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Reduce growth rate of light-duty vehicle travel to meet 2050 global climate goals

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Abstract
Strong policies to constrain increasing global use of light-duty vehicles (cars and light trucks) should complement fuel efficiency and carbon intensity improvements in order to meet international greenhouse gas emission and climate targets for the year 2050.

Keywords: transportation, sustainability

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Transportation systems require fundamental change to meet greenhouse gas (GHG) emission and climate reduction goals for the year 2050. International agreements have advocated limiting temperature increase to 2 °C or less [1, 2], which limits the total amount of carbon that can be moved to the atmosphere [3, 4]. Under plausible assumptions and emissions pathways, year 2050 global carbon dioxide (CO_2) emissions levels consistent with a 2 °C temperature limit can be close to 80% below year 2007 emissions [5]. Even greater emission reductions may be sought in sectors such as electricity generation and light-duty vehicle (LDV) transportation, given both their relatively large range of mitigation options [6] and their impacts for long- and near-term climate change [7, 8]. We show that reducing LDV emissions by 80% becomes much more feasible if policies and infrastructure are put in place today that ultimately reduce demand for LDV travel.

Reducing LDV emissions is often framed as a technological challenge [9, 10]. Low-carbon fuel standards aim to stimulate production of fuels that produce fewer GHGs per unit energy; vehicle efficiency policies aim to reduce the fuel used and emissions produced per distance traveled. However, by decomposing transport sector emissions into technological and behavioral drivers, we show that even significant technological advances will be insufficient to meet climate goals, unless the growth in LDV use slows or reverses. While policy options aimed to reduce the need for LDV travel typically receive far less attention than do technological measures [11], we find such demand avoidance options are likely essential to meeting mid-century GHG reduction goals [12, 13].

Emissions from LDV fleets are rapidly increasing in many emerging economies and already account for about 6% of total global CO_2-eq emissions (or about 45% of the transport sector's emissions). As much current research suggests that 'limiting (climate change) impacts to acceptable levels by mid-century and beyond' will likely require an 80% cut in global emissions by 2050 (relative to 1990), we set our 2050 LDV emissions targets at this level [14]. Assuming 9 billion people in 2050, these targets imply per capita annual LDV emissions of only 50–100 kg CO_2-eq (see tables S3–S6 available at stacks.iop.org/ERL/6/024018/mmedia). This range, today seen only in the world's poorest countries, would need to be the global average while providing dramatically better services. Some developed countries (e.g., the US) have LDV emission rates 30–60 times higher than this target. Many other countries with historically low vehicle ownership (e.g., India and China) are rapidly motorizing, increasing such emissions by more than 5% yr^{-1}.

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When considering the prospect of rapidly increasing LDV use, the Stern Review (Economics of Climate Change) found:

> ... at the global level, in the absence of policy interventions, the long-run positive relationship between income growth and emissions per head is likely to persist. Breaking the link requires significant changes in preferences, relative prices of carbon-intensive goods and services and/or breaks in technological trends. But all of these are possible with appropriate policies [15].

We concur with this assessment, and here lay out a set of interrelated targets needed to achieve low-carbon mobility.

We find that innovation in a single area such as fuel economy does not offer a realistic, affordable, or resilient pathway to the LDV emission reductions necessary by mid-century. Instead, as social, technical, and infrastructural drivers of LDV GHG emissions interact multiplicatively, the responsibility should be spread over a portfolio of achievable improvements across the transport system. The following analytic decomposition identifies five potential areas for improvement:

$$\bar{C} = \underbrace{(C/E \times E/V)}_{\text{LDV propulsion GHG intensity}} \times \underbrace{(V/D \times D/T \times T)}_{\text{Per capita LDV transport use}}. \qquad (1)$$

In this equation, the per capita LDV GHG emission rate ($\bar{C}$) is expressed as the product of two sets of variables representing the GHG intensity and per capita rate of LDV use. Current policy discussion is dominated by attention to the first set, propulsion GHG intensity (g CO_2 VKT^{-1}, where VKT is vehicle-kilometers traveled). This set can be improved by decreasing fuel carbon intensity, C/E (g CO_2 MJ^{-1}), and decreasing energy intensity, E/V (MJ VKT^{-1}). The second set, representing LDV use, has three components, offering three broad strategies for improvement: increasing the vehicle occupancy rate, here expressed as its inverse (V/D) (VKT PKT^{-1}, where PKT is person-kilometers traveled); decreasing the mean per-trip distance D/T (PKT $trip^{-1}$); and reducing the per capita trip rate T (trips yr^{-1} $person^{-1}$). In principle, the analytical relationship in equation (1) can be extended to encompass mode shifting. However, for the purposes of illustration, we constrain our quantitative discussion to the LDV sector.

In order to quantify the CO_2 mitigation challenge for the transport sector, we surveyed 2007 LDV usage and fuel economy in an economically diverse set of countries (see figure 1, and tables S1 and S2 available at stacks.iop.org/ERL/6/024018/mmedia). We find that the large differences in per capita LDV GHG emissions (range: ~100–4000 kg CO_2-eq yr^{-1}) are principally explained by differing national per capita LDV use (range: 300–13 000 VKT yr^{-1}), rather than by fleet average fuel efficiency and carbon intensity factors, which reflect broadly similar car technology worldwide. In upper-income countries, intensive LDV use results in present-day emissions that exceed the 2050 target range of 50–100 kg CO_2-eq yr^{-1} by a factor of 10–80.

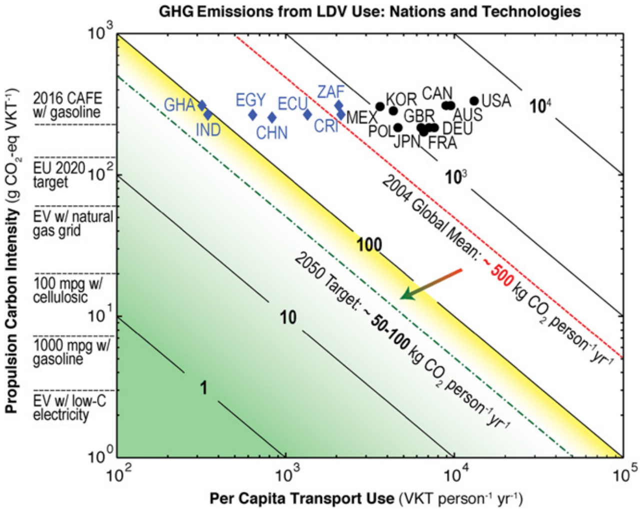

Figure 1. Average per capita light-duty vehicle (LDV) transport CO_2 emissions (kg CO_2 $person^{-1}$ yr^{-1}) for a global sample of countries (2007) with a wide range of per capita incomes. Blue diamonds denote low-income nations, and black circles are medium/high-income OECD member states. Per capita transport CO_2 emissions are decomposed into the product of two terms affected by transport policy choices over the next 40 years: per capita LDV use (horizontal axis, veh-km $person^{-1}$ yr^{-1}) and propulsion carbon intensity (vertical axis, g CO_2 veh-km^{-1}); the text on the vertical axis highlights indicative vehicle standards and technologies. Any given per capita transportation CO_2 target can be met through combinations of policies to reduce propulsion carbon intensity (see figure 2) and/or vehicle usage (see diagonal isolines). Ambitious transport CO_2 targets (such as the yellow 2050 target region, roughly consistent with established 2 °C climate goals) require widespread deployment of extremely efficient vehicles and low-carbon fuels. In addition, even with a dramatic (~10×) reduction in propulsion carbon intensity, meeting such targets requires transport use substantially lower than currently typical of most industrialized countries. The 1000 mpg gasoline mark illustrates the exceptional demand that would be placed on propulsion technology in order to meet climate targets if 2050 global transport use were to converge to current high-income country levels. See tables S1–S10 (available at stacks.iop.org/ERL/6/024018/mmedia) for calculations, key to country abbreviations, and sources.

Global growth of per capita LDV use to levels on a par with contemporary high-income countries would likely be incompatible with climate goals. For example, with global per capita LDV use of 10 000 km yr^{-1}, GHG propulsion intensity would need to decline from current levels of ~300 to ~5–10 g CO_2-eq km^{-1} on a 'well-to-wheel' (WTW, fuel lifecycle) basis. As the matrix of vehicle technology options in figure 2 shows, this performance level would require universal deployment of one or more of the following clusters: electric vehicles (EVs) running on nearly zero-carbon electricity, cellulosic-biofuel-powered vehicles achieving 300 miles per gallon (mpg; 0.78 L 100 km^{-1}), or gasoline-fueled vehicles achieving in excess of 1000 mpg (0.24 L 100 km^{-1}). Such levels of performance exceed optimistic technology scenarios for the year 2050 [16, 17].

It is likely that 2050 climate targets will be feasible only with global implementation of robust policies to slow the growth rate of LDV VKT in low-income countries, and

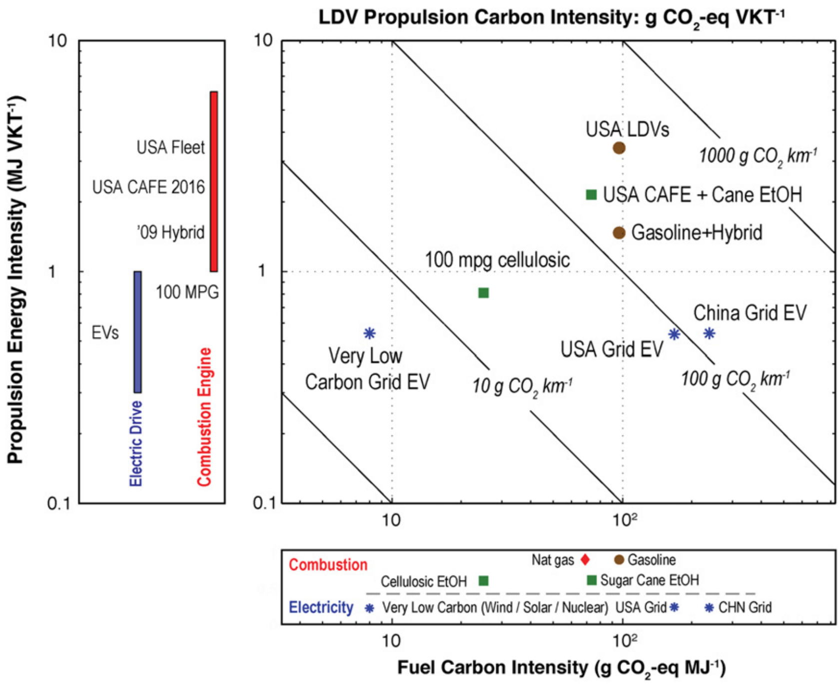

Figure 2. Light-duty vehicle (LDV) propulsion carbon intensity (g CO_2-eq veh-km^{-1}) decomposed into interacting effects of fuel types (g CO_2 MJ^{-1}, horizontal axis and box) and propulsion technology (MJ veh-km^{-1}, vertical axis and box). Isolines indicate combinations of fuel and propulsion technologies with equal well-to-wheel (WTW) GHG emissions. Few commercially available vehicle systems (fuel + vehicle) currently provide well-to-wheel mobility at less than 100 g CO_2 km^{-1}. In the medium term, combinations of low-carbon biofuels, clean electricity, and efficient electric or plug-in hybrid electric vehicles may offer WTW performance substantially below 100 g CO_2 km^{-1}. In the long term, dramatically lower LDV emissions may be possible given a sufficiently large supply of near-zero CO_2 electricity. See tables S7–S10 (available at stacks.iop.org/ERL/6/024018/mmedia) for calculations and sources.

reduce VKT in high-income countries [18]. For example, if global 2050 per capita LDV VKT instead converges at levels currently typical of middle-income countries such as Mexico (∼3000 km yr^{-1}), a per capita LDV GHG target of 100 kg CO_2-eq yr^{-1} could be met with medium-term technologies, such as 100 mpg (2.35 L 100 km^{-1}) plug-in hybrid electric cars fueled on a mix of cellulosic biofuels and low-carbon grid electricity. This strategy would require constraining the cumulative global PKT 2010–50 increase to 60% (1.25% annual growth) against the baseline projections of a 100% increase (1.8% annual, see table S11 available at stacks.iop.org/ERL/6/024018/mmedia). It would further require load factor convergence to around 1.65 persons per vehicle, typical of European averages in 2000. Our sensitivity analysis (table S11 available at stacks.iop.org/ERL/6/024018/mmedia) shows that even with a 85% reduction in GHG propulsion intensity (to ∼50 g CO_2-eq km^{-1}, ∼160 MPG on gasoline) over the next 40 years, per capita LDV GHG emissions (140 kg CO_2-eq yr^{-1}) would still exceed the target ceiling by 40% under current baseline estimates. It is important to note that these baselines already assume declining rates of PKT growth over the next 40 years.

Developed countries already have VKT-intensive infrastructure in place; adjustments would be incremental at first, undertaken jointly and over time. Consider for example a high-income country attempting to reduce LDV use from ∼10 000 to ∼3000 km yr^{-1}. The multiplicative effects of equation (1) suggest that a threefold reduction in LDV VKT can be achieved by coordinated policies. For example, reducing average trip length and frequency by ∼33% each while increasing the average load factor from ∼1.5 to ∼2 people per vehicle would be sufficient for the goal. While likely challenging, such efforts would not imply privation.

In fact, mid-range levels of LDV use can support a very high standard of living, given sufficient attention to urban planning and viable public or non-motorized ('alternative') transport. Citizens of Hong Kong, Seville, Turin, Valencia, Lisbon, Bologna, and Moscow use between 5000 and 11 000 MJ capita^{-1} yr^{-1} for travel through relatively compact development, with more than half of all trips taken by foot, bicycle, or public transport (assuming a 2.5 MJ VKT^{-1} ratio and the fact that only a portion of this energy is used in LDV travel, this range of energy expenditure indicates LDV use of 3000 km yr^{-1} or less). Meanwhile, in cities with higher personal vehicle use, such as Chicago, Houston, San Diego, or Washington, inhabitants use 44 000–86 000 MJ capita^{-1} yr^{-1}, with less than 16% of all journeys accomplished through non-motorized or public means [19].

The order-of-magnitude variation in per capita urban LDV energy consumption among this sample of high-income cities suggests that currently developing regions may have a wide range of potential infrastructure trajectories to choose from. LDV ownership is relatively low in middle- and low-income countries, with transport requirements met in large part through alternative modes (that may operate at inadequate service levels) [20]. Such nations can avoid the recent development trend of locking in VKT-intensive models [21], choosing low-carbon infrastructure choices that will enable cheaper and easier future abatement. Leaving aside climate considerations, wise investment in low-carbon mobility can also have compelling near-term co-benefits for air pollution, congestion, energy security, noise, aesthetics, economy, health, and equity [22–25].

Strategies for a less VKT-intensive trajectory over the next half century must contend with formidable obstacles. Fast, cheap personal transportation based on liquid fossil fuels was a cornerstone of 20th century economic growth. Personal mobility grew in lockstep with GDP [26]; in high-income nations LDVs became the dominant mode of personal transportation, with alternative transport's modal share declining almost everywhere [27, 28]. The US and its freeway system exemplify this trend: the share of trips on public transportation in US cities has shrunk to 3%, while LDVs account for 80–90% of personal travel [29]. This car-centered model has recently dominated international development, aided by financial support from multilateral institutions that privileged LDVs and road infrastructure over other forms of transport. Such well-established path dependencies in the global political economic system—especially institutional investment in autos and their infrastructure—will require policy aimed at several leverage points at once, in order to shift global transport from what might be thought of as a 'hard' to a 'soft' path (see Lovins, 1976) [30]. In short, the difficulty of getting people out of their cars corresponds to the degree to which economic and urban/inter-urban systems make cars an optimal solution.

