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PERSPECTIVE

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Crafting strong, integrated policy mixes for deep CO_2 mitigation in road transport

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Transport CO_2 emissions continue to grow globally despite advances in low-carbon technology and goal setting by numerous governments. In this Perspective, we summarize available evidence for the effectiveness of climate policies and policy mixes for road transport relative to 2030 and 2050 mitigation goals implied by the Paris Agreement. Current policy mixes in most countries are not nearly stringent enough. We argue that most regions need a stronger, more integrated policy mix led by stringent regulations and complemented by pricing mechanisms as well as other efforts to reduce vehicle travel.

While present transport systems provide numerous benefits, the negative societal impacts are enormous. In particular, the global transportation sector is responsible for almost one-quarter of greenhouse gas (GHG) emissions (mostly CO_2), with about 72% thereof from road transport[1]. Despite decades of progress for alternative and low-carbon fuels and technologies, most developed countries remain locked-in to the dominance of privately owned, fossil fuel-powered vehicles[2,3]. Transport emissions are expected to grow further in scenarios produced by the International Energy Agency (IEA), even if currently announced policies are implemented (Fig. 1)[4–6].

This Perspective summarizes available evidence for which policy mixes can be highly effective in reducing GHG emissions within road transport in the long-term while pointing out directions for further policy and research development. Clearly the transportation sector needs to carry its weight in meeting deep decarbonization goals. Compared to 2019, both the 1.5 °C and 2.0 °C Paris Agreement scenarios require global GHG reductions of about 30–40% by 2030, 60–80% by 2050 and likely close to 100% (or zero net emissions) thereafter[5,7]. GHG mitigation ambitions are higher in Organisation for Economic Co-operation and Development (OECD) countries because they are the source of most historical emissions and are thought to have more flexibility for large-scale investment in low-carbon technologies[8]. Because expected mitigation costs are lower in road transport than in aviation or shipping[9–11], we start with the assumption that road transport should at least proportionally fulfil the ambition of the total mitigation targets noted above. That said, emissions from aviation and shipping are growing more quickly and require additional GHG mitigation policies[2].

We focus on national and regional policymaking. Cities are important in the transition towards more sustainable transport, but their scope for governmental climate change action tends to be smaller than on the national level[12]. While we identify insights with global relevance, most of the available literature analyses developed countries, mainly in Europe and North America—pointing to a clear research need to better understand climate policy design for developing countries. Further, our analysis focuses more on passenger travel which is responsible for most GHG emissions in transport, though we call for more attention to road freight.

The importance and complexity of policy mixes

A single policy instrument (simply referred to as a policy) is not likely to be enough to realistically achieve climate targets. Rather, evidence suggests that an integrative mix of strong policies is needed to induce a low-carbon transition, likely a combination of pricing mechanisms, subsidies, regulations and infrastructure implementation[13–19]. Transport researchers have understudied rationales and approaches for policy mixes as well as the complexities of policy interactions[19,20]. We presently define policy mix simply as the presence of multiple policies implemented in the same country or region, during the same time period, relating to the same societal objective—in this case, deep GHG mitigation. Other literatures provide more nuanced definitions of policy mixes, which can include policy process, objectives and strategies[16].

The design of an effective and integrated policy mix requires sophisticated understanding of policy interactions. The goal of an 'integrated' policy mix is set as having both cohesiveness across policy goals (for example, GHG mitigation as well as other desirable co-benefits) and consistency across specific policies[21]. Complementarity across policies is ideal, especially 'synergy' if possible, where the presence of two (or more) policies gives a greater social benefit than the sum of benefits from each policy alone[22]. Our consideration of policy interactions is guided by an interdisciplinary policy mix evaluation framework (Table 1)[19], where the addition of a given policy to a policy mix can incrementally impact (negatively or positively):

- Effectiveness, or the net impact on GHG mitigation (our present priority)
- Cost-effectiveness, meaning impacts on general social welfare (say, per tonne of CO_2e mitigated), as well as sub-components such as consumer utility, industry profits and government expenditure
- Political acceptability, which includes perceptions among the public or voters (in democratic countries) and stakeholders (especially industries with political clout)
- Transformative signal, which describes support for a long-term societal and technical push towards low-carbon systems (technology and practices)[23]

In the effort to have cohesion across policy goals, we add consideration of 'co-benefits' that may be supported (or negated) by par-

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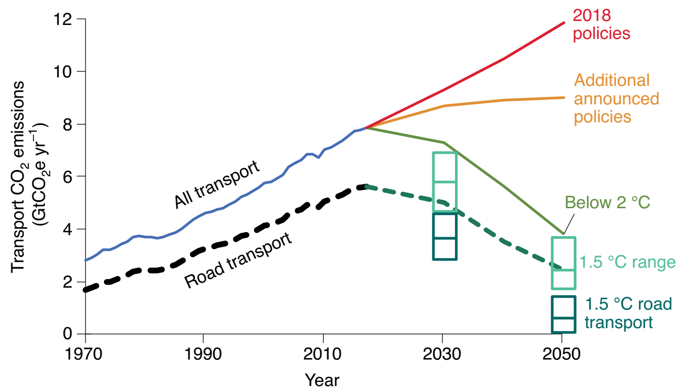

Fig. 1 | Historical and future global GHG emissions from transport. Lines represent global emissions from all transport modes (solid lines) and road transport only (dashed line). Historical values are indicated in blue and black, as well as the 2018 legislated policies (red), additional announced policies (orange) and well-below 2 °C scenarios (green) of the IEA. Small boxes show ranges of transport emissions compatible with 1.5 °C overshoot scenarios for all transport (green boxes) and road transport only (dark-green boxes). Figure based on data from refs. [4–6].

ticular climate policies—such as improving public health (through reduced pollution or increased physical activity), equity or economic activity—or reducing congestion. Such co-benefits might also improve the cost-effectiveness or political acceptability of the policy mix.

A wide range of policies can potentially reduce GHG emissions in the transport sector. Here we consider the identity used by policymakers in California and elsewhere[14], which breaks down total transportation GHGs into three mitigation measures (top of Fig. 2): (i) switching to low-carbon fuels (reducing grams of CO_2-equivalent, or $gCO_2e\ MJ^{-1}$), (ii) improving vehicle efficiency (reducing $MJ\ km^{-1}$) and (iii) reducing vehicle travel (fewer vehicle km, either from mode switching or reduced travel activity). This framework allows comparison of the focus and comprehensiveness of the policies we consider, namely: pricing mechanisms (which can induce a wide variety of mitigation actions), regulations that target specific pathways (low-carbon fuels, zero-emissions vehicles (ZEVs) or more efficient vehicles) and other policies aiming to reduce vehicle travel (including incentives and infrastructure relating to the built environment, active travel and public transit). We do not explore research and development (R&D) subsidies and information provision programmes, as these are unlikely to deliver deep GHG mitigation alone, though they might play complementary roles in a strong, integrated policy mix.

Pricing as the complement, not the Silver Bullet

Pricing is considered by many economists to be the ideal climate policy mechanism due to potential effectiveness and efficiency. A carbon price is technology-neutral, allowing each rational consumer or firm to choose the lowest-cost mitigation option, be it low-carbon fuels, efficiency or reduced travel, or simply to pay the tax and continue with the status quo[24]. Among pricing mechanisms, more research has focused on carbon taxes for the case of road transport, though there are some proposals and explorations of cap-and-trade systems, another form of pricing with the potential for similar efficiency benefits[15,25,26].

Pricing can indeed play a strong role in deep GHG targets—if the price is high enough. The High-Level Commission on Carbon Prices indicates that Paris Agreement goals require carbon pricing in the range of US$40–80 per tonne CO_2 by 2020, and US$50–100 per tonne CO_2 by 2030 (ref. [27]). Modelling suggests that a price-based mitigation strategy may need to reach well over these ranges by 2040 and 2050 (refs. [28,29]). Further, while carbon and fuel pricing can help to modestly increase the fuel efficiency of the light-duty vehicle fleet[30,31], consumers are found to systematically underestimate fuel savings when making a vehicle purchase and tend to have an inelastic response fuel price changes[32]. That said, consumer response is particularly uncertain in the long-term[33], where responses to taxes may be stronger (more elastic) than responses to changes in fuel prices through other means[34–36].

In any case, pricing mechanisms presently exist in regions that account for only 20% of global GHG emissions[37]. Examples of stringent pricing are scarcer still—less than 5% of those priced emissions are at levels consistent with Paris Agreement goals, with the few examples being Sweden (US$127 per tonne), Switzerland (US$96), Finland (US$70), Norway (US$59) and France (US$50)[37]. About half of pricing initiatives are below US$10 per tonne[37].

The concept of road (or mobility) pricing is related and can include carbon pricing and fuel taxes, but more often refers to cordon pricing (a charge to drive into a particular area), congestion-based pricing (higher prices at peak times), distance-based pricing (such as 'pay as you go' insurance plans) and parking prices. Although road pricing policies are often focused on congestion reduction or raising funds for transportation management, they can also cut CO_2 emissions by 2–13%[38] and vehicle travel by 4–22% if implemented over decades[39]. Across the different design types, road pricing schemes are most effective at CO_2 mitigation if based on travel or fuel consumption rather than congestion reduction or other goals[38,39].

Although pricing mechanisms can have a substantial impact on GHG mitigation, we argue they are not likely to take the lead in successful policy mixes for two main reasons. First is the challenge of political acceptability, where pricing evokes more public debate and opposition than other climate policies[40–43]. While there is evidence that opposition can be somewhat overcome through careful design (such as revenue recycling)[44,45] and through clear, positive framing about the price's goals and potential benefits[46,47], it seems that strong taxes will remain a political challenge. Second, carbon pricing alone does not address other market or 'system transformation' failures that prevent transitions to low-carbon technologies, such as knowledge spillover effects and infrastructural failures[23,29].

Thus, pricing is better thought of as a complement to other strong climate policies. Studies show that the addition of pricing to efficiency regulation in a policy mix can help to reduce mitigation costs, in part due to co-benefits such as reduced congestion, accidents and air pollution as well as lessening rebound effects from efficiency improvements[15,16,48]. Thinking more long-term, pricing can mitigate the anticipated rebound effects from cheap travel offered by future transport innovations, namely electrification, automation[49] and ride-hailing[50]. We also note the potential for further exploration of cap-and-trade systems for road transport due to the potential for such a mechanism to have the effectiveness of a carbon price[25] while being more publicly acceptable[41]; however, proposed systems to date seem unrealistic due to administrative complexity.

Fuel-switching regulations can lead the mix

Turning to more technology-specific policies, we start with the broad category of low-carbon fuels and vehicles. 'Fuel-switching' is the goal of moving away from the dominant fossil fuels used in transportation (gasoline and diesel) to lower-carbon replacements, namely electricity, hydrogen and biofuels (each from low-carbon sources). Policies in this category can target changes to the fuel directly or support or require the uptake of vehicle drivetrains that use low-carbon fuels, namely plug-in hybrid vehicles, battery electric vehicles or hydrogen fuel-cell vehicles—often collectively referred

Table 1 | Framework for evaluation of climate policy interactions in road transportation

Policy interaction criterion	Explanation	Quantitative measure	Sub-components
Effectiveness at GHG mitigation	Does the policy lead to additional GHG mitigation?	Tonnes of CO_2e abated in a given year; for example, 2030 or 2050 (ideally well-to-wheel or full Life Cycle Analysis).	Can be evaluated in aggregate or split by: 1. Carbon intensity of fuel ($gCO_2e\ MJ^{-1}$) 2. Vehicle efficiency ($MJ\ km^{-1}$) 3. Vehicle usage (VKT)
Cost-effective	Does the policy help the policy mix to achieve the GHG target at the least cost to society?	US$ per tonne of CO_2e abated, or welfare.	Can be evaluated in aggregate (total social welfare) or broken down; for example, by: 1. Consumer utility 2. Industry profit 3. Government expenditure 4. General equilibrium impacts
Political acceptability	Does the policy improve (or worsen) the political acceptability of the policy mix?	Not as clear. Percentage of citizens or stakeholders that support or oppose the policy? Directly ask the perceptions of the policymaker?	Can be split between citizens and special interest groups. May need to focus on interest groups with particular clout in a particular context (for example, automakers in a region with more auto-related manufacturing).
Transformational signal	Aside from the above factors, does the policy provide an added 'push' in transition towards the low-carbon goal?	Unclear. Specific measures could be US$ invested in R&D activity or number of patents or prototypes per year. Infrastructure can be measured by density (relative to gasoline or diesel equivalent). Requires qualitative measures to provide a complete picture.	Can draw from Weber and Rohrachers's qualitative framework[23], including: 1) Signal for R&D investment 2) Provision of physical infrastructure 3) Break 'lock-in' 4) Pathway directionality

Adapted from ref. [19].

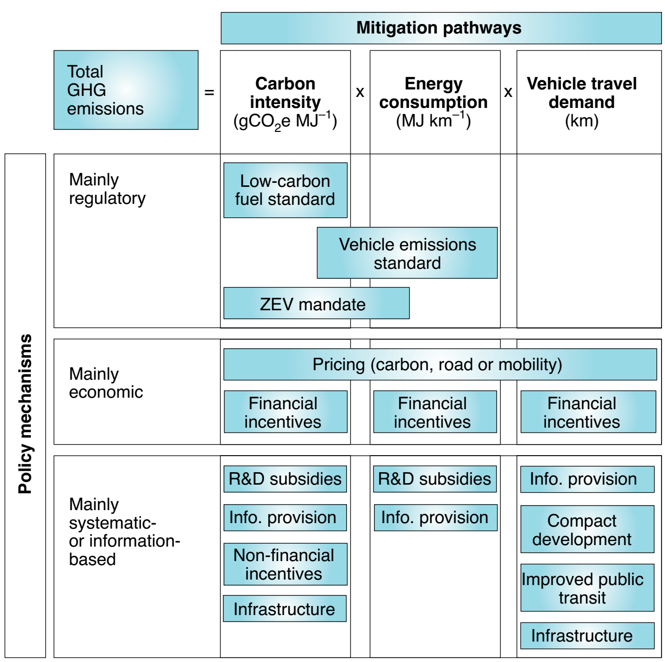

Fig. 2 | Categorization of road transport policies summarized in this paper. The *x*-axis is divided by mitigation pathway, being carbon intensity, energy consumption or travel. Some policies address multiple pathways. The *y*-axis categorizes policies by basis in regulation, economic incentives or disincentives, or systemic impacts.

to as ZEVs. From a well-to-wheels perspective, ZEVs reduce GHG emissions compared to conventional and hybrid vehicles in many present and future scenarios in most regions globally[51–54]. For this reason, the IEA organized the Clean Energy Ministerial's EV30@30 campaign to promote the goal of ZEVs accounting for at least 30% of new light-duty vehicle sales by 2030 (ref. [55]).

We consider several regulatory approaches that support ZEVs in addition to incentive-based approaches. Most of the ZEV literature focuses on four-wheelers for developed countries, though in some developing countries, electric two-wheeler vehicles in particular might be more appropriate and affordable[56].

Low-carbon fuel standard. This policy focuses on reducing the carbon content of the fuels used to power transportation ($gCO_2e\ MJ^{-1}$). In response to concerns about 'renewable' fuel requirements leading to higher GHG emissions, California pioneered and implemented the first low-carbon fuel standard (LCFS) in 2007, requiring fuel suppliers to reduce the lifecycle carbon intensity of transportation fuels sold in the state by 10% by 2020 (ref. [57]). The policy assigns well-to-wheel emissions factors for each fuel type (including ethanol, biodiesel, electricity and hydrogen) made from different feedstocks or sources. Compliance credits are tradeable among fuel suppliers (including electric utilities), which aims to improve the economic efficiency of compliance[57]. Versions have since been implemented elsewhere in the USA, the EU and Canada, and there seems to be a high level of public support in at least some regions[58]. The most stringent version is in British Columbia, Canada, requiring a 20% reduction in carbon intensity of all fuels sold by 2030 relative to 2007 levels.

To date, such policies have been shown to successfully send a substantial transformative signal, driving innovation activities for low-carbon fuels and increasing the market share of low-carbon alternative fuels[57]. Model simulations suggest that an LCFS could play a large role in GHG mitigation if implemented to require (well-to-wheel) carbon intensity reductions of 40–75% or even greater by 2050 (refs. [59,60]). Though, as will be noted further, an LCFS can have important interactions with electric vehicle-focused policies.

ZEV mandate. A ZEV mandate targets automakers by requiring sales of a certain amount (or market share) of ZEVs. Pioneered by California in 1990, versions have since been adopted in ten other US states, two Canadian provinces and China as a nation. Most versions require around 15% ZEV new market share by 2025. Compliance is enforced with a strong financial penalty, and, like the LCFS, efficiency is somewhat improved through the trading of compliance credits among automakers. British Columbia's version has the highest stringency and longest time horizon, requiring 30% ZEV sales by 2030 and 100% sales by 2040.

California's ZEV mandate (which has the longest history and thus is the best source of data) has been shown to send a strong transformative signal, effectively channelling innovation activities towards ZEV development[61,62] and increasing the availability of ZEVs for sale[63], where supply constraints have proven to be a major barrier to widespread uptake[64–67]. Several forward-looking modelling studies indicate that a stringent ZEV mandate can play a strong role in GHG mitigation in the USA[68–70], Canada[60,71] and China[72]. To do so, it would likely need a requirement of at least 30% ZEV sales by 2030, and 50% or greater by 2040 (ref. [71]). Notably, a ZEV mandate can have strong interactions with other regulations, potentially reducing the additive mitigation impact of a low-carbon fuel standard[60] or vehicle emissions standard (noted below).

Internal combustion engine car bans. Relatedly, car bans prohibit the sale or use of conventional internal combustion engine (ICE) vehicles in a given region—thus allowing only ZEVs for sale or use[73]. Although more than a dozen regions have announced some sort of ICE car ban over the past few years, we caution that most merely state targets without mechanisms of enforcement[73]. To be effective in GHG mitigation, such a ban would need to: (i) apply to the sale of gasoline, diesel and conventional hybrid (non-plug-in) vehicles; (ii) specify a start year; and (iii) include strong financial penalties for noncompliance. As an example, British Columbia's legislated ZEV mandate (noted above) provides one of the only true ICE bans, as it requires 100% ZEV sales by 2040 with large financial penalties for non-compliance. There has been comparatively little research on ICE bans, though we suspect that such policies will tend to score lower on cost-effectiveness and political acceptability in most regions.

ZEV incentives (financial and non-financial). There are a wide variety of other policies that can induce ZEV uptake and GHG mitigation. Most common are those that incentivize ZEV sales through purchase subsidies (or exemptions from taxes), exemptions from tolls, access to high-occupancy vehicle lanes or bus lanes, or improved charging infrastructure[74,75]. Generally speaking, such incentives tend to have high public acceptability[41,76,77]. ZEV purchase subsidies can range from US$2,500–20,000 per vehicle, where larger incentives can indeed boost ZEV sales[66,78–81]. However, such incentives need to be in places for a long duration to have sustained GHG impacts[78,82], potentially for a decade or longer[66]. Purchase incentives are generally found to be a less cost-effective and potentially inequitable policy, though such impacts can be improved through various design principles, such as putting caps on retail prices for eligible ZEVs and caps on household incomes for those receiving the subsidy[80].

'Non-financial' incentives, such as access to high-occupancy vehicle lanes for ZEVs (regardless of vehicle occupancy), are typically found to have a weak impact on long-term ZEV adoption[75,76]. The rollout of charging infrastructure can also weakly support the adoption of electric-powered vehicles, where improved home charging opportunities in particular have a larger impact than increased public- or work-based charging[75,83–85].

As one particular exception, Norway currently achieves the highest ZEV new market share in the world (more than 50% of sales) using a variety of incentives (with many in place for over a decade), including what amounts to an enormous purchase incentive (exemptions from taxes of €10,000–15,000 per vehicle), toll exemptions and bus lane access, along with the carbon tax noted above[86]. Of these measures, the purchase tax exemption has had a particularly large impact due to its uniquely high value and long duration[87,77]. To date, Norway is unique in having the capital and political will to sustain such a policy mix.

Strengthen vehicle emissions standards, cut the loopholes

Vehicle emissions standards set a minimum performance requirement on fuel consumption and/or tail-pipe CO_2 emissions for newly sold vehicles ($gCO_2e\ km^{-1}$). For example, in 2009, the USA amended its vehicle emissions standards to require GHG reductions in new vehicles of about 5% per year from 2017 to 2025 (ref. [88]). Many other countries and regions have implemented their own versions for light-duty vehicles, including Brazil, Canada, China and the EU (Fig. 3)[89]. Design features tend to be similar across countries, with strong penalties for non-compliance and variations in requirements by vehicle size based on mass or footprint.

Many of the current emission standard designs are helping to reduce GHG emissions and will continue to do so in the future. Most ambitious is the EU 2030 requirement of 59 $gCO_2\ km^{-1}$, which is expected to lower well-to-wheel GHG emissions from cars by 40% in 2030 compared to 2010 (ref. [90]). A more stringent version could cut GHG emissions by 88% by 2050 (ref. [91]). Canada's current 2025 emission requirements can reduce 2030 GHG emissions from each light-duty vehicle (on average) by up to 35% compared to 2015, and a more stringent design could cut 2030 emissions by 50% and 2050 emissions by 60%[71]. Unfortunately, both the USA and Canada have recently considered freezing their emission requirements at 2020 levels, which could increase light-duty vehicle emissions by about 20% in 2030 (compared to 'holding firm' to the current policy) and by 45% in 2050 (ref. [92]). Due to long time lags of vehicle stock turnover (with vehicles lasting 15–25 years), the impacts of a freeze are especially detrimental in the long-run[93].

Despite the relative success of vehicle emissions standards to date, they come with a number of drawbacks. To start, the focus on improving vehicle efficiency (rather than usage) can lower operation costs and induce rebound effects (increased usage, in terms of vehicle km travelled (VKT)) that could cancel out a proportion of GHG benefits[94]. In most versions, there are also a number of design 'loopholes'—that is, compliance mechanisms or strategies that ultimately reduce policy effectiveness[89], including various 'gaming' tactics[95]. One well-known problem is that these standards are more relaxed for larger vehicle classes, which may incentivize automakers to put more effort into marketing and selling such vehicles—for example, the emergence and dominance of sport utility vehicles and 'crossovers' in many developed countries[96]. Second, in current standards, credits are also earned through sales of ZEVs and other alternative fuel vehicles, typically favouring ZEVs beyond their actual well-to-wheel GHG benefit. Third, relatedly, there can be general overlap between emissions standards and a ZEV mandate, where compliance with a mandate may reduce the overall effectiveness of a vehicle emissions standard that offers extra compliance credits for ZEV sales[97,98]. Fourth, measurement protocols for tail-pipe emissions are often inaccurate, where the difference between test cycle and actual emissions can be up to 40%[99,100]. Finally, ramping up emissions standards can increase the cost of future vehicles, encouraging consumers to hold on to used, less-efficient vehicles for longer, potentially eliminating 13–16% of the expected fuel savings[101].

However, vehicle emissions standards can play a key role in a successful policy mix due mainly to their demonstrated effectiveness, public acceptability[41] and ability to channel innovation into low-carbon technologies[102]. We advise that current vehicle emission standards be strengthened with schedules for more ambitious reductions beyond 2030. Each of the above noted drawbacks can be mitigated through careful design of the regulation itself as well as other policies in the mix. Rebound effects can be at least partially addressed through carbon or road pricing[15,41]. Emissions test protocols can be improved in accuracy, and credit systems can be

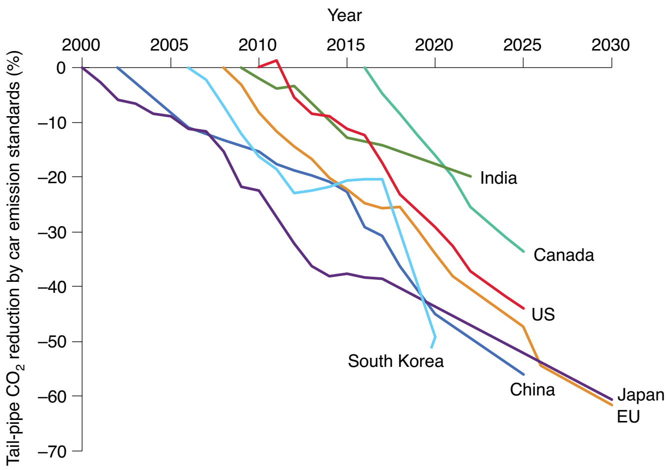

Fig. 3 | Tail-pipe CO_2 reductions from emission standards for passenger vehicles in several major countries. Lines represent authors' calculation based on the ICCT[154].

altered to avoid unduly favouring ZEVs, larger vehicles or other technologies that diminish GHG effectiveness. Further, policymakers that implement multiple regulations in the same region will need to carefully consider interaction effects, especially relating to a ZEV mandate and LCFS. Finally, developing countries that implement standards will want to carefully adapt such policies to their own context rather than uncritically borrowing features from developed countries[103].

