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Decarbonising Transport to Achieve Paris Agreement Targets

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Abstract

Many global transport sector decarbonisation studies assert that it is difficult for the transport sector to decarbonise and to contribute its proportional share to the ambitious climate targets set by the Paris Agreement. We challenge this argument by establishing that deep decarbonisation is possible in the transport sector, through original research that is anchored in a global meta-analysis of long-term transport sector emission pathways from over 500 bottom-up modelling estimates from 81 countries, rather than relying on aggregated regional data and modelling efforts.

First, we translate the aspirational 1.5-degree Celsius (1.5DS) target to an indicative 2050 transport sector emission target of 2 $GtCO_2$, based on proportional down-scaling of existing economy-wide 2DS studies to a transport-specific 1.5DS target. We then compare this with mitigation potential derived from the aggregation of bottom-up estimates for business-as-usual growth and low-carbon scenarios from individual country studies, which we aggregate at national and global levels. This analysis suggests that in the absence of additional action, transport sector emissions could outpace earlier projections and thus become a major roadblock to avoiding dangerous climate change. Yet, if countries collectively maximize efforts to implement comprehensive low-carbon measures, the sector could achieve reductions approaching a 1.5-degree scenario.

Realizing the full mitigation potential of transport will require balanced implementation of low carbon mitigation policies that avoid (or reduce) the need for transport trips; promote a shift towards more efficient travel modes; and improve performance of vehicles and fuels. The chances that such a comprehensive approach is taken will increase if countries, cities and companies establish medium- to long-term commitments to transport decarbonization and accelerate short-term implementation of market-ready low-carbon transport measures. Setting more ambitious low-carbon transport target with mid-term

implementation milestones, and closely integrating these plans with sustainable development objectives, can help to spur mitigation action consistent with a 1.5DS target.

To conclude, we discuss potential limitations of a transport sector-specific analysis of emission pathways, and we offer recommendations for further refining pathways for the transport sector to realize Paris Agreement targets.

Keywords: Transport, climate change, GHG emissions, mitigation, low-carbon scenarios

Introduction

The transport sector requires transformational change to meet its full emissions reduction potential. In the Paris Agreement on climate change, 195 countries agreed to limit global warming to "'*well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C"* (United Nations 2015, p. 3). This can be interpreted as a call for transformational global climate action in the transport sector. The Paris Agreement is the first international climate agreement that refers to the need for net-zero emissions by achieving a balance between greenhouse gas (GHG) emissions by sources and removals by sinks (Day et al. 2015).

The Paris Agreement commitments now need to be transformed into actions across multiple sectors. Research has established that the bulk of the emission reductions needed to meet the Paris Agreement target needs to come from GHG emission mitigation taking place in power generation and end-use sectors (e.g. transport, buildings, industry) (International Energy Agency (IEA) 2017a). However, effective mitigation will not be achieved if individual sectors advance their own interests independently (Intergovernmental Panel on Climate Change (IPCC) 2014a). For example, aviation and shipping together with the current growth could contribute between 10% and 32% of total CO_2 emissions in 2050 in a two-degree pathway (Lee et al. 2013).

The transport sector (including aviation and shipping) currently accounts for 7.5 Gt of CO_2 emissions (tank to wheel), about 28% of global final energy demand, 14% of economy-wide global anthropogenic greenhouse gas emissions, and about 23% of emissions due to fuel combustion (IEA 2016a; IEA 2017a). Transport sector emissions are growing more rapidly than most others due to demographic, behavioural and economy-driven transformations, which are leading to large increases in transport demand, especially in developing countries (Creutzig et al. 2015). Since transport infrastructure related decisions "lock-in" transport demand for decades to come, public policy in the next five to ten years will determine whether we are set on a course for a high or low-carbon transport future (Gota et al. 2015a). If present trends continue, the transport sector could potentially become a major roadblock to heading off dangerous climate change, though this is an avoidable path, as argued in this paper.

Most global multi-sectoral studies to date have considered the transport sector difficult to decarbonise (see Clapp et al. 2009; ITF 2017; Pietzcker et al. 2014; Sims et al. 2014, Shafiei et al. 2017). At present, transport is the least diversified energy end-use sector, with about 93% of the sector fuelled by petroleum products in 2015 (IEA 2017a; Paris Process on Mobility and Climate (PPMC) 2015). The IPCC Fifth Assessment Report (AR5) quotes, *“Decarbonizing the transport sector is likely to be more challenging than for other sectors, given the continuing growth in global demand, the rapid increase in demand for faster transport modes in developing and emerging economies, and the lack of progress to date in slowing growth of global transport emissions in many OECD countries”* (Sims et al. 2014, p. 604). The IPCC Fourth and Fifth Assessment Reports (AR4 and AR5) both suggest modest mitigation potential in the transport sector when compared to many other sectors.

The Paris Agreement encourages countries to raise mitigation ambition through Nationally Determined Contributions (NDCs) through the formulation of long-term low greenhouse gas emission development strategies. Overall, implementation of the first generation of NDCs would lead to lower emission growth rates when compared with pre-NDC trajectories. However, the NDCs currently in place still significantly exceed a 2-degree Celsius scenario (2DS) and would likely result in warming of about 2.8°C above pre-industrial levels (Climate Action Tracker 2016).

Among the 160 NDCs that were submitted as of August 1, 2016, 75% explicitly identify the transport sector among targeted mitigation sectors, and more than 63% of NDCs propose transport sector-specific mitigation measures (Gota et al. 2016a). However, only about 9% of NDCs include a specific transport sector emission reduction target, and only about 12% of NDCs include assessments of country-level transport mitigation potential, suggesting a general lack of prioritization of transport measures among mitigation strategies.

Given the urgency to reduce economy-wide carbon emissions and the growing ambition of different stakeholders to take transformative action on transport and climate change, it is critical to better understand the transport sector’s potential role in economy-wide mitigation. This paper sets out to investigate the global mitigation potential of the transport sector and answer the following overarching research question: *Can the transport sector achieve mitigation compatible with a 1.5DS, in the broader context of achieving sustainable development goals?*

1. Methodology and data

To answer this primary research question, we do not carry out new bottom-up modelling, but instead rely on available transport literature to understand overall implications through a research approach comprised of three main steps.

In the first step, we sketch out a potential decarbonisation scenario for the transport sector, compliant with possible 2° C and 1.5° C economy-wide pathways (2DS and 1.5DS, respectively), to provide evidence of the scale and depth of the transformation required in the sector. This study considers the proportional share of transport sector emissions in a 2DS and a possible 1.5-degree emission trajectory for economy-wide emissions. Thus, we assume a simple proportional downscaling of proposed sectoral contributions under a 2DS to a 1.5-degree target (i.e. transport is assumed to have a 22% share of total emissions in 2050 once a 2DS has been realized, and transport is assumed to have the same final share under a 1.5DS for purposes of this study, as explained in Section 3).

In the second and third steps, new global sectoral business-as-usual (BAU) and low-carbon scenarios (LCS) are developed, built upon a comprehensive meta-analysis of long-term transport sector emissions by aggregating over 500 "bottom-up" country transport CO_2 estimates for 2050, as well as studies for international aviation and maritime transport. A database of studies, including detailed study characteristics, BAU projections, low carbon scenarios, and transport mitigation measures is found in a supplementary spreadsheet file.

In this analysis, all countries are considered individually and emission estimates for BAU and low carbon scenarios from the different studies from a particular country are compiled to determine average projection for 2020, 2030, 2040 and 2050. The average values for different countries are combined to derive the global estimates (e.g. for Canada, seven BAU estimates and four 2050 LCSs were compiled and averages derived). In addition, alternate high and low global transport scenarios by only aggregating only the highest and lowest BAU country estimates, and the highest and lowest LCSs, are developed.

The studies in the database cover 81 countries responsible for about 92% of global transport emissions. To derive global emission trajectories, BAU transport emission growth rates are extrapolated separately for low, middle and high-income countries (World Bank 2018) based on current income groupings and a current population share of low, middle and high-income countries of 8%, 76% and 16%, respectively. For the LCSs, a similar approach based on mitigation potential was used to derive the most optimistic scenarios (i.e. those with greatest difference between 2050 BAU and LCS) and the most conservative scenarios (i.e. those with least difference) (see Section 5).

The database includes 445 and 259 BAU estimates, and 347 and 218 low-carbon scenarios, for 2030 and 2050 respectively. These include studies from 81 countries, which are nearly evenly split between OECD and non-OECD countries (Figure (Fig. 1), with international aviation and shipping having two and eight studies respectively. A large majority of the country forecast and mitigation literature is from the 2008 to 2017 period.