Recognizing the latter, some cities (San Francisco, Milwaukee (US), and Seoul) have dismantled or declined to rebuild city highways as a way of revitalizing fading urban cores and shifting passengers to mass transit [31]. Many early local modal shift policies, such as those of Portland, Oregon (US), were attempts to enhance local energy and economic security in the face of 1970s oil price shocks [29]. Yet smart-growth policies that reduce the role of automobiles have been urged for nearly five decades [32] as a way of protecting neighborhoods and cities from the functional problems of auto infrastructure and associated low building densities. Such measures will likely have economic co-benefits: one recent study found the proportion of GDP allocated to citizen mobility ranges from 5% in average- to high-density areas with strong alternative transportation options to 12% in sprawling, auto-dependent areas [24].

The successful Transmilenio project in Bogota, Colombia provides a good example of a project that reversed expected sharp gains in VKT over the last decade, while earning GHG mitigation credits under the UN's Clean Development Mechanism. CO_2 emissions there cost \$13–\$66 dollars per ton eliminated, compared to \$148–\$3500 per ton for vehicle technology changes [27].

While the analytic decomposition above (equation (1)) helps identify the mix of high-level technical and social factors that influence LDV emissions, there are different policy levers for constraining VKT. Vehicle activity is not a single variable to be manipulated but emerges from the supply of, and demand for, travel. Technology policies focus on reducing emissions for a given intersection of supply and demand, while activity policies focus on moving this intersection. The LDV demand curve tends to shift outward as populations increase and less-developed nations become wealthier; this challenging trend can be opposed in two main ways. Policies that reduce the benefits from LDV travel—this includes providing better substitutes in the form of mass transit and urban design—tend to shift demand inward, as would policies that increase the cost of LDV propulsion. A carbon tax would not only shift the mix of technologies used to power LDVs, but would also tend to decrease the supply of LDV power at a given fuel cost. Finally, note that technology policies such as improved vehicle efficiency and cheap substitutes for oil tend to shift supply outward (technologies such as smart highways could also shift demand outward), which would counteract some of the gains produced by lower per-mile emissions.

In the United States, LDV demand-shifting goals would utilize four decades of innovation on long-term, transit-oriented land-use policy; new public transport options; and smart growth. Pricing policies, such as fuel carbon, parking, and congestion fees [33], also influence travel behavior—and can offset the social costs of congestion, pollution, and other externalities of LDV use. Steadily increasing fuel taxes have proven especially useful in many developed countries, for example Germany, in reducing VKT and encouraging automakers to increase fuel efficiency over time [34]. The United States, with some of the lowest fuel taxes in the developed world, seems ripe for such a measure; while many US economists see it as beneficial [35], political barriers are substantial. Yet both road pricing and subsidies for public transportation have been shown to produce substantial emissions gains (the evidence for driving restrictions is less clear) [36].

Reduction in the rate of LDV growth requires action at all levels of government. California's Senate Bill 375, enacted in 2008, provides an important example of forward-looking state policy, requiring regional transport planners to cut 5 million metric tons of CO_2-eq through integrated land-use planning—a small, but positive step [37]. Meanwhile, strengthening the mandate of municipal planning organizations (MPOs) or regional planning agencies is also vital. The ultimately unsuccessful American Clean Energy and Security Act of 2009 mandated an economy-wide 83% GHG reduction by 2050, yet relied on technological fixes—which we have shown to be insufficient by themselves—to meet this goal in the LDV sector. While the bill mandated MPOs make 'efforts to increase public transportation ridership' and the use of other alternative transportation [38], more concrete measures are needed. Hard annual and long-term modal shift targets for MPOs should be set. Innovative guidelines, such as a minimum 50% combined modal share for walking, cycling, and public transport in US cities for the medium term, would require policies that contain VKT. Such measures would also necessitate a strengthening and standardization of data collection on personal travel.

We have quantified the need for complementary policies required to achieve global climate targets in the light-duty vehicle sector. A truly unified framework would also account for freight interactions, technological options for mass transit, electricity sector emissions, and life-cycle assessments of LDVs and infrastructure [39]. It would also explore in greater detail the substantial co-benefits of lower LDV usage by assessing, for instance, reductions in urban air pollution [40]. It is crucial to develop the institutional capacity for this effort; to share tailored policy implications with national, regional, and local governments across the world; and to establish standardized data collection mechanisms necessary for global policy evaluation.

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