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Quantifying the potentials of transport CO_2 emissions reductions through prospective scenarios analysis

Aurélien BIGO

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Contact: Aurélien BIGO – aurelien.bigo@hotmail.fr

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Abstract

Prospective scenarios are essential to study the future possible paths to reach climate goals, their necessary changes and measures associated. This is especially the case for the ambitious target of reaching carbon neutrality by 2050 in France, which plans almost zero emission for the transportation sector. The French low carbon strategy identifies 5 drivers to limit transport CO_2 emissions: transport demand, modal shift, vehicle load factor, energy efficiency, and carbon intensity of the energy. This paper compares 13 passenger and 10 freight transport prospective scenarios for France, in order to quantify the potential of these drivers in limiting transport CO_2 emissions, using a decomposition analysis of emissions changes. The main conclusions of the analysis are the following: (1) Among the 5 drivers, energy efficiency and carbon intensity bring the most important CO_2 emissions reductions for all transport scenarios. (2) The comparison with past trends shows the need for important accelerations on these two factors, questioning the realism of such rapid changes. (3) It highlights the importance of action also on transport demand, modal shift and load factors, which may allow up to -20% emissions each for the most ambitious scenarios. (4) The national strategy shows little ambition on these drivers and especially on transport demand; the most ambitious scenarios indicate an additional potential of -32% of passenger and -50% of freight energy demand reduction due to these three drivers, then facilitating the climate target achievement, and allowing significant co-benefits in terms of transport externalities, resources pressures and transition costs reductions.

Keywords

Prospective scenarios; transport; CO_2 emissions; France; index decomposition analysis; 2050

1. Introduction

In 2017, the French government announced the new target of reaching carbon neutrality by 2050, in order to be aligned with the global ambition of limiting climate change below the +2°C limit. This goal implies that national emissions in 2050 equal greenhouse gases absorbed by ecosystems. The national low carbon strategy (SNBC in French) targets for the transportation sector to reach zero direct emission for land transport by 2050. The only oil-based fuel within metropolitan transports is kerosene, which still represents half of aviation fuels in 2050, while the other transport modes are fueled by electricity and biomass-sourced energies (MTES, 2020). This target is an important challenge for this sector, which is the first greenhouse gas emitter in France with 31% of national emissions in 2018, and which is still fueled by oil for more than 90% of the energy consumed (CGDD, 2019).
The strategy also fixes short term and medium term carbon budgets. The first budget over the period 2015-2018 was missed, with actual emissions 8.1% greater in average than the objective. New carbon budgets have been fixed in 2019, with for instance an indicative transport carbon budget for 2030 that is 28% below the 2015 level (MTES, 2020).
The SNBC highlights the need to take action on the five drivers of transport CO_2 emissions: transport demand, modal shift, vehicles load factor, energy efficiency of vehicles, and carbon intensity of fuels.

Given the important transformations needed within the next three decades, it is essential to study the possible paths and the expected potentials of these five drivers to reduce emissions. Prospective scenarios are then crucial to provide different visions of possible changes in transport organization, behaviors and technologies, which are compatible with the targeted contribution of transport to carbon neutrality.
Many prospective scenarios of transport energy transition exist in France. They are conducted by public authorities, research institutes, companies or NGOs. A first comparison of these scenarios in 2016 gathered 13 studies including 27 scenarios to 2050 (Bigo, 2016). Some scenarios have been updated since 2016 and others have been published in order to conform to the new carbon neutrality goal. The number of studies and their variety are rich for the public debate. But with this diversity also comes the difficulty to understand and compare existing scenarios, their corresponding hypotheses and results. It may prevent their interpretation and use by policymakers, companies or citizens.
The first objective of this paper is then to facilitate the comparison of scenarios through their main hypotheses and corresponding emissions results, in order to highlight their common features and main divergences.

Secondly, the five drivers of transport CO_2 emissions are used within an index decomposition analysis (IDA), in order to inform their relative potentials in terms of CO_2 emissions reductions. This decomposