Worldwide Greenhouse Gas Reduction Potentials in Transportation by 2050
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Summary

Reductions in the greenhouse gas (GHG) intensity of passenger and freight transportation are possible through adoption of fuel-saving technologies, demand switching between modes, and large-scale electrification of fleets, in addition to other actions. In this study, future scenarios to 2030 and 2050 are the basis for assessment of GHG reduction potentials for major passenger and freight modes (automobiles, buses, trains, aircraft, and oceangoing vessels) across eight regions of the world. New fuel-saving technologies can significantly reduce the life-cycle GHG footprint of both passenger and freight vehicles, but not uniformly worldwide. Countries outside of the Organization for Economic Cooperation and Development (OECD) lag behind OECD countries in GHG reduction potentials for all modes but oceangoing vessels owing to a combination of slower adoption of fuel-saving technologies and a slower decarbonization of electricity generation and other processes. The reduction of GHG intensity will occur more slowly for freight modes than for passenger modes. However, improved fuel efficiency has negative feedbacks to the effectiveness of mode-switching and alternative fuel adoption policies through 2050 because improvements in the fuel efficiency of vehicles alone may cause the marginal benefits of GHG abatement policies to diminish over time. This trend may be reversed if alternative fuel pathways decarbonize at faster rates than conventional transportation fuels. The largest opportunities for GHG reductions occur in non-OECD countries. Given the many factors that distinguish transportation systems between developed and developing nations (e.g., availability of new technologies, the financial ability to acquire them, and policies to incentivize their adoption), many benefits could be gained through interregional cooperation.

Introduction

Reducing greenhouse gas (GHG) emissions from the global transportation sector is a critical step needed to slow the worsening effects of climate change. In 2010, passenger and freight vehicles emitted 7.0 gigatonnes of carbon dioxide equivalents (CO₂-eq) of GHGs into the atmosphere or 23% of the world’s anthropogenic GHGs (IPCC 2014). The relative contributions of transportation-related GHGs between countries depend upon many regional factors (population size, travel demand, fuel sources, and levels of economic activity), where the overall trend is that the developed world (e.g., Organization for Economic Cooperation and Development [OECD] countries) emits a higher amount of GHGs than developing countries on a per capita basis (ITF 2010). Given the historically strong link between economic performance and transportation-related GHGs (Schipper 2011; Eom et al. 2012; ITF 2013), accelerating economic development of non-OECD countries could change the magnitude and distribution of global GHG emissions in the future.

Keywords:
- developing countries
- environmental policy
- global warming potential (GWP)
- industrial ecology
- transportation and environment

Supporting information is available on the JIE Web site

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Around the world, reductions in the GHG emissions intensity of moving people and goods are driven by both technological advancements as well as targeted governmental policies. Vehicle fuel efficiency which influences the majority share of vehicle life-cycle GHG emissions (Facanha and Horvath 2007; Winebrake et al. 2007; Chester and Horvath 2009, 2012; Hawkins et al. 2013), depends heavily on both vehicle design and key powertrain characteristics. Across passenger and freight modes, lightweighting and downsizing, thermodynamic cycle improvements, hybridization, and aerodynamic improvements (ICAO 2010; IEA 2012a; ICCT 2013; NRC 2014) represent proven technological strategies for reducing fuel usage and thereby the GHG intensity of vehicles. However, the adoption of fuel-saving technologies within vehicle fleets depends on many regional factors, including income, geography, climate, and culture. To spur implementation, the world’s largest GHG emitters have set incremental fuel economy and CO₂ emission standards for new light-duty passenger vehicles (ICCT 2014a), heavy-duty vehicles (ICCT 2012a), and ocean-going vessels (OGVs) (IMO 2013), modes that represent 85% of all transportation-related GHG emissions (ICCT 2012b). Private industries have also set fuel economy improvement goals for both rail (UIC 2012) and aircraft (ICAO 2012). However, because of differences in fleet characteristics (e.g., vehicle age and stock turnover rates), the benefits accrued from these policies, which target new vehicles, will likely occur at different rates around the world.

Whereas fuel efficiency improvements are critical steps toward curbing the GHG intensity of personal mobility and goods movement, there are other pathways to GHG reductions in the transport sector. Importantly, studies suggest that mode-switching and alternative fuel (e.g., electricity and biofuels) adoption strategies offer many potential climate benefits (Williams et al. 2012; Chester and Horvath 2012; Scown et al. 2012, 2013; Craig et al. 2013; IPCC 2014; Nahlik et al. 2014), though the success of these policies is often location dependent. Structural policies require governmental intervention owing to economic, technical, and preferential barriers resisting their mass adoption (Chester et al. 2014). Nevertheless, for profound changes, many GHG reduction scenarios require mode-switching and alternative fuel adoption strategies in order to meet future climate mitigation goals (IEA 2009; Yang et al. 2009; Hill et al. 2012).

All told, previous research has advanced our understanding of the climate impact of transportation systems on a global scale while offering possible pathways for reducing the sector’s net GHG emissions. However, relying on existing comparative analyses to gauge the potential effectiveness of climate-change mitigation policies as they relate to current and future transportation systems is still challenging, given that differences in regionally and temporally specific model assumptions, emissions inventory data, and system boundaries induce many uncertainties (Hertwich et al. 2015; Reyna et al. 2015). Overall, there is limited information on how the unit GHG benefits of climate-oriented transportation policies will change over time as vehicle modes and energy systems decarbonize. Addressing these challenges is important, especially at a regional level (Cicas et al. 2007; Chester et al. 2010), because it is unlikely that there exists a single, long-term strategy for reducing GHG emissions within the transportation sector (e.g., one policy best for all locations). Moreover, given the differences in regionized characterization factors, such as vehicle fuel efficiency, load factors, fuel pathways, and typical trip distances, it is also unlikely that the opportunities to decarbonize the transportation sector are equivalent across global regions over time.

This article is one in a series of technology assessments initiated through the International Resource Panel (IRP) of the United Nations Environmental Program (UNEP). The collaboration seeks to quantify the environmental and natural resource benefits and trade-offs associated with wide-scale adoption of advanced energy technologies, with each assessment sharing consistent methods, system boundaries, and background life-cycle inventory (LCI) data. The goal of this study is to evaluate how an extensive, but feasible, adoption of low-carbon energy and efficient demand-side technologies would affect the incremental GHG benefits (e.g., on functional unit and trip basis) of modal shift and vehicle electrification within and across OECD countries (i.e., mostly wealthy economies) and non-OECD countries (mostly developing economies). Given a wide variety of transportation modes across the globe, we limit the scope of this assessment to the world’s most common vehicle types: automobiles, buses, trains, aircraft, and OGVs. We also set our system boundaries to include only globally prominent transportation fuels (e.g., gasoline, diesel, bunker fuel, and jet fuel) as a basis for comparison. Though other alternative fuels—such as biofuels, biogas, and natural gas—are also used in some countries, they are supplied at relatively low volumes and/or to niche applications.

We provide estimates for the life-cycle cradle-to-grave GHG footprint of both passenger and freight transportation following a prominent global energy and material production scenario established by the International Energy Agency (IEA) (IEA 2010) for reference years 2010, 2030, and 2050. Results show how the incremental GHG benefits of modal shift and vehicle electrification policies vary across all global regions through 2050 and where the largest opportunities for GHG reductions occur. We assess the sensitivity of GHG abatement policies within the transportation sector to key assumptions regarding the levels of services these modes provide (i.e., ridership and total payload), the evolution of electricity generation mixes through time and space, as well as offer a discussion on the relevance and uncertainty of the results.

**Methods**

The goal of this study is to assess the GHG reduction potentials associated with mode-switching and vehicle electrification policies across the world in 2030 and 2050. The scenarios that are presented in this study have been guided by previous global assessments of mobility and goods movement (IEA 2009; IPCC 2014) as well as literature focusing on transportation systems in...
specific regions of the world. The scope of the study includes
the production, distribution, storage, and in-vehicle use of
transportation fuels (i.e., well-to-wheel [W2W] processes), ve-
hicle, vessel, and aircraft manufacturing and maintenance, in-
cluding battery manufacturing for battery-electric (BEVs) and
plug-in hybrid electric vehicles (PHEVs) (Majeau-Bettez et al.
2011; Hawkins et al. 2013), as well as end-of-life (EOL) pro-
cesses. A complete mapping of the system boundaries is provided
in the Supporting Information available on the Journal’s web-
site. Emissions associated with the construction, maintenance,
and operation of supporting infrastructure are not considered
because of global data unavailability, though we recognize that
these emissions are important for certain transportation modes
(Chester and Horvath 2009, 2010).

The scenarios show the life-cycle GHG emissions associated
with major passenger and freight modes for eight regions: OECD
Europe (EU), OECD Pacific (PAC), OECD North America
(NA), China (CN), India (IN), Latin America (LA), Africa
and the Middle East (AME), and economies in transition (EIT),
for example, Eastern European countries and Russia. Because
of insufficient information on emerging vehicle fleets, developing
countries in South Asia (e.g., Thailand and Indonesia) were
excluded from the assessment. The regions reflect the system
boundaries established across the collaborative of UNEP IRP
studies on the environmental impacts and resource utilization
of low-carbon energy and efficient demand-side technologies
(Hertwich et al. 2015; Gibon et al. 2014).

In each region, GHG emission factors were reported based
on an optimistic, yet attainable, evolution of electricity and
material production technologies according to the BLUE Map
energy scenario from the IEA Energy Technology Perspectives
(ETP) (IEA 2010). The IEA’s 2012 ETP was available be-
fore publication, but appears similar to the earlier version (IEA
2012b). BLUE Map employs target-oriented policies that aim
to halve global GHG emissions from a 2005 baseline by 2050
through the implementation of currently available technologies
(e.g., renewable energy, more efficient technologies, and carbon
capture and storage). Results for the IEA’s baseline scenarios,
which assume business-as-usual activities, are also provided in
the Supporting Information on the Web. In each scenario year
(2010, 2030, and 2050), GHG emissions associated with the
production, distribution, and storage of transportation fuels,
vehicle manufacturing and maintenance, as well as EOL pro-
cesses were estimated using the THEMIS model (Technology
Hybridized Environmental-economic Model with Integrated
Scenarios) (Hertwich et al. [2015] and Supporting Information
on the Web). It is a regionalized model for electricity genera-
tion and materials production that integrates commercial and
academic life-cycle assessment (LCA) software (ecoinvent and
EXIOPOL) with original data from life-cycle emissions and re-
source consumption inventories of energy technologies in the
future (ecoinvent Center 2010; Tukker et al. 2013; Hertwich
et al. 2015; Gibon et al. 2014). The THEMIS model accounts
for projected advances in efficiencies in low-carbon electricity
technologies, such as photovoltaic power systems, as well as
energy efficiency improvements in key industrial sectors, such
as raw material production and chemical manufacturing, using
the IEA’s underlying energy scenario data and assumptions
(IEA 2010).

There are advantages of building upon previous global sce-
narios using a consistent methodology, system boundary, and
supporting inventory data. Although there are many benefits
to utilizing life cycle tools that are tailored to specific regions
of the world (Cicas et al. 2007; ANL 2012; EcoTransIT 2011),
these tools do not consistently account for all transportation
modes or economy-wide technological changes (e.g., electricity
generation, metal production, and chemical production)
that influence the GHG intensity of vehicles. By estimating
the environmental performance of passenger and freight trans-
portation through a consistent approach dedicated to global
assessments, our study makes possible comparisons between
transportation modes within and across different world regions
from 2010 through 2030 and 2050.

Table 1 provides a list and brief description of the representa-
tive vehicles analyzed in this study. We compare four passenger
transportation modes (automobile, bus, rail, and airplane) and
three freight modes (truck, rail, and OGV) that represent the
bulk of the world’s vehicle kilometers traveled (VKT) and total
freight turnover (World Bank 2014). Data suggest that there
is more variability in demand for different fuel types within
light-duty passenger vehicles globally (gasoline, diesel, electricity,
biofuels, natural gas, and so on) than for any of the other
modes considered (IEA 2009). We analyze only electricity as
an alternative to conventional petroleum-based fuels because
its supporting infrastructure is more broadly available and more
is known about the evolution of its carbon intensity through
2050 (IEA 2010). Other alternative transportation fuels, such
as biofuels (Scown et al. 2012, 2013), could also be potential
substitutes for high-carbon fuels in some areas of the world,
but are not considered herein owing to uncertainties regard-
ing system scalability (e.g., material sourcing and infrastructure
expansion) and adoption (McKone et al. 2011; Strogen et al.
2012).

The results of the LCI for each vehicle are normalized by ei-
ther passenger-kilometer (pkm) or metric ton-kilometer (tkm)
to obtain the life cycle GHG emission factor (equation 1):

$$e_f = \sum_i T_i \frac{T_i}{\text{VKT} \cdot \text{A}} = \sum_i E_i \frac{E_i}{A}$$

(1)

where, $e_f$: life-cycle emission factor (personal travel: grams [g]
CO$_2$-eq/pkm; freight: g CO$_2$-eq/tkm), $T$: total number of
life-cycle phases i considered, $T_i$: total GHG emissions for each
life-cycle phase i (g CO$_2$-eq: weighted CO$_2$, methane, nitrous
oxide emissions), VKT: lifetime vehicle kilometers traveled (km),
$E_i$: emissions rate for each life phase i (g CO$_2$-eq/km), $A$: ac-
tivity or level of service (personal travel: passengers; freight:
metric tons, t).

The process of normalizing GHG emissions from the vehicle
manufacturing, maintenance, and EOL stages slightly differs
from W2W emissions because of the way in which emissions
are reported. The former are estimated based on a lump-sum

Taptich et al., World GHG Reduction Potentials in Transport, 2050 331
value (e.g., the manufacturing of one vehicle results in \(X\) g CO\(_2\)-eq), whereas the latter is estimated over a continuum (e.g., g CO\(_2\)-eq/km). These differences can have an impact on the formation of the life cycle emission factor (Taptich and Horvath 2014) and are important for understanding the relative role each life cycle phase has on influencing the vehicle’s total GHG footprint. These factors are discussed in the following sections. For a summary of model inputs used for each of the modes, see the Supporting Information on the Web.

Fuel consumption estimates (g fuel/km) for each mode were derived based on current and projected fuel economy standards (IEA 2012a; ICCT 2012a; US EIA 2014; ICCT 2014a), fleet-specific inventory data (OAG 2008; KPMG 2011; Lissys Ltd 2010; Clarkson Research 2014), and industry-specific fuel consumption forecasts (ICAO 2009; ICAO 2012; UIC 2012) (table 1). Overall, information detailing the fuel efficiency of specific vehicles was more readily available for the OECD regions (Europe, North America, and the Pacific Rim) than for the non-OECD countries and regions. In cases where little data were available, we assumed fuel economies based on regional fleet compositions, known fleet turnover rates, as well as information provided in the literature. For instance, the world’s high-speed rail (HSR) infrastructure currently only exists in three study regions (OECD Europe, OECD Pacific, and China), but plans are in place to expand this network to other regions by 2030 (IEA 2009). Information regarding HSR fuel consumption is available over a range of values for older systems, and we rely on fuel consumption estimates from Chester and Horvath (2012) for new HSR technologies to represent theoretical fleets (20 kilowatt-hours [kWh]/VKT) because these technologies would reasonably be adopted upon initial implementation. A full list of fuel consumption estimates used in this study and their respective references are provided in the Supporting Information on the Web. Table 2 provides an overview of future trends within each mode considered.

Methods for estimating operational GHG emissions vary by mode. For on-road vehicles and rail, operational GHG emission rates, \(E_{op}\) (g CO\(_2\)-eq/km), are calculated from fuel consumption rates, which are already reported over distances traveled. However, the standard for aircraft and OGVs is to report total fuel usage per trip, which is a function of time spent at varying operational modes and loading conditions (ICCT 2013, 2014b). For aircraft, we estimate \(E_{op}\) for intraregional trips using a linear regression model of fuel consumption simulations of an Airbus 320, a commonly used, average-size aircraft under varying loadings and trip distances (Lissys Ltd 2010) and using historical flight data (OAG 2008) such that (equation 2):

\[
E_{op} = \frac{\beta_0 + \beta_1 d}{d} \gamma
\]

where \(\beta_0\): fuel usage associated with ground-based operations (idling, takeoff, and landing) (g of fuel), \(\beta_1\): fuel usage rate associated with flight operations (climbing and cruising) (g fuel/km), \(d\): distance traveled per trip (km), \(\gamma\): carbon dioxide emissions to fuel mass ratio (g CO\(_2\)-eq/g fuel).

For OGVs (containerships and crude tankers), fuel consumption rates are reported in terms of engine braking power (g fuel/kWh) for both primary and auxiliary vessel engines. We rely upon vessel composition data obtained from the World Fleet Register (Clarkson Research 2014) and vessel-specific engine loading estimates from the literature (ICCT 2013) to

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**Table 1** Brief description of the representative vehicles used in this study and their respective major fuel source references

| Vehicle                          | Description                                                                 |
|---------------------------------|-----------------------------------------------------------------------------|
| Automobile (gasoline, G)        | Gasoline-powered passenger car with five-seat capacity                       |
| Automobile (diesel, D)          | Diesel-powered passenger car with five-seat capacity                         |
| Electric vehicle (BEV)          | Compact car with 160-km range (2010)/320-km range (2030–2050), 214-kg LiNCM battery (Majeau-Bettez et al. 2011, Hawkins et al. 2013). |
| Plug-in hybrid vehicle (PHEV)   | Compact car with 64-km range, 120-kg LiNCM battery (Majeau-Bettez et al. 2011; Hawkins et al. 2013) |
| Transit (city bus)              | 12-m-long diesel-powered transit bus with two doors and capacity of approximately 80 passengers |
| Airplane                        | Medium-range, single aisle, commercial aircraft. Reference vehicle: Airbus 320. |
| Passenger rail (diesel)         | 340-seat diesel-powered train. Reference locomotive: General Electric ES44AC (AMTRAK). |
| Passenger rail (electric)       | 340-passenger electric-powered multiple unit train. Reference locomotive: Talgo 250. |
| High-speed rail (HSR)           | 670-seat electric-powered train. Reference vehicle: Deutsche Bahn ICE         |
| Medium heavy-duty truck (MHD)   | 52-metric-ton\(^1\) capacity truck. Reference vehicle: class-6 truck under U.S. classification. |
| Heavy heavy-duty truck (HHD)    | 24-metric-ton capacity truck: Reference vehicle: class-8b truck under U.S. classification. |
| Freight rail                    | Diesel-powered locomotive with eight wagons                                 |
| Containership                   | 60,000 deadweight metric ton capacity containership, fleet average           |
| Crude tank                      | 160,000 deadweight metric ton capacity crude tanker, fleet average           |

