity and mobility demand changes. The use of consistent indicators and reporting process will enhance the comparability of the regions and transport modes and minimise uncertainty in reported progress.

Another example of the need to go beyond immediate operational emissions to consider the compliance of electric vehicles is generally applicable. While EVs produce no carbon emissions when they're driving, their climate impact includes the carbon emissions generated by electricity production and EV manufacturing. The mitigation benefits of the swift deployment of EVs can only be realised when the electricity grid is carbon intensive, or when EVs and batteries are themselves highly polluting (Ren et al., 2023). That is, a zero tailpipe emissions-based regulatory requirement may overestimate near-term climate benefits. These should be supplemented by an evaluation of the carbon intensity of electricity, the embodied emissions in the production of the vehicle, the vehicle's lifetime, and the time needed for the operational carbon savings to exceed the production carbon emissions.

Lifecycle carbon assessment can be of assistance in trying to solve this problem. Electric vehicle emissions can be evaluated across various phases of the vehicle's life, including its manufacturing, usage, and disposal, and these impacts can vary depending on the specific vehicle, its usage patterns, and the electricity used to power it, among other factors (Gao et al., 2023). There is a clear demand for harmonised accounting rules due to these differences. The regulators need to establish clear boundaries, clear data requirements, clear methods for the calculation of emissions, and clear periods for reporting emissions in order for emission claims to be compared on a consistent basis. They can also help to minimize the possibility of selective reporting or misleading environmental claims focusing on the lowest emission life stage of a given technology. The major stages of the lifecycle of EVs which should be taken into account when evaluating EV carbon emissions, ranging from raw material acquisition to vehicle treatment at the end of life, are shown in Figure 1.

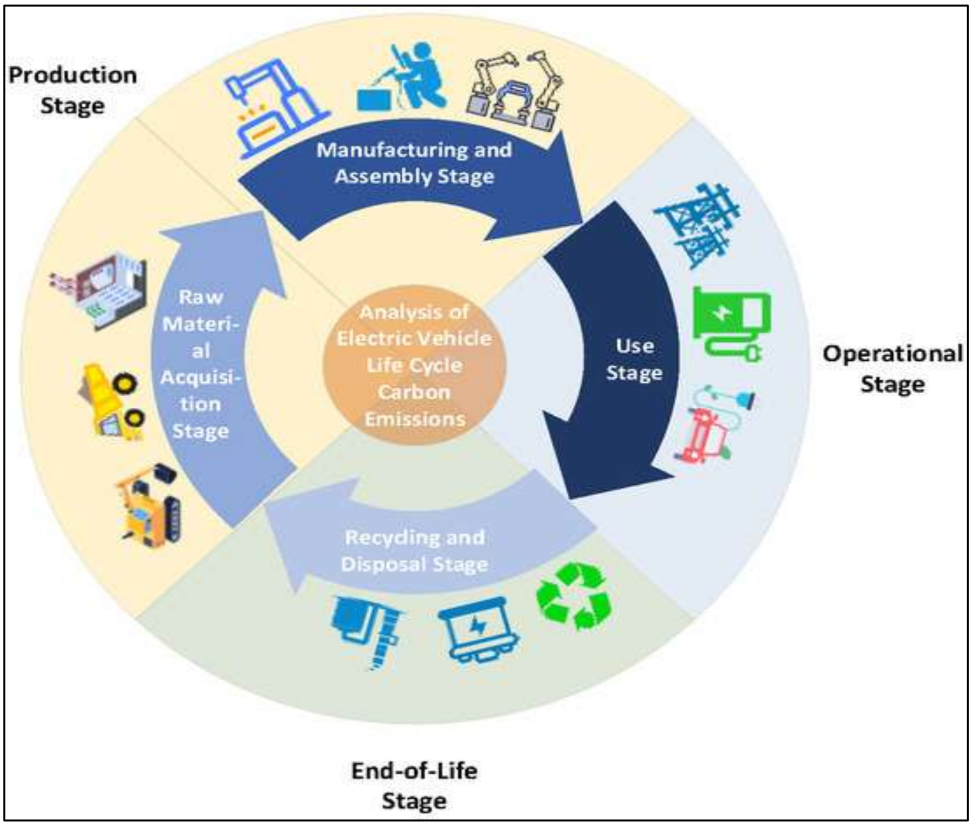

Figure 1. Lifecycle Stages Considered in the Carbon Emission Assessment of Electric Vehicles
Source: Adapted from Xiao et al. (2025)