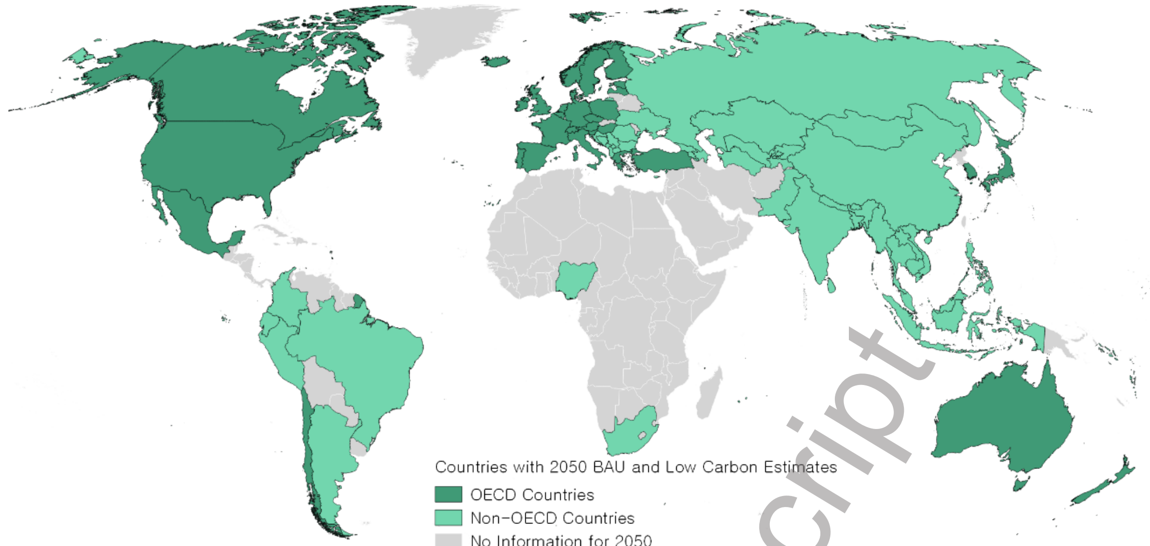

Fig. 1: Countries with 2050 BAU and Low Carbon Estimates

(Fig. 1 derived from supplemental database)

LCSs cover different types of studies including government plans and reports (e.g. NDCs, National Communications), back-casting studies to achieve climate change targets in transport, climate modelling studies, and detailed bottom-up mitigation potential analyses. The scenarios in these studies are developed by a variety of stakeholder entities, including governments, NGOs, academia, and multilateral institutions (Table 1).

# Studies	Study Stakeholder Type
160	Government
104	Development Agency
123	NGO
117	University/Research
20	Private
524	*All stakeholders*

Table 1: Mitigation Potential Studies (by Stakeholder Type)

Transport BAU estimates within each country vary widely as different studies may use a diverse set of assumptions for socio-economic drivers, varied modelling techniques and data parameters for the base year. Annex I summarizes 15 mitigation potential studies representing various regions and income levels, study stakeholder types, and degrees of projected mitigation potential, to give a more in-depth view of a sample of studies considered. An analysis of assumptions and methodologies across the 500+ country studies is beyond the scope of this research.

The country studies predominantly explore mitigation potential and possible low-carbon scenarios for the transport sector, along with other aims. In some cases, these studies identify no particular target, in many cases the studies are compatible with a 2DS, and in some cases, the studies express ambition which goes beyond a 2DS. Thus, while not all of these scenarios are developed with an explicit view toward a 1.5DS, the mitigation potential expressed in a number of these studies is compatible with this level of ambition.

Compared to global mitigation studies based on multi-sectoral integrated assessment models (IAMs) or sectoral transport models, the key differences of such country-specific studies are (1) assumptions are more detailed and based on locally-verified data, (2) a better reflection of each country's transport sector, and (3) consideration of local context, constraints, and (in many cases) sustainable development policy objectives rather than climate change targets alone. These differences, in combination with the bottom-up study approach described above, yield an outcome that diverges meaningfully from previous estimates and makes a novel contribution to estimating the aggregate mitigation potential of the global transport sector in 2050 under a plausible LCS.

2. Deriving Paris Agreement-Compatible Transport Sector Emission Pathways

As noted above, the Paris Agreement sets out the goal to limit global warming to well below 2 °C above pre-industrial levels; however, there is not yet a commonly agreed definition of what would constitute a "well below 2-degree" outcome (IEA 2016b).

The 2012 Cancun Agreements' objective of keeping average global temperature rise below two degrees Celsius resulted in the development of several pathways for a 2DS for economy-wide transition (UNFCCC 2011). The IPCC AR5 estimated a carbon budget of roughly 1000 Gt to limit global warming to a 2DS, which translates to a cumulative 630–1180 Gt over the 2011–2100 period for having a likely (>66%) chance to achieve a 2DS (IPCC 2014a, 2014b). Different studies have utilised this carbon budget concept in different ways to arrive at net-zero carbon emissions between 2060 and 2080 (Climate Action Tracker 2016; IEA 2017a; IEA and IRENA (2017); IPCC 2014b; Rogelj et al. 2015; United Nations Environment Programme (UNEP) 2016). Literature indicates that 2DS for economy-wide emissions could translate to 15 to 34 Gt by 2050 (with an average of 25 Gt, i.e. about 47% below 2010 levels) (IPCC 2014b; Climate Action Tracker 2016; UNEP 2016).

While the climate policy objectives are often formulated on an economy-wide basis at international and national levels, in practice such objectives need to be implemented on a sectoral basis. Different sectors have different approaches to reducing CO_2 emissions, and allocation of emission reduction targets to different sectors (i.e. national 'burden-sharing') is based on a combination of factors (e.g. local priorities, cost effectiveness, marginal costs, growth projections, mitigation potential, co-benefits) (Keating 2014).

The IEA's 2DS for the energy sector describes a scenario of cutting global energy-related CO_2 emissions by more than half in 2050 (compared with a 2009 baseline) and ensuring that emissions continue to fall thereafter (IEA 2016c). Importantly, the 2DS acknowledges that transforming the energy sector is vital, but not the sole solution, as non-energy sectors also need to make significant contributions to reach this target. For the transport sector, CO_2 emissions must be restricted to about 4.7 Gt in 2050 as the IPCC AR5 Scenario Database of 450 scenarios derives an average about 4.7 Gt by 2050 (6 Gt if aviation and shipping is considered) or about 10% below 2010 levels (IIASA 2014). Other studies have proposed 3.1 Gt to 6.5 Gt in 2050 as possible transport sector CO_2 targets (Climate-KIC and IEA 2015; IIASA 2014).

The average transport sector emission share relative to total economy-wide emissions, in this case, would increase significantly from 1990 levels (see Fig. 2). This increase in the transport sector share reflects the fact that the 2DS establishes more stringent emission targets for several other sectors (IEA 2016c).

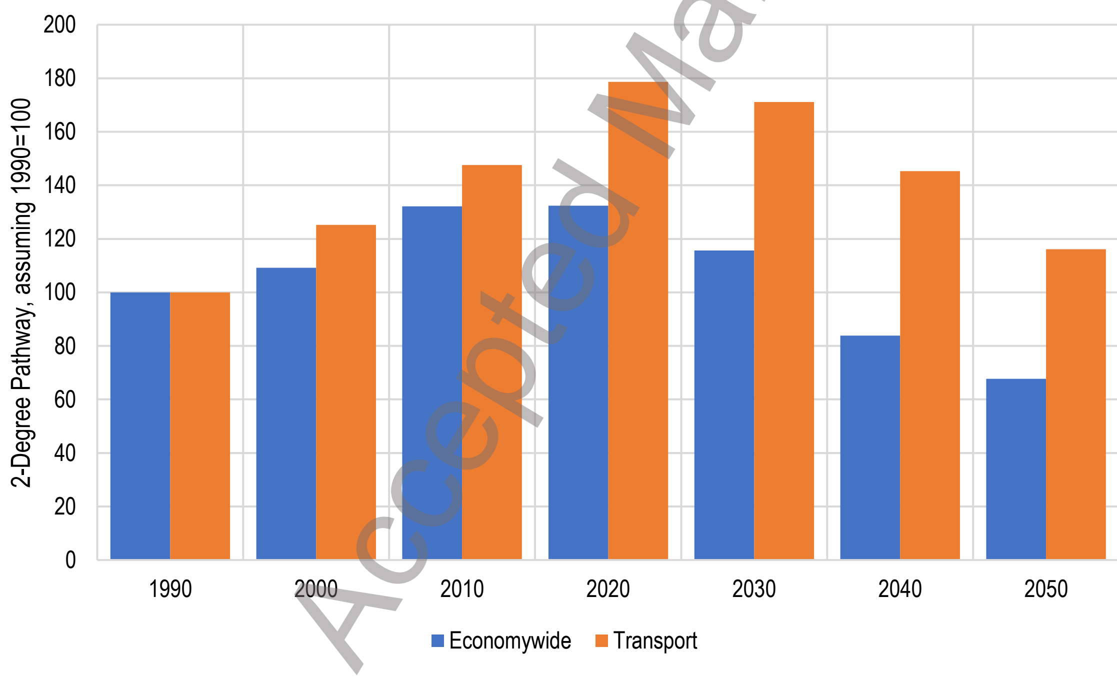

Fig. 2 Economy-wide and transport sector share of energy-related emissions under 2DS

(Fig. 2 is derived from IEA 2016c data)

For an economy-wide 1.5DS, the discussion is still very much evolving. There exist limited scientific studies which chart out the degree of transformation required for this scenario. Based on available literature for a 1.5DS, estimates suggest 2050 economy-wide emissions range varying from 4 to 19 Gt (e.g. Climate Action Tracker 2016; Rogelj et al. 2015; UNEP 2016; UNFCCC 2016a) with an average of about 10 Gt.

While some studies for economy-wide emissions under a 1.5-degree trajectory exist, projections of the magnitude of reductions required by 2050 in the transport sector (including international aviation and shipping) are still very limited. The following are examples of studies which consider transport emission trajectories below a 2DS target:

- The IEA has proposed a beyond 2°C scenario (B2DS) which sets out a rapid decarbonisation pathway for the energy sector in line with the Paris Agreement. Under the B2DS, the energy sector reaches net zero emissions by 2060 (to limit future temperature increases to 1.75°C by 2100), while transport sector CO_2 emissions decrease to about 3.1 Gt by 2050 and about 1.5 Gt by 2060 (IEA 2017a).

- A comparison of eleven models (integrated assessment and energy-environment-economy, aiming to be compatible with a 'well below 2 degrees' scenario) for passenger transport resulted in a range of 1.6 to 6.7 Gt CO_2/year in 2050 (Edelenbosch et al. 2017).