Note: \(^1\)The terms “ton,” “tons,” and “ton-km” found in this document refer to the metric ton, which is equivalent to 1,000 kg.
### Table 2  Future fuel efficiency trends by vehicle mode

| Mode   | Trend overview                                                                                                                                                                                                 | Major references                                                                                                                                 |
|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| Automobile | Fuel economy trends are based on current and projected fuel economy standards. Regions without future fuel economy standards adopt new technologies slower and see an average reduction by 15% by 2030 and 30% by 2050. Based on best data available, we also assume that diesel cars achieve a 10% better fuel efficiency than gasoline-powered cars. Given that EVs and PHEVs are relatively new technologies, we rely on estimates from the U.S. Energy Information Administration for all regions. | IEA (2012a); ICCT (2014a); US EIA (2014); Hawkins and colleagues (2013); Scown and colleagues (2013)                                                                                       |
| Truck  | Heavy-duty vehicles in OECD regions adopt fuel reduction technologies that amount to a 15% reduction in fuel consumption by 2030 and 30% by 2050 from the 2010 baseline. Non-OECD regions maintain relatively older fleets and subsequently are one technology generation behind. | NRC (2014); ICCT (2012a); US EIA (2014); ITF (2010); KPMH (2011); Eom and colleagues (2012)                                                                                             |
| Bus    | Non-OECD regions have a large share of older buses and are therefore a generation behind OECD countries in fuel efficiency. In the next 20 years, we expect hybridization of diesel buses to improve fuel consumption rates by 30% across all regions. Looking out to 2050, we assume buses achieve a further 15% improvement in fuel consumption through advances in engine technologies, tires, and weight reduction. | NRC (2014); ICCT (2012a); US EIA (2014); ITF (2010)                                                                                                                                 |
| Rail   | For diesel-powered rail, we assume a 10% improvement in fuel efficiency (l/100 km) or 0.5% per year by 2030 and 20% improvement by 2050. We assume that electric rail, which is currently only available in select regions, achieves a 25% efficiency improvement (kWh/km) by 2030 and an additional 10% improvement (0.5% per year) by 2050. | Chester and Horvath (2009); UIC (2012); AMTRAK (2014); AEA (2009)                                                                                                                                 |
| Aircraft | Based on optimistic adoption of new aircraft fuel use technology, we assume an average improvement of 1.5% per year in fuel usage across all fleets.                                                                 | ICAO (2010); ICAO (2012); Lissys Ltd (2010); OAG (2008)                                                                                                                                 |
| OGV    | Oceangoing vessels reduce GHG emissions at 1.5% per year until 2030, based upon the Energy Efficiency Design Index (EEDI) standards. Additional technology improvements are added to the industry to 2050 at 1.5% per year. | IMO (2013); Clarkson Research (2014)                                                                                                                                  |

Note: OGV = oceangoing vessel; EV = electric vehicle; PHEVs = plug-in hybrid vehicles; OECD = Organization for Economic Cooperation and Development; km = kilometers; kWh/km = kilowatt-hours per kilometer; GHG = greenhouse gas.

**Results**

The share of GHG emissions from W2W life-cycle stages relative to a vehicle’s total life-cycle footprint is a function of vehicle fuel efficiency and lifetime levels of service (i.e.,
ridership or freight turnover). Results from the 2010 scenario show that high-capacity, long-distance modes have significant shares of W2W emissions (93% to 100%). These modes include heavy heavy-duty (HHD) trucks, rail, aircraft and OGVs. This finding has previously been reported across the literature for LCAs of vehicles (Winebrake et al. 2007; Facanha and Horvath 2007; Chester and Horvath 2009, 2012) and provides direction for developing policies that aim to reduce GHG emissions from these modes. For instance, focusing on policies that only improve the W2W GHG intensity (e.g., fuel-saving technologies or low-carbon fuels) of light-duty vehicles ignores a significant portion (17% to 33%) of their full GHG impact (Majeau-Bettez et al. 2011; Hawkins et al. 2013). For modes such as buses, heavy-duty trucks, rail, and OGV, lowering the GHG intensity of vehicle manufacturing, maintenance, and EOL stages will result in small savings over the lifetime of these vehicles. In summary, the sensitivity of life cycle GHG emission factors to the adoption of new fuel-saving technologies or alternative fuels varies across modes. Small improvements to the W2W GHG intensity of high-capacity, long-distance modes will have greater marginal improvements to emission factors.

Figure 1 summarizes our findings for autos, buses, heavy-duty trucks, trains, and OGVs for the 2030 and 2050 scenario years. Overall, non-OECD countries lag behind OECD countries in GHG reduction for all modes, excluding OGVs, owing to a combination of slower adoption of fuel-saving technologies and a slower decarbonization of electricity generation and other industrial processes. The largest differences between these two economic classifications can be observed for vehicles powered entirely or in part by electricity (BEV, PHEV, and HSR). For instance, the life-cycle GHG footprint of a BEV operated in India could be over 2.5 times larger than the footprint of the same vehicle operating in North America as a result of higher GHG emissions from electricity generation (using mostly coal).
In fact, we find that there would be no difference between BEV and gasoline-powered cars in India for the 2030 scenario year. This highlights an important insight derived from this study: there is no one strategy for all modes and all regions. Each region has its own unique levels of ridership, freight turnover, and other technological characteristics that influence its respective GHG footprint.

The results also show that reduction of the GHG intensity of freight modes occurs more slowly than of passenger modes around the world by 2050. The reason is twofold. First, for the most part, fleet turnover rates occur more slowly within freight modes than within passenger modes. The longer vehicle lifetimes (e.g., 30 years for rail, aircraft, OGV, and HHD truck) (IEA 2009) and infrastructure design choices (e.g., nonelectricified rail) lock in the technologies available for long periods of time. Hence, if there are large improvements to new vehicle stock relative to older generations of vehicles, these savings may not be realized until years later as fleets gradually adopt these technologies. Second, freight vehicles face performance conditions that are unlike those for most passenger modes. Higher levels of service (e.g., tonnage) come at a cost of higher required power rating for engines and therefore fuel usage. Reducing fuel usage given these constraints is challenging even for an economic sector with incentives to reduce fuel costs. Meanwhile, passenger modes (e.g., cars) can feasibly roll back the power delivered by engines or the mass of a vehicle, reducing total fuel usage, without affecting levels of services. For the same reasons stated, passenger vehicles have a greater variety of alternative fuels available, which may reduce the GHG footprint of these modes. Because of data availability and large supply potential, we only consider electricity as an alternative fuel in this study, but other lower-GHG fuels should also be considered in future work, such as biofuels, hydrogen, and natural gas.

The unit GHG reduction potentials associated with mode-switching and vehicle electrification policies across all eight regions through 2050 is evaluated in figure 2. The results of the 2010, 2030, and 2050 global scenarios show both positive (net savings) and negative (net gains) reduction potentials. This variability in benefits again reinforces the importance of regional considerations when comparing the effectiveness of GHG abatement policies on a global scale. Though the efficiency of these policies varies between regions, the overall trend is that GHG reductions converge on a similar range of numbers over time, and the range of unit GHG reduction potentials is smaller in 2050 than it is in 2010 and 2030. In terms of meeting future climate mitigation goals (IEA 2009; Yang et al. 2009; Hill et al. 2012), this finding is both positive and negative. We see that the effectiveness of some policies to reduce GHGs increases over time and, in some cases, switches from negative to positive reduction potentials, whereas the benefits of other policies diminish over time. Overall, the long-term effectiveness of mode-switching and vehicle electrification policies depends on the policy type and region of interest.

The results of the trip-based assessment (kg CO2-eq saved per passenger trip or metric ton trip) also indicate that mode-switching policies will be the most effective in the short term, whereas vehicle electrification policies achieve the largest savings by 2050. The differences between these trends can be attributed to differences in improvements in fuel efficiency between vehicles and the rate at which well-to-pump processes decarbonize for petroleum-based fuels relative to electricity generation. Vehicle electrification coupled with both fuel efficiency improvements and large reductions in the carbon intensity of electricity generation under the IEA BLUE Map energy scenarios result in a net improvement over time. It is important to note, however, that this scenario does not consider the role of advanced biofuels as a liquid fuel additive or substitute (Scown et al. 2013), which could lower the incremental GHG benefits of electrification policies. In contrast, mode-switching policies for vehicles powered by petroleum-based fuels do not receive the added benefit of well-to-pump decarbonization. Thus, as the fuel efficiency for each vehicle within a respective scenario improves over time, the difference between modes in terms of GHG intensity diminishes. These findings strengthen the position that environmental assessments of transportation modes should extend beyond characterizations of tailpipe emissions alone. Here, the key factors influencing the climate benefits of these policies occur upstream of the vehicle's operation.

Figure 2 also shows that the largest unit savings per policy occur in non-OECD countries. Under the same reasoning from the preceding policy assessments, larger benefits occur in these regions as a result of their currently higher W2W GHG intensities (i.e., large emissions factors tend to have larger relative GHG reduction potentials). Because GHGs are global pollutants, we could achieve the greatest GHG reductions if the more affluent OECD countries facilitated mode switching and alternative fuel adoption polices in less affluent countries. For example, the GHG savings resulting from switching freight deliveries by HHD truck to freight rail in OECD Europe is nearly 6 times less effective than the same policy in EIT on a unit-trip basis.

**Sensitivity of Policies to Levels of Service and Electricity Mixes**

In each of the scenarios presented, we assume that levels of service remain constant through 2050. This assumption introduces varying levels of bias into the reporting of GHG emission factors (see Taptich and Horvath [2014] for more), the largest of which occurs within smaller modes. We provide a range of values for each vehicle-region pair in the Supporting Information on the Web. However, we assess the sensitivity of our conclusions for each of the six policies analyzed under different assumptions of average ridership and freight turnover.

Figure 3 shows a comparison of two policy scenarios (Auto to Bus, TOP; Diesel Rail to HSR, BOTTOM) under varying levels of feasible load factors for each region. Assumptions of levels of services for each vehicle map onto a region where the alternative vehicle is preferred (gray region). For high-capacity, long-distance modes, small variability (±20%) in the levels of ridership or freight turnover does not affect the recommendation to choose the alternative vehicle given that
The table presents the results of a unit assessment of GHG reduction potentials for six abatement policies on a trip basis. The results show both diminishing and increasing benefits by 2050 under the BLUE Map energy scenario. The policies with the greatest 2050 GHG reduction potentials are highlighted in gold and occur in non-OECD regions. GHG refers to greenhouse gas, kg CO$_2$-eq to kilograms carbon dioxide equivalents, and OECD to the Organization for Economic Cooperation and Development.

### Figure 2
Results of a unit assessment of GHG reduction potentials for six abatement policies on a trip (average kg CO$_2$-eq saved per pass-trip or metric ton-trip) basis show both diminishing and increasing benefits by 2050 under the BLUE Map energy scenario. We highlight the regional policies with the greatest 2050 GHG reduction potentials in gold; each occurs in non-OECD regions. GHG = greenhouse gas; kg CO$_2$-eq = kilograms carbon dioxide equivalents; OECD = Organization for Economic Cooperation and Development.

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For each policy scenario, we model GHG reduction potentials assuming an optimistic, yet attainable, decarbonization of electricity and material production technologies. To test our findings that vehicle electrification policies improve through time, we reanalyze the life-cycle GHG footprint of each mode under the IEA’s baseline energy scenario (IEA 2010), which assumes modest reduction in the carbon intensity of the grid by 2050. Under these assumptions, we find that GHG reduction potentials for all policies, excluding passenger rail to HSR, result in diminishing, but still positive, benefits by 2050. This result arises because the rates at which W2W processes decarbonize
Transportation GHG reduction policies are sensitive to load factors (ridership or payload). For each region and mitigation strategy (e.g., Auto to Bus, TOP; Diesel Rail to HSR, BOTTOM), the gray domain implies that the y-axis mode is less GHG intensive than the x-axis mode, and the white domain implies that the x-axis mode is less GHG intensive than the y-axis. The overlying red region represents the feasible set of all load factor combinations between low- and high-ridership conditions for each respective vehicle. The dot in each graph represents average load factors estimated for each region. Results for the other four cases are provided in the Supporting Information on the Web. GHG = greenhouse gas; HSR = high-speed rail.

Figure 3  Transportation GHG reduction policies are sensitive to load factors (ridership or payload). For each region and mitigation strategy (e.g., Auto to Bus, TOP; Diesel Rail to HSR, BOTTOM), the gray domain implies that the y-axis mode is less GHG intensive than the x-axis mode, and the white domain implies that the x-axis mode is less GHG intensive than the y-axis. The overlying red region represents the feasible set of all load factor combinations between low- and high-ridership conditions for each respective vehicle. The dot in each graph represents average load factors estimated for each region. Results for the other four cases are provided in the Supporting Information on the Web. GHG = greenhouse gas; HSR = high-speed rail.

are comparable for both vehicles in mode-switching or electricity adoption partnerships. Hence, the difference between the status quo and the alternative vehicle decreases over time. This diminishing return on GHG abatement policies caused by reductions in the GHG intensity of fuel-related, life-cycle processes has policy implications, which we discuss in greater detail in the following section. To view the results of our scenarios under the baseline assumption, see the Supporting Information on the Web.

Uncertainty and Scenario Limitations

The scenario results presented are subject to many uncertainties regarding the types of energy technologies that will be adopted across transportation modes, as well as how these modes will be utilized in the future. Fuel consumption rates and other vehicle performance metrics (e.g., annual distances traveled, vehicle age, and load factors) by transportation mode are the best estimates available from the literature and various governmental agencies (table 2). However, regions and individual vehicles may experience differences in the GHG intensity reported in this study based on vehicle size and technology adoption, including material composition, model year, setting (e.g., urban vs. rural), demand level (e.g., on- vs. off-peak), and topology (Reyna et al. 2015). We also recognize that additional low-carbon fuels other than electricity could be used to reduce the GHG footprint of passenger and freight transport (Yang et al. 2009; Hill et al. 2012; Scown et al. 2013). In addition, though we offer information regarding trends in the GHG footprint of different modes within a region, considerations of...
costs are not within the scope of our study, but are critical for defining the optimal pathways for meeting our long-term climate-change mitigation goals in an efficient manner. On the issue of selecting a specific climate-change mitigation pathway, we chose the IEA’s BLUE Map scenario to maintain a consistent analytical structure and system boundaries with other studies in the UNEP IRP collaboration (Hertwich et al. 2015; Gibon et al. 2014).

Discussion

Through a life-cycle GHG assessment at a global scale, we offer estimates on the marginal GHG benefits of new technologies, mode-switching, and electrification polices for both passenger and freight transport. We show that new technology adoption can greatly reduce the GHG intensity of passenger and freight transport by 2050. Passenger vehicles are projected to see larger fuel efficiency improvements than freight vehicles, amounting to reductions as large as 90% from the 2010 scenario baseline. The analysis also reveals that the unit GHG intensity of vehicle modes varies across the world, suggesting that effectiveness of GHG mitigation policies will be location dependent. Accordingly, accounting for region-specific technology adoption, vehicle productivity, as well as supply-chain processes occurring along fuel pathways facilitates the identification of GHG abatement policies with the greatest net benefits. We find that investments into decarbonizing fleets in non-OECD countries may amount to the greatest net reductions in the years to come. It is important to note, however, that many factors distinguish transportation systems between developed and developing nations, such as the availability and cultural appropriateness of new technologies, the financial ability to acquire them, and policies to incentivize their adoption. To mobilize the human and financial capital needed to achieve the greatest global GHG reductions, interregional cooperation should be encouraged.

There are both short- and long-term benefits to GHG abatement policies analyzed in this study. Overall, we find that the GHG reduction potentials of mode-switching policies were greatest in 2010 and see diminishing, but still positive, benefits through 2050 resulting from fuel efficiency improvements in the status quo vehicle. This effect can be considered a negative feedback caused by equal rates of improvements to W2W GHG intensity between currently utilized and alternative passenger and freight vehicles. The most apparent impact on transportation policy is that it incentivizes the early adoption of modal shift; however, it may limit the value of these policies from a GHG perspective in the future. In contrast, vehicle electrification policies become more effective over time under the IEA’s BLUE Map energy scenario. In the policy cases considered, we could see an increase as high as 400% in net benefits as economies transition away from carbon-intensive electricity generation. However, the long-term success of these policies requires a progressive decarbonization of electricity. Without this, alternative fuel policies may also be subjected to diminishing marginal benefits over time.

There are many opportunities to improve the way we perform transportation-focused analyses at a global scale. Data availability, especially in the developing world, remains a key contributor to uncertainty in the studies. A first step toward reducing these uncertainties is identifying which pieces of information influence the final decision-making process the greatest. For smaller modes, understanding the extent and skew of ridership or payloads can have a large impact on the calculated GHG intensity of these modes. In contrast, modes that provide large levels of services throughout their lifetime are not sensitive to such variability. For these modes, identifying how fuel rates differ over time and space are more important for improving the certainty of life-cycle GHG estimates. Future work should consider the influence of these important factors for other important GHG abatement policies, such as coloading or ride sharing services, vehicle automation, and the adoption of alternative fuels not discussed herein. It is important to also note that supporting infrastructure systems coevolve with the deployment of low-carbon vehicle technologies and that this codependency is shaped by additional economic, political, social, and cultural factors (Chester et al. 2014). In this article, these considerations were outside the analysis boundaries, but future research should examine their influence on GHG reduction potentials.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher’s web site:

Supporting Information S1: This supporting information illustrates the study’s LCA system boundary and representative vehicles. It summarizes the major process model inputs and other major inputs to the global assessment of passenger and freight modes of transportation. Finally, it shows the results of the load factor sensitivity analysis and the results under IEA scenario baseline conditions.