The system-level assessment of transport emissions also needs to be done. The carbon outcomes are the result of the interaction of economic activity, energy structure, infrastructure, technological efficiency and travel demand (Ferrer & Thome, 2023). Vehicle efficiency gains could be offset by an increase in overall travel, and cleaner fuels might be of little value to the overall vehicle fleet if overall vehicle activity grows quickly. Adhere to frameworks should differentiate between emission intensity reductions and actual emission reductions. Both the indicators are helpful but they address different questions. The intensity measures reflect whether transport is getting cleaner per unit of transport activity, while absolute emissions reflect whether in practice the sector is moving toward the climate targets.

Monitoring and reporting is only effective if there is credible enforcement. There should be straightforward procedures in place to identify non-compliance and what to do about it within regulatory systems. The type of policy instrument will determine what methods are used to enforce it, such as financial penalties, corrective action, retracting credits, changing reporting requirements, or limiting access to regulated markets. Independent verification can be particularly crucial when carbon credits or low-carbon fuel claims or technology incentives are in play, as the system could lose credibility if the whole process is not supervised well.

Compliance architecture systems should thus be linked together in a single regulatory process, with measurement, lifecycle accounting, transparent reporting, independent verification and enforcement. With the emergence of more diverse transport systems, there is a need for regulators to have ways to consistently compare conventional fuels, electricity, alternative fuels and emerging technologies. The direct emission data and indicators of lifecycle and system level provide a better tool to assess the actual effectiveness of transport policies in achieving real, long-term and verifiable emissions reductions.

5. Decarbonisation Strategies Across Different Transport Modes

There are many differences between the energy demand, degree of infrastructure dependency, operating conditions, and technological readiness of road transport, maritime transport, aviation, and other mobility systems, there is no single transport decarbonisation pathway. The solutions used in passenger vehicles will not necessarily be directly applicable to long-distance transport or goods transport. A more realistic approach should seek to integrate decarbonisation actions into the technical and economic features of each mode and

take into account characteristics of energy supply sources, environmental trade-offs, infrastructure needs, and policy feasibility.
Road transport continues to be an important mode as it still uses a lot of fossil fuels and is closely coupled to the increase in transport of passengers and goods. The analysis of China and India indicates that the decarbonisation of road transport will need a multi-faceted approach of vehicle electrification, more efficient fuel use, use of more polluting fuels, increasing road public transport services and actions impacting travel demand (Loo et al., 2023). These strategies are effective to varying degrees across countries due to the fact that the conditions of vehicle ownership, electricity systems, urban development and income differ significantly. This implies that national decarbonisation paths should take local transport conditions into account, not the application of a one-size-fits all policy approach.
Light-duty road transport is likely to be an important use case for electrification. Direct emissions during operation of battery-electric vehicles can be significant, particularly if low carbon electricity is used. They're not just good for the tailpipe, though. They have environmental impacts along their entire lifecycle, including battery production, mineral extraction, manufacturing processes, electricity generation, and end-of-life treatment. Studies show that electric light-duty vehicles show a high potential for decarbonisation, but do not necessarily address all environmental impacts of mobility (Chen et al., 2024). This underlines the importance of having a mix of electrification, cleaner electricity generation, better battery design, recycling, responsible sourcing and better vehicle utilisation. The transport transport decarbonisation solutions and facilitating conditions for their implementation are summarised in table 2.

Table 2. Decarbonisation Strategies and Enabling Conditions Across Transport Modes

Transport Segment	Primary Decarbonisation Approach	Enabling Conditions
Passenger road transport	Electrification	Clean electricity and charging infrastructure
Urban mobility	Public transport and demand management	Integrated mobility planning
Road transport taxation	Road-user charging and fiscal reform	Revenue stability and equity
Maritime transport	Alternative low-carbon fuels	Fuel supply and port infrastructure
Shipping operations	Efficiency and operational improvement	Fleet optimisation and investment
Transport energy systems	Clean-energy integration	Coordinated transport and energy policy