- Rogelj et al. (2015) estimate that worldwide CO_2 emissions from energy and industry would have to reach zero around 2050 to stay within a 50% chance of returning warming to below 1.5°C by 2100. For the transport sector, they estimate that a 1.5DS would necessitate about 40% to 55% (i.e. about 2.4 to 3.2 Gt) greater reductions than a 2DS in 2050 (Rogelj et al. 2015).

To arrive at a possible 1.5DS-compliant trajectory for the transport sector by 2050, this study considers the proportional share of transport sector emissions in a 2DS and a possible 1.5DS emission trajectory for economy-wide emissions. Thus, we assume a simple proportional downscaling of proposed sectoral contributions under a 2DS to a 1.5DS target: transport is assumed to have a 22% share of total emissions in 2050 once a 2DS has been realized (Climate-KIC and IEA 2015; IIASA 2014), and transport is assumed to have the same final share under a 1.5DS for purposes of this study. This assumption imposes a less stringent reduction requirement for sectors having achieved earlier lower emission share due to rapid decarbonisation under a 2DS and a higher magnitude of reduction from sectors having a higher share of emissions.

It is acknowledged that a proportional allocation of transport emissions neglects magnitude of mitigation capability and costs and benefits involved in emission reductions, and efficient burden sharing among sectors remains a controversial topic (Keating 2014). However, as economy-wide emission reduction targets become more stringent, there is less opportunity for prioritizing sectors for more and less ambitious reduction targets. Further, IEA in its 2017 World Energy Outlook has confirmed that despite marginal costs dictated by the most expensive technologies, the total investment needs in achieving the 2DS and B2DS are lower than for the BAU scenario (IEA 2017a).

Assuming a proportional share, realizing a 1.5DS would translate to transport emissions in the range of 0.8 Gt to 4.1 Gt, with an average of 2.3 Gt in 2050. For further analysis in this paper we assume 2 Gt as an average benchmark for a 1.5DS target, which corresponds to a global transport emission reduction of 70% below 2010 levels. In terms of per-capita transport CO_2 emissions, the 1.5DS would require an average reduction from 1.0 tons/capita in 2010 to 0.2 tons/capita in 2050, which is a substantial challenge.

The derived 1.5-degree target of 2 Gt is contingent on emission reductions in other sectors (Schaeffer et al. 2015), and thus sectors such as transport, industry and buildings may need to bear a higher share of reductions (relative to sectors already decarbonised to a great extent under a 2DS). Indicative 1.5DS transport targets for 2020 and 2030 include 8 Gt and 6.6 Gt, respectively, based on SLoCaT calculations (see supplementary material). It is useful to note that the deviation of the transport sector 1.5-degree trajectory with the 2-degree trajectory is only 2% in 2020, but increases to 16% in 2030, and widens further to about 62% in 2050 (see Fig. 3; the referenced global "bottom-up" average BAU is derived in Fig. 4 below). Over time, the remaining global carbon budget will change and more accurate targets for a transport sector 2DS and 1.5DS could be derived.

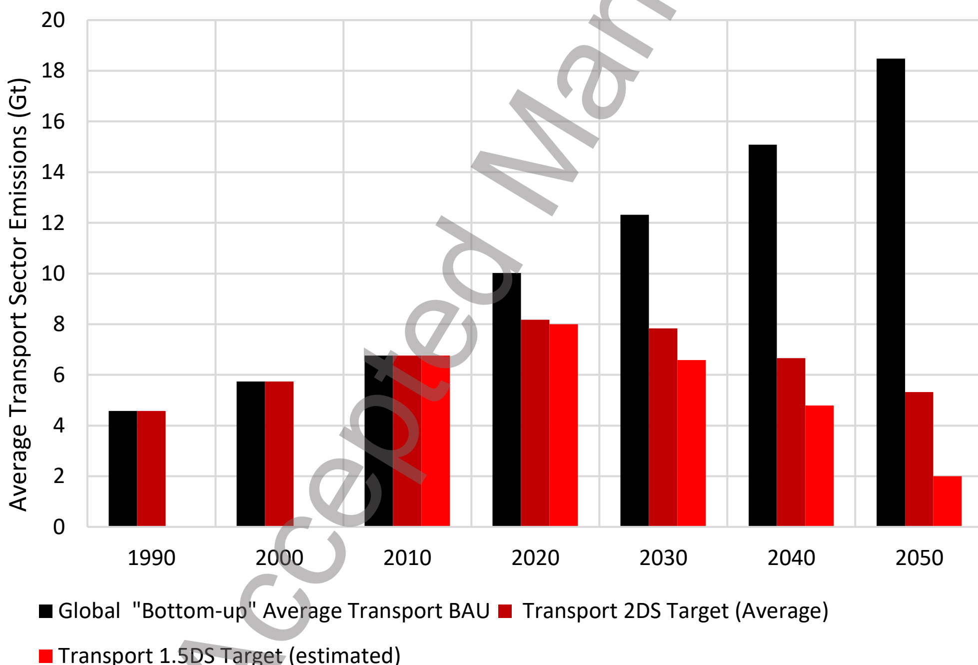

Fig. 3 Transport Emission BAU Estimates and 2DS/1.5DS Targets

(Fig. 3 BAU is based on bottom-up analysis in this article (see Fig. 4); 2DS target is average from existing literature; and 1.5DS target is derived from 2DS based on proportional downscaling)

3. Business-as-usual transport sector emissions

In this section we review BAU emission estimates for 2050 from existing literature, and then develop a new BAU scenario based on bottom-up country studies. There are a large number of national, regional and global BAU emission estimates for the transport sector in existing literature. These BAU projections for GHG emissions are estimated based on the assumption that no additional low-carbon policy actions are adopted (Gota, et al, 2016b), and they assume a continuation of transport sector investments to keep the existing transport capacity operational for the full length of analysis (e.g. to include a realistic level of needed investments and maintenance to maintain capacity and level of service and avoid deterioration of the transport network). Such scenarios consider economic forecasts but do not envisage shifting transport-related investments to lower-carbon modes or technologies. An average BAU trajectory serves as a benchmark for comparison with a low carbon transport trajectory and 2DS and 1.5DS requirements.

The global transport BAU literature presents a wide range of future carbon emission trajectories in the absence of additional low-carbon policy actions. These global studies can be broadly classified into multi-sectoral studies by integrated assessment models (IAMs) of the energy-environment-economy system (Pietzcker et al. 2014; Edelenbosch et al., 2017; Yeh et al., 2017) and global transport modelling initiatives (e.g. Climate-KIC and IEA 2015; International Council on Clean Transportation (ICCT) 2012; International Transport Forum (ITF) 2017; Fulton et al. 2009; World Energy Council 2011). IAMs are generally limited in technical and sector-specific detail, but excel in analysing trade-offs between different sectors, while transport-only models are often more detailed and can better reflect the dynamics of the transport sector. These studies estimate that by 2050, BAU global transport CO_2 emissions could be in the range of 9 to 20 Gt with an average of about 13 Gt (i.e. 93% above 2010 levels). This estimate is very close to the IPCC AR5 projection of 14 Gt by 2050 (IPCC 2014b).

These global modelling initiatives are often based on regional data and can be biased toward countries with higher transport emissions, and it is therefore challenging to use aggregated data to estimate future scenarios (e.g. how far people and goods travel, by what modes, and how energy- and emission-efficient are these modes). For example, Cambodia and Tajikistan are two countries from the Asian continent with similar current GDP/capita; however, from 2010 to 2050, country-level estimates indicate that transport CO_2 emissions in Tajikistan could grow with twice the intensity as in Cambodia (Asian Development Bank 2018; ITPS & Clean Air Asia, 2014). In this regard, BAU scenarios derived from global or regional perspectives do not necessarily represent the most likely national transport growth trajectories. On the other hand, some country-level modelling efforts highlight transport demand rather than emissions; for example, US per-capita passenger travel demand could increase 30-50% by 2100 over 2010 levels, and could be multiplied by a factor of 2.5 to 3.1 if accounting for projected 90% population growth in that period (Schäfer 2017). Such findings support but are not easily aggregated into an emissions projection analysis for the global transport sector.

In this section, we extract detailed transport sector-related bottom-up projections from country studies (see Section 2) for BAU scenarios for 2020, 2030, 2040 and 2050 and aggregate these projections to get a global estimate.

The added value of the BAU assessment carried out in this paper is that all countries are considered individually, and within each country, studies by multiple institutions are averaged and finally aggregated to derive a bottom-up global estimate. To derive a global BAU emission trajectory, insights from 81 countries were expanded to 196 countries (i.e. from 92% to 100% of global emissions) by extrapolating BAU transport emission growth rates separately for low, middle and high-income countries (World Bank 2018) based on current income groupings and a current population share of low, middle and high-income countries of 8%, 76% and 16%, respectively. Two alternate trajectories representing maximum and minimum BAU scenario by aggregating only the highest and lowest BAU country estimates are shown in Fig. 4, compared against existing model estimates.

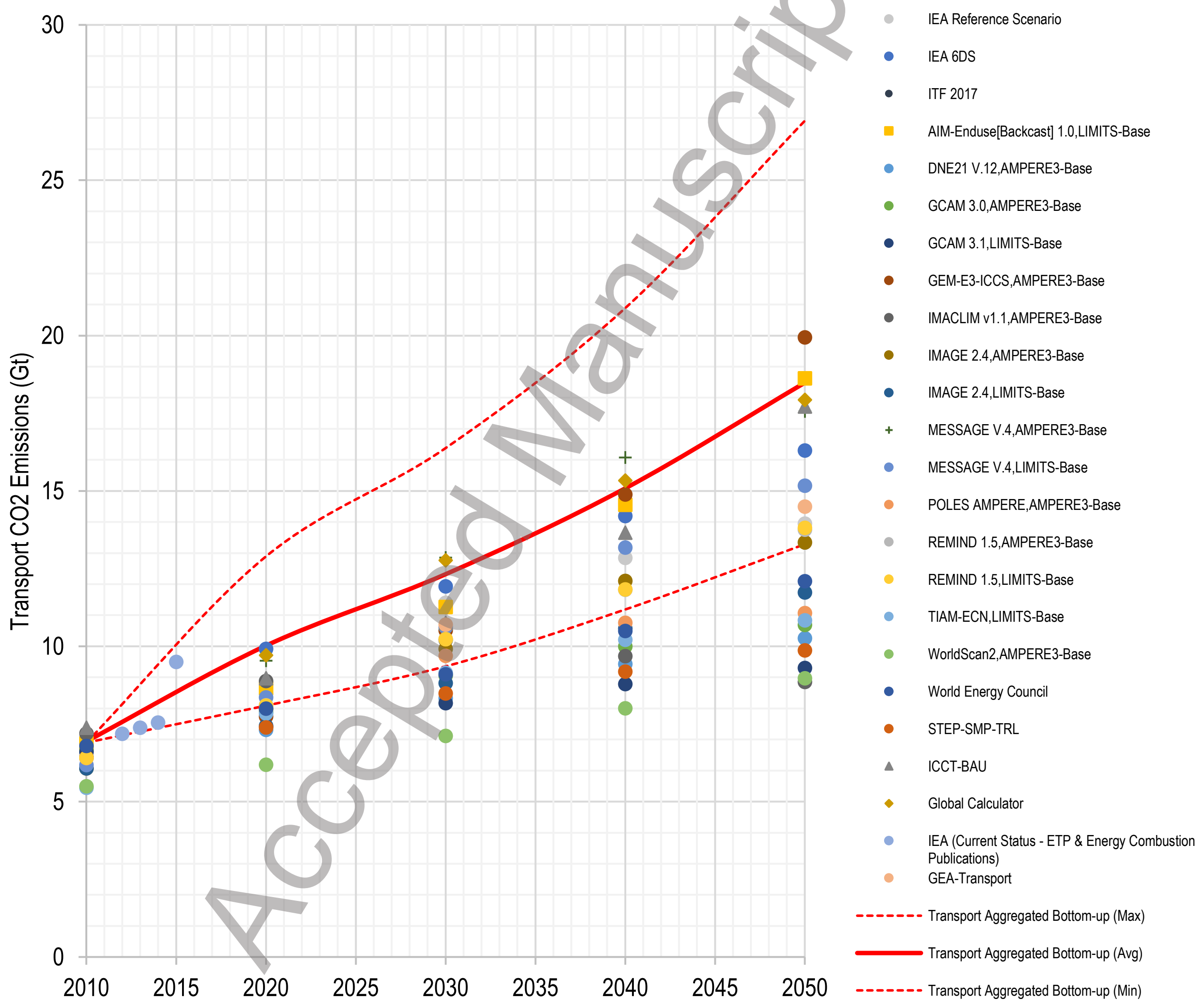

Fig. 4 Transport BAU Trajectories: Bottom-up Estimates vs. Existing Models

(Fig. 4 curves are derived from bottom-up mitigation potential studies in supplemental database, representing conservative, average, and optimistic projections among scenarios, respectively)

This figure suggests that if the global transport sector trajectory followed the same path as depicted by the 81 countries considered in this study, transport sector emissions would increase to between 13 and 27 Gt by 2050 with an average of 18 Gt (i.e.166% above 2010 levels). This average is significantly higher than the IPCC AR5 upper limit projection of 14 Gt by 2050 (Sims et al., 2014), and the high estimate exceeds the highest model projections significantly. By 2050, the observed transport sector emission share of economy-wide emissions (as assumed by IPCC) could increase from the current 14% to an average of 23% (with a min-max range of 16% to 33%, based on available BAU estimates for other sectors). This would imply that transport sector emissions may be growing faster compared with other sectors than has been assumed in research to date.

Under an average scenario, the combined middle-income countries and aviation/shipping emission share would increase from 51% to 75% by 2050 (see Fig. 5) mainly due to high growth in transport demand in these countries and sectors (especially freight) and fewer policies that are currently in place (relative to high-income countries) whose impact would be included in BAU estimates. In 2010, high-income countries (representing only 16% of global population) generated close to half of global transport sector emissions. By 2050 this emission share would be reduced to about one-quarter of global transport emissions, while the share of low-income countries (representing 8% of global population) would still be only 1%. In addition to slower economic growth, this would be mainly due to the relative stabilisation of emissions growth in high-income countries, which is due to the implementation of a combination of efficiency improvements (often due to legislation) and changes in consumer behaviour and preferences (e.g. use of shared mobility and less car-dependent lifestyles) in the past decade (European Energy Agency (EEA) 2016).

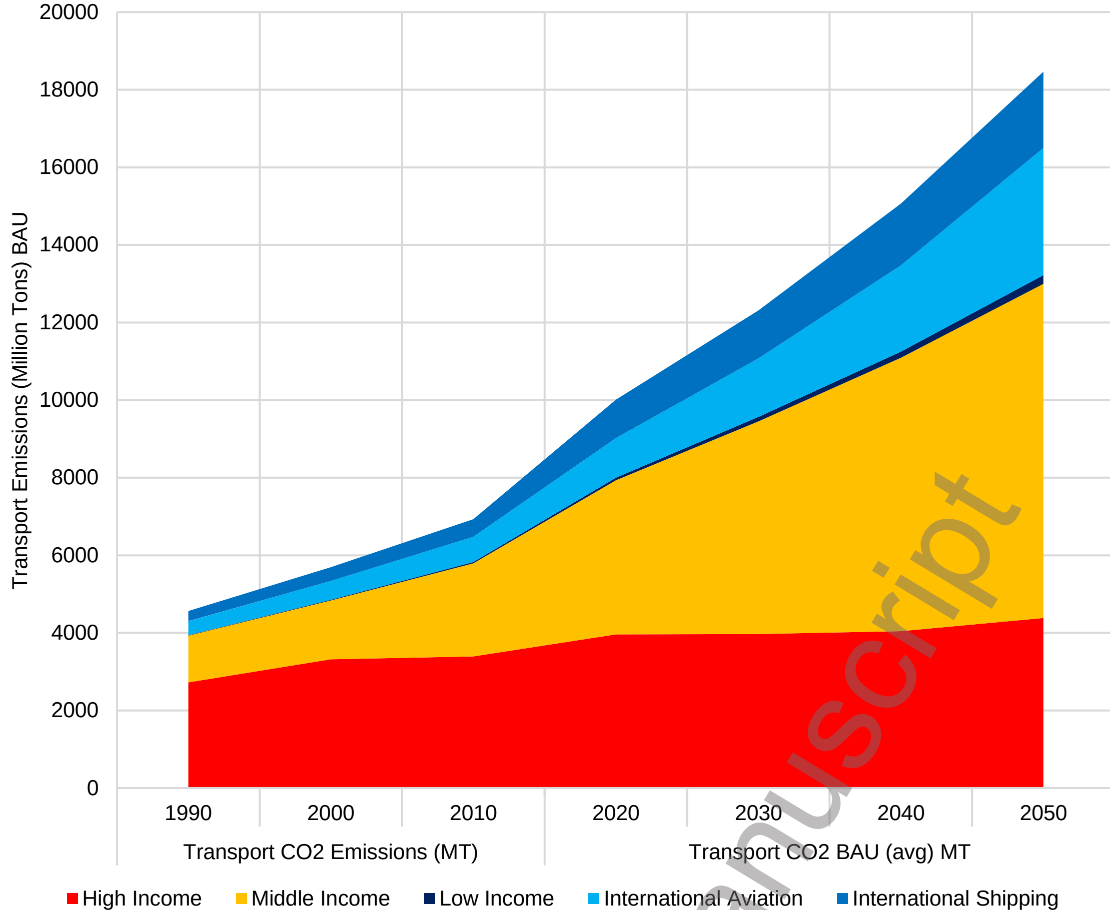

Fig. 5: Transport sector BAU scenario (average)

(Fig. 5 is based on and aggregation of bottom-up country studies in supplemental database)

From 1970 to 2010, transport sector emissions grew at an annual rate of 2.7%, and from 2010 to 2050, transport CO_2 emissions would continue to grow at an average annual rate about 2.5%. Transport CO_2 per capita would nearly double from 1 to 1.9 tons globally from 2010 to 2050, with an increase of 0.1 to 0.2 tons in low-income, 0.5 to 1.2 tons in middle-income, and 3 to 3.5 tons in high-income countries, respectively.

4. Low Carbon Transport Trajectories

While there is political momentum behind the Paris Agreement call for transformation in economy-wide emission pathways, pathways within the transport sector to achieve the required transformation are still uncertain. In this section, we investigate whether an emissions trajectory derived from the country-level LCSs is compatible with the Paris Agreement-specified 1.5DS target.

In the past, it has been estimated that for the transport sector, a reduction in total CO_2 emissions of 15% to 50% by 2050 could be plausible compared to baseline activity growth

(IPCC 2014b; ITF 2017). This would mean that only about half of total transport reductions required under the proposed 1.5DS (which implies a nearly 90% reduction compared to BAU) could be achieved under the most ambitious scenario. It should be noted that these estimates are related to less ambitious climate change targets and assume more rapid decarbonisation in the second half of the century by low-carbon vehicles. In addition, the nature of IAMs (e.g. a single carbon price across sectors, limited consideration of co-benefits), and limited consideration of 'Avoid' and 'Shift' measures (Edelenbosch et al. 2017), may influence the scale of potential reductions.

