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# What Can Transport Deliver? Contrasting Scenario Pathways with New Technology Penetration

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# What Can Transport Deliver? Contrasting Scenario Pathways with New Technology Penetration

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DISCUSSION PAPER

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## ABSTRACT:

We compare detailed projections of transport energy consumption and $CO_2$ emissions up to the year 2050 and review representative pathways towards the specific mitigation targets outlined in the Fifth Assessment report by the Intergovernmental Panel on Climate Change (IPCC-AR5), contrasting sectoral and integrated assessment model studies. Considering the potentials of various measures for $CO_2$ emission reduction, we find that the projections for prospective energy use reduction and fuel switching are broadly consistent between sectoral and integrated studies. Both types of studies indicate that near-term actions emphasizing the intensification of efficiency improvements, modal shifts, and other behavioural changes along with a longer-term transition to low-carbon fuels offer a high mitigation potential for $CO_2$ emission reduction. Further, these actions are contrasted with the current trends in the evolution of penetration rates for new car and fuel technologies globally. The current level of penetration for hybrids, electric vehicles and biofuels is 2-3% globally, which is far below of the level of 30% or higher required by 2°C scenario in the 2050 time frame. The results of this study suggest there is a mismatch between current penetration rates and those needed for global transport to reach identified targets as part of achieving broader climate stabilization targets. Of paramount significance is the strong improvement rates in vehicle efficiency and countries should redouble their efforts to set strong targets and policies, rather than backtracking at this time.

## Keywords:

Transport Sector, Scenario Analysis, Energy Reduction, CO2 Reduction, Mitigation Technologies, Fuel Efficiency

## 1. INTRODUCTION

In light of the COP-21 Paris agreement signed in April, 2016, countries have made new commitments to cutting $CO_2$ emissions with the goal of limiting the temperature rise to 2°C or even 1.5°C. However, the details of many of the national plans are vague, including contributions from different sectors such as transportation. There is a great need for a clearer picture of how much $CO_2$ reduction the transport sector can deliver, and the pathways and strategies for achieving such reductions.

$CO_2$ emissions from the transport sector have more than doubled since 1970, increasing at a faster rate than any other end-use sectors to reach 6.7 $GtCO_2$ (23 % of total energy-related $CO_2$ emissions) in 2010. The final energy consumption for transport reached 27 % of total end-use energy in 2010, and over 53 % of global primary oil consumption was used to meet 94 % of the total transport energy demand (IPCC, 2014). Since transport demand is closely related with economic growth, and the transport sector relies strongly on oil-based fuels, the strategy of $CO_2$ emission reduction from the transport sector is very important to achieve a stringent 2°C stabilization target.

In the literature, there are many scenarios for predicting the impacts of the transport sector on emissions, including those that explore how the future develops without additional and explicit efforts to mitigate climate change ("baseline scenarios") and those including policies to limit emissions ("mitigation scenarios"). During the course of IPCC-AR5 activities, we[1] were involved in collecting and assessing detailed sectoral studies and comparing these to integrated assessment model (IAM) studies. This comparison was used to explore global transformation pathways for various transportation $CO_2$ mitigation targets. Since only a partial analysis was

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[1] The paper's three co-authors participated as lead authors in the Transport chapter of IPCC-AR5 report.

possible during the chapter writing process, and only a small part of the results for the whole transport sector and none of the results for light duty vehicles (LDVs)[2] were published in the assessment report due to the page limit, further analyses and more detailed results are presented here. A clear understanding of the potential emission reduction contributions from LDVs is needed since road vehicles contribute three quarters of the total transport emissions (IEA, 2012a) and LDVs are targets for air quality and congestion reduction policies (IPCC, 2014). This paper has two objectives: to review and compare the representative pathways of the transport sector towards the specific mitigation targets, discussing the potentials of various measures for $CO_2$ emission reduction; and to contrast this with new car and fuel technology penetration rates, projecting mitigation potentials observed from their current evolution.

At the core of this paper is the question: what can global transport deliver to the required climate mitigation? This question has been approached following two tracks of information. One track has been to expand and deepen the discussion first presented in IPCC-AR5 (IPCC, 2014) through comparison of results obtained with two distinct scenarios carried out in sectoral and integrated assessment model (IAM) studies. The second track has been to increase the focus on how these (sectoral and IAM) models rely on a rapid penetration rate of new fuel and vehicle technologies, and the challenges posed in achieving such rapid advances. Particular attention has been drawn toward the technology potential of the LDV subsector, which includes personal passenger cars such as smaller pickup trucks, vans, and SUVs, because the LDV subsector is an important source of $CO_2$ and because modelling details tend to be available for these vehicles, allowing a comparison of decompositions related to carbon intensity of fuels, energy efficiency of vehicles, and modal shift (Fulton et al. 2013; Creutzig et al., 2011; Schipper et al., 2000). We

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[2] Light-duty-vehicle (LDV) is essentially identical to passenger cars in most of countries, but like US, it also includes additional cars used for personal passenger cars such as smaller pickup trucks, vans, SUVs and so on.

recognize that the mitigation potential of a modal shift and demand reduction is significant, but the additivity, synergies and trade-offs of these type of measures at a regional or global scale are not methodologically well-integrated into the models considered here and deserves further research (Creutzig, 2015).

The paper is structured as follows: the following section describes the data and methodology used for the comparison and the third and final section reviews the findings and the analysis of the projections for the whole transport sector and for the LDV subsector. This section also explores an analysis of the feasibility of options for reaching stabilization targets.