There are also important fiscal implications of road transport decarbonisation. In many countries, fuel taxes and other taxes on fuel are important sustainable sources of public revenue for governments. With the increasing electrification of transport and the reduction of fossil fuel use, these revenues could decrease, thereby affecting the funding of transport and public budgets. The cost impact of the decarbonisation of road transport can be substantial and alternative revenue instruments may be needed (Victor-Gallardo et al., 2024) as evidenced by a study in Costa Rica. New and revised road taxes, or congestion charging could be more relevant as the distance of the journey increases. These should be carefully structured to ensure that they do not reduce income but encourage adoption of cleaner technologies and do not overly burden low-income groups.
The requirement of long-distance shipping over sea water with high energy density fuels is different to that of other shipping methods and presents a different technological challenge to the maritime transport sector. Reduction in shipping emissions will therefore be achieved as a result of vessel efficiency, operational changes, alternative fuels and port and fuel infrastructure. Other fuels of low carbon content, such as methanol, ammonia, fuels produced from hydrogen, and biofuels, have been suggested as alternatives to marine fuels. This depends on their production pathway, storage needs, energy density, infrastructure requirements, safety aspects and emissions characteristics. There are many trade-offs to the maritime energy transition and no one fuel will be the all-encompassing fuel of every type of shipping (Ramsay et al., 2023).
There are also other emissions to be reviewed beyond carbon emissions, with the environmental performance of alternative marine fuels. Some fuels might result in reduced greenhouse gas emissions, but have other environmental or operational impacts. Their decarbonisation contribution is reliant on their mode of production, transport, storage and consumption. This emphasises the need for LCA when considering future maritime fuels. To realize the use of cleaner fuels beyond pilot projects and to scale up their commercial use, investments will also be required in port infrastructure, bunkering systems, vessel retrofit and production of low-carbon fuels.

The need for a more comprehensive energy-transition perspective is the fact that transport technology is closely linked to electricity generation, fuel production, and infrastructure systems. To achieve sustainable transport, an integrated approach is needed between energy policy, technology development, mobility planning and regulatory design (Collazos et al., 2024). Cleaner electricity and robust charging infrastructure are essential for electric mobility, while low-carbon hydrogen production and distribution are crucial for hydrogen mobility, and significant growth of new supply chains is needed for alternative maritime fuels. Decarbonisation strategies need to be considered in the context of the whole energy and transport system, and not just as a single technology substitution.

The data available indicates that the various modes of transport will move towards emissions reductions via various technology and policy mixes. Electrification is well suited for light-duty road transport, whereas a portfolio of alternative fuels, efficiency gains, and operational changes is more likely to be required for maritime transport. The fiscal systems will also have to evolve in the wake of a reduction in the consumption of fossil fuels. In order to successfully decarbonise transport, it is essential that technology, infrastructure, low carbon energy, and policy interventions are coordinated, backed by lifecycle assessment and planning that takes place on a case by case basis.

6. Clean Transport Technologies and Low-Carbon Fuel Alternatives

Clean Mobile and Low Carbon fuels play a key role in the transition from fossil fuels. The contribution they can make to decarbonisation however can't be measured solely based on the emissions from the vehicles themselves. A more comprehensive assessment will need to take into account energy production, vehicle manufacturing, infrastructure, fuel pathways, fuel resource use, and end-of-life processes. Therefore, life cycle assessment (LCA) is gaining greater significance as a tool to compare emissions of transport technologies with greater scope, including emissions associated with the production, operation and disposal of the technology (Zhang et al., 2024). When considering battery electric vehicles, conventional vehicles, hydrogen vehicles and alternative fuels, this larger picture is of major importance.

BEVs are one of the most developed low carbon solutions for road transport passenger vehicles. The biggest benefit is that they do not emit carbon directly from their tailpipes while operating – but they have a large carbon footprint due to the energy generation and battery production. Recent research shows that BEVs have a lower LCCF than other passenger-car technologies on various energy decarbonisation scenarios, especially where the carbon emissions of the electricity system are reduced (Simaitis et al., 2025). This reinforces the argument for electrification as one of the key road transport strategies, and highlights the environmental impact of electrification is very dependent on the broader energy system transformation.