To better understand the typology of transport measures being proposed in the low-carbon trajectories, we have aggregated 1500 measures from LCSs from 81 countries, about 307 transport measures from 160 NDCs, as described in Section 1 (Gota et al. 2016a), and 186 transport measures from 28 technology needs assessment (TNA) reports, which detail to the UNFCCC national technology priorities and needs for climate change mitigation and adaptation (UNFCCC 2017).

A typical low-carbon trajectory considers significant additional policy measures and investments in low-carbon modes and technologies, which allows the transport sector to deviate from a BAU emission trajectory. Measures required for a transition to low-carbon transport include a combination of 'Avoid' strategies, which reduce the need for transport trips (e.g. transport demand management); 'Shift' strategies, which move transport trips to more efficient modes (e.g. public transport and rail freight); and 'Improve' strategies, which increase the energy and carbon efficiency of vehicles (e.g. fuel economy standards) (Bakker et al. 2014; EEA 2016).

This analysis reveals that nearly two thirds of measures are related to fuel efficiency or fuel decarbonisation (i.e. 'Improve' measures) and about one third of measures are related to changes in travel behaviour (i.e. 'Avoid' and 'Shift' measures). This analysis is consistent with the findings of an analysis of transport measures in NDCs (Gota et al. 2016a), which reflects a higher prioritisation of 'Improve' measures (e.g. fuel efficiency and decarbonisation) over 'Avoid' and 'Shift' measures, and an analysis of TNAs, which shows a similar dominance of 'Improve' measures (see Fig. 6).

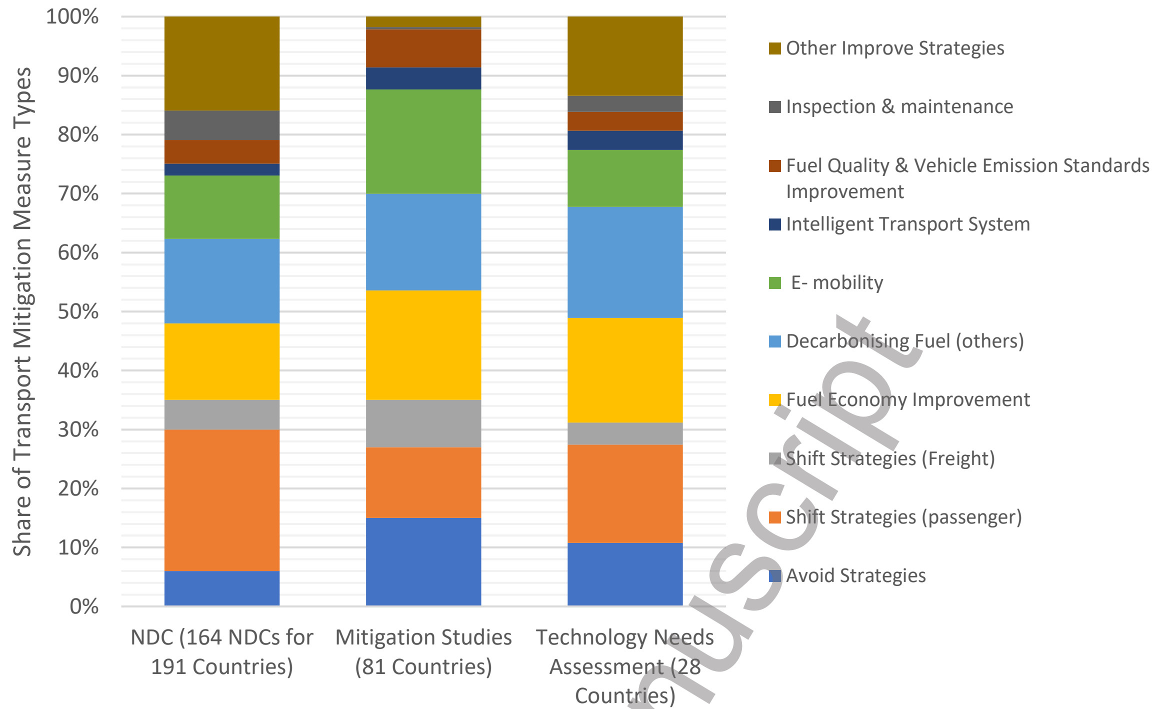

Fig. 6 Share of Transport Mitigation Measure Types in NDCs, Country Mitigation Studies and Technology Needs Assessments

(Fig. 6 based on Gota et al. 2016a (NDCs), bottom-up country studies, and internal analysis (TNAs))

It should be noted that the number of measures in each of these categories is not directly correlated to the projected GHG reductions of each of those measures, and thus is not a clear indicator of mitigation potential (e.g. a ban on fossil fuelled vehicle in conjunction with renewable energy may have greater mitigation impacts than a number of 'Avoid' and 'Shift' measures). However, it can also be argued that the domination of 'Improve' measures in the bottom-up studies indicates that many countries assume that these strategies can provide the bulk of required emission reductions, and demonstrates a possible lack of consideration of co-benefits of 'Avoid' and 'Shift' measures. This is consistent with Creutzig (2016), who also concludes that the mitigation potential of behavioural and infrastructural mitigation options is higher than what is assumed in many modelling studies.

To assess potential overall reductions in the transport sector (in absolute terms), we used the country studies introduced in Section 2. We first combined the low carbon emission projections as a simple average within each country which were then aggregated at the global level. To derive a global low-carbon transport emission trajectory, insights from these 81 countries were expanded to 196 countries by extrapolating mitigation potential estimates separately for low, middle and high-income countries, which are 23%, 59% and 82% below BAU for low, middle and high-income countries respectively.

Since different estimates for each country vary significantly, we constructed two alternate low carbon transport trajectories representing both a ‘conservative’ and an ‘optimistic’ low carbon scenario by aggregating, respectively, the less ambitious and more ambitious country low-carbon estimates. The *conservative* LCS reflects a hypothetical scenario where the low carbon measures are less comprehensive and/or less-effectively implemented, while the *optimistic* low carbon scenario assumes that transport mitigation measures are implemented with high intensity and stringency and at a broad scale. A similar approach was adopted to create conservative and optimistic scenarios for international aviation and shipping based on a limited set of studies (see Fig. 7 below).

Annex I presents a sample of country studies, showing more detail on policy instruments included in the low-carbon scenarios, and where information is available, on the relative level of stringency for these instruments (i.e. mandatory targets, performance standards, assumed level of behavioural change). While many studies reveal a lack of detail, others provide quantified targets and assumptions to substantiate mitigation ambition.

For example, among 'Improve' measures, specificity and stringency of measures on vehicle electrification and biofuels is roughly correlated with overall mitigation ambition (with % corresponding to 2050 reduction under LCS relative to BAU):

- Brazil (59.3%): Hybrids and electric vehicle (31% of total vehicle fleet), biofuels (50% of trips made on ethanol); energy efficiency in freight transport
- Germany (71.0%): Biofuels to play stronger role, increase of hybrid and electric vehicles to two thirds of fleet by 2050 leading to reduction of overall final energy consumption of transport
- Canada (96.4%): Electrification of transport modes, all new vehicles to decarbonize in the early 2030s. Heavy freight vehicles to decarbonize by 2040, carbon tax, fuel decarbonisation by electric, cellulosic ethanol and biodiesel

Among 'Avoid' and 'Shift' measures, details are even more sparse, but key quantified examples are found among countries with higher-than-average ambition levels:

- Lao PDR (72.5%): (Avoid measures) Reduction of trips by more than half through better land use planning and freight transport reduction by a third until 2050; (Shift measures) Increase of public transport share to 67%, shift from individual transport to BRT by 10% and to rail by 15% until 2050, for freight a 45% shift to rail by 2050
- Mexico (78.5%): Shift to public transport, cycling and walking, intercity travel mostly shifts to bus and rail, 45% of freight transported on rail

These examples suggest that more conservative scenarios include a more limited set of detailed mitigation measures (and lower targets for each), while more optimistic scenarios contain higher degrees of clean technology adoption and behaviour change, which would require more stringent policies and higher investments to fully realize.

If a global transport sector trajectory were to follow the same path as depicted by the 81 countries considered in this study, 2050 transport sector emissions could decrease to 9.3

Gt (under a *conservative* low carbon scenario) or to 2.5 Gt (under an *optimistic* low carbon scenario), with a scenario average of 5.4 Gt (i.e. based on average for each country).

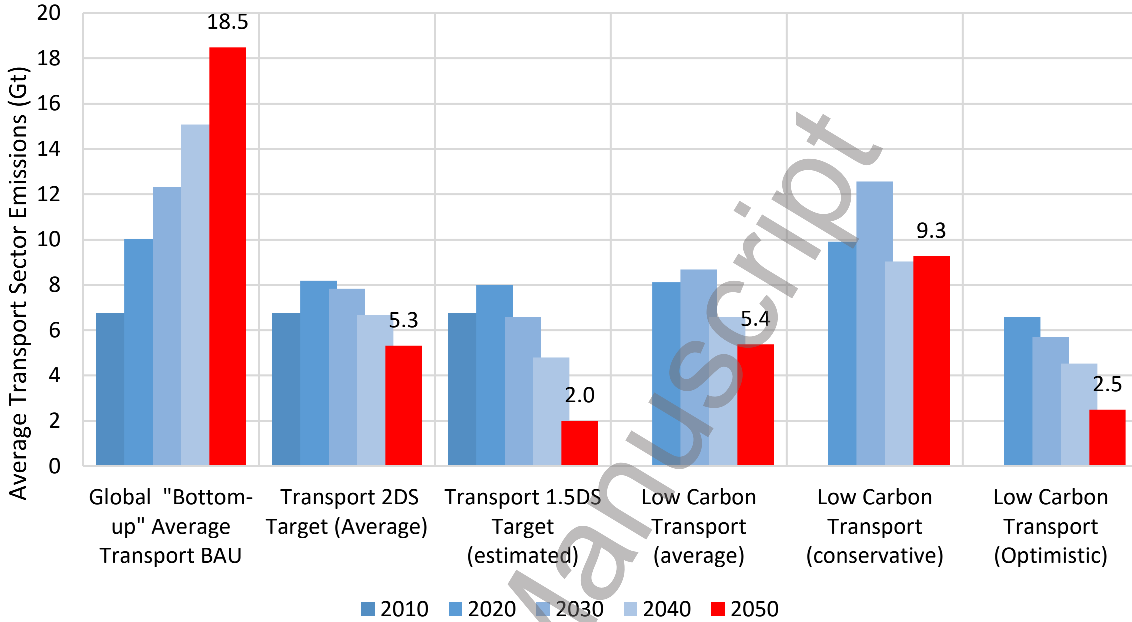

Fig. 7: Low Carbon Transport Emission Trajectories

(Fig. 7 based on aggregation of bottom-up country mitigation studies in supplemental database)