## 2. METHODOLOGY

One of the main contributions of this paper is the development of a comparison of data results between sectoral scenario studies and integrated assessment model (IAMs) studies, in the context of examining the feasibility of scenarios for a 2°C global temperature rise (2DS). In particular, we consider the following variables: total energy consumption, fuel mix, $CO_2$ emission projections, and activity of passenger and freight transport. IAMs typically incorporate all sources and demand sectors to comprehensively model pathways of global emissions reductions that can achieve threshold mitigation targets at the lowest economic cost; alternatively, the sectoral studies focus exclusively on the transport sector and its potential for emissions reductions including potential contributions from infrastructure change and modal shift.

The data sources of the detailed sectoral scenarios (henceforth referred to as sectoral scenarios) are IEA-WEO (2011, 2012a), IEA-ETP (2008, 2010, 2012b), GEA (2012), WEC (2011), and IEEJ (2011). The data for IAM scenarios were taken from the IPCC-AR5 Scenario Database, where more than 1200 published mitigation and baseline scenarios have been collected. It should be noted that not all studies provide the data necessary for the comparison. For the analysis of the whole transport sector, only about 600–750 scenarios were used. Furthermore, since this database does not provide data for LDVs, the analysis here presented for LDVs is based on data from sectoral studies only.

We have grouped both IAM and sectoral scenarios into three categories (see Table 1): 1) 6DS, including scenarios such as Baseline, Reference, and Current Policies, 2) 4DS, including scenarios such as New Policies and ACT, and 3) 2DS, including scenarios such as 450ppm and Blue Map. The 6DS scenario is an extension of past trends (pre-Paris agreement) and offers a baseline picture of how global energy markets would evolve without any new policy intervention, with an average global temperature rise of around 6°C in the long term. The 4DS scenario takes into account the policies and implementing measures affecting energy markets that have been adopted today, together with relevant policy proposals, leading to a global average long-term temperature increase of around 4°C. The 2DS scenario illustrates what it would take to achieve an energy and $CO_2$ emission trajectory consistent with limiting the long-term increase in average global temperature to 2°C.

**Table 1.** Scenario categories and their characteristics.

| | 6DS | 4DS | 2DS |
|---|---|---|---|
| ETP2012 | 6 °C Scenario | 4 °C Scenario | 2 °C Scenario |
| WEO2012/2011 | Current Policies Scenario | New Policies Scenario | 450 Scenario |
| ETP2010/2008 | Baseline scenario | ACT scenarios | BLUE Map scenario |
| WEC (2011) | Freeway scenario | Tollway scenario | |
| IEEJ (2011) | Reference case | | Tech. Promotion case |
| GEA (2012) | Reference | ACT scenarios | GEA scenarios |
| Description of scenarios | Government policies that had been enacted or adopted continue unchanged. | Existing policies and recently announced commitments and plans are implemented. | Policies are adopted for limiting the global temperature rise to 2°C. |

In the IPCC-AR5 report (IPCC, 2014), scenarios were grouped into different categories based on the predicted emission level in 2100[3] and median values of whole data sets were used. However, given no information on the emission level and the limited number of sectoral scenarios for each specific category (between 4-10), we proceeded to change to the grouping based on the name of scenarios and to use the average (mean) values of each category. For the data of IAM scenarios, average values of both 6DS/4DS/2DS grouping (based on the name of scenarios) and grouping according to median values of >650ppm/530-650ppm/430-530ppm were compared and found to be very similar to one another.

## 3. RESULTS AND DISCUSSION

### 3.1 Comparison between Sectoral and IAM Scenarios.

As shown in Figure 1, the projections of energy consumption for both sectoral and integrated scenarios up to the year 2050 closely match each other. The reduction rates of energy consumption from baseline 6DS to 4DS and 2DS scenarios shown by vertical arrows also agree well; this is a rather surprising finding because of the very different nature of these two types of models. For example, bottom-up sectoral scenarios are often based on back-casting analyses that show ranges for a low-carbon scenario capable of hitting specific targets. In the case of IAM scenarios, future projections typically reflect least-cost pathways across several sectors, given a global $CO_2$ constraint. The greater variability could result as a function of assumptions and included policies. In the building sector, sectoral scenarios show a larger energy savings potential by 2050 than do IAM scenarios (IPCC, 2014). On the other hand, detailed industry sector scenarios tend to be more conservative than IAM scenarios.

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[3] In the sectoral scenarios, information on the emission level in 2100 is not available and the same grouping based on the emission level is not possible.

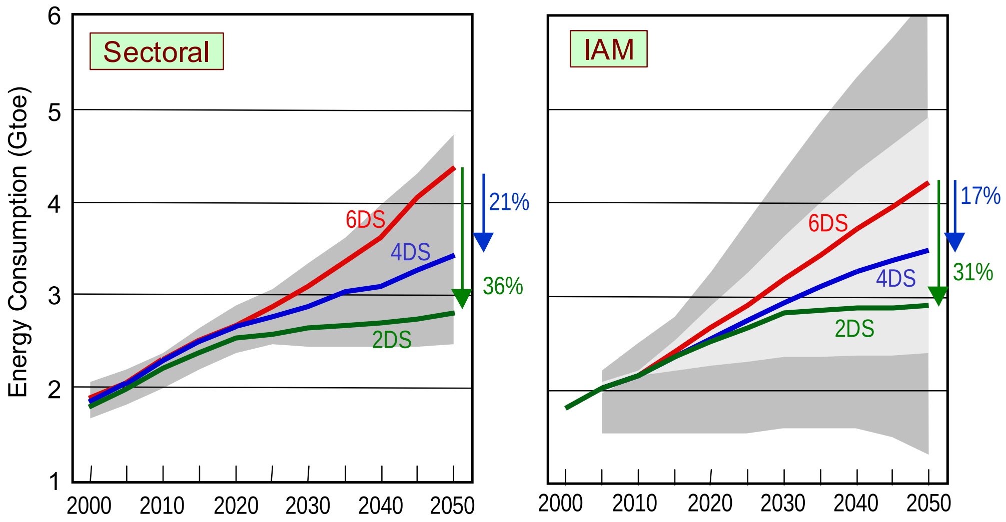

**Figure 1.** Comparison of energy consumption of the transport sector in the sectoral and IAM scenarios. Lines show the average values of all available data. The grey zones indicate the full range of data for the sectoral scenario, and the full range (dark grey) and the 25–75th percentile range (light grey) for IAM scenarios.

Apart from cutting fuel use, fuel switching to potentially very low carbon fuels (including liquid biofuels, electricity, and hydrogen) is likely to play a key role in achieving $CO_2$ reduction targets. Low carbon fuel shares of the total transport sector energy by 2050 for 4DS and 2DS mitigation scenarios are shown in Figure 2. In the 4DS scenarios, IAMs show slightly higher use of biofuels, electricity and hydrogen in 2050, but in the 2DS the mean values are nearly the same for all three fuel types; only the variance differs significantly between sectoral and IAM projections.

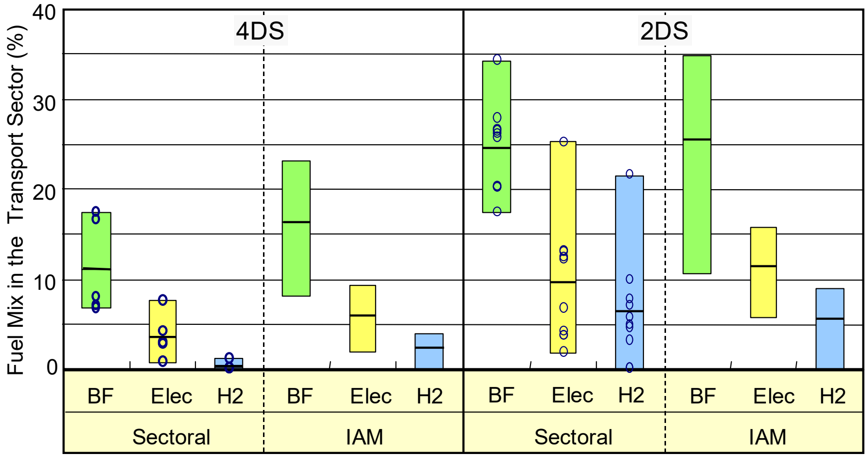

**Figure 2.** Fuel mix of low carbon fuels in 2050 for 4DS and 2DS scenarios: BF-biofuel, Elec-electricity, H2-hydrogen. For each fuel, the box indicates the full range of data for sectoral scenarios and 25–75th quartile range for IAM. Average lines are shown within the boxes. Individual data from sectoral studies are shown as open circles.

Since the trends of energy consumption and the fuel mix and carbon intensity combine to directly determine the overall $CO_2$ emissions from transport, the fact that these variables are very similar for both sectoral and IAM scenarios would be expected to result in similar $CO_2$ emission projections. However, as shown in Figure 3, the trends of average values of direct tank-to-wheel (TTW) $CO_2$ emissions are fairly different; one possible reason may be the different methodologies used for accounting the “fuel cycle” emissions of biofuels.

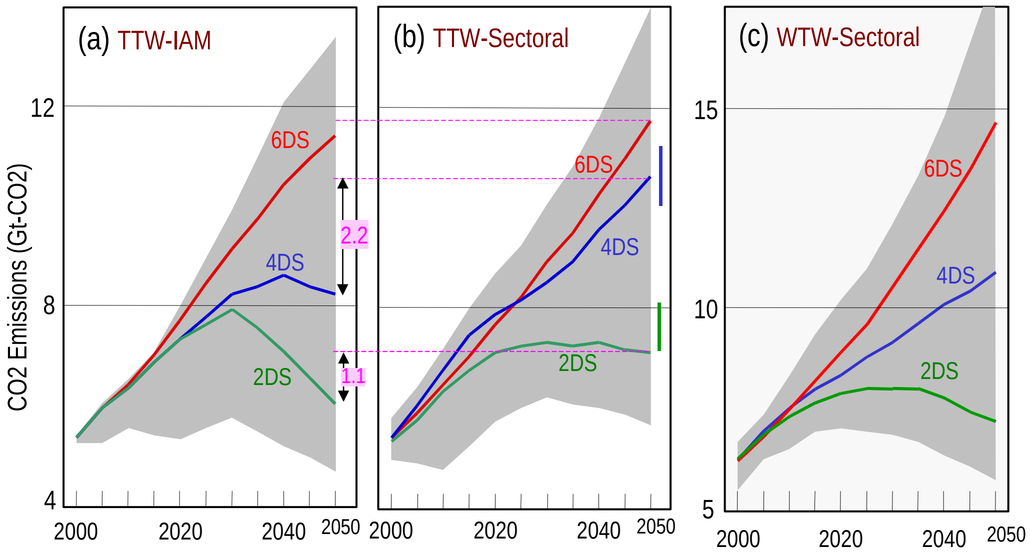

**Figure 3.** $CO_2$ emission projections: a) direct (TTW) emissions in IAM scenarios, b) direct (TTW) emissions in sectoral scenarios, and c) WTW* emissions in sectoral scenarios. Lines show the average values of all the available data and the grey zones indicate the full range of data for the sectoral scenario, and 25th to 75th percentile range for IAM.

*WTW (Well-to-Wheel): both direct emissions from vehicles and indirect emissions during fuel processing.

There are two ways of accounting for the emissions projections presented in Figure 3:

1) the $CO_2$ absorbed during photosynthesis and the emissions due to the energy used for fuel processing are considered to be a well-to-tank emission and the emissions from biofuel burning considered to be tank-to-wheel emission (direct emission);

2) tank-to-wheel (direct) emissions of $CO_2$ are set to zero, as the same amount of $CO_2$ is absorbed during the growth of the feedstock from which the biofuel is produced, and only emissions from the fuel processing is counted as well-to-tank emissions.

Most sectoral scenarios adopt the first method, but it seems that most IAM scenarios use the second method, since this is the method recommended in the IPCC Guidelines (IPCC, 1996). The impact of using different methods to estimate $CO_2$ emissions is an approximately 1.5–2 $GtCO_2$ discrepancy, which is roughly consistent with the difference indicated by the vertical arrows in Figure 3a. Using the data of fuel mix (oil, gas, and biofuels) for IAM scenarios, TTW emissions based on the accounting method 1 of biofuel emissions were calculated. Since full fuel mix data (gasoline/diesel, LPG/natural gas, and ethanol/biodiesel) are not available in the IPCC database, the upper and lower limits of emissions were estimated by using the emission factor values of fuels corresponding to each category of fuel mix (oil, gas, and biofuels). The results for 4DS and 2DS scenarios in 2050 are shown by the vertical lines in Figure 3b, indicating a fairly good agreement with the sectoral scenario data. It is difficult to be sure that the major part of the difference between sectoral and IAM scenarios observed in Figure 3 is caused by using the different accounting method of $CO_2$ emissions for biofuels, but this explanation is consistent with the data.

### 3.2 Analyses of the Projections for the Transport Sector.

In this subsection, the impact of factors contributing the evolution of energy consumption and $CO_2$ emissions are analysed, including transport activity, fuel efficiency, and fuel switching.

The energy use projections shown in Figure 1 are a result of the amount of passenger travel and goods transport that are projected in the models along with the efficiency of the modes used. As economies and populations grow, transport activities continue to increase, especially in developing countries. In most projections, both passenger and freight activities double the current level by 2030, and triple by 2050 (IPCC, 2014). If there is no improvement in vehicle efficiency and no fuel switching, this will lead to commensurate increases in energy consumption and $CO_2$ emissions, accordingly. However, even in the baseline 6DS scenario projection, global transport energy use increases only by a factor of 2.5 between 2000 and 2050, which because of efficiency improvements is 15–25 % lower than the growth rate of transport activity. For 4DS and 2DS scenarios, the efficiency improvements of 30–40 % and 40–50 %, respectively, between 2000 and 2050 decreases the energy use in 2050 by 17–18 % and 30–31 % from the baseline scenario of 6DS, respectively. The share of low carbon fuels increases with time and with the intensity of climate policies from 6DS to 2DS. In 2050, fuel carbon intensity (calculated by dividing the well-to-wheel $CO_2$ emissions by the energy consumption) is decreased by 10 % and 40 % from the 6DS scenario to 4DS and 2DS, respectively (see Figure 5). The small change in the carbon intensity for 4DS is due to the balance of a slight increase of indirect (well-to-tank) emissions from fossil fuels and due to the reduction of $CO_2$ by the use of low carbon fuels. For 2DS, the higher share of low carbon fuels (biofuels, 25 %; electricity, 10 %; and hydrogen 7 %; see Figure 2) leads to a significant reduction of well-to-wheel $CO_2$ emissions, as shown in Figure 3c. In 2050, the emission for 2DS is only 9 % higher than the level in 2000, which is in great contrast to the growth rate of energy consumption of 61–74 % over the same time period (Figure 1). The efficiency improvement can explain more than 60 % of the reduction of WTW-$CO_2$ emissions from 6DS to 2DS in 2050, although fuel switching is also needed to account for the large reduction of emissions.

As described in the previous subsections, the comparison between sectoral and IAM models has revealed their contrasting representative pathways for the evolution of the transport sector towards mitigation targets, and the potentials of various measures toward stringent $CO_2$ reduction targets. The scenarios describing pathways for achieving climate stabilization targets are largely consistent across sectoral and IAM models, which suggests robustness in identifying the most promising pathways for achieving the 2°C target. Concurrently, the scenario comparisons have made it clear that the 2°C scenario is very challenging and requires strong and sustained efforts to achieve the targets.

### 3.3 Analyses of the Projections for LDVs.

In 2012, road vehicles accounted for almost three-quarters of the total transport energy use, with light-duty vehicles (LDVs) responsible for 40 % of the total (IEA, 2015). Since LDVs are the highest energy-using mode in the passenger transport with good potential to cut $CO_2$ emissions (e.g. via electrification), LDVs were chosen for the focus of this subsection, which overviews the future trends of energy consumption and $CO_2$ emissions and discusses the potentials of emission reduction measures. The analyses in this section are based on sectoral scenarios only, because no LDV-level data is available for the IAM scenarios.

As shown in Figure 4, the average energy consumption is predicted to increase by a factor of 2.3 between 2000 and 2050 for all the 6DS scenarios of the whole transport sector, road sector, and LDVs. However, due to the different potentials of energy efficiency improvement, growth rates of 2DS over 2000 are 61 %, 37 %, and 21 % for the whole sector, road sector, and LDVs, respectively. In LDVs, both vehicle stock and activity (vehicle-km) are predicted to grow about three times the level in 2000 by 2050. Future efficiency improvements lead to the predicted slower growth of energy consumption and $CO_2$ emissions (details are discussed later with fuel switching). Here, it is worth considering that LDVs have the highest potential for $CO_2$ emission reduction among all fossil fuel based modes within the transport sector (IEA, 2015).

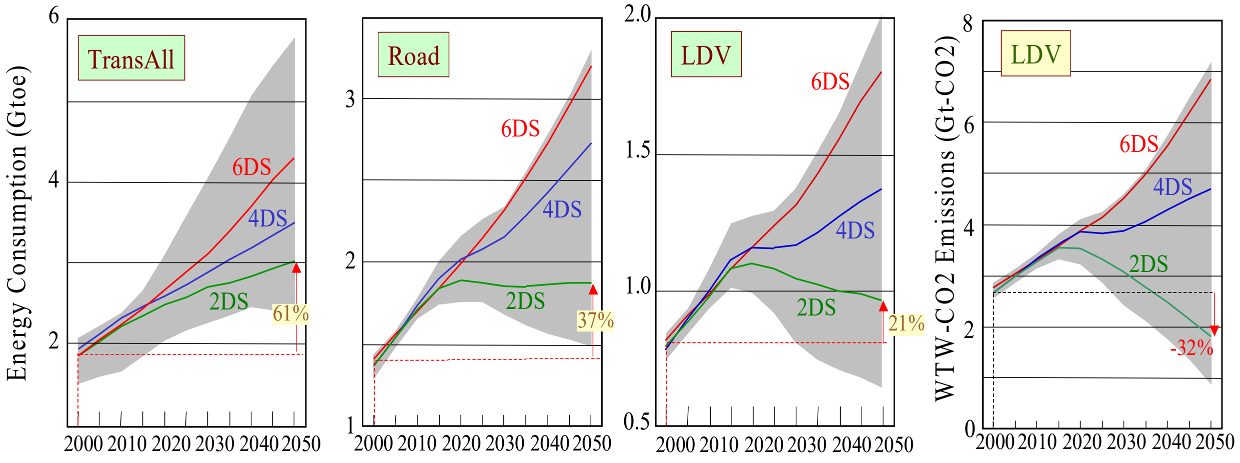

**Figure 4.** Comparison of energy consumption among the whole transport sector, road transport sector and LDVs, and $CO_2$ emission projections for LDVs. Lines show the average values of all the available data and grey zones indicate the full range of data for sectoral scenarios. Gtoe = gigatonne of oil equivalent.

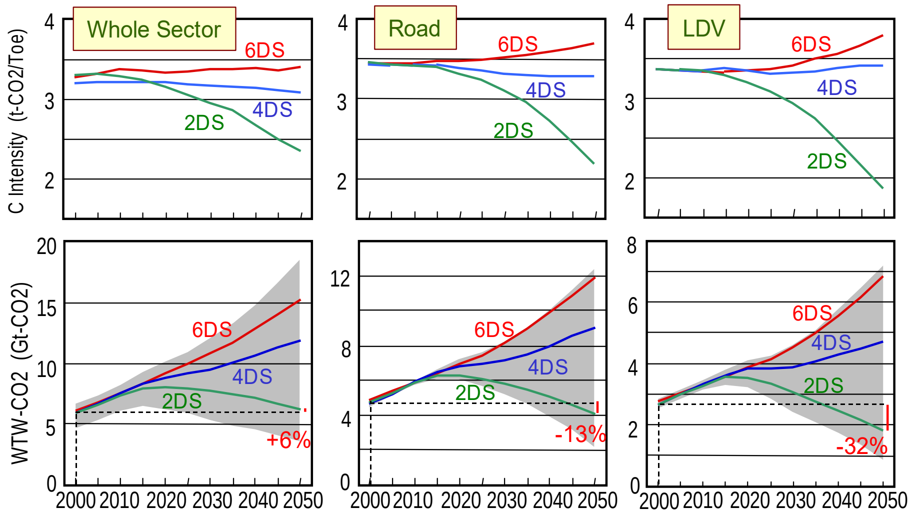

**Figure 5.** Comparison of Well-to-Wheel $CO_2$ emissions and carbon intensity among the whole transport sector, road transport sector and LDVs in sectoral scenarios. Lines show the average values of all the available data and grey zones indicate the full range of data.

$CO_2$ emissions are predicted to grow almost proportionally with the energy consumption up to 2050 in the 6DS scenario (Figure 4). The growth rate of $CO_2$ emissions in the 2DS scenario is slower than that of energy consumption largely due to the increasing share of low carbon fuels, as indicated by carbon intensity trends (see Figure 5). This impact is largest for the LDVs compared to the whole sector and road sector. The emission level of 2DS for LDVs is 32 % lower than that in 2000. It should be emphasized that LDV stock and activity are predicted to grow almost three times during the same period, leading to a growth rate of 150 % in the 6DS scenario. The reduction of emissions from 6DS to 2DS is as high as 74 % in 2050.

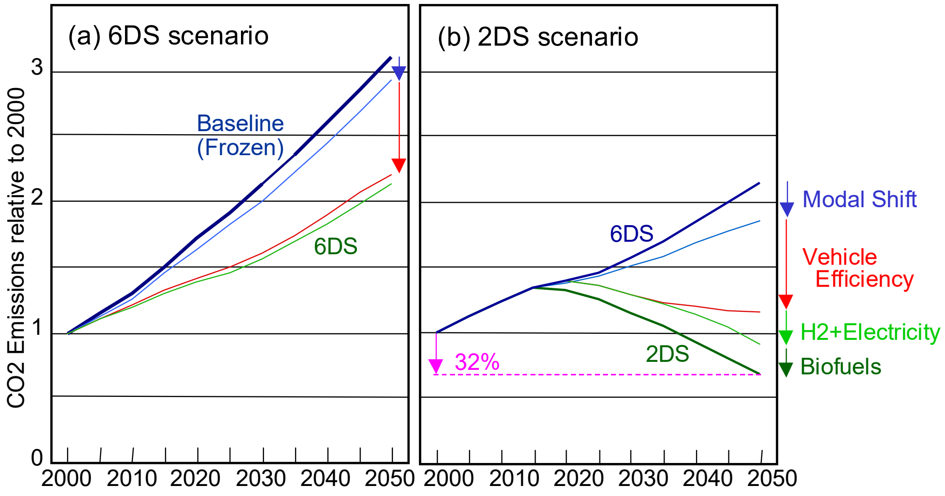

**Figure 6.** Analyses of factors for $CO_2$ emission reduction in the LDV subsector based on the average values of sectoral scenarios: (a) baseline to 6DS, and (b) 6DS to 2DS.

Figure 6 breaks down the contribution of the different factors to the future reduction of energy consumption and $CO_2$ emissions in the LDV subsector by analysing the average growth rate of vehicle stock, energy consumption, TTW-$CO_2$ and WTW-$CO_2$ emissions in sectoral scenarios. Without any efficiency improvement or fuel switching (frozen scenario), energy consumption and $CO_2$ emissions should increase in accordance with the LDV stock, as shown in Figure 6. A modal shift (including both reduction of vehicle stock and annual driving distance) and efficiency improvement contribute to a reduction of 30 % of emissions compared to the frozen baseline of 6DS in 2050; however, more than 75 % of this reduction is made possible by the improvement of vehicle efficiency alone.

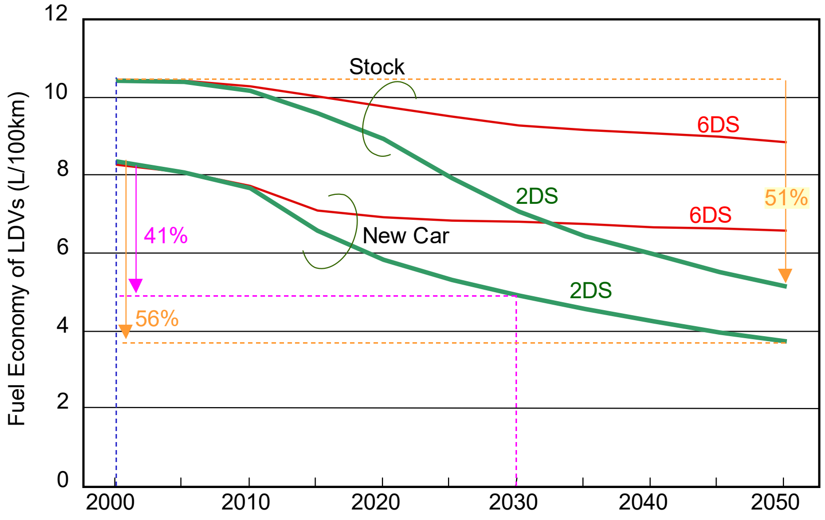

**Figure 7.** Projection of fuel economy improvement for stocks (on-road value) and new car sales (test value) of LDVs based on the average values of sectoral scenarios.

From 6DS to 2DS, the $CO_2$ emissions in 2050 are reduced by about 70 %, of which 50 % comes from the efficiency improvement and 30 % from the low carbon fuels. Therefore, energy efficiency improvement is the most important measure of future climate mitigation strategies in the transport sector. Figure 7 shows the trends of average fuel economy for stocks (on-road value) and new car sales (test value) of LDVs, based on the average values of sectoral scenarios.

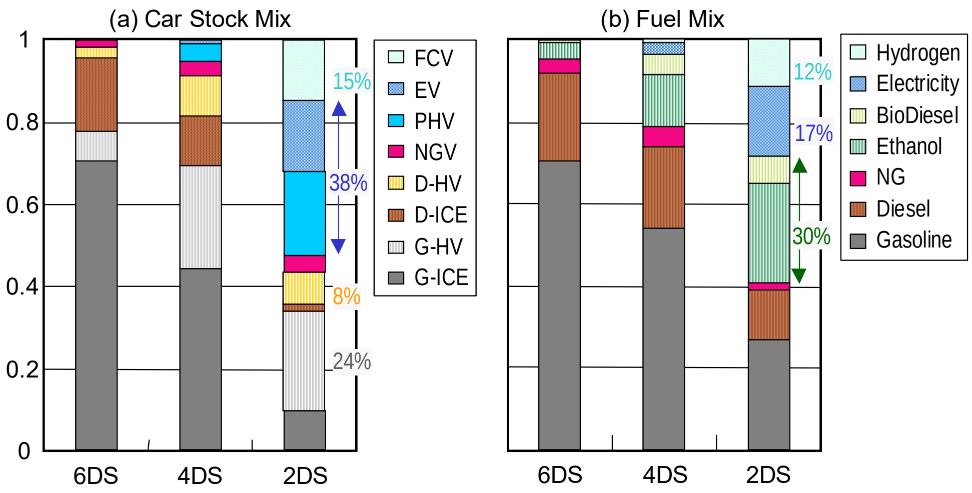

**Figure 8.** Average technology mix of stocks and fuel mix for LDV data of sectoral scenarios in 2050. Abbreviations are as follows: gasoline (G), diesel (D), internal combustion engine (ICE), hybrids (HV), natural gas vehicles (NGV), plug-in hybrid vehicles (PHV), battery-powered electric vehicles (EV), fuel cell vehicles (FCV), natural gas (NG).