Vehicle electrification and electricity-sector transition are particularly critical in countries with variations in electricity-grid architecture. For carbon-intensive regions, where the source of electricity generation is not low carbon, the near term climate impacts of EVs could be less than in a region with a higher proportion of renewables or low carbon resources. Vehicle electrification is thus a promising approach to enhance the lifecycle emission performance if harmonized with the power-sector decarbonisation (Koroma & Alwosheel, 2026). Thus, electric-mobility policy cannot take place without energy policy. Charging infrastructure, EV incentives, renewable electricity generation, grid expansion and energy storage investments must move forward in parallel to maximize the transport electrification climate benefits. Table 3 lists the key potential clean transport technologies and the enabling conditions that need to be met to allow the technologies to play a key role in achieving transport decarbonisation.

Table 3. Clean Transport Technologies and Enabling Conditions for Decarbonisation

Transport Technology / Pathway	Main Application	Decarbonisation Benefit	Key Condition
Battery-electric vehicles	Passenger road transport	Lowers lifecycle carbon emissions	Cleaner electricity supply
Electric freight vehicles	Freight transport	Reduces fossil-fuel dependence	Charging and grid infrastructure
Hydrogen and fuel-cell systems	Heavy-duty and long-range transport	Supports low-carbon mobility where batteries are less suitable	Low-carbon hydrogen production
Sustainable and synthetic fuels	Aviation and other hard-to-electrify modes	Reduces reliance on conventional fuels	Scalable low-carbon fuel production
Methanol, ammonia, and	Maritime transport	Supports shipping decarbonisation	Port and bunkering infrastructure

biofuels			
Integrated clean-energy systems	All transport modes	Strengthens overall emission reduction	Coordination of transport and energy policy

Despite the recent surge in EV growth, a number of factors remain to impact EV adoption. Vehicle cost, availability of charging stations, battery performance, demand for raw materials, battery recycling capacity and consumer confidence are also significant factors. Road transport decarbonisation policies must thus focus on providing technology support and building infrastructure and maintaining regulatory stability. Electronic vehicles will play a significant role in helping to reduce emissions in sustainable road transport, but their increased deployment requires coordinated policies to tackle costs, charging stations, electricity generation, battery sustainability, and market development over the long term (Patil et al., 2024). Especially significant in countries where charging infrastructure and charging networks are not evenly distributed.

Low-carbon transport doesn't only refer to EVs for passenger transport. The technological and operational requirements of freight transport solutions are much more varied than those of passenger cars, due to the different weights, ranges, duty cycles and infrastructure requirements of different types of vehicles. This means that national freight decarbonisation policies should address the transition of vehicle technology, fuel, logistics efficiency, modal shift and infrastructure planning to achieve decarbonisation instead of focusing on a single technological pathway (Briand et al., 2026). Battery-Electric Trucks can be considered on certain routes and could be used more extensively in other scenarios, where hydrogen, low carbon fuel and rail expansion and optimization of logistics can be utilized. This was a reminder of the importance of flexible technology portfolios which take into account national transport systems and freight characteristics.

Progress in a number of technologies and transport modes will be needed at a global scale to achieve near zero transport emissions. The results of the integrated modelling indicate that a decarbonisation of deep transport requires a high degree of electrification, clean energy systems, efficiency gains, the use of alternative fuels, and a change in transport demand (Speizer et al., 2024). Those segments that are hard-to-electrify are likely to demand even more hydrogen-based fuels, sustainable biofuels, synthetic fuels or other low-carbon energy vectors.

7. Policy Effectiveness, Governance, Equity, and Research Gaps

More than mere ambition will be needed to achieve transport decarbonisation policies. It also relies on the design and combination, implementation and adaptation of policy instruments in the different transport systems. Emission reduction can be achieved through a range of different regulatory actions and carbon pricing, as well as fiscal incentives, public investments and mobility-management measures, but these are effective in different national and local contexts. These policies have outcomes that are influenced by institutional capacity, infrastructure quality, energy systems, market structure and user behaviour. The focus is therefore shifting more and more from a technical challenge to a governance challenge for transport decarbonisation.