The complementary benefits of travel reduction

We consider four sub-categories of travel reduction policies: (i) support of active travel (cycling and walking), (ii) improvement of public transit, (iii) changes to the built environment (or compact development) and (iv) reducing the need for travel. The literature on long-term GHG impacts from VKT policy is relatively under-developed, making it difficult to directly compare with efficiency and low-carbon fuels policies.

Our interpretation of the available literature is that such measures are not likely to achieve deep GHG mitigation targets on their own, though effectiveness can be boosted if the policy mix includes stringent road pricing[39,104–106]. Travel reduction policies can play important, complementary roles in an integrated policy mix, including provision of numerous co-benefits and mitigation of rebound[107,108] effects from efficiency policies and low-carbon technologies. Further, GHG benefits may be greater in growing cities in the developing world, where investment in travel reduction can help to attenuate the expected growth in vehicle ownership and usage[109,110].

The first subcategory, 'active travel', offers substantial health benefits to most populations[111]. Among developed countries, active travel can account for as few as 12% of trips (in the USA), and up to 44% (in the Netherlands)[111]. In some cities, the mode share of bikes can be increased through a mix of policies, including infrastructure improvements, safety measures and information campaigns[112–114]. Yet, other contextual factors can limit the potential for active travel, including climate, altitude and city size[115]. Several North America-based studies indicate that strong active travel measures could serve to offset expected growth in emissions rather than yielding a net decrease[116–118]. On the other hand, a modelling study of Albuquerque, New Mexico, suggests that increasing cycling mode share to 20% can play a substantial role in a land-use policy mix that would achieve 40% GHG reductions; however, the authors admit that such a mode share might not be achievable[106]. The rapid emergence of electric bikes, as well as bike and scooter share programs, might change the potential for GHG reductions from active travel[119], though the magnitude of impact is unclear.

Second is public transit development, which in practice tends to be motivated by a variety of goals, including: alleviating traffic and parking congestion; enhancing mobility options, access or equity; reducing traffic accidents; reducing energy use and air pollution; and, often of lower priority, GHG mitigation[120]. Depending on the goals of transit agencies, improved transit holds the potential to reduce vehicle ownership and vehicle travel, and transit-oriented development has the potential to reduce VKT in auto-oriented regions[121–123]. Other studies indicate that the GHG impacts from public transit investment alone tend to be weak[39,108,124,125]. Though, from an interaction perspective, transit is likely to complement road pricing, enhancing its ability to reduce vehicle travel[126,127].

Third, improvements to the built environment (also known as compact development, smart development and smart growth) shape the energy use and transportation patterns of inhabitants. Although denser neighbourhoods are associated with fewer vehicle kilometres, it is difficult to tease out cause and effect. Trying to account for such endogenous factors (for example, residential self-selection and demographic characteristics), one study indicates that the built environment can explain 12% of variance in household vehicle travel[128]. Systematic reviews indicate that built environment strategies can impact vehicle travel in the long-term, though these impacts tend to be weak individually[39,129,130]. Vehicle travel reduction potential is low when population density and destination diversity are increased, and relatively larger (but still low) when destination accessibility is improved (shorter distance to downtown and improved job accessibility)[114]. As with public transit, the long-term impacts of increased urban densification are unlikely to offset the expected increase in GHG emissions by 2050, let alone contribute to a net reduction; however, the inclusion of pricing policies could improve the impact[105]. More research is needed to better understand interactions among numerous VKT-impacting policies[131]. Other studies point to the complexity of impacts, which can vary strongly by type of neighborhood[119,122,132] and can be non-linear—in some cases only being effective in VKT reductions once certain thresholds are reached[133,123].

The final category is reducing the need for travel via fewer and shorter journeys. In addition to the mode switching and built environment strategies noted above, travel reduction can be achieved through increased uptake of home-based working and education as well as online deliveries that replace shopping trips. There has been extensive work on telecommuting or teleworking in particular, where a recent systematic review finds at best 'modest' net energy savings[134]. While telecommuting could cut the number of work-based trips, it could also lead to increases in acceptable commute distances (living further from the workplace), other vehicle travel and home energy consumption[135]. Online shopping also has mixed potential, as it can help to reduce vehicle travel but also may increase air pollution from the diesel vehicles used for delivery[136]. Some see hope in the extreme travel reductions induced by recent COVID-19 physical distancing protocols, which have led to increased home-based work and education while reducing demand for extraneous trips (for example, holiday travel). However, even in these extreme (and temporary) lockdown situations, overall transport activity fell only by about 50% in the most restricted regions[137]. While it is unclear if efforts to reduce travel activity will have long-term effectiveness in GHG mitigation, it seems likely that such measures would prove complementary to road pricing initiatives in particular.

In summary, active travel, public transit, changes in the built environment and reducing the need for travel can contribute to deep GHG mitigation in transport, as well as reducing vehicle ownership and usage. The impacts of individual policies and strategies seem to be modest, though particularly strong policies might be more effective, and integrated policy mixes even more so. In any

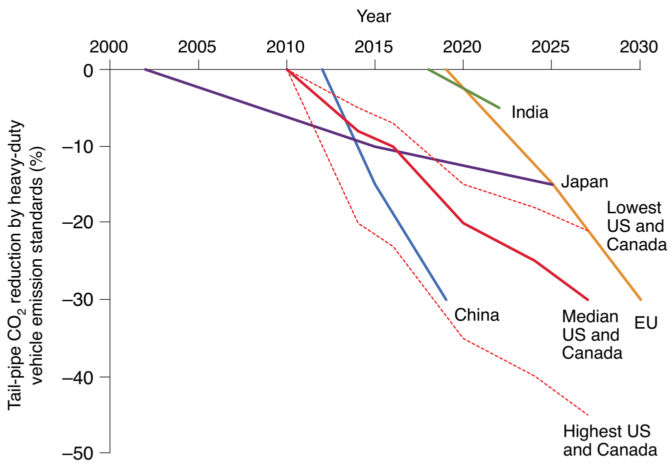

Fig. 4 | Tail-pipe CO_2 reduction required by heavy-duty vehicle emission standards relative to baseline in several major countries. Levels of ambition vary between vehicle types in the US and Canada. Authors' calculation are based on data from the ICCT[155].

case, VKT reduction measures are not substitutes for strong regulations or pricing mechanisms.

Don't forget road freight

Relative to passenger travel, there is much less research and policy focus on freight, though it accounts for about 40% of CO_2 emissions from road transport globally[138] and can be a major contributor to urban air pollution due to its reliance on diesel[139]. Mitigation pathways for freight can be conceptualized in a similar way to passenger travel, including switching to low-carbon fuels, improved vehicle efficiency and mode switching (from trucks to rail or to marine). Reductions in freight activity would also be effective, though this is especially controversial due to the apparently tight coupling of road freight and economic growth[140,141]. Freight may also be more complicated than passenger vehicles (and thus more difficult to regulate) as there is a wider range of vehicle types, loads and usage profiles (for example, short-haul versus long-haul freight and various vocational uses for trucks). Relatedly, the most viable options for low-carbon fuels and vehicles in the freight sector seem to vary widely by usage[142–144]. Examples include: heavy-duty battery electric vehicles (>3.5 tonnes gross vehicle weight) may be better for shorter distance vehicles (delivery vans and trucks, and refuse trucks) and regional delivery; electric catenary vehicles might work better for medium- to heavy-duty trucks and drayage trucks; and hydrogen might be better for long-haul operation[138,142,143].

Current freight mitigation policies in most regions are relatively weak[103,138,145], including many voluntary information provision programs[146] as well as R&D subsidies, and some deployment of charging and fuelling infrastructure[138]. There is more promise in recent heavy-duty vehicle emissions standards introduced in several markets, including the EU, the USA, Canada, China, Japan and India (Fig. 4)[147,148]. Required reductions range from 5–30% tailpipe GHG reductions in newly sold vehicles over 5–20 years, with around a 5% reduction per year in the most ambitious cases. We calculate that the more stringent standards (in the USA and EU) can reduce tail-pipe emissions by about 10–20% by 2030. However, due to the limited coverage of these policies (applying to only certain types of heavy-duty vehicles) and large variations in stock turnover of heavy-duty vehicles, these standards are likely to be less effective than the more comprehensive passenger vehicle emissions standards.

Many of the policy mix principles identified for passenger transport apply similarly to road freight. First, carbon or road pricing could efficiently incentivize a range of freight mitigation actions if the price is high enough. Second, the LCFS policies in place in North America apply to fuels used by freight vehicles, and modelling suggests that a stringent LCFS might have an even larger mitigation impact in the freight sector than for passenger vehicles[60]. Third, modelling suggests that a ZEV mandate for heavy-duty vehicles could play a strong role in freight mitigation[144]. California has recently implemented the first such policy, requiring 40–75% of new truck sales to be ZEVs by 2035 (requirements vary by vehicle class)[149]. Fourth, the vehicle emissions standards noted above could be strengthened, mainly by covering more vehicle types with more stringent reductions, requiring at least 5% annual reduction. Taken together, as with passenger vehicles, an integrated policy mix is required to reach mitigation targets for freight. For example, one study demonstrates that even with a doubling of freight activity, GHG emissions can by reduced by 60% from current levels through a stringent policy mix with mechanisms to increase vehicle efficiency, optimize operations and support various low-carbon fuels[145]. However, because an effective policy mix will inevitably increase the cost of freight activity and potentially limit growth in economic activity, there is likely to be continued political opposition in many regions.

Crafting effective policy mixes in the real world

We do not see evidence that any single policy alone can (or should) achieve 2030 or 2050 mitigation targets for road transport. Strong, integrated policy mixes are needed, not just to reduce GHG emissions, but also to optimize other, often more difficult to quantify, attributes, namely co-benefits, cost-effectiveness, political acceptability and transformative signal. Given the importance of such mixes, more policy discussion and research needs to consider such interactions, in particular the optimal combining of regulations, pricing mechanisms and VKT reduction strategies. Such a mix needs to be effective with reasonably low costs while maintaining enough political acceptability to be implemented in the first place, and maintained in the long-term. Further, there is need for exploration of the subtleties of policy design, such as what design features can avoid unintentional side effects or negative interactions across policy mixes.

We emphasize several regulations that can play lead roles in policy mixes for many countries and regions due to their potential effectiveness and political acceptability. First, an LCFS can send the transformative signal to switch to alternative fuels that effectively reduce well-to-wheel emissions for both passenger and freight vehicles. Second, a ZEV mandate can push the uptake of electric-powered passenger vehicles; British Columbia (Canada) provides the strongest example. ZEV mandates should also be more actively considered for freight, drawing inspiration from California's recent policy. Third, current vehicle emissions standards for passenger vehicles in several countries (including the EU and Canada) are likely to produce substantial GHG mitigation. These standards provide a platform for even stronger reductions in the future, and, at the very least, existing standards should be maintained at their current level (avoiding the 'rollback' occurring in the USA). Taken together, these three regulations need to be carefully designed to avoid loopholes such as undue favouritism for ZEVs or larger vehicles while avoiding negative interactions across policies.

We argue that pricing mechanisms are best viewed as playing a complementary role in an integrated policy mix. In particular, the addition of carbon taxation has been shown to improve the efficiency of a regulation, especially by mitigating rebound effects from reduced travel costs induced by a vehicle emissions standard or ZEV mandate. Further, pricing can greatly improve the effectiveness of other VKT reduction policies relating to mode switching and the built environment while producing valuable co-benefits, such as reducing congestion and improving public health. Of course, the stringency of pricing is more likely to be limited by political acceptability rather than any calculation of optimality.

Similar to pricing, we view the other VKT reduction policies as complementary measures. There is considerable uncertainty about the long-term impacts of such policies, though GHG mitigation is likely to be relatively low unless stringent pricing is included[104,105]. But the co-benefits of VKT reduction are quite compelling: increased active travel offers clear health benefits, improved public transport can improve access and equity, and improvements to the built environment can support both (albeit at a typically slow rate).

Another important theme is that transport policies vary widely by country or region; even those with some mitigation success have followed quite different approaches. Norway has developed a unique and powerful strategy to support ZEVs through a combination of incentives and tax exemptions complemented by a high carbon tax. California has pioneered a very different policy mix driven largely by regulations (LCFS, ZEV mandate and vehicle emissions standard) and complemented by financial and non-financial incentives for ZEVs. Either approach can be effective—both regions have had success in stabilizing transport emissions. Though, different strategies may better suit a particular regional and technical context. For example, simulation modelling indicates that a 'Norway-like' strategy would not be as effective if replicated in North America due differences in baseline vehicle demand[67]. Relatedly, stronger carbon pricing might be more politically acceptable in some regions, such as some Nordic countries, and less acceptable in others, such as North America—suggesting that each region may have different levels of 'political allowance' for pricing. There are likely to be even more striking differences in how a successful, integrated policy mix should look in a developing country—this is an area needing substantially more research.

While this Perspective takes a long-term focus, it has omitted explicit mention of several 'new mobility' innovations that may become even more prominent in the coming decades, including ride-hailing and shared vehicle systems (for cars, bikes or scooters), as well as the potential for vehicle automation[150]. Several modelling studies demonstrate the potential for dramatic energy and GHG reductions from a fleet of shared, automated electric vehicles, albeit under idealized conditions[151–153]. More helpfully, a boundary analysis shows the enormous uncertainty, where, depending on assumptions, impacts could range from a doubling to a halving of GHG emissions[49]. Despite these uncertainties, we believe our policy recommendations remain valid. In fact, a strong, integrated policy mix may be the best way to improve certainty regarding net GHG impacts. Requirements to improve efficiency, switch to low-carbon fuels and improve the built environment and support VKT reduction will still produce benefits in scenarios with widespread shared and/or automated mobility, and pricing mechanisms will remain as the most direct way to disincentivize GHG emissions. Particular VKT reduction strategies may become even more important in such scenarios; for example, where improving the built environment might be necessary to avoid exacerbating suburban sprawl in a scenario of widespread vehicle automation.

Our Perspective is shaped by numerous research gaps, including the already noted limitations in policy interaction research. We have omitted explicit consideration of city-level planning and policy, and more research is needed to understand interactions between the different levels of policy (regional, national, sub-national and city). Further, we did not explore the potential complementary role of information provision, behaviour change programs and R&D subsidies in a policy mix, where, again, more research is needed.

While numerous uncertainties remain, there is sufficient evidence to state that for most countries, deep GHG mitigation in the road transport sector requires implementation of strong, integrated policy mixes. We believe that efficiency and low-carbon fuel regulations are most likely to be successful in leading such policy mixes, where some forms of pricing and VKT reduction provide needed complementary benefits. Exceptions may exist, such as Norway's success to date in relying on the combination of strong pricing and incentive-based strategies for ZEVs. Moving forward, the task is inevitably challenging and needs regular review, consultation and updating over time (especially in the face of technical change). Future research can help to improve this process by helping to fill in many of the gaps identified.

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