Fuel economy is improved via better conventional powertrains and switching to advanced powertrains such as hybrids, battery-powered electric vehicles, and fuel cell vehicles (see Figure 8 based on the analysis of average values of sectoral scenarios). The improvement in 6DS is moderate. In 2DS, the fuel economy of new cars in 2030 and stocks in 2050 is improved by 41 % and 51 % over 2000, respectively, on an energy use per km basis. This is nearly consistent with the 50 by 50 target (calling for 50 % improvement in new LDV fuel economy by 2030, and 50 % for stocks by 2050) proposed by GFEI (2009, 2014). In 2050, the fuel economy of stocks was predicted to improve by 40 % from 6DS to 2DS. As seen in Figure 8, this is largely caused by the wide penetration of advanced powertrains (hybrids, 32 %; EV, 38 %; FCV, 15 %). At the same time, fuel switching to low carbon fuels (biofuels, 30 %; electricity, 17 %, $H_2$, 12 %) provides large $CO_2$ emissions reductions relative to 6DS (Figures 4-6).

### 3.4 Feasibility of the 2DS Scenario.

In the foregoing analysis of LDV projections, it was shown that the $CO_2$ emissions were reduced by 70 % from 6DS to 2DS in 2050 (Figures 4 and 5). This was made possible mainly by two strategies: the widespread adoption of advanced powertrains and other efficiency measures, and the adoption of low carbon fuels, although some reduction in activity growth also occurred. IPCC-AR5 (2014) stated as one of its key messages that mitigation under a 2DS scenario involves major technological, behavioural and institutional challenges. Given the rates of efficiency improvement and uptake of alternative fuels in these scenarios, it appears that the transport sector is no exception; the 2DS scenario is very demanding regarding required changes and transitions. To assess progress made in this area so far, this section elaborates on one key aspect of this challenge; the new technology penetration rate in LDV subsector.

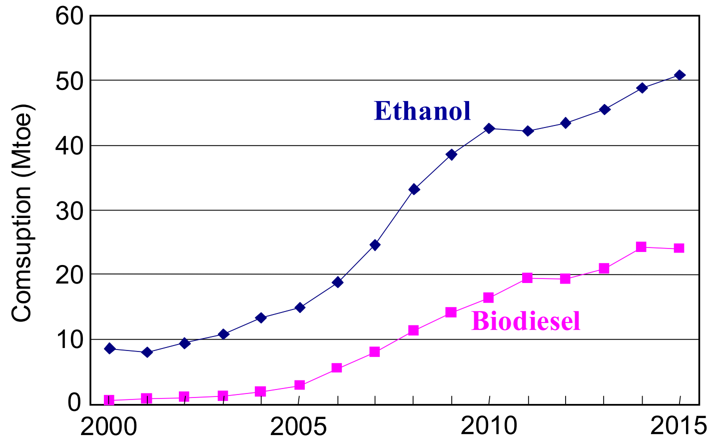

**Figure 9**. Global biofuel consumption in the road transport sector, 2000-2015.

The global biofuel consumption in road transport has increased almost 6 times since 2000 (see Figure 9). In 2013, biofuels made up a share of about 3 % of road transport fuel worldwide, and considerably higher shares were achieved in certain countries; about 20 % in Brazil and 10% in U.S. (USDA, 2013; RFA, 2015). The global biofuel consumption is very geographically heterogeneous, and its growth has slowed down in the past few years (see Figure 9) (US-EIA; REN21, 2016). During these 10 years, the biofuel share in the road transport has increased by 0.3% per year in average. The share of biofuels in 2050 in the 2DS scenario is about 30 %, as shown in Figure 8, of which 80 % is advanced biofuels. Advanced, drop-in biofuels are especially important for aviation and shipping that do not have the option of electrification as LDVs do. Looking at the advanced biofuel research in the national projects of US (US-DOE), Japan (NEDO), and EU-funded Horizon 2020 project (EU), progress is steadily being made. However, the full-scale commercial production of cellulosic ethanol has not started yet and algae-based biofuels are still in the phase of research and development. In order to increase the biofuel share up to 30 % with 80 % share of advanced biofuels in 2050, a fairly rapid rate of introduction, scale-up and commercialization of the relevant technologies will be needed in the coming decade. Whether sufficient research, development, demonstration and commercialization support is being provided for this to occur is an open question.

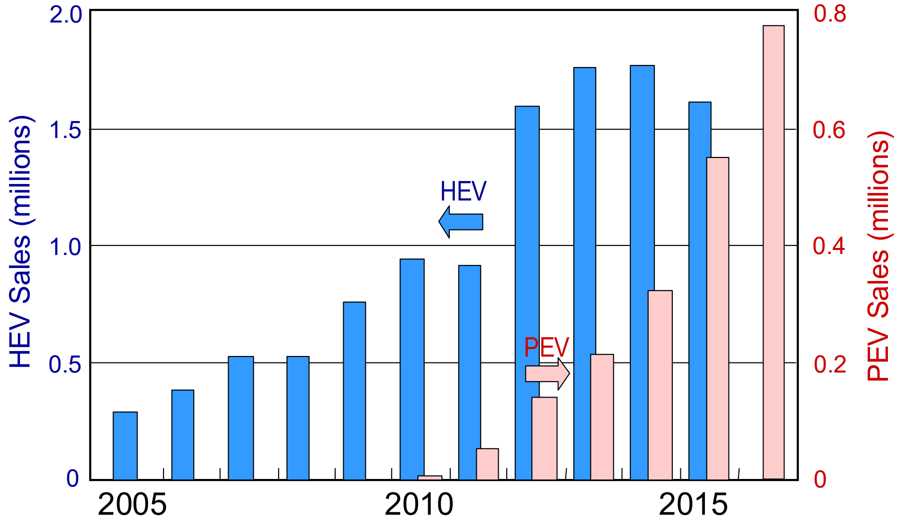

**Figure 10**. Global LDV vehicle sales for hybrids (HEV; blue) and plug-in electric vehicles (PEV includes plug-in hybrids and battery-powered electric vehicles; red).

Hybrid cars can provide efficiency improvements up to 30–40 % (GEA, 2012) compared to similar non-hybridized cars (on an energy use per km basis) and have become a mass-market product in many countries, but hybrids still account for only about 3 % of new car sales globally (Fourin, 2016). In 2005, global hybrid sales amounted to 0.3 million and continued to increase to more than 1.7 million in 2013-14 (see Figure 10). The market share of hybrid sales has increased from less than 1% to about 3% by 0.2% per year in average during these 10 years. Even if the current growth rate continues, the market share in 2050 would be much lower than the value projected by the sectoral 2DS scenarios (Figure 8). This suggests that current policies promoting hybrids may not be sufficient to grow the market. One example where strong hybrid promotion has succeeded is Japan, where more than one million hybrids were sold in 2016, representing 38 % of the national LDV market sales (JAPA, 2017). The hybrid sales in Japan jumped up twice in 2009 and 2012, when new models and/or remodeled ones were introduced in the market and significant new purchase incentives were simultaneously implemented. This indicates that the penetration of advanced cars can be promoted by an introduction of new attractive products and strong support of policies. Compared with hybrids, the market of plug-in electric vehicles (PEVs, including plug-in hybrid electric and battery-powered electric vehicles) is still a very small niche (see Figure 10) and their global sales in 2016 was about 0.9% of global passenger car sales (Fourin, 2016, EV-volumes). Even in the leading market of the US, the market share of PEVs was only 0.9 % in 2016 (EDTA). However, there are some examples of more successful introduction of battery electric and plug-in hybrid vehicles using incentives such as purchase subsidies and tax reductions along with a range of complementary policies. Such incentives have been offered in California, Norway, the Netherlands and China (JRC, 2015; ICCT, 2014). The current penetration rate of PEVs in the US and Japanese markets is slightly faster than that of the early stage of hybrids, but is still slower than the recent trends of hybrid sales. There are several barriers to PEV deployment, including the vehicle cost, the short all-electric driving range, the long battery-charging time, uncertainties about battery life, etc (NRC, 2015). The key component in all of these issues is the battery, and Li-ion batteries have become dominant as they have experienced significant cost reductions in recent years. However, the energy density and potential to increase the driving range may be limited in Li-ion batteries. New types of batteries with much higher energy density and lower cost may be required to compete with the conventional vehicles. Their development is still in the phase of R&D, and definitely needs strong government support.

In addition to vehicle technology and fuel-related measures, travel-related measures such as travel reduction (e.g. shorter trips in more compact cities) and modal shift (to more efficient modes) can play a significant role in cutting $CO_2$. Cutting $CO_2$ in this manner has many co-benefits, as many cities worldwide are facing major challenges in terms of congestion, traffic accidents and air pollution caused by urban transport, especially motorized personal vehicles. Switching passenger transport from personal vehicles to trains, buses, and non-motorized means can be very effective for solving these challenges, but much greater infrastructure investment, stronger integrated land use and transport planning systems, and more supporting policies are needed to significantly change the trajectory of most cities. Trends in shared mobility (car sharing and ride sharing) and vehicle connectedness and automation may also offer opportunities for cutting overall vehicle travel, but such impacts (especially for automation) are highly uncertain at this time (Waduda et al., 2016; Fulton et al., 2017).

## 4. CONCLUSIONS

The comparison of sectoral and integrated assessment models has contrasted their represented pathways for the evolution of the transport sector towards mitigation targets, and the potentials of various measures toward stringent CO2 reduction targets. The scenarios describing pathways for achieving climate stabilization targets are largely consistent across IAM and sectoral models, which suggests robustness in identifying the most promising pathways for achieving the 2°C target. The two modelling exercises also made clear that the 2°C scenario is very challenging and great effort is needed to achieve the targets including rapid technology penetration options and policy measures to manage institutional and behavioral components.

The second half of our exploration has focused on the observed penetration rates of new fuel and LDV technologies worldwide. While the scenarios make clear the need for widespread adoption of advanced powertrains and low carbon fuels, along with a reduction in travel activity, a review of trends and examples in the most advanced cases reveals that stronger efforts are needed. Efficiency improvement has perhaps the greatest potential for near term vehicle CO2 reduction, stronger measures are needed in more countries in order to hit a “50-in-50” target as set by the GFEI. Recent indications that the U.S. may roll back it’s light-duty vehicle CAFE standards is a step in the wrong direction.

Policy measures like price incentives for hybrid and electric vehicles have worked to some degree, but have not resulted in large market penetrations so far except in a few cases like Japan (hybrids) and Norway (electric vehicles) where incentives are quite large.

Transitions to low carbon fuels represented by biofuel (US, Brazil) and natural gas (USA) are still limited. If biofuel will play a role in aviation (as the models project), much stronger policy efforts will be needed, perhaps including pricing systems that successfully bring advanced bio-jet fuels to commercialization.

All in all, the global trends of penetration of new technologies in transport require a boost and recognition by governments if transport will play its role to achieve 2DS mitigation targets.

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