Shared mobility is a good example of public policy and market behaviour. Car sharing, ride sharing and other shared mobility services can contribute to sustainable mobility when they do not lead to a higher reliance on the private motor transport sector, but are linked to public transport. Their contribution to the environment, however, is heavily dependent on business models and the incentives these provide through regulation. Public policy instruments can have an impact on pricing, fleet composition, services offered and how shared mobility providers integrate their services into urban transport systems (Kriukelyte et al., 2024). Policies are more likely to facilitate decarbonisation if they promote low-emission vehicles, connectivity with PTV, efficient use of vehicles and increased accessibility. Needless to say, poorly designed incentives will have the opposite effect to what they are supposed to accomplish, either by encouraging more kilometres driven or by diverting passengers from less carbon-intensive means of transportation.

Judgements about the performance of policies are also influenced by the way emissions are measured. Carbon emissions and carbon footprints are similar, but not equal. The transport operations emissions are captured in the direct emissions approach while the broader impacts of energy production, vehicle manufacturing, vehicle infrastructure, and other lifecycle stages are captured in the carbon-footprint approach (Ling et al., 2024). This distinction is significant because a policy can cause a decrease in tailpipe emissions, but can have no impact on upstream emissions. Implementing a lifecycle approach to policy evaluation can shed light on the true climate impact of transport policies and can enhance the level of understanding gained from the comparisons between EVs, other alternative fuels, public transport and other mitigation measures.

National economic and institutional conditions must also be taken into consideration when designing a policy. The transport emission policies cover carbon taxes, fuel price reform, fuel efficiency standards, incentives for electric vehicles, investment in public transport, support for renewables, and policies aiming at changing behavior. They can be very efficient but not always, due to income levels, fuel dependency, infrastructure, and administrative capacities (Solaymani & Botero, 2025). The effectiveness of a good policy in a country with advanced public transport, high income and a low carbon electricity generation could be very different in a country where mobility demands are high, and transport systems are still in the process of evolving.

The impact of the policy is another key dimension of policy effectiveness. Decarbonising transport means making decisions regarding different measures that have varying capital needs, running costs, emission reduction potential and implementation time. Greenhouse-gas mitigation costs for transport technologies and interventions vary widely, as evidenced by the results of the reviews (Ricci et al., 2025). This variation necessitates considering the cost associated with a carbon saving as well as the amount of carbon that a measure will save. There may also be opportunities for low-cost solutions, that might not be cost-effective enough for a high-level decarbonisation target, but which can help to enable infrastructure, technological learning or long-term decarbonisation.

Equity must be taken into account along with the cost and environmental efficiency. Households can be impacted differently by carbon taxes, fuel charges, road pricing and technology mandates, based on a variety of factors including income, geographical location, mobility requirements and alternative options. In rural or less well-connected urban communities, residents may have less choice when it comes to decreasing vehicle usage, and rural communities with low incomes may have a harder time to afford cleaner cars. The issues of affordability, public transport access, financial support for public transport and the sharing of transition costs, should be addressed in fair transport policy.

8. CONCLUSION

The decarbonisation of transport needs to happen in a coordinated manner, both in terms of regulation, technology, energy supply and infrastructure and mobility systems. The various modes of road transport, aviation, maritime shipping, freight and urban mobility have distinct operational needs, and thus it is impossible to achieve significant emission reductions for the sector as a whole with a single measure. While electric mobility, low-carbon fuels, hydrogen, sustainable aviation fuels, cleaner marine fuels, public transport, and efficiency improvements are all important elements, their climate impacts rely on cleaner energy systems, adequate infrastructure, and a thorough evaluation of lifecycle emissions. Vehicle and fuel standards and fiscal incentives for low carbon transport, infrastructure investment and sector-specific regulations can help to accelerate the transition to low carbon transport, if they are accompanied by clear monitoring, reporting, verification and enforcement. To ensure that reductions in emissions are real and not just shifted from the operation of vehicles to the generation of electricity, the production of fuels, or the manufacture of vehicles, it is necessary to have reliable accounts of the carbon emissions over the lifecycle of these products. The impact of such actions also differs among countries as there are differences in income level, institutional capacity, infrastructure, energy systems, and access to clean technologies. The policy of the future for transit needs to, then, be both environmentally aspirational and financially sustainable and equitable. For long-term progress, policy frameworks need to be integrated and flexible, to connect technology innovation to decarbonizing energy systems, to provide credible compliance frameworks and be context-specific with regard to governance.

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