WORKING PAPER 20

PROSPECTS FOR FUEL EFFICIENCY, ELECTRIFICATION AND FLEET DECARBONISATION

GLOBAL FUEL ECONOMY INITIATIVE
FOR ZERO CARBON VEHICLES BY 2050

icct
THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

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INTRODUCTION

The Global Fuel Economy Initiative (GFEI) was founded in 2009 with the purpose of promoting and supporting government action to improve energy efficiency of the global light duty passenger vehicle fleet. The group developed and promoted a target of doubling passenger vehicle fleetwide fuel economy (halving passenger vehicle fuel consumption) by 2050 – known as "50 by 50" – relative to 2005 levels.[1] This 2050 fleetwide target, which assumed a halving of *new* vehicle fuel consumption by 2030, was achievable using existing, cost effective fuel economy technologies as well as full hybridization, but did not require plug-in hybrid or full electric vehicles (EVs). In the following decade, continued policy and technology developments have resulted in increased availability of cost effective internal combustion engine (ICE) technologies and substantial reductions in the costs of battery electric and plug-in hybrid vehicles.

In 2015, the Paris Agreement on global climate change codified the consensus ambition among world governments to limit warming to well below 2 degrees Celsius and pursue efforts to limit the temperature increase further to 1.5 degrees Celsius. It also established a framework for national commitments to reduce emissions. With respect to the decarbonization of road transport, previous studies, including those conducted by GFEI partners, underscore the vital role of policies that improve vehicle fuel economy and accelerate the transition to zero emission vehicles, in combination with measures that avoid the need for motorized travel and shift activity to less carbon intensive modes.

In this context the GFEI Partners have revisited the GFEI targets to account for ongoing developments in vehicle fuel efficiency, expand the focus to incorporate all road transportation vehicles, and to frame the targets in terms of both vehicle efficiency and greenhouse gas emissions. The purpose of the present report is to launch the renewed GFEI targets.

APPROACH

The analysis presented here was conducted by the International Council on Clean Transportation (ICCT), in close coordination with the International Energy Agency (IEA) and with input from all GFEI partners to support the updating of existing targets and development of new targets that are appropriately **ambitious, trackable, policy relevant, and easily communicated**. The information presented is intended to update, expand, and redefine GFEI efficiency targets to both incorporate the latest technological developments and provide a more robust characterization of on-road global transportation decarbonization potential by 2050. The material examines the existing near-term targets for new light duty passenger vehicles and new heavy duty freight vehicles and proposes new near-term targets for two and three wheeled vehicles and buses, and new longer-term targets for all road transport classes. Potential efficiency improvements are evaluated separately for internal combustion engine technology alone and internal combustion engine technology in combination with vehicle electrification.[2]

[1] https://www.globalfueleconomy.org/media/46127/50by50-report-2009-lr.pdf

[2] In practice, electric vehicles include plug-in hybrid electric (PHEV), battery electric (BEV), and fuel cell (FCV) vehicles. This analysis does not intend to constrain this practical definition and views the entire range of such vehicles as important to achieving the defined targets. However, since the analysis relied on the projected performance and sales of battery electric vehicles in combination with defined electricity grid CO_2 intensities to derive both average new vehicle and fleetwide performance goals, we refer to all such goals in terms of battery electric vehicle goals. It is, nevertheless,

To develop the updated targets, existing technology and market data from both GFEI partners and independent authorities were reviewed. These data were carefully weighed to develop best estimates of aggressive, but achievable, goals for new vehicles by 2050. Although care was taken to establish goals specific to each road transportation sector, the project also developed an estimate of the overall impact of the individual policies on net road transportation carbon emissions through 2050 given expected travel demand growth.

Existing GFEI targets are established in terms of new vehicle tank-to-wheel efficiency,[3] as that is an appropriate measure of the efficiency over which vehicle manufacturers have direct control. In a market dominated by internal combustion engine technology, upstream emissions generally change in step with tank-to-wheel efficiency, but as the road transport market transitions from internal combustion engine technology to vehicle electrification, net upstream emissions are a function of the relative market shares of each technology and the carbon intensity of the electricity grid. With a mix of internal combustion and electric vehicles, there is no way to infer the decarbonization impacts of changes in tank-to-wheel efficiency, therefore the new GFEI targets are established in terms of well-to-wheel CO_2 emissions.

KEY FINDINGS

From the analysis performed, GFEI partners reaffirm our existing targets for *new* light and heavy duty vehicles in 2030 and 2035 respectively, establish more stringent 2050 targets for *new* light- and heavy-duty vehicles, establish first-ever targets for 2 and 3 wheeled vehicles and buses in 2035 and 2050, and compile these targets into a vision for achieving major reductions in greenhouse gas emissions from the transportation sector by mid-century. Vehicle class-specific and fleetwide targets and findings are as follows:

1. **Light duty (passenger) vehicles (LDVs).** The GFEI partners reaffirm our target of doubling fuel economy of new passenger vehicles globally by 2030 (relative to 2005) through continued improvements in internal combustion engine efficiency plus the introduction of electric passenger vehicles, and extend this target to a 50% reduction in new passenger vehicle per-kilometer CO_2 emissions by 2030 (see Figures 1a and b[4]). The GFEI partners also establish a new passenger vehicle per-kilometer CO_2 emissions reduction target for 2050 of 90% (also relative to 2005). To achieve this target, combustion engine fuel consumption will need to improve by an average of 2.1% per year from 2020 to 2050, the global sales fraction of electric passenger vehicles will need to increase to 35% of sales in 2030 and 86% of sales in 2050, and the carbon intensity of the global electricity grid will need to decrease by at least 90% between 2020 and 2050.

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important to recognize that the stated goals may be achievable by a mix of PHEVs, BEVs, and FCVs as long as aggregate sales and performance are equivalent to the BEV-specific sales and performance cited in this report. By extension, this analysis assumes that internal combustion engine (ICE) vehicles include hybrid vehicles that maintain their charge solely through ICE-derived energy.

[3] "Tank-to-wheel" efficiency is a measure of the energy consumed onboard a vehicle, or the emissions generated by such operation. "Well-to-wheel" efficiency is a measure of the energy consumed both onboard a vehicle and throughout the supply chain that generated that energy, or the emissions generated during the production and consumption of that energy.

[4] Note that CO_2 is evaluated in this analysis under two electricity grid intensity scenarios. The first, denoted as the Moderate Grid Intensity Scenario (MGIS), assumes a 50% reduction in grid CO_2 intensity between 2005 and 2050. The second, denoted as the Aggressive Grid Intensity Scenario (AGIS), assumes a 95% reduction in grid CO_2 intensity between 2005 and 2050.

2. **Heavy duty (freight) trucks (HDTs).** The GFEI partners reaffirm our target of cutting per-kilometer fuel consumption from new heavy duty trucks 35% by 2035 (relative to 2005) through continued improvements in internal combustion engine efficiency plus the introduction of electric heavy duty trucks, and extend this target to a 35% reduction in new heavy duty truck per-kilometer CO_2 emissions by 2035 (see Figures 2a and b). The GFEI partners also establish a heavy duty truck per-kilometer CO_2 emissions reduction target for 2050 of 70% (also relative to 2005). To achieve this target, combustion engine fuel consumption will need to improve by an average of 1.7% per year from 2020 to 2050, the global sales fraction of electric heavy duty trucks will need to increase to 19% of sales in 2030 and 66% of sales in 2050, and the carbon intensity of the global electricity grid will need to decrease by at least 90% between 2020 and 2050.

3. **Two and three wheeled vehicles (2WVs and 3WVs).** The GFEI partners establish new targets for 2 and 3 wheeled vehicles to reduce per-kilometer CO_2 emissions by 80% by 2035 and 95% by 2050 (both relative to 2005, see Figures 3a and b). To achieve these new targets, the fuel efficiency of internal combustion engine powered 2 and 3 wheelers will need to improve by 1.4% per year from 2020 to 2050, the global sales fraction of electric 2 and 3 wheelers will need to increase to 74% of sales in 2030 and 100% of sales in 2050, and the carbon intensity of the global electricity grid will need to decrease by at least 90% between 2020 and 2050.

4. **Transit buses**.[5] The GFEI partners establish new targets for buses to reduce per-kilometer CO_2 emissions by 65% by 2035 and 95% by 2050 (see Figure 4a and b). To achieve these new targets, the fuel efficiency of internal combustion engine powered buses will need to improve by 2.0% per year from 2020 to 2050, the global sales fraction of electric buses will need to increase to 37% of sales in 2030 and 93% of sales in 2050, and the carbon intensity of the global electricity grid will need to decrease by at least 90% between 2020 and 2050.

5. **Decarbonizing the transport sector.** The GFEI partners recognize the importance of supporting government actions and policies that bring the transportation sector into compliance with the Paris Accord. Based on our analysis, we reach the following conclusions:

    a. Continued improvements in vehicle efficiency plus aggressive introduction of electric vehicles combined with decarbonization of the electricity grid can achieve a 55-70% reduction in fleetwide well-to-wheel CO_2 emissions by 2050 (from a 2050 baseline) with combustion engine efficiency responsible for 50-65% of the overall reductions (see Figure 5). The ranges result from two grid decarbonization scenarios: a moderate grid intensity scenario (MGIS) offering a 50% reduction in global grid CO_2 intensity by 2050 (relative to 2005), and an aggressive grid intensity scenario (AGIS) offering a 95% reduction during that same period.

    b. By 2050, per-kilometer CO_2 reduction targets for new vehicles of greater than 90% can be established for the LDV, 2WV and 3WV, and bus classes, assuming aggressive development of EV markets and aggressive decarbonization of the electricity grid. The corresponding reduction for new HDTs is lower at 70% due to the greater challenge of electrifying vehicle operations in the sector.

[5] For this analysis, transit buses are defined as including a broad range of vehicles, from small minibuses to large urban and intercity buses.

c. Decarbonizing the electricity grid becomes increasingly important post 2035 as EV sales approach or exceed 90% in all but the heavy duty truck sector. Grid CO_2 intensity becomes the dominant influence on the CO_2 impacts of these EVs, driving CO_2 reductions from about 55% (relative to an internal combustion engine powered vehicle) for today's global average grid characteristics to 90-100% under an aggressive grid decarbonization scenario.

d. On a fleetwide basis, growth in the population and annual usage rates of on-road vehicles results in significant growth in total vehicle kilometers of travel (VKT), which offsets the net fleetwide CO_2 emission reduction achievable though efficiency technology and electrification. This analysis does not investigate measures to constrain such growth. VKT is estimated to increase by a factor of 3.2 between 2005 and 2050. As a result, the GFEI targets deliver well-to-wheel CO_2 emission reductions of about 55-70% from a 2050 baseline (depending on the level of grid decarbonization assumed), but this only represents a reduction of up to 30% from a 2005 baseline (see Figures 5, 6a, and 6b). While not quantified in this analysis, it is important to recognize that introducing zero emissions vehicles, such as EVs, will also deliver major air quality benefits regardless of the level of grid decarbonization.

e. We establish a fleetwide well-to-wheel CO_2 emissions target of 2.2 gigatonnes in 2050 (see Figures 5, 6a, and 6b), which represents a 65% reduction from a 2005 baseline. This target draws on recent modeling that complies with the Paris Agreement commitment to limit the global average temperature increase to "well below" 2ºC.[6] There is a degree of uncertainty with this target, not least because it exists in the context of wider energy sector developments.[7] But it is important to realize that there is general agreement that anthropogenic CO_2 emissions need to reach net zero in the second half of the century to limit global impacts to the levels envisioned in the Paris Agreement. Thus, the target has been set at an ambitious level.

f. We expect the reduction in emissions due to compliance with the proposed GFEI new vehicle standards to deliver reductions of up to 1.9 gigatonnes (see Figures 5 and 6b). This is less than what is required to achieve the targeted 65% reduction from 2005 emissions by 2050. In effect, the reaffirmed and newly established targets for new vehicles deliver 46% of the required reduction in fleetwide emissions by 2050 (under the most aggressive electricity grid CO_2 intensity scenario analyzed).

g. This analysis looks at efficiency and emissions only through 2050, at which time EV sales are projected to approach a 100% market share for all road transport sectors except heavy duty trucks. If this analysis were to continue beyond 2050, there would be additional CO_2 emission reductions due to the increasing share of travel associated with electric vehicle operation. We would expect CO_2 emission reductions to nearly double from 30%, to over 55%, from a 2005 baseline when a

[6] We derive our fleetwide target broadly based on the IEA's Beyond 2 Degrees Scenario (B2DS) emissions projections for 2050, which is generally consistent with estimates produced by a range of integrated assessment models (IEA, "Energy Technology Perspectives 2017, Catalysing Energy Technology Transformations," 2017).