Under a conservative LCS, transport sector emissions would increase from 7 Gt (2010) to 9.2 Gt by 2050. This would exceed emissions levels required for a 2DS by more than 70%, and a 1.5DS by more than 360%. This is plausible in a scenario where the global community does not collectively prioritise mitigation in the transport sector. However, under an optimistic LCS, transport emissions could decrease to 2.5 Gt by 2050, falling below a 2DS and closely approaching a 1.5DS. This scenario is plausible if the global community collectively prioritises mitigation in the transport sector, with low carbon measures implemented stringently and comprehensively. Under an average of conservative and optimistic LCSs, transport sector emissions would be limited to 5.4 Gt, and thus would have the potential to approach the 5.3 Gt targeted by a 2DS in 2050.

Under an average LCS, global transport CO_2 would decrease from 1.0 to 0.6 tons per capita from 2010 to 2050, with the decrease mainly driven by high-income countries. Transport CO_2 per capita emissions in high-income countries would decrease from 3.0 tons to 0.6 tons, and in middle and low-income countries, per capita emissions would decrease marginally to 0.5 and 0.1 tons respectively, creating a convergence among middle- and high-income countries in the range of 0.5 to 0.6 tons per capita (Table 2).

	2010	2050 Average LCS

	Emissions/capita (tons)	Emissions share (%)	Emissions/capita (tons)	Emissions share (%)
High-Income	3.0	49%	0.6	15%
Middle-Income	0.5	35%	0.5	66%
Low-Income	0.07	0.5%	0.1	3%
International Aviation and Shipping	Not applicable	16%	Not applicable	16%
Total (excl. Int'l Aviation/Shipping)	1.0	Not applicable	0.6	Not applicable

Table 2: Development of Emissions per Capita and Emission Share for Average LCS by 2050

(Table 2 based on aggregation of bottom-up country mitigation studies)

In 2010, high-income countries accounted for close to half of global transport sector emissions; by 2050 this share would decrease to about 15% under an average LCS. The 2050 transport emissions share of middle-income countries would increase to 66% under an LCS, mainly due to greater reductions in transport emissions in high-income countries compared with middle-income countries. Under an average LCS, transport emissions are expected to peak around 2030 in middle-income countries and are expected to continue to rise beyond 2050 in low-income countries (Fig. 8).

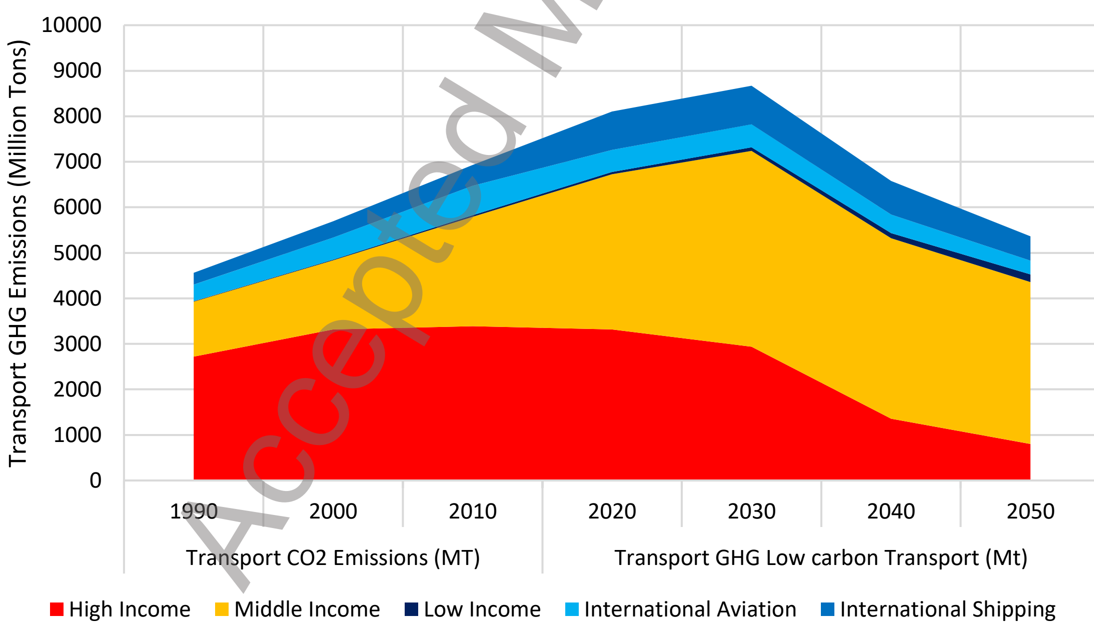

Fig. 8: Average Low Carbon Transport Scenarios

(Fig. 8 based on aggregation of bottom-up country studies; see 'Methodology' section for details)

Differences among high- and middle-income countries could be explained by a number of factors. First, there may be in general a greater incentive for governments in developed countries to low carbon transport pathways (as consistent with the principle of common but differentiated responsibilities), and thus, there are in general more mitigation studies for high-income countries, and on average the targets in these studies are more ambitious. Second, high-income countries are in general experiencing less growth relative to middle-income countries, and thus BAU projections are general rising faster in middle-income countries. A discussion of these differences in terms of specific mitigation measures within country studies is beyond the scope of this research.

By 2020, the conservative, average and optimistic LCS would deviate from the average BAU trajectory by about 1%, 20%, and 34%, respectively; however, historical data show that in 2014 transport emissions had only deviated from the average BAU scenario by 4% (IEA 2017b); thus, it is clear that transport mitigation measures considered under the low carbon scenarios are not being implemented at scale to date, as discussed further in the following section.

One of the findings of IPCC AR5 (IPCC 2014b) was that "reducing global transport greenhouse gas (GHG) emissions will be challenging since the continuing growth in passenger and freight activity could outweigh all mitigation measures unless transport emissions can be strongly decoupled from GDP growth (high confidence)." In contrast, a key finding of this analysis (as illustrated through the above arguments), is that mitigation potential in the transport sector is *perceived* by the authors of many country studies as being higher than previously assessed, though the feasibility of implementing measures to meet the potential projected in these studies remains to be determined.

5. Discussion

Scenario Analysis

The findings in this paper contribute to existing literature on mitigation in the transport sector by broadening the scope of available analyses, in a novel bottom-up approach based on country studies. We establish new BAU estimates for 2050, which are higher than existing projections. A possible explanation is that many country studies use different modelling approaches in combination with higher growth assumptions on economic development, transport demand, vehicle ownership and vehicle use, in comparison to aggregated global and regional studies. We also develop additional low-carbon scenarios, with an optimistic low-carbon scenario projecting significantly lower emissions than the mitigation potential captured in an aggregation of previous projections.

In country studies, a larger range of measures is found than in many global modelling studies - particularly 'Avoid' and 'Shift' measures, which can make greater contributions to sustainable development objectives. IAMs tend to consider these measures in a more limited way, though initiatives are underway to better reflect behaviour change, including modal shift options (Mittal et al. 2017; Yeh et al. 2017). This is linked to a larger discussion on technology versus behaviour in low-carbon transport futures (Creutzig 2016) and the role of sustainable development objectives in this context (Figueroa et al. 2014).

In sum, with this research, we have analysed a broad range of country studies, most of which investigate mitigation potential (and low-carbon scenarios, particularly the more ambitious scenarios). While we acknowledge that it's not possible to *precisely* quantify the 2050 mitigation potential due to the different methodologies and assumptions in these studies, our results do give a valuable indication of the *likely* mitigation potential by reflecting a bottom-up country-level perspective based on a significant number of studies.

This analysis asserts that a marginal progression of current transport mitigation policies will not be sufficient to reach a 2DS, and that limiting climate change to a 1.5DS means nothing short of de-carbonizing transport around mid-century; thus, more transformational changes in the transport sector are required (e.g. increased mode shift, coordinated planning practices, electrification, shared mobility) (Banister 2008; Fulton et al. 2017).

Since IAM analyses do not view the mitigation potential of the transport sector in isolation, they tend to have other sectors decarbonise more quickly due to assumed lower abatement costs, and they tend to underemphasize 'Avoid' and 'Shift' measures, which often have low/negative abatement costs (Creutzig 2016). In addition, potentially IAMs may not reflect recent findings on EV battery cost curves (Kittner et al. 2017). As a result, targeted emission reductions for transport in 2050 in IAMs are often relatively modest, and in that sense may not reflect the *full* mitigation potential in the transport sector. In contrast, our transport-focused analysis establishes that low-carbon scenarios that are more ambitious than transport targets found in IAMs are technically *feasible*, and that the most optimistic of these scenarios fall within range of a 1.5DS-compatible trajectory.

Thus, this study illustrates that by combining country mitigation pathways there is a *possibility* that the transport sector could provide significant reductions, provided that countries implement modelled mitigation strategies comprehensively and stringently. The average low carbon scenario at 2050 reaches below the 2000 levels, which is much lower than any global low-carbon estimate; thus, if we combine country low-carbon scenarios at the highest levels of impact, the sector could plausibly meet or exceed a 2DS target.