[7] Total direct transport-related CO_2 emissions of scenarios that limit global warming to 1.5°C in the Intergovernmental Panel on Climate Change (IPCC) database range from 1 to 7 gigatonnes in 2050, the median being around 3.5 gigatonnes. These estimates include non-road modes such as marine vessels and aircraft. We excluded such sources to derive our 2.2 gigatonne target.

100% EV market share for all sectors – other than heavy duty trucks – is combined with an aggressively decarbonized electricity grid. A simultaneous 20 percentage point increase in heavy duty truck EV shares would push the fleetwide reduction to 70% (and, of course, fully electrifying the heavy duty sector and fully decarbonizing the electricity grid would result in a 100% CO_2 emissions reduction).

h. As expected, there will be a need for additional policies to further reduce road transport emissions. However, as discussed in the previous item, the required magnitude of such reductions is dependent on the timing of EV market saturation. Such policies can include those targeting VKT reduction, congestion mitigation, vehicle class shifting, incentives for the purchase and utilization of more fuel-efficient vehicles, and incentives designed to accelerate the transition to a zero emission fleet more quickly than assumed in this analysis. This analysis assumes that the light duty passenger vehicle, two and three wheeled vehicle, and bus fleets will all ultimately transition to 100% zero emission vehicles either by, or shortly after, 2050. Conversely, due to complications associated with operating characteristics, the analysis assumes that internal combustion engine powered vehicles will retain a significant sales share in the heavy duty truck sector through at least 2050. This, combined with significant growth in heavy duty truck VKT between 2005 and 2050, serves to constrain emissions reductions for both the heavy duty truck sector and for the on-road transportation sector as a whole.

i. Although it is not possible to foresee the EV future with certainty, it is possible to ground longer-term projections in near-term estimates. For LDVs, this analysis assumes global EV sales of 22% by 2025 and 35% by 2030. Automaker announcements indicate global sales of 15 million EVs by 2025, which represents a sales share of 14% in a global market of 107 million annual sales. Existing government commitments indicate a demand for 22 million EVs by 2030. This represents a 19% sales share on a global basis. Thus, both automakers and regulators will have to build on their commitments to meet the EV trajectory envisioned in this analysis. The analysis trajectory is aggressive, but achievable, and essential to delivering an EV dominated fleet by 2050.

Figure 1a. On-Road TTW Efficiency for New LDVs

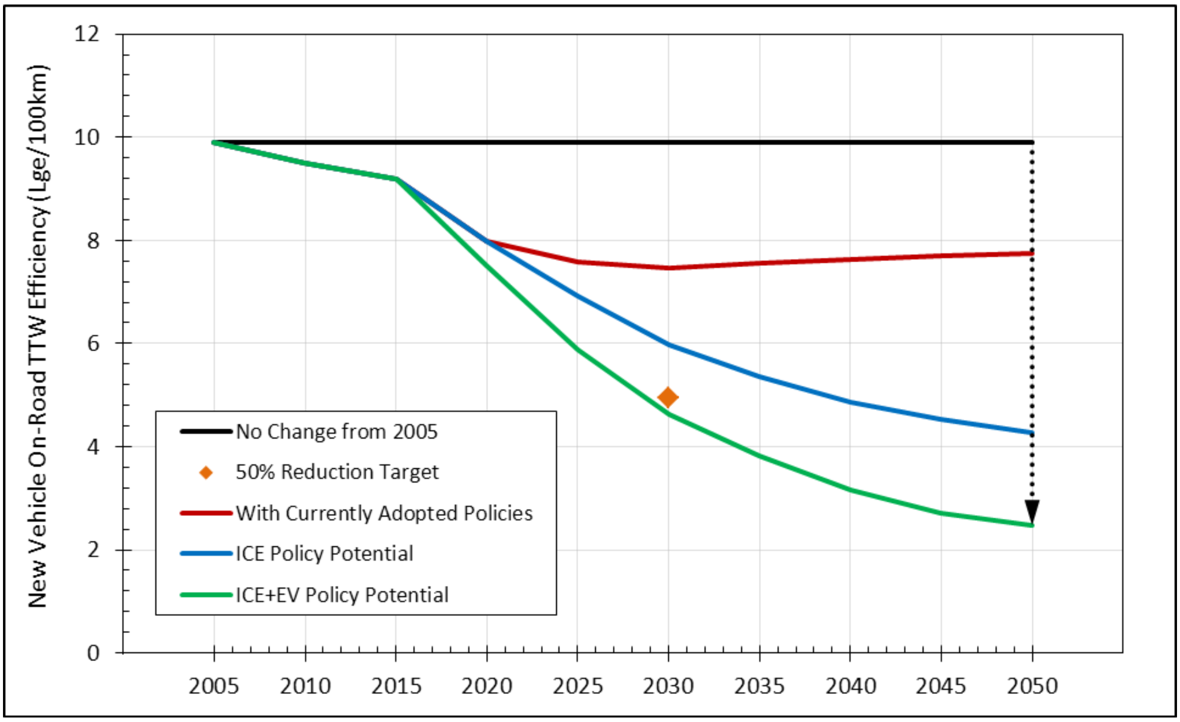


Figure 1b. On-Road WTW CO_2 Emissions for New LDVs

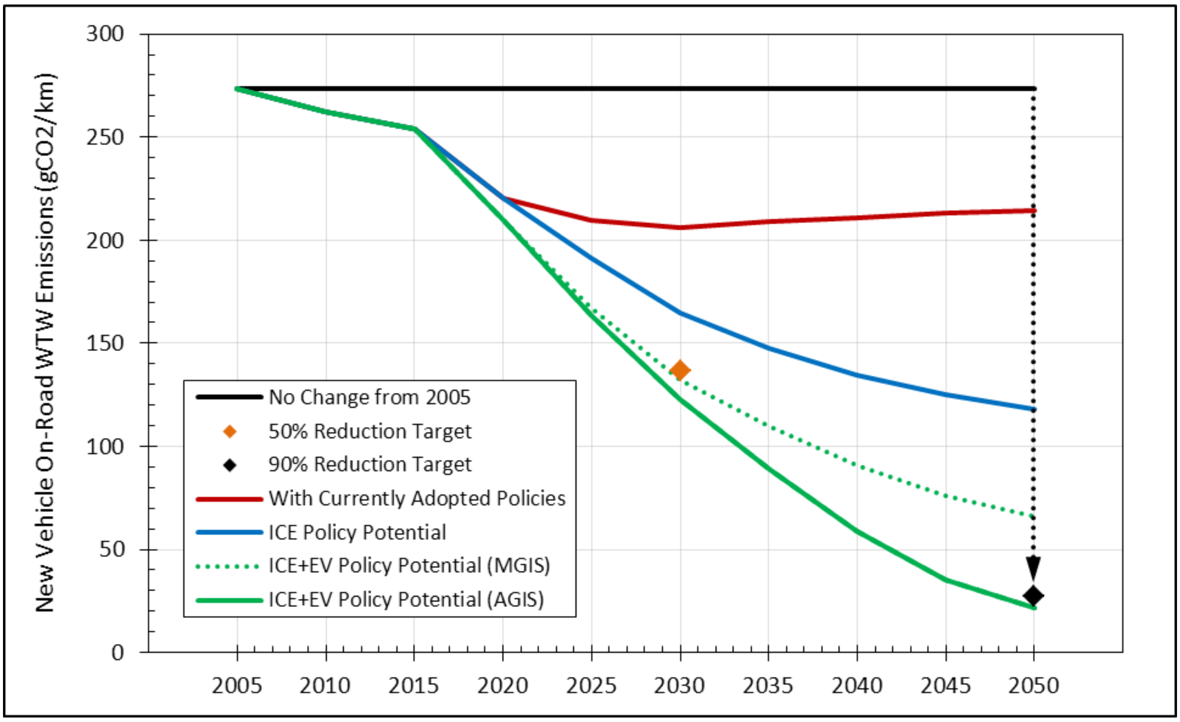


Figure 2a. On-Road TTW Efficiency for New HDTs

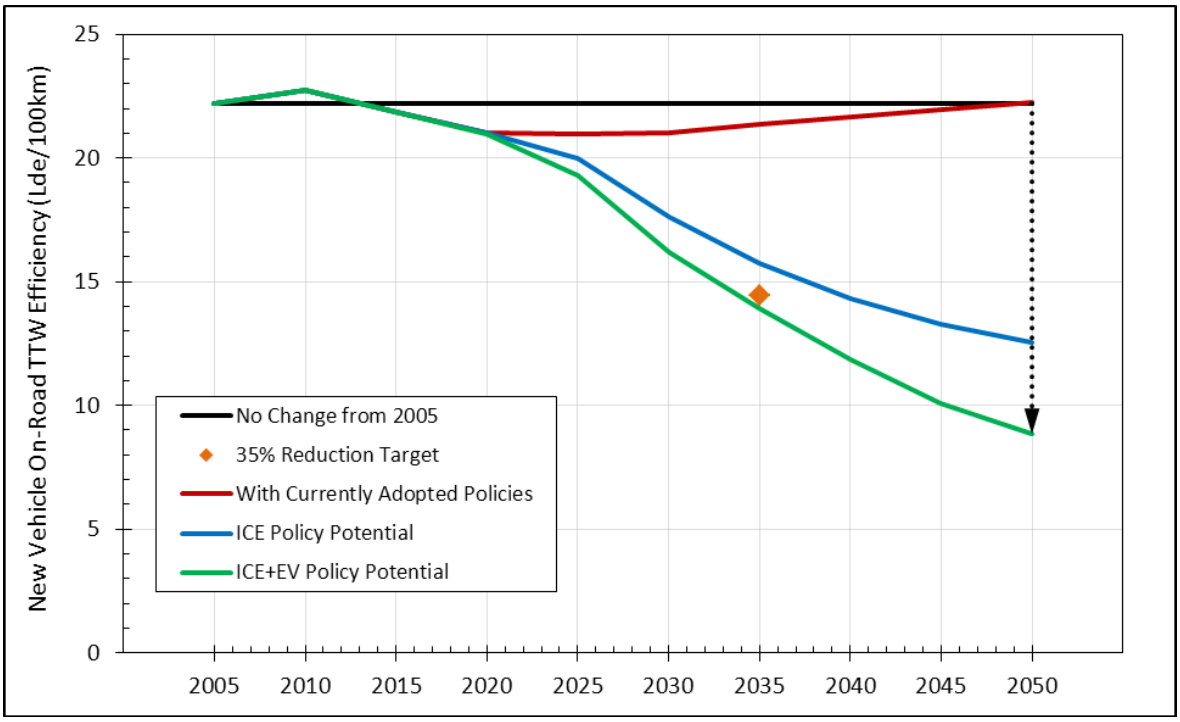


Figure 2b. On-Road WTW CO_2 Emissions for New HDTs

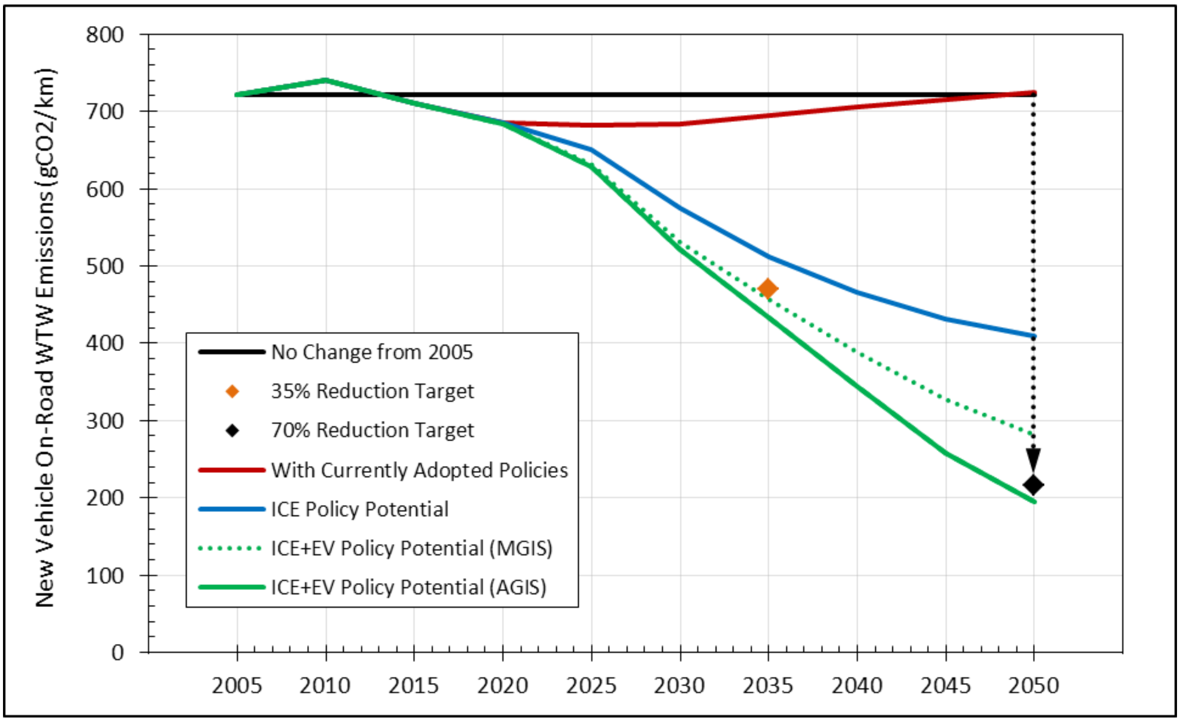


Figure 3a. On-Road TTW Efficiency for New 2WVs and 3WVs

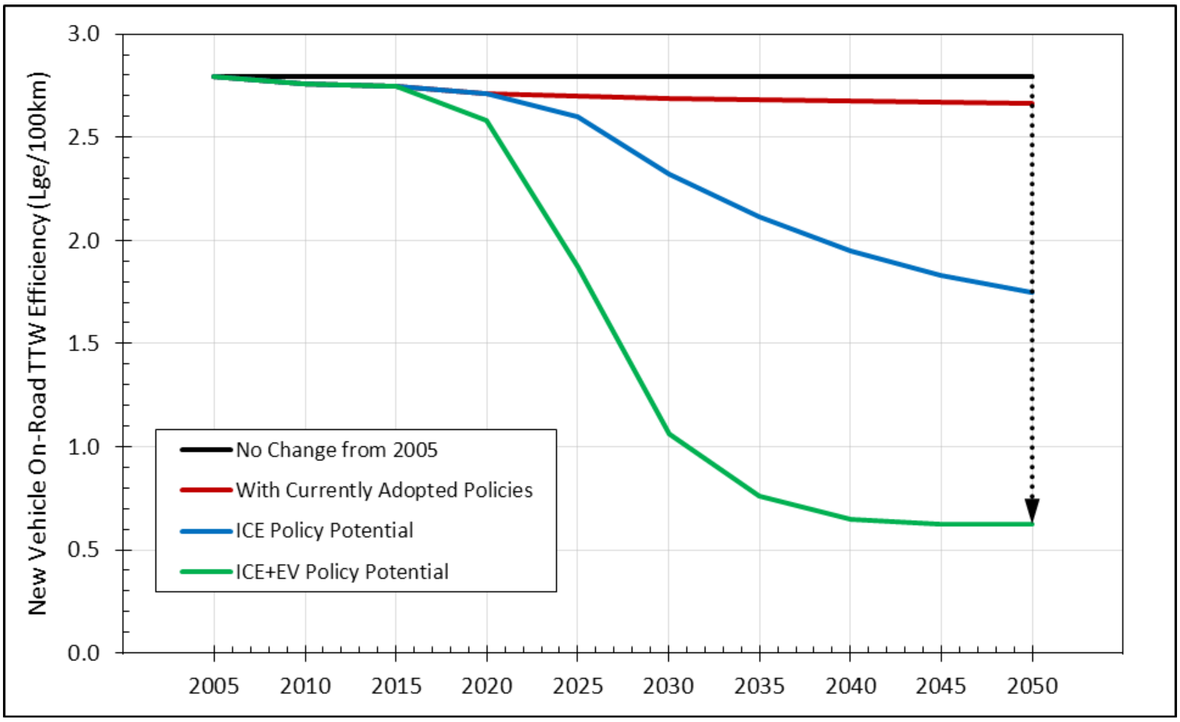


Figure 3b. On-Road WTW CO_2 Emissions for New 2WVs and 3WVs

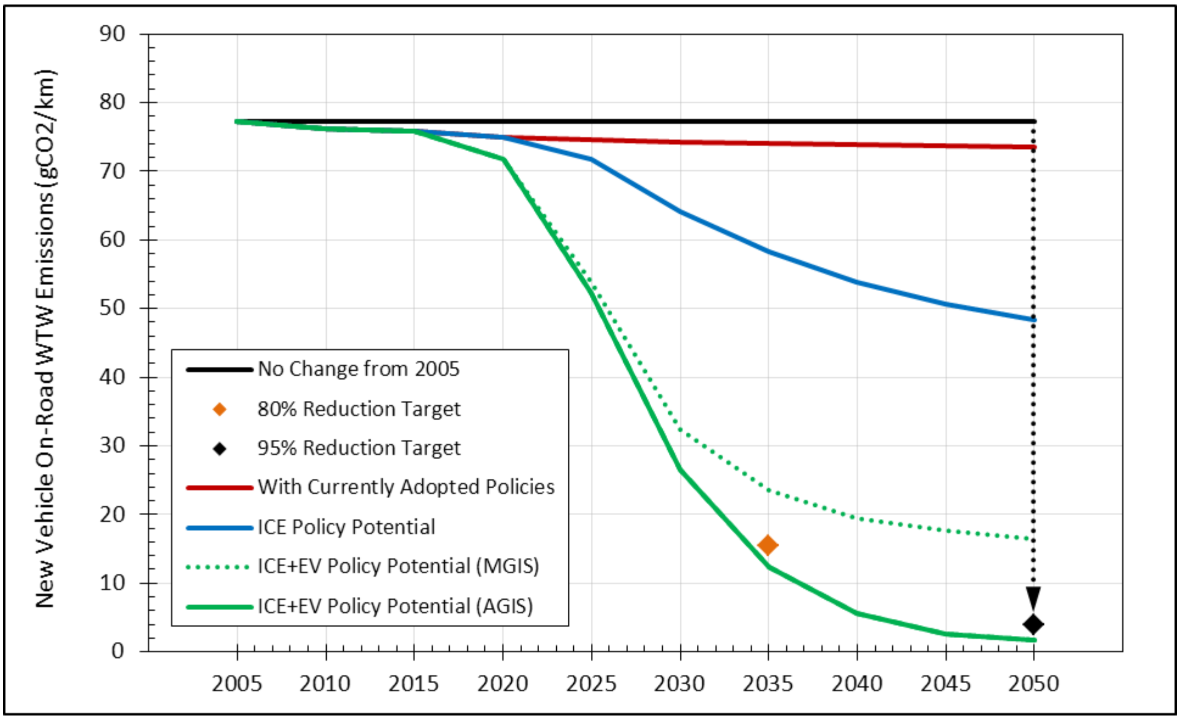


Figure 4a. On-Road TTW Efficiency for New Buses

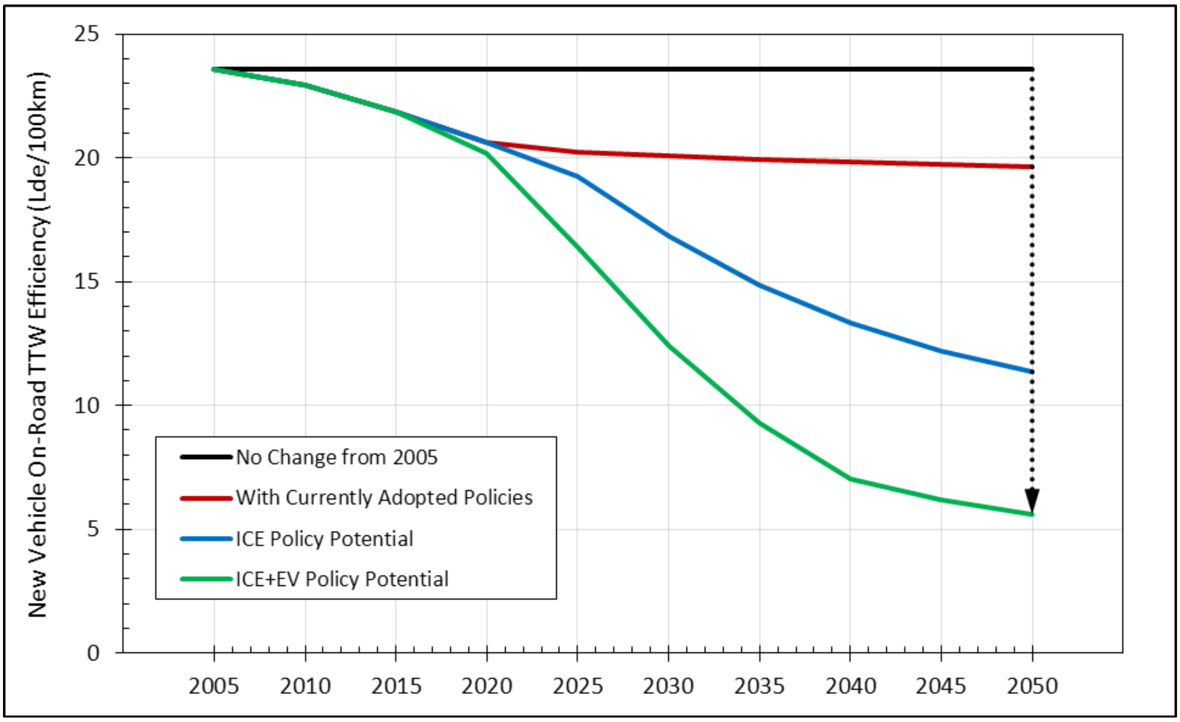


Figure 4b. On-Road WTW CO_2 Emissions for New Buses

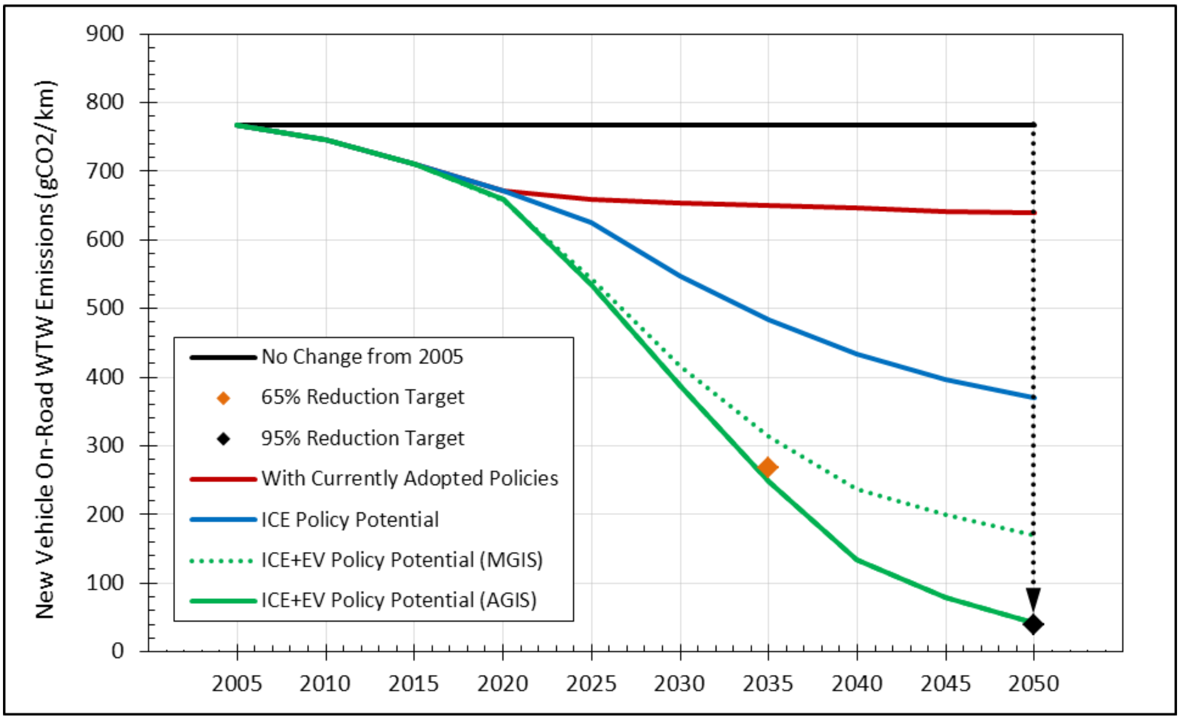


Figure 5. Change in Global Fleetwide Emissions Over the Projection Period

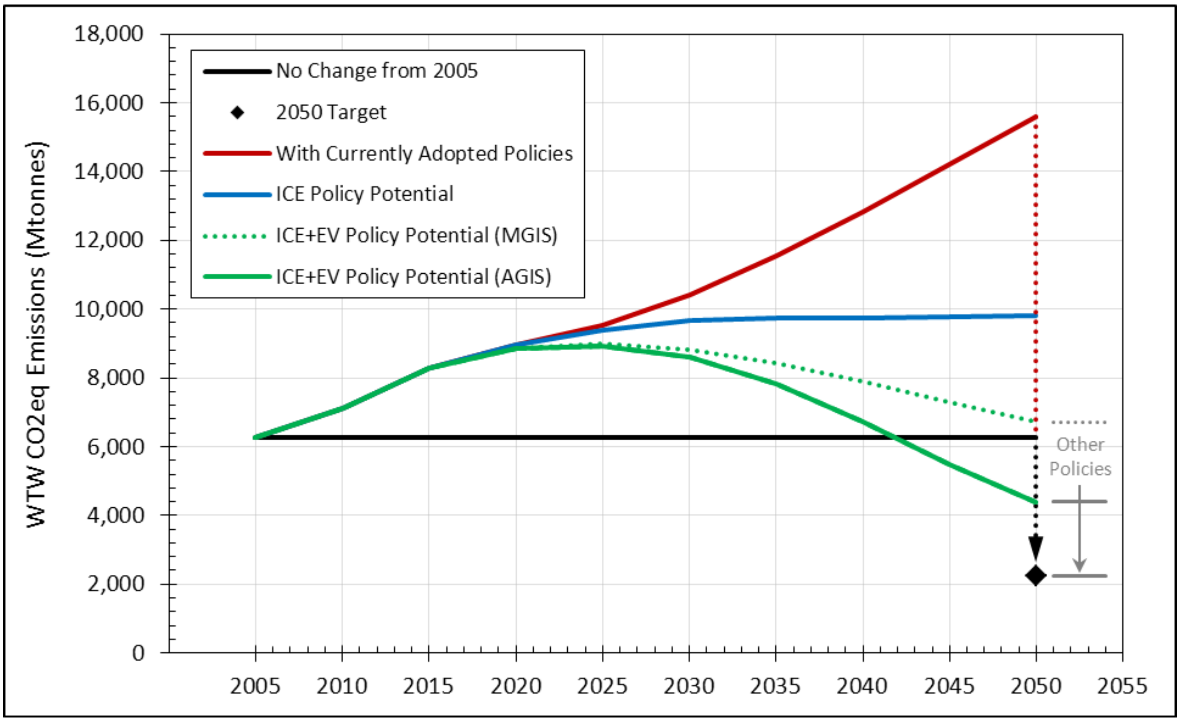


Figure 6a. Class-Specific Emission Reductions for the Moderate Grid Intensity Scenario

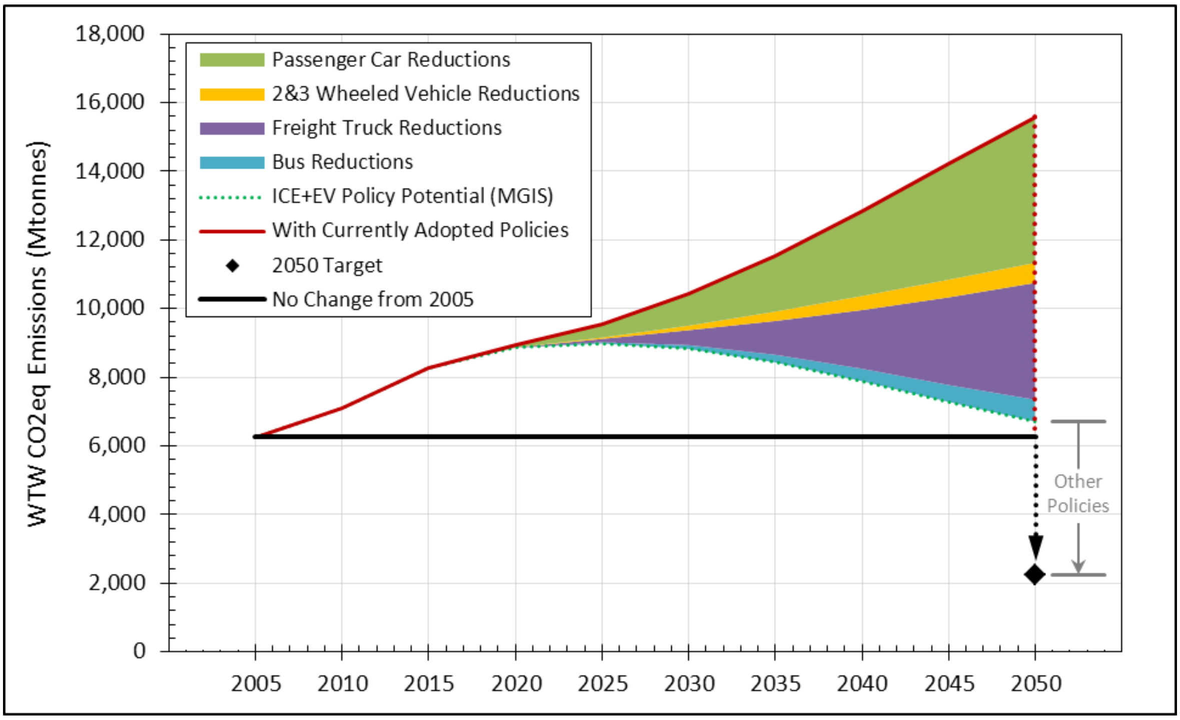
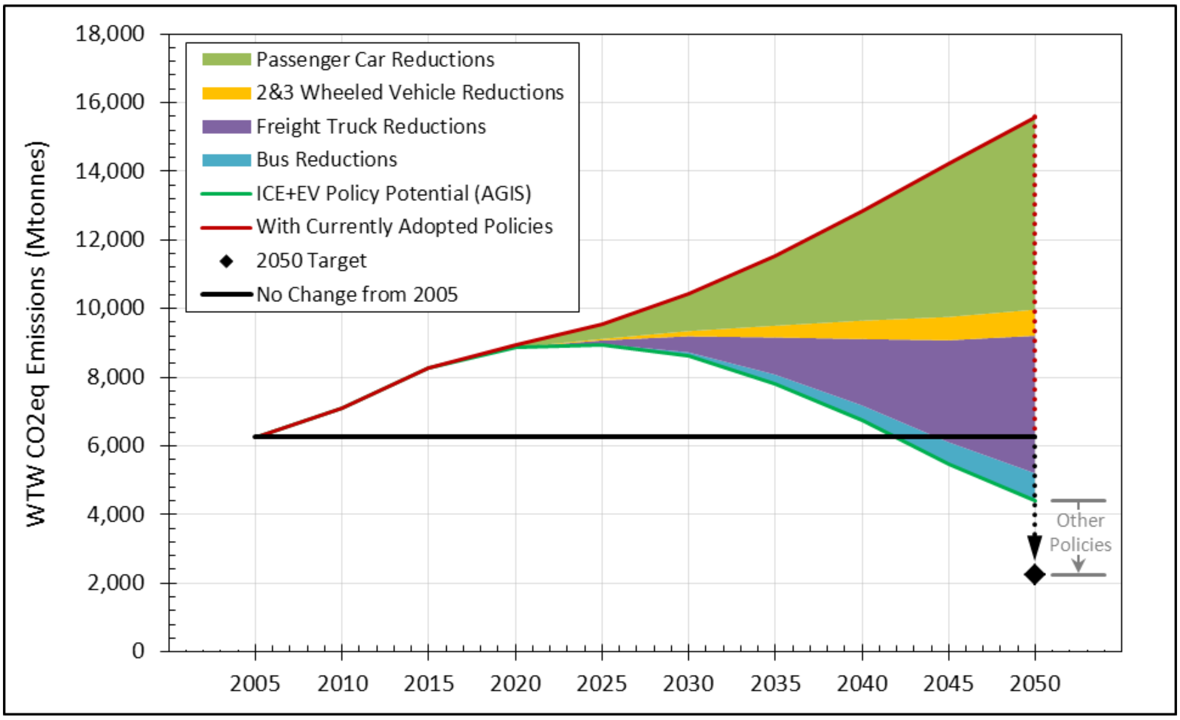


Figure 6b. Class-Specific Emission Reductions for the Aggressive Grid Intensity Scenario



GENERAL ANALYSIS METHODOLOGY

This analysis apportions road transport vehicles into four sectors: light duty passenger vehicles (LDV); heavy duty freight trucks (HDT), 2 and 3 wheeled vehicles (2WV and 3WV), and buses. For each sector, an estimate was made of the potential improvement in fuel efficiency that can be expected between now and 2050 for vehicles powered by internal combustion engines (ICE).[8] This estimate was used to derive efficiency and CO_2 emissions estimates for an "ICE Policy Potential" scenario. Corresponding estimates were made for the expected efficiency of electric vehicles, the fraction of sales (and travel) that electric vehicles can garner between now and 2050, and the CO_2 intensity of the electricity grid over that same period. These latter data were used to derive efficiency and CO_2 emissions estimates for an "ICE+EV Policy Potential" scenario. These scenarios reflect aggressive, but achievable aspirational futures.

All modeling was performed using the ICCT's Roadmap model. As defined in its baseline state, the model includes appropriate data reflecting all currently adopted global fuel consumption policies. These baseline data were extracted from the model without change, and comprise the scenarios labeled in this analysis as "No Change from 2005" and "With Currently Adopted Policies." All GFEI targets are expressed relative to the 2005 baseline.

To develop the modeling data used in this analysis, existing technology and market data developed by both GFEI partners and independent authorities were reviewed. These data were carefully weighed to ensure that the developed estimates were not based on the most optimistic assumptions, but rather on an aggressive, although somewhat more conservative future. Thus, the GFEI targets developed through this methodology represent reasonable expectations under a policy approach based on the continuing global evolution of current transportation efficiency programs.

Each of the sections that follow provides specific details on the modeling assumptions employed in this analysis (and their derivation). Before presenting these discussions, it is important to understand some of the issues not addressed explicitly in the analysis.

First, this analysis does not look at any policies other than efficiency improvements driven by more stringent ICE standards and increasing EV sales. No consideration is given to programs designed to reduce travel, alter consumer vehicle preferences, or otherwise reduce transportation sector impacts. The GFEI targets are efficiency-based targets and that is the sole focus of this analysis.

Second, this analysis does not look explicitly at the potential impacts of fuel switching (to fuels such as biofuel, natural gas, or hydrogen). For a macro-level analysis such as this, a detailed assessment of fuel switching (excepting from fossil onboard to electric onboard) is not warranted. Moreover, although some advanced biofuel pathways have the potential to reduce carbon emissions, that potential has yet to be demonstrated in large scale applications. Similarly CNG is subject to losses throughout the production, distribution, and consumption chain, and releases CO_2 when combusted. Hydrogen could indeed play a role in a low carbon future, but essentially represents a somewhat nuanced version of an EV, so a separate accounting is not necessary. All energy consumption estimates are standardized in terms of

[8] ICE vehicles include hybrid vehicles that maintain their charge solely through ICE-derived energy, but exclude plug-in hybrid and electric vehicles.

either gasoline (light duty) or diesel (heavy duty) consumption equivalent. This standardized metric can easily by "unstandardized" for application to a specific alternative fuel should the need arise.

Third, this analysis is not a backcast. It does not assume a "required future" and then back into the efficiency responses that are necessary to deliver that future. Instead, the analysis is a forward looking evaluation that starts from current global conditions and applies a set of reasonably aggressive assumptions regarding the adoption of efficiency technologies to derive an estimate of how conditions in 2050 might look. The analysis can be used to estimate how much more (or less) technology might be needed to meet a specific future goal, but that is not the design basis for the work.

Fourth, the analysis presents all efficiency and emissions estimates in terms of what a consumer could expect to achieve during everyday use of the vehicle. We purposefully undertake this approach to avoid issues related to the performance "gap" between the efficiency at which manufacturers certify vehicles and the in-use efficiency achieved by consumers. To the extent the performance gap remains unchanged over time, the relative improvement assumed for efficiency in this analysis will apply equally to both certification and consumer metrics. Alternatively, manufacturers could undertake efforts to close the performance gap and thus reduce the required relative improvement in certification efficiency.

Currently Adopted Policies Reflected in the ROADMAP Model Baseline

The Roadmap model baseline includes only actually adopted policies – meaning policies that are backed by enforceable regulations. Aspirational "policy" statements that have been issued by some governments are not included. For LDVs, the Roadmap model baseline includes the following: US 2025 efficiency standards (not rolled back), Canada 2025 efficiency standards (not rolled back), Mexico 2017 efficiency standards, Brazil Inovar-Auto 2017 efficiency standards, EU 2030 efficiency standards, China 2020 efficiency standards, Japan 2020 efficiency standards, India 2021 efficiency standards, and Korea 2020 efficiency standards. For HDTs, the Roadmap model baseline includes US Phase 2 standard, Canada Phase 2 standards, China 2020 standards, Japan 2025 standards, and India 2020 standards. Currently adopted EV policies (specifically those of the US, China, and EU) are expected to function in coordination with ICE policies, such that the combination of the EV plus ICE policy results in the same efficiency as the ICE policy alone. As a result, the Roadmap model attributes current EV policy emission reductions to ICEs, even though some of the reductions will actually be delivered through the sale of EVs.

Metrics Employed

This analysis presents efficiency estimates in terms of tank-to-wheel (TTW) energy consumption, expressed as either gasoline equivalent (light duty vehicles) or diesel equivalent (heavy duty vehicles) fuel consumption per 100 kilometers. Emissions estimates are presented in terms of well-to-wheel (WTW) CO_2 emissions per kilometer of travel. For ICEs, TTW energy consumption is generally the method used to track compliance with regulatory requirements. Vehicle manufacturers generally do not have the ability to control upstream production and distribution efficiency, so they are not generally required to account for energy consumed during such activity. The energy consumption of EVs is treated similarly on a TTW basis, but it is important to recognize that there are fundamental differences between ICE and EV fueling that bias TTW consumption in favor of EVs.[9] Some regulatory programs apply adjustments to EV TTW energy consumption estimates in an effort to overcome this bias,[10] but this analysis does not undertake such efforts and presents all TTW estimates as calculated on the sole basis of onboard energy consumption. WTW CO_2 estimates for ICEs and EVs are unbiased metrics, but introduce the issue of upstream accounting for both petroleum-based ICE's and grid-based EVs. Regulatory approaches to account for upstream impacts are evolving. This analysis uses a standardized accounting methodology based on the upstream factors described below.

Gasoline and Diesel Upstream Factor

This analysis uses an upstream factor of 1.2 for gasoline and diesel fueled ICEs (i.e., total energy consumption equals onboard energy consumption times 1.2). This factor was derived from regulatory parameters for the US fuel economy program,[11] and is validated against data provided by the IEA that indicate a virtually identical upstream factor for gasoline (1.195) and diesel (1.203).[12]

CO_2 Intensity of the Electricity Grid (Production and Consumption)

This analysis includes two electricity grid CO_2 intensity scenarios, a Moderate Scenario (MGIS) and an Aggressive Scenario (AGIS). The MGIS assumes a 50% reduction in CO_2 intensity between 2005 and 2050, while the AGIS assumes a 95% reduction. Both scenarios assume a global average CO_2 intensity for electricity production of 546 gCO_2/kWh for 2005 based on historic IEA data.[13] Production CO_2 intensity for interim years is broadly based on scenarios developed by the IEA. Both the MGIS and AGIS scenario assume transmissions and distribution losses of 9% (so that consumption intensity is 9.9% higher than production

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[9] TTW efficiency is not a reliable indicator of the relative efficiency of ICEs and EVs. ICEs carry fuel in a liquid form. The chemical energy stored in this fuel is converted onboard the vehicle to the mechanical energy used for propulsion. This conversion takes place through a relatively inefficient combustion process. Conversely, EVs store and consume energy as electricity, which is converted to mechanical energy with substantially higher efficiency. However, the bulk of the electricity used by EVs is itself generated from chemical energy released via the combustion of fossil fuels, so that the relatively inefficient extraction of energy performed onboard ICEs (and, therefore, quantified in the measure of ICE efficiency) is also a component of the production of EV fuel, but a component not captured by measuring the efficiency of the vehicle itself (since it occurs offboard). Should electricity production characteristics shift to the point where renewable energy sources become dominant, this distinction could become less important, but production characteristics today are such that TTW efficiency measures are not a good indicator of the relative efficiency of EVs relative to ICEs. On a TTW basis, a current passenger car EV will indicate an efficiency that is about 75% better than a comparable ICE. However, if the efficiency of the chemical to electricity energy conversion process is considered, the EV efficiency advantage will drop to about 20% (electricity production extracts chemical energy under higher efficiency, steady state operating conditions that are not generally possible onboard vehicles subject to transient operation). The actual advantage will be higher (on the order of 25%) due to lower transmission and distribution losses than are inherent in the liquid fuel distribution system, but the point remains that TTW efficiency measures are highly skewed in favor of EVs. Moreover, this bias will be exacerbated as ICE efficiency improves if electricity production does not shift to more efficient energy sources.

[10] See for example, US CAFE regulations at US Code of Federal Regulations, Title 10, §474.3 and supporting information at US Department of Energy, "Electric and Hybrid Vehicle Research, Development, and Demonstration Program; Petroleum-Equivalent Fuel Economy Calculation," Final Rule, Federal Register, 65FR36986, June 12, 2000.

[11] US Department of Energy, "Electric and Hybrid Vehicle Research, Development, and Demonstration Program; Petroleum-Equivalent Fuel Economy Calculation," Final Rule, Federal Register, 65FR36986, June 12, 2000.

[12] http://publications.jrc.ec.europa.eu/repository/bitstream/JRC85326/wtt_report_v4a_april2014_pubsy.pdf

[13] IEA, "Energy Technology Perspectives 2017, Catalysing Energy Technology Transformations," 2017 and associated data available at: https://www.iea.org/etp/etp2017/restrictedaccessarea/.

intensity), consistent with data compiled by both US researchers and the IEA.[14,15] Figure 7 depicts the developed CO_2 intensity scenario data.

It is important to recognize that neither the MGIS nor AGIS reflect business as usual production practices. Although the MGIS assumes a substantially lower level of grid decarbonization than the AGIS, it still assumes significant reductions from current grid intensity and is roughly consistent with grid decarbonization *goals* announced by various global governments. In contrast, the AGIS assumes a fundamental transformation of the global electricity grid to a near neutral carbon status.

Electric Vehicle Market Penetration

Data on estimated EV travel fractions in 2050 was available from work performed by the ICCT and the IEA.[16] These data show very similar global penetration estimates for LDVs, 2WVs, 3WVs, and large HDTs. Estimates for small and medium HDTs and buses are somewhat different, with IEA estimating higher travel fractions for small and medium HDTs and lower travel fractions for buses. For this analysis, we discount the more optimistic estimates by using the average of the ICCT and IEA estimates to derive a less aggressive estimate of 2050 EV travel fractions. We do this on a regional basis for the 16 global regions included in the Roadmap model, rounding all results to the nearest 5% to avoid unmerited precision. We develop EV travel fractions for years before 2050 by maintaining the ratio of IEA-estimated fractions for each year to the IEA-estimated fraction for 2050, again rounding all results to the nearest 5%. The resulting travel fractions are depicted in Figure 8.

Sales fractions for EVs are estimated on the basis of sales-to-travel fraction relations developed from the IEA sales and travel fraction estimates included in their 30 by 30 scenario analysis. The IEA data included EV sales and travel fraction estimates for over 100 data points for each vehicle class. From these data, an average statistical relation between EV sales and travel was developed and this relation was applied to the estimated travel fractions used in the analysis to derive corresponding EV sales estimates. The derived estimates are included in Figure 8.

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[14] Title 10, US Code of Federal Regulations, 10 CFR §474.3, Petroleum-equivalent fuel economy calculation.

[15] International Energy Agency, "World Energy Outlook 2018," OECD/IEA 2018.

[16] ICCT data are included in the technical assumptions underlying their Vision 2025 policy analysis that investigates pathways to decarbonizing the transportation sector. IEA estimates are included in the data for their EV30@30 modeling scenario (the modeling scenario is based on an aspirational goal of a 30% electric vehicle market share across all road transport modes, with the exception of 2 and 3 wheelers, by 2030).

Figure 7. Electricity Grid CO_2 Intensity

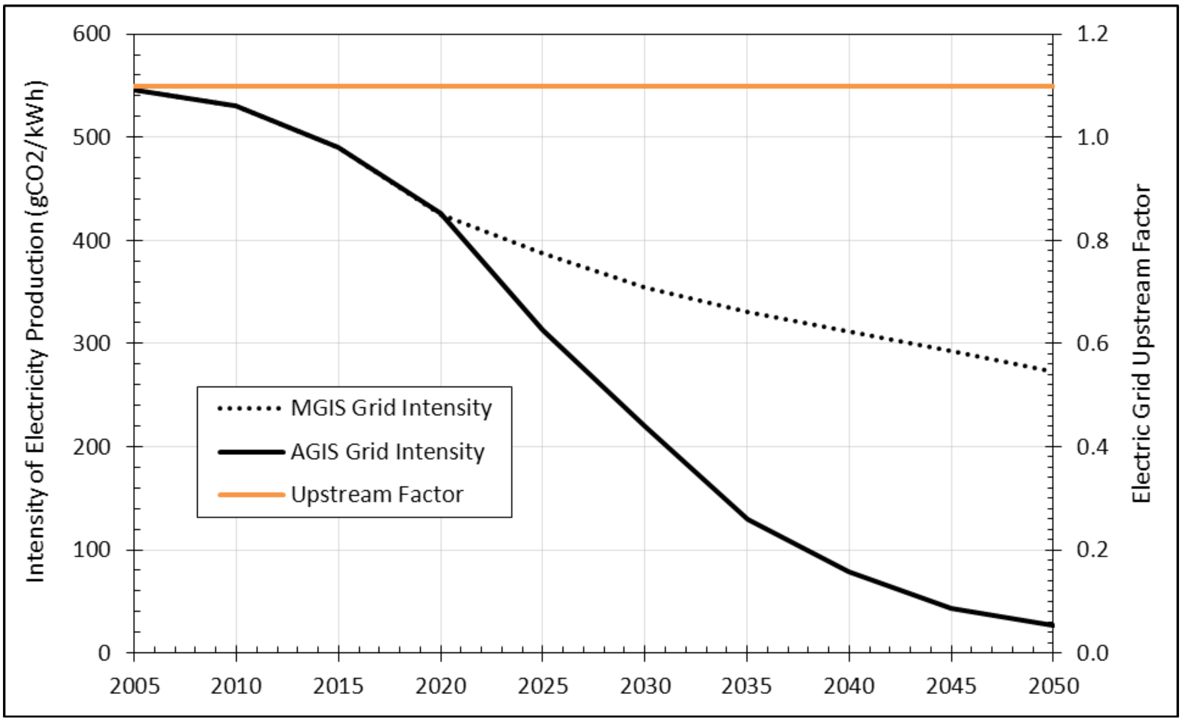
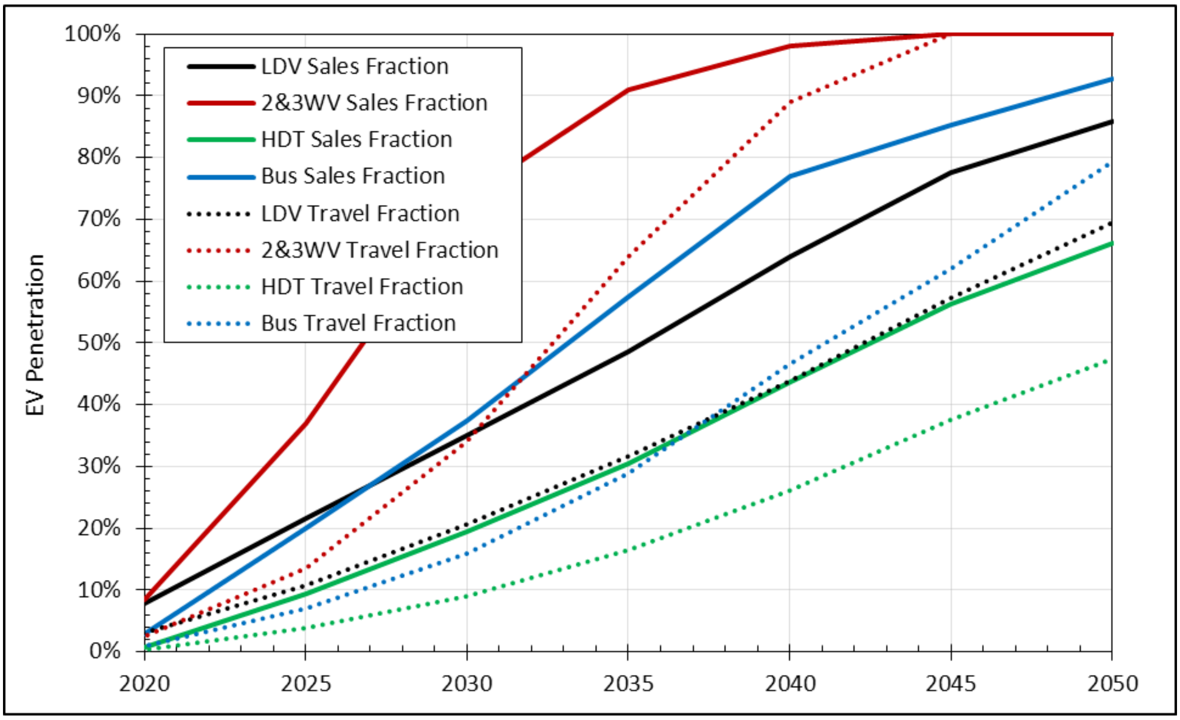


Figure 8. EV Market Penetration



Light Duty Passenger Vehicle Efficiency

Primary data on the estimated improvement in ICE fuel efficiency by 2050 was taken from the IEA.[17] These data indicate a global per-kilometer fuel consumption reduction potential of 57% between 2005 and 2050 (for LDVs). The data were validated by comparing the reduction potential for the US region (59%) using data and analysis tools from the USEPA[18] and the US National Academy of Sciences (NAS).[19] USEPA data (as adjusted by the ICCT to include additional technology such as dynamic cylinder deactivation and electronic boost) indicate that a 65-68% reduction in per-kilometer fuel consumption is possible using technology under development today (with the range indicative of the fact that the same technology package applied across vehicle classes ranging from small passenger cars to large passenger trucks produces modestly different effects). NAS data, which reflect more aggressive assumptions with regard to technology potential and assume advances beyond the level of technology known today, indicate potential per-kilometer fuel consumption reductions of 68-75% under a "midrange" (i.e., moderately aggressive) technology potential case and 75-81% under an optimistic (i.e., very aggressive) technology case. It is important to note, however, that there are differences in the EIA and USEPA/NAS baseline efficiency assumptions. When normalized to a common baseline, the IEA data implies a 66% reduction potential – quite consistent with that of the USEPA data and only modestly lower than the midrange NAS data. Thus, we utilize the IEA ICE fuel efficiency data for LDVs as a reasonably aggressive indicator of ICE fuel efficiency potential in 2050.

We apply the IEA estimates on a regional basis for each of the 16 regions included in the Roadmap model. Regional effects are then aggregated to derive net global impacts.[20] This results in a net 38% per-kilometer fuel consumption reduction (by 2050) on a global basis as compared to global 2025 efficiency.[21] Such reduction is equivalent to an annualized reduction of 1.9%. However, we do not apply the reduction proportionally over time. Instead, we assume a "front loaded" reduction path, wherein near term reductions are larger in accordance with the greater availability of efficiency technology in the early years of implementation. On a global basis, interim five year targets between 2025 and 2050 reflect five-year annualized reductions of 2.9% (2025-2030), 2.2% (2030-2035), 1.9% (2035-2040),

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[17] IEA estimates are included in the data for their EV30@30 modeling scenario (the modeling scenario is based on an aspirational goal of a 30% electric vehicle market share, with the exception of 2 and 3 wheelers, by 2030).

[18] The OMEGA (Optimization Model for reducing Emissions of Greenhouse Gases from Automobiles) modeling platform, version 1.4.56. Vehicle efficiency estimates were derived using the embedded Vehicle Energy Effects Estimator V 4.3 (as updated through November 17, 2016, the latest available update). This is the modelling platform used to develop the 2025 efficiency standards that the current US administration has proposed to repeal.

[19] National Research Council, "Transitions to Alternative Vehicles and Fuels," The National Academies Press, 2013. Specifically, the energy audit model supporting this study was evaluated for the 2050 hybrid-electric ICE scenarios documented in the NAS report.

[20] It is important to recognize that global impacts reflect a combination of regional efficiency and travel changes. Since travel growth varies by region, regional travel weighting varies by year so that global efficiency can improve at a faster or slower rate than a given local efficiency depending on changes in travel distributions over time.

[21] We select 2025 as the comparative year here simply because it represents a "reasonable" approximation of when current efficiency policies expire. Some regions (e.g., the EU) have current policies that run through 2030, others 2020, and some have no current policies at all. In this analysis, we do not modify current policies in any way, but rather account for any additional efficiency improvement potential only after current policies expire. Thus, additional ICE potential is implemented beginning in different years for different regions. We select 2025 as a global "average" here simply to define a baseline for comparative estimates of the reduction potential of future ICE policies relative to the ICE policies currently in place.

1.4% (2040-2045), and 1.2% (2045-2050). These assumptions generate the specific levels of efficiency depicted for the for the "ICE Policy Potential" scenario in Figure 1a above.

For EVs, we estimate efficiency using data developed by the ICCT.[22] The ICCT data provide efficiency data for EVs of various driving ranges (150, 200, and 250 miles), configurations (passenger cars, small crossover SUVs, and large SUVs), and years (2018 and 2030). Since efficiency is expressed on a per-kilometer basis, it is less sensitive to range than to vehicle configuration.[23] For this analysis, we base efficiency estimates on an EV with a 200 mile range. We further assume that EV penetration will transition from the smallest vehicle configurations to the larger configurations over time (i.e., as penetrations increase they must ultimately cover the entire range of configurations). Finally, we extrapolate the annual efficiency improvement estimated by the ICCT for each vehicle class from 2030 to 2050. ICCT data for 2018 and 2030 indicate an annual 0.59% efficiency improvement for passenger cars, 0.74% for small SUVs, and 0.69% for large SUVs. Annual improvements of this magnitude result in 2050 efficiency estimates that are 11% better than those estimated by the ICCT for passenger cars in 2030, 14% better for small SUVs, and 13% better for large SUVs. However, transitioning from smaller to larger vehicle configurations over time imposes a counteracting force, so that the net effect is such that average fleetwide EV efficiency is assumed to remain relative static over the forecast period of this analysis.[24] The net global efficiency values (in kWh/km) assumed for EVs in the LDV sector in this analysis are as follows:

2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
0.193	0.186	0.186	0.180	0.186	0.186	0.193	0.193	0.193	0.193

Discussion of LDV Forecasts: Forecast estimates for new LDVs are as presented in Figures 1a and 1b above. It is important to recognize that the ICCT Roadmap model functions on a five year temporal scale, so that transitional impacts are only "visible" at a five year level of resolution. While the EU standards continue through 2030, most other currently adopted policies end in 2025. The upswing of the "With Currently Adopted Policies" trend in the post 2030 period is not due to any relaxation of standards, but rather due to shifts in global travel trends that favor regions with less stringent standards.

The "ICE Policy Potential" forecast achieves a 40% reduction in per-kilometer fuel consumption and CO_2 emissions from new LDVs by 2030 (relative to 2005, about 2.0% per year on an annualized basis), falling 10 percentage points short of the 50% GFEI target. Reductions continue in the post-2030 period, reaching 57% by 2050.

The "ICE+EV Policy Potential" forecast achieves a 53% per-kilometer fuel consumption reduction for new LDVs by 2030 (relative to 2005, about 3.0% per year on an annualized basis), exceeding the 50% GFEI target by 3 percentage points. Per-kilometer CO_2 emissions from new LDVs decline by 52-55% by 2030 depending on the assumed electricity grid CO_2

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22 Lutsey, N. and Nicholas, M., "Update on electric vehicle costs in the United States through 2030," ICCT Working Paper 2019-06, April 2, 2019.

23 While efficiency does decrease with range, it does so at a marginal rate for a given vehicle configuration as the only effective influence in increased battery weight. The ICCT work estimates an efficiency differential of 0.01 kWh/mile for each additional 50 miles of range.

24 It is important to note that we assume that EVs are not credited with efficiency improvements beyond those warranted from an engineering standpoint. If EVs instead receive additional credits, actual fleetwide efficiency improvements will be less than estimated.

intensity. Reductions continue in the post-2030 period, reaching 75% for per-kilometer fuel consumption and 76-92% for per-kilometer CO_2 emissions by 2050.

The indicated reductions are directly dependent on three critical drivers:

1. Stringent ICE efficiency improvements, backed by imposed policies, continue to be achieved through 2050.

2. EV market share begins ramping quickly in the 2030 and later period, and becomes predominant by 2040.

3. The electricity grid is significantly decarbonized (on the order of a 35-95% reduction in energy-specific CO_2 for the two grid scenarios assumed in this analysis) between 2020 and 2050.

The failure of any one of these drivers will negatively affect achievement of the indicated reductions.

Heavy Duty Freight Truck Efficiency

Heavy duty freight trucks (HDTs) are comprised of a wide range of vehicle configurations ranging from relatively small trucks and commercial vehicles to very large long haul tractor-trailers. Given the broad variation in fuel efficiency associated with vehicles that span such a wide range of applications, the HDT sector is generally split into three subsectors consisting of light HDTs (LHDTs, generally less than 9 tonnes gross vehicle weight), medium HDTs (MHDTs, generally in the 9-15 tonne range), and heavy HDTs (HHDTs, generally greater than 15 tonnes gross vehicle weight). Reported estimates for HDTs reflect the aggregation of LHDT, MHDT, and HHDT impacts.

As with LDVs, primary data on the estimated improvement in ICE fuel efficiency by 2050 was taken from the IEA.[25] These data indicate a global per-kilometer fuel consumption reduction potential of 57%, 50%, and 49% between 2005 and 2050 for LHDTs, MHDTs, and HHDTs respectively. The net reduction for the HDT class as a whole is sensitive not only to each of the subclass reduction potentials, but also the differential baseline fuel efficiencies of the subclasses, the fraction of travel associated with each subclass, and how that travel fraction changes over time. Each of these factors impacts net reductions for the composite class. For example, if HHDT travel grows at a faster rate than that of the other subclasses, overall HDT fuel efficiency will decline even if there is no change in the fuel efficiency of the component subclasses. For this analysis, this complex interaction results in a net reduction in global per-kilometer fuel consumption of 43%.[26]

The IEA data were validated by comparing the reduction potential for the EU region (39% and 52% respectively for MHDTs and HHDTs) using data from a detailed ICCT simulation

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[25] IEA estimates are included in the data for their EV30@30 modeling scenario (the modeling scenario is based on an aspirational goal of a 30% electric vehicle market share, with the exception of 2 and 3 wheelers, by 2030).

[26] Baseline (2005) fuel consumption values are 12.3, 21.1, and 43.3 Lde/100km for LHDTs, MHDTs, and HHDTs respectively. The corresponding VKT fractions are 53%, 20%, and 26% for 2005 and 45%, 17%, and 38% for 2050. These data yield net HDT class fuel consumption values of 22.2 and 12.6 Lde/100km (as shown in Figure 2a), for a net reduction of 43%.

modeling study of HDV fuel efficiency potential in the EU.[27] The ICCT study includes MHDT and HHDT vehicle simulations, and indicates a respective reduction potential of 36%-43% for MHDTs and 43%-45% for HHDTs between 2015 and 2030. Although the time scale for this analysis is extended relative to that of the ICCT simulation modeling work, it is notable that the ICCT evaluated an extensive range of "long term" technologies so that it is comprehensive with respect to current expectations of heavy duty technology potential. The ICCT study estimates for MHDT potential are quite consistent with those of the IEA data, but indicate a modestly lower potential for HHDTs. However, it is notable that ICCT baseline emissions for HHDTs are significantly lower than those assumed in this analysis for the EU in 2015, so it is likely that the baseline technology assumptions for the ICCT work are more advanced than the baseline technology assumed in this analysis for 2005. The absolute long term HHDT fuel consumption potential of about 19-20 Lde/100km from the ICCT study is quite consistent with the 19 Lde/100km assumed in this analysis. As a result, we view the IEA reduction potentials as reasonable indicators of long term ICE technology potential in the heavy duty truck sector.

We apply the IEA estimates on a regional basis for each of the 16 regions included in the Roadmap model. Regional effects are then aggregated to derive net global impacts.[28] This results in a net 37% per-kilometer fuel consumption reduction (by 2050) on a global basis as compared to global 2025 efficiency.[29] Such reduction is equivalent to an annualized reduction of 1.8%. However, we do not apply the reduction proportionally over time. Instead, we assume a "front loaded" reduction path, wherein near term reductions are larger in accordance with the greater availability of efficiency technology in the early years of implementation. On a global basis, interim five year targets between 2025 and 2050 reflect five-year annualized reductions of 2.5% (2025-2030), 2.2% (2030-2035), 1.9% (2035-2040), 1.5% (2040-2045), and 1.1% (2045-2050). These assumptions generate the specific levels of efficiency depicted for the for the "ICE Policy Potential" scenario in Figure 2a above.

We estimate the baseline (i.e., 2005) energy demand for LHDV, MHDV, and HHDV EVs by multiplying baseline (i.e., 2005) LDV EV demand by the ratio of LHDV, MHDV, and HHDV ICE per-kilometer energy demand to LDV ICE per-kilometer energy demand. In other words, we assume that baseline (pre-policy) efficiency is a direct indicator of energy demand for an average vehicle in each class. For non-baseline years, we estimate EV energy demand using the annual EV efficiency improvement factors derived from an ICCT study of EV efficiency[30] combined with effects of moving from the easiest electrified vehicles in the class to the larger, more challenging vehicles as required for high EV market shares. Additional detail on these effects is presented in the preceding discussion on LDV efficiency

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[27] Delgado, O.; Rodríguez, F.; and Muncrief, R.; "Fuel Efficiency Technology in European Heavy-Duty Vehicles: Baseline and Potential for the 2020-2030 Time Frame," July 2017.

[28] It is important to recognize that global impacts reflect a combination of regional efficiency and travel changes. Since travel growth varies by region, regional travel weighting varies by year so that global efficiency can improve at a faster or slower rate than a given local efficiency depending on changes in travel distributions over time.

[29] We select 2025 as the comparative year here simply because it represents a "reasonable" approximation of when current efficiency policies expire. Some regions (e.g., the EU) have current policies that run through 2030, others 2020, and some have no current policies at all. In this analysis, we do not modify current policies in any way, but rather account for any additional efficiency improvement potential only after current policies expire. Thus, additional ICE potential is implemented beginning in different years for different regions. We select 2025 as a global "average" here simply to define a baseline for comparative estimates of the reduction potential of future ICE policies relative to the ICE policies currently in place.

[30] Lutsey, N. and Nicholas, M., "Update on electric vehicle costs in the United States through 2030," ICCT Working Paper 2019-06, April 2, 2019.

estimates. The net global efficiency values (in kWh/km) assumed for EVs in the HDT sector in this analysis are as follows:[31]

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
LHDTs	0.283	0.274	0.274	0.265	0.274	0.274	0.283	0.283	0.283	0.283
MHDTs	0.467	0.452	0.452	0.437	0.452	0.452	0.467	0.467	0.467	0.467
HHDTs	0.947	0.916	0.916	0.886	0.916	0.916	0.947	0.947	0.947	0.947

Discussion of HDT Forecasts: Forecast estimates for new HDTs are as presented in Figures 2a and 2b above. It is important to recognize that the ICCT Roadmap model functions on a five year temporal scale, so that transitional impacts are only "visible" at a five year level of resolution. Note that the upswing of the historic trend line between 2005 and 2010 is not due to any relaxation of standards in any given global region, but rather due to shifts in global travel trends that favor regions with less stringent standards. Similarly, the upswing in per-vehicle emissions after 2030 in the "With Currently Adopted Policies" scenario is not due to growth in travel per se, but rather to changes in the distribution of travel across both regions and HDT subclasses (toward higher emitting HHDTs).

The "ICE Policy Potential" forecast achieves a 29% reduction in per-kilometer fuel consumption and CO_2 emissions from new HDTs by 2035 (relative to 2005, about 1.1% per year on an annualized basis), falling 6 percentage points short of the 35% GFEI target. Reductions continue in the post-2035 period, reaching 43% by 2050.

The "ICE+EV Policy Potential" forecast achieves a 37% per-kilometer fuel consumption reduction for new HDTs by 2035 (relative to 2005, about 1.5% per year on an annualized basis), exceeding the 35% GFEI target by 2 percentage points. Per-kilometer CO_2 emissions from new HDTs decline by 37-40% by 2035 depending on the assumed electricity grid CO_2 intensity. Reductions continue in the post-2035 period, reaching 60% for per-kilometer fuel consumption and 61-73% for per-kilometer CO_2 emissions by 2050.

The relatively lesser reductions achieved by HDTs (as compared to other vehicle classes) is generally reflective of the increased difficulty of achieving full-electric operation in the sector due to the wide range of vehicle operating demands. As with all vehicle classes, the reductions that are achieved are dependent on three critical drivers: (1) stringent ICE efficiency improvements, (2) a rapidly increasing EV market share, and (3) a significantly decarbonized electricity grid. The failure of any of these drivers will negatively affect achievement of the forecasted reductions.

Two and Three Wheeled Vehicle Efficiency

Two and three wheeled vehicles (2&3WVs) are reported in the aggregate, but efficiency estimates are developed for each class individually. Primary data on the estimated improvement in ICE fuel efficiency by 2050 was taken from the IEA.[32] These data indicate a global per-kilometer fuel consumption reduction potential of 37% and 38% between 2005 and 2050 for 2WVs and 3WVs respectively. 2WVs dominate the aggregate class and the

[31] It is important to note that we assume that EVs are not credited with efficiency improvements beyond those warranted from an engineering standpoint. If EVs instead receive additional credits, actual fleetwide efficiency improvements will be less than estimated.

[32] IEA estimates are included in the data for their EV30@30 modeling scenario (the modeling scenario is based on an aspirational goal of a 30% electric vehicle market share, with the exception of 2 and 3 wheelers, by 2030).

magnitude of this dominance is not expected to change between 2005 and 2050, so the net reduction for the combined class is 37%.

We apply the IEA estimates on a regional basis for each of the 16 regions included in the Roadmap model. Regional effects are then aggregated to derive net global impacts.[33] This results in a net 33% per-kilometer fuel consumption reduction (by 2050) on a global basis as compared to global 2025 efficiency.[34] Such reduction is equivalent to an annualized reduction of 1.6%. However, we do not apply the reduction proportionally over time. Instead, we assume a "front loaded" reduction path, wherein near term reductions are larger in accordance with the greater availability of efficiency technology in the early years of implementation. On a global basis, interim five year targets between 2025 and 2050 reflect five-year annualized reductions of 2.2% (2025-2030), 1.9% (2030-2035), 1.6% (2035-2040), 1.3% (2040-2045), and 0.9% (2045-2050). These assumptions generate the specific levels of efficiency depicted for the for the "ICE Policy Potential" scenario in Figure 3a above.

We estimate the baseline (i.e., 2005) energy demand for 2WV and 3WV EVs by multiplying baseline (i.e., 2005) LDV EV demand by the ratio of 2WV and 3WV ICE per-kilometer energy demand to LDV ICE per-kilometer energy demand. In other words, we assume that baseline (pre-policy) efficiency is a direct indicator of energy demand for an average vehicle in each class. For non-baseline years, we estimate EV energy demand using the annual EV efficiency improvement factors derived from an ICCT study of EV efficiency[35] combined with effects of moving from the easiest electrified vehicles in the class to the largest vehicles as required for high EV market shares. Additional detail on these effects is presented in the earlier discussion on LDV efficiency estimates. The net global efficiency values (in kWh/km) assumed for EVs in the 2&3WV sector in this analysis are as follows:[36]

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
2WVs	0.053	0.051	0.051	0.049	0.051	0.051	0.053	0.053	0.053	0.053
3WVs	0.066	0.064	0.064	0.062	0.064	0.064	0.066	0.066	0.066	0.066

Discussion of 2&3WV Forecasts: Forecast estimates for new 2&3WVs are as presented in Figures 3a and 3b above. It is important to recognize that the ICCT Roadmap model functions on a five year temporal scale, so that transitional impacts are only "visible" at a five year level of resolution.

The "ICE Policy Potential" forecast achieves a 17% reduction in per-kilometer fuel consumption and CO_2 emissions from new 2&3WVs by 2030 (relative to 2005, about 0.7%

[33] It is important to recognize that global impacts reflect a combination of regional efficiency and travel changes. Since travel growth varies by region, regional travel weighting varies by year so that global efficiency can improve at a faster or slower rate than a given local efficiency depending on changes in travel distributions over time.

[34] We select 2025 as the comparative year here simply because it represents a "reasonable" approximation of when current efficiency policies expire. Some regions (e.g., the EU) have current policies that run through 2030, others 2020, and some have no current policies at all. In this analysis, we do not modify current policies in any way, but rather account for any additional efficiency improvement potential only after current policies expire. Thus, additional ICE potential is implemented beginning in different years for different regions. We select 2025 as a global "average" here simply to define a baseline for comparative estimates of the reduction potential of future ICE policies relative to the ICE policies currently in place.

[35] Lutsey, N. and Nicholas, M., "Update on electric vehicle costs in the United States through 2030," ICCT Working Paper 2019-06, April 2, 2019.

[36] It is important to note that we assume that EVs are not credited with efficiency improvements beyond those warranted from an engineering standpoint. If EVs instead receive additional credits, actual fleetwide efficiency improvements will be less than estimated.

per year on an annualized basis). Reductions continue in the post-2030 period, reaching 37% by 2050.

The "ICE+EV Policy Potential" forecast achieves a 62% per-kilometer fuel consumption reduction for new 2&3WVs by 2030 (relative to 2005, about 3.8% per year on an annualized basis). Per-kilometer CO_2 emissions from new 2&3WV decline by 58-66% by 2030 depending on the assumed electricity grid CO_2 intensity. Reductions continue in the post-2030 period, reaching 78% for per-kilometer fuel consumption and 79-98% for per-kilometer CO_2 emissions by 2050.

As with all vehicle classes, the reductions that are achieved are dependent on three critical drivers: (1) stringent ICE efficiency improvements, (2) a rapidly increasing EV market share, and (3) a significantly decarbonized electricity grid. The failure of any of these drivers will negatively affect achievement of the forecasted reductions.

Bus Efficiency

Primary data on the estimated improvement in ICE bus fuel efficiency by 2050 was taken from the IEA.[37] These data indicate a global per-kilometer fuel consumption reduction potential of 39-52% between 2005 and 2050, depending on the global region considered. On a global basis, reductions are at the high end of this range (52%) because the regional distribution of VKT for buses changes dramatically between 2005 and 2050, favoring regions with smaller, more fuel efficient buses.[38] This shift reinforces technology impacts resulting in global reductions that are larger than would be expected from technology application alone.

As with all vehicle classes, we apply the IEA estimates on a regional basis for each of the 16 regions included in the Roadmap model. Regional effects are then aggregated to derive net global impacts.[39] This results in a net 41% per-kilometer fuel consumption reduction (by 2050) on a global basis as compared to global 2025 efficiency.[40] Such reduction is equivalent to an annualized reduction of 2.1%. However, we do not apply the reduction proportionally over time. Instead, we assume a "front loaded" reduction path, wherein near term reductions are larger in accordance with the greater availability of efficiency technology in the early years of implementation. On a global basis, interim five year targets between 2025 and 2050 reflect five-year annualized reductions of 2.6% (2025-2030), 2.5%

[37] IEA estimates are included in the data for their EV30@30 modeling scenario (the modeling scenario is based on an aspirational goal of a 30% electric vehicle market share, with the exception of 2 and 3 wheelers, by 2030).

[38] The bus class is comprised of a broad range of vehicles, from small minibuses to large urban and intercity buses. Although the bus class is treated in the aggregate and thus reflects the combination of all component vehicles, significant differences in aggregate performance can be manifested across regions with significantly differing makeups of their bus fleets.

[39] As stated earlier, it is important to recognize that global impacts reflect a combination of regional efficiency and travel changes. Since travel growth varies by region, regional travel weighting varies by year so that global efficiency can improve at a faster or slower rate than a given local efficiency depending on changes in travel distributions over time.

[40] We select 2025 as the comparative year here simply because it represents a "reasonable" approximation of when current efficiency policies expire. Some regions (e.g., the EU) have current policies that run through 2030, others 2020, and some have no current policies at all. In this analysis, we do not modify current policies in any way, but rather account for any additional efficiency improvement potential only after current policies expire. Thus, additional ICE potential is implemented beginning in different years for different regions. We select 2025 as a global "average" here simply to define a baseline for comparative estimates of the reduction potential of future ICE policies relative to the ICE policies currently in place.

(2030-2035), 2.1% (2035-2040), 1.8% (2040-2045), and 1.4% (2045-2050). These assumptions generate the specific levels of efficiency depicted for the for the "ICE Policy Potential" scenario in Figure 4a above.

We estimate the baseline (i.e., 2005) energy demand for bus EVs by multiplying baseline (i.e., 2005) LDV EV demand by the ratio of bus ICE per-kilometer energy demand to LDV ICE per-kilometer energy demand. In other words, we assume that baseline (pre-policy) efficiency is a direct indicator of energy demand for an average vehicle in each class. For non-baseline years, we estimate EV energy demand using the annual EV efficiency improvement factors derived from an ICCT study of EV efficiency[41] combined with effects of moving from the easiest electrified vehicles in the class to the largest vehicles as required for high EV market shares. Additional detail on these effects is presented in the earlier discussion on LDV efficiency estimates. The net global efficiency values (in kWh/km) assumed for EVs in the bus sector in this analysis are as follows:[42]

2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
0.516	0.499	0.499	0.482	0.499	0.499	0.516	0.516	0.516	0.516

Discussion of Bus Forecasts: Forecast estimates for new buses are as presented in Figures 4a and 4b above. It is important to recognize that the ICCT Roadmap model functions on a five year temporal scale, so that transitional impacts are only "visible" at a five year level of resolution.

The "ICE Policy Potential" forecast achieves a 29% reduction in per-kilometer fuel consumption and CO_2 emissions from new buses by 2030 (relative to 2005, about 1.3% per year on an annualized basis). Reductions continue in the post-2030 period, reaching 52% by 2050.

The "ICE+EV Policy Potential" forecast achieves a 47% per-kilometer fuel consumption reduction for new buses by 2030 (relative to 2005, about 2.5% per year on an annualized basis). Per-kilometer CO_2 emissions from new buses decline by 46-49% by 2030 depending on the assumed electricity grid CO_2 intensity. Reductions continue in the post-2030 period, reaching 76% for per-kilometer fuel consumption and 78-95% for per-kilometer CO_2 emissions by 2050.

As with all vehicle classes, the reductions that are achieved are dependent on three critical drivers: (1) stringent ICE efficiency improvements, (2) a rapidly increasing EV market share, and (3) a significantly decarbonized electricity grid. The failure of any of these drivers will negatively affect achievement of the forecasted reductions.

VKT Influences on Fleetwide Impacts

Generally, the fleetwide impacts depicted in Figures 6a and 6b above incorporate the impacts of the same analysis assumptions described above for individual vehicle classes. However, the depicted trends are also sensitive to influences that do not affect new vehicle

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[41] Lutsey, N. and Nicholas, M., "Update on electric vehicle costs in the United States through 2030," ICCT Working Paper 2019-06, April 2, 2019.

[42] It is important to note that we assume that EVs are not credited with efficiency improvements beyond those warranted from an engineering standpoint. If EVs instead receive additional credits, actual fleetwide efficiency improvements will be less than estimated.

comparisons. The biggest such influences are growth in travel and the rate of fleet turnover. While these influences are dependent on the assumptions included in the ICCT's Roadmap model rather than on assumptions specifically developed for this analysis, it is nevertheless important to understand the magnitude of these effects. Fleet turnover rates serve to buffer new vehicle impacts for several years, but do not ultimately impact the fleetwide level of emission reduction achievable. VKT growth on the other hand directly influences the level of emission reduction achievable from a fixed historic baseline, as some fraction of emission reduction must go toward offsetting fleetwide emissions growth before any reduction from the given baseline can be achieved.

In this analysis, travel in 2050 is 3.2 times higher than 2005 baseline travel. Growth in baseline emissions over the period is somewhat lower due to the implementation of existing efficiency standards, but 2050 baseline emissions are higher than 2005 baseline emissions by a factor of 2.5. Thus, emissions in 2050 must be reduced by 60 percent just to reach 2005 baseline emissions.[43] This "consumes" a large portion of the emission reductions achievable through new vehicle efficiency improvements.

As shown in Figure 5 above, ICE efficiency policy alone does not provide fleetwide benefits sufficient to fully offset the effects of VKT growth. Although ICE efficiency policy reduces emissions growth between 2005 and 2050 by 62%, 2050 emissions remain 57% higher than those of 2005. ICE+EV policy can reduce 2050 fleetwide emissions below those of 2005, but much of the potential is still consumed by offsetting the emissions growth remaining after the implementation of ICE efficiency policy alone. Should fleetwide EV market penetration continue toward 100% and the CO_2 intensity of the carbon grid continue toward zero, it may be possible to achieve near-100% emission reductions from any baseline, but there are vehicles, primarily in the heavy duty sector, for which a 100% EV penetration is a significant challenge.

LIST OF ACRONYMS AND ABBREVIATIONS

AGIS .... Aggressive (electric) Grid (CO_2) Intensity Scenario
BEV .... Battery Electric Vehicle
B2DS .... Beyond 2 Degrees Scenario (an IEA modeling scenario)
CO_2 .... Carbon Dioxide
CO2eq .... CO_2 equivalent (accounts for CO_2 plus greenhouse gases other than CO_2)
EU .... European Union
EV .... Electric Vehicle
FCV .... Fuel Cell Vehicle
gCO2/km .... grams of CO_2 per kilometer
gCO2/kWh .... grams of CO_2 per kilowatt hour
GFEI .... Global Fuel Economy Initiative
HDT .... Heavy Duty (freight) Truck

[43] Of course, emission reductions can be achieved by both improving per-vehicle efficiency and reducing VKT. For this work, however, we hold VKT constant at the growth rates assumed in the Roadmap model and investigate only the former.

HHDT .... Heavy Heavy Duty (freight) Truck
ICCT .... International Council on Clean Transportation
ICE .... Internal Combustion Engine
IEA .... International Energy Agency
IPCC .... Intergovernmental Panel on Climate Change
kWh/km .... kilowatt hours per kilometer
kWh/mile .... kilowatt hours per mile
Lde/100km .... diesel equivalent liters per 100 kilometers
LDV .... Light Duty (passenger) Vehicle
Lge/100km .... gasoline equivalent liters per 100 kilometers
LHDT .... Light Heavy Duty (freight) Truck
MGIS .... Moderate (electric) Grid (CO_2) Intensity Scenario
MHDT .... Medium Heavy Duty (freight) Truck
Mtonnes .... megatonnes (million tonnes)
NAS .... United States National Academy of Sciences
PHEV .... Plug-In Hybrid Electric Vehicle
TTW .... Tank-to-Wheel (a measure of the energy consumed onboard a vehicle, or the emissions generated by such operation)
VKT .... Vehicle Kilometers of Travel
USEPA .... United States Environmental Protection Agency
WTW .... Well-to-Wheel (a measure of the energy consumed both onboard a vehicle and throughout the supply chain that generated that energy, or the emissions generated during the production and consumption of that energy).
2WV .... 2 Wheeled Vehicle
3WV .... 3 Wheeled Vehicle
2&3WVs .... 2 and 3 Wheeled Vehicles

GLOBAL FUEL ECONOMY INITIATIVE

FOR ZERO CARBON VEHICLES BY 2050

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