We acknowledge, however, that these calculations are based on an assumption that policies are *implemented* as they have been modelled and formulated. We also note that over the past few years, countries have not deviated significantly from the baseline and thus that countries would need to ramp up political will and private sector action (in tandem with technological developments and behaviour change) to achieve modelled potential. Therefore, countries will need to significantly strengthen their NDCs (set mid-term policy implementation milestones) and to integrate more closely with sustainable development objectives in order to spur transport mitigation action that will allow the sector to have a *reasonable* chance of a proportional contribution toward a 1.5DS target.

This research also establishes that mitigation potential required to approach a 1.5DS as targeted by the Paris Agreement exists for transport, but the likelihood that this potential is ultimately realized will depend on the development of plausible 1.5DS policy pathways.

Policy Pathways

Although the low-carbon scenarios depicted in this study are technically feasible, political leadership has not so far matched potential, as current trends reveal considerable delays in action during the 2010-2017 period (Gota et al. 2015b), thus increasing the intensity at which mitigation must take place in the coming decades. Thus, despite known solutions to decarbonizing transport (and known timeframes to reach 1.5DS emissions targets), several clear policy failures have overshadowed incremental successes: the rising trend of private ownership and use of ICE 4-wheelers with increasing preference for larger vehicles and no clear gains in modal split (EEA 2016, ITF 2017); the "Dieselgate" scandal and the widening gap between fuel economy standards and real-world CO_2 emissions (Tietge et al. 2017); and the halting energy efficiency gains for freight transport in the past decade, notably in the European Union (Muncrief & Sharpe 2015).

In this context, two key elements are needed to shift these policy failures to success and enable transformational change for transport. The first is to establish medium- to long-term commitments (ideally with quantified sectoral targets) to achieve transport sector decarbonization; the second is to adopt short-term actions to accelerate implementation of market-ready low-carbon measures to promote promising new technologies and behaviour change to set emission pathways to reach these long-term commitments.

Long-term commitments by countries and cities, along with private sector commitment to broad decarbonisation, are key factors to realizing potential mitigation ambition in the transport sector. Countries, as signatories to the Paris Agreement, have committed to meeting emission reduction objectives and must establish national legal frameworks for transforming their transport sectors. Cities will play an increasingly important role in implementing low-carbon mobility, as the world population becomes increasingly urbanized, with urban congestion and air quality likely to be key drivers for more ambitious policies. Much of the investment needed to transform transport will need to be borne by the private sector, which has the potential to disseminate low carbon transport-oriented paradigms through multi-national operations. Such a collaboration is a pre-requisite to steer transport climate action in a pragmatic direction, which can be focused through broad initiatives such as the Transport Decarbonization Alliance (PPMC 2017c).

Increasing ambition and urgency required to meet a 1.5DS will likely require long-term commitments which emphasize sectoral targets to accelerate mitigation action in the transport sector. Sectoral targets take various forms, including absolute GHG targets, vehicle CO2 standards, modal split, technology targets (e.g. EV penetration rates), and renewable energy share. Breaking down a global target of 2 Gt by 2050 to country-level (absolute) targets for the transport sector is one way of elaborating such sectoral targets. This can be done by each country based on appropriate indicators, such as mitigation potential, or on a per capita basis (ITPS & Clean Air Asia, 2014). In addition, nationally appropriate indirect targets can be set by each country, or at the regional (inter-governmental) level, to support the sector-wide target.

Recently, a growing number of countries, cities and companies have adopted policies with ambitious targets to reduce transport sector emissions potentially consistent with achieving a 1.5DS. For example, countries such as Germany (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) 2016), Norway (Stortinget 2015), and Sweden (Swedish Government 2017); cities such as London (Transport for London 2017), Seattle (Seattle City Council 2013), Stockholm (Stockholms Stad 2014) and Sydney (City of Sydney 2017) and companies such as DHL (DHL 2017) and participants in the World Wildlife Fund's Science-Based Targets initiative (Science-Based Targets Initiative 2015) are considering ambitious 2050 transport emissions targets. Realizing policy targets will require detailed short- and medium-term milestones for a range of low carbon measures; however, in most cases these targets are not yet backed by detailed pathways and milestones, such as those established in global decarbonization roadmaps with regional and/or national adaptations (PPMC 2017a).

Transport targets in NDCs are relatively limited, with only 13 direct targets (i.e. targeting transport emission reductions) and 20 indirect targets (e.g. targeting public transport mode share, renewable energy share, fuel consumption reduction, fuel efficiency) among all NDCs submitted (GIZ 2017) and in some cases NDCs do not reflect transport targets included in national plans (e.g. Germany, BMUB 2016). However, some countries have established NDC transport targets with increasingly detailed transport measures in revisions to date (e.g. Morocco: UNFCCC 2015; UNFCCC 2016b), and other countries have signalled intentions to expand transport measures and introduce transport targets in forthcoming NDC revisions (e.g. Argentina, Vietnam PPMC 2017b).

It is also important to emphasize the importance of pre-2020 action in the transport sector, as the majority of the 60-plus countries that developed 2020 economy-wide targets (but not transport-specific targets) have failed to derive significant reductions in the transport sector. A report published by Mission 2020 isolates transport-focused 2020 targets for EVs, vehicle efficiency, public transport share, and aviation/shipping emission reduction strategies necessary to meet long-term 1.5DS to 2DS targets (Revill and Harris 2017), thus creating a blueprint for deriving pre-2020 transport targets. In sum, while transport-specific sectoral targets may not be widely embraced in the short term, they are a necessary element for reducing transport emissions in the medium- to long-term to make a proportional contribution toward a 1.5DS.

To illustrate the short-term interventions needed to accelerate progress toward a 1.5DS, we consider electric vehicles (EVs) as a representative example of deep emission reduction pathways. EV commitments by countries and cities are increasingly ambitious, as indicated by Gota et al. 2017; however, EVs currently account for just 0.2% of total passenger light-duty vehicles globally (IEA 2017c). Research indicates the challenge of reaching 25% of total EV share by 2030 (about 100 million vehicles under a favourable policy scenario, which assumes cost reductions and range increases) (Fulton 2017).

However, to achieve a 1.5DS, studies indicate that passenger cars must be completely electrified by 2050 (with the last conventional passenger car to be sold in 2030) (Lindegaard et al. 2014), and to achieve a 2DS, about 40% of the passenger fleet (i.e. nearly 1 billion vehicle) would need to be electric by 2050 (IEA 2016d). IEA has estimated that to reach net-zero GHG emissions from transport shortly after 2060, the global EV stock must reach 25 million by 2020 and must exceed 200 million by 2030, and by 2060 EVs would need to account for 85% of global passenger vehicle stock (IEA 2017c).

To further leverage EVs as a focal point, it is necessary to initiate a broader set of complementary policy interventions. While tax breaks and purchase subsidies for EVs are important to shape short-term demand, the total cost of EV ownership (including purchase and operation) will be a key determinant for scaling up in the medium term. In this context, stringent targets to phase-out internal combustion engines (ICEs) send a strong signal to all stakeholders that transformational change is imperative. ICE phase-out targets, established by governments such as France, Ireland, Netherlands, Norway, Slovenia, Sri Lanka, and United Kingdom and poised to take effect from 2025-2040, and can help drive a range of electrification measures described in the following paragraphs.

First, electrification must be intensified for two- and three-wheelers, in addition to the current focus on four-wheelers. Due to a motorbike ban in China and rising popularity of e-bikes in Europe, e-bikes outnumbered four-wheeled EVs by a more than 30:1 ratio in 2016 (IEA 2017; Navigant 2016). When compared to conventional motorcycles, mobility by electric two-wheelers results in substantial CO_2 reductions regardless of electricity generation mix (IEA 2014). In addition, efforts must be made to expand penetration of EVs in public transport and other shared applications, to extend use of efficient vehicles to a wider share of transport trips, among other shared mobility principles (Chase 2017).

Second, electrification must be expanded for freight as well as passenger transport, however, particularly for heavy trucks, electric road systems are required (Mulholland et al. 2018), though development is still in an early stage. Electrification of trucks may require a transition management approach to further stimulate technology deployment. 'Strategic niche management' is such an approach, with key components including the "creation, development and controlled phase-out of protected spaces" (Kemp et al. 1998, p. 186) for promising technologies, successive experiments, and further articulation of policies and design. The private sector is already active in freight electrification: Deutsche Post DHL has a global presence and aims for net-zero delivery by 2050, in part through electric- and human-driven last-mile freight (Hannappel 2017).

Third, electrification of vehicles must take place in concert with coordinated roll-out of charging infrastructure to facilitate broader and more rapid uptake. Norway is setting an ambitious example in this respect, paired with EV purchase incentives, and China, Japan and the United Kingdom are also leading the charge (IEA 2017c). Charging stations are a key element in the shift from financing less- to more-sustainable modes.

Fourth, electrification efforts must be complemented in the short- and medium-term by fuel economy standards. Nearly 80% of new LDVs sold globally are currently subject to some kind of GHG emission or fuel economy standards (ICCT 2017), to date nine countries and the European Union have adopted fuel economy targets for LDVs, and four have adopted targets for HDVs. Stringent fuel efficiency standards can also be a bridge to electrification through a transition from ICEs to hybrids to EVs.

Fifth, to deliver significant emission reductions, fleet electrification must be achieved in parallel with decarbonisation of power generation, as carbon-intensive electricity grids offset potential reductions (IEA 2017c). If all subsectors of road transport were electrified by 2050 and combined with a decarbonised grid, a 1.5DS could potentially be reached.

Finally, while electrification potential for land transport is uncertain, extending this to modes such as aviation and shipping is even more challenging, and modal shift is difficult in the absence of close substitutes. Emission reductions in sectoral studies on aviation and shipping are generally assumed to come from operational, design and technology energy efficiency measures and low-carbon fuels, including biofuels, synthetic fuels and liquid hydrogen (see also Annex I). Implementing these, and thereby realizing the low-carbon scenario of Fig. 8, will require stringent policy efforts, as current policies are likely to lead to relatively limited improvements; however, a recent study on the potential to decarbonise the shipping sector by 2035, paired with anticipated discussions of targets for longer-term sector-wide decarbonization suggest a potential for broader shifts in the coming decades (ICTSD 2018; ITF 2018).

In sum, transport mitigation efforts to date have relied heavily on technological transformation (i.e. 'Improve' measures), and considerable hope remains in these measures to reach a 1.5DS. Such a technology-oriented foundation has shifted policy focus away from “behavioural changes” which have been difficult to implement in the past, and thus, the potential mitigation impact of 'Avoid' and 'Shift' strategies has been reduced (World Energy Council 2011; IEA 2015). However, it is by no means certain that the rapid deployment of EVs and supportive strategies described above can be realized under the required timeframe. With this in mind, it is necessary to pursue complementary 'Avoid' and 'Shift' measures in parallel, which also tend to have lower short-term societal costs.

However, a number of emerging developments are increasing the potential of 'Avoid' and 'Shift' measures by improving user information and in turn increasing potential for sharing and connecting low-emission modes (Fulton et al. 2017). In this regard, comprehensive policies like the recent draft strategy of the City of London (Transport for London 2017) that combine behavioural change with technological measures increase the odds of realizing ambitious transport emission targets. For example, if global passenger activity and freight movement were reduced 50% through concerted public transport mode shift and land-use planning, significant emission reductions could be achieved. Vehicle restrictions (e.g. quotas) in China are another strategy to curtail motorisation (Kenworthy 2017), and regulations in Singapore have resulted in zero growth of personal four-wheelers (Land Transport Authority (LTA) 2017). Such restrictions can be complemented by ICE phase-out policies, which are non-coercive in the short term but have potential to guide near-term decisions in the context of a long-term commitment.

The cost-effectiveness of mitigation measures among different sectors will also remain a key issue in determining the speed with which individual sectors can decarbonise. A determination of the cost-effectiveness of all possible transport measures is challenging (Hoen et al. 2009). While we do not assess costs independently in this study, research has confirmed that total investment needs in achieving a 2DS or B2DS are lower than for the BAU scenario (IEA 2017a), mainly due to savings from 'Avoid' and 'Shift' measures on vehicles, fuel consumption and infrastructure, which compensates for the cost of 'Improve' measures such as decarbonising fleets. These savings could be significant in middle-income countries, as non-OECD countries could account for 85% of new transport infrastructure in the next 40 years (Dulac 2013).

In sum, the full mitigation potential of the transport sector can only be realized if low carbon policies optimize the use of 'Avoid,' 'Shift,' and 'Improve' measures. The chance that a comprehensive approach is taken will be higher if countries, cities and companies actively integrate sustainable development objectives into policies on transport and climate change. For example, supporting greater use of public transport can reduce GHG emissions, but also has the potential to reduce diesel-related air pollution, reduce urban road congestion, and improve access and mobility. Therefore, development benefits of a comprehensive set of 'Avoid,' 'Shift,' and 'Improve' measures (e.g. with improving air quality a primary policy driver) may have a greater value to policy makers than anticipated climate change mitigation value, which is often in fact a co-benefit.

6. Conclusions

This paper set out to analyse the global mitigation potential of the transport sector, in the context of the 1.5DS of the Paris Agreement and the wider 2030 sustainable development agenda. The methodology is based on a bottom up analysis of over 500 existing low-carbon transport studies for 81 countries and international aviation and maritime transport, which is a novel approach.

Existing global modelling scenarios (mostly aligned with a 2DS) assume a relatively low mitigation potential and high abatement cost for transport, resulting in relatively modest carbon reductions by 2050, and rapid decarbonisation in the second half of the century. An initial finding of this paper is that based on a proportional emission reduction share (as previously defined), global transport emissions should be 70% below 2010 levels and about 90% below BAU projections to achieve a 1.5DS.

A second finding of this paper is that 2050 transport BAU emissions could be between 13 and 27 GtCO_2-eq, with an average of 18 Gt. These figures are higher than existing projections, which could be due to higher growth assumptions on economic development, transport demand, and vehicle ownership and use in country studies compared to aggregated global and regional studies. This increase would mainly stem from emissions growth in middle-income countries, although per capita emissions in high-income countries would still be three times as high. Low-income countries (accounting for 8% of global population) are expected to contribute a 1% share of transport emissions in 2050.

Third, an aggregation of country low-carbon trajectories yields global transport mitigation scenarios ranging from 2.5 to 9.2 Gt in 2050, with an average of 5.4 Gt. These range from a 60% decrease to a 31% increase in transport emissions compared to 2010 levels. The average and optimistic scenarios suggest a higher emission reduction potential than is traditionally assumed in models, with the optimistic scenario being close to what is needed in a 1.5DS, and with per-capita emissions for high and middle-income countries could converge by mid-century under the same scenario. It is acknowledged, however, that the conservative and average scenarios fall well short of a 1.5 DS, indicating that improving the probability of meeting this target will require higher ambition and more comprehensive measures in low-carbon transport plans.

Fourth, in low-carbon scenario country studies, approximately one-third of the measures included are in the realm of 'Avoid' and 'Shift' measures. In existing scenarios, particularly in IAMs, such measures play a smaller role relative to 'Improve' measures.

In sum, realising full mitigation potential of the transport sector will depend critically on establishing medium- to long-term commitments to transport sector decarbonization, and adopting short-term actions to accelerate implementation of market-ready low-carbon transport measures to reach these long-term commitments. Setting more ambitious low-carbon transport plans with mid-term implementation milestones, and integrating these plans more closely with sustainable development objectives, can help to spur transport mitigation action consistent with a 1.5DS target.

Uncertainty in transport sector mitigation potential remains considerable. To increase harmonisation between mitigation assessment and low-carbon scenario modelling, it is recommended to improve consistency among key assumptions (e.g. transport demand growth, motorisation rates) and to include a more comprehensive set of possible mitigation measures, in particular those related to behaviour change, which can contribute to broader sustainable development goals as well as mitigation targets.

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Annex I: Sample of Bottom-Up Country Studies

Country	Avoid Measures	Shift Measures	Improve Measures	Reference
Brazil		Shift to public transport, walking and cycling in cities; freight to shift to rail and water transport	Hybrids and electric vehicle (31% of total vehicle fleet), biofuels (50% of trips made on ethanol); energy efficiency in freight transport	(Empresa de Pesquisa Energética 2016)
Canada		Freight mode shift, shift to walking, cycling and public transport, use of rail and bus in intercity travel	Electrification of transport modes, all new vehicles to decarbonize in the early 2030s. Heavy freight vehicles to decarbonize by 2040, carbon tax, fuel decarbonisation by electric, cellulosic ethanol and biodiesel	(Bataille et al. 2015)
China			Vehicle efficiency, biofuels and electricity (produced through solar energy) to power transport	(Greenpeace 2010)
EU-27	Spatial planning, lower speed limits, vehicle taxes	Modal shift	Fuel economy of vehicles, introduction of alternative fuels, driver training	(Skinner et al. 2010)
Germany		Shift to rail, esp. for freight,	Biofuels to play stronger role, increase of hybrid and electric vehicles to two thirds of fleet by 2050 leading to reduction of overall final energy consumption of transport	(Kirchner and Matthes 2009)
India		Bus rapid transit and metro systems, green freight measures	Electric vehicles, fuel economy, biofuels	(UNEP 2015)
Indonesia		Public transport increases modal share from 40% in 2010 to 46%-52% in 2050	Switch to biofuel (biogas) and natural gas in transport, the deployment of electric vehicles, fuel efficiency improvements; Fuel carbon intensity reduction from 73 to 49-39 gCO_2/MJ	(Siagian et al. 2015)

Country	Avoid Measures	Shift Measures	Improve Measures	Reference
Lao PDR	Reduction of trips by more than half through better land use planning and freight transport reduction by a third until 2050.	Increase of public transport share to 67%, shift from individual transport to BRT by 10% and to rail by 15% until 2050, for freight a 45% shift to rail by 2050	Freight to consume 20% CNG by 2050, electric vehicle and hybrid promotion, rail electrification, eco-driving	(Institute for Transport Policy Studies 2013)
Mexico	Urban planning, mixed land-use, reduced travel distance	Shift to public transport, cycling and walking, intercity travel mostly shifts to bus and rail, 45% of freight transported on rail	Electric buses and cars to be employed, increase of vehicle efficiency	(Secretaria de Energia 2015)
Republic of Korea		Public transport shift, modal shift reinforcement	Hybrids or electric cars, biofuels	(Hong et al. 2016)
South Africa	Reducing travel demand, Vehicle occupancy	Shift to lower emission technologies, freight mode shift	Efficiency improvement for passenger and freight vehicles	(Department of Environmental Affairs 2015)
United States of America	Land use planning		Eco-driving, heavy-duty freight vehicle efficiency, e-mobility	(National Renewable Energy Laboratory 2015)
Vietnam		BRT and metro development	Fuel efficiency in road transport	(Asian Development Bank 2018)
Int'l Aviation	Reduce travel demand		Technological improvements: energy efficiency and alternative fuels	(Cames et al. 2015)
Int'l Shipping			Energy efficiency measures (technology, design and operational) and 5-15% due to low-carbon fuels	(International Maritime Organization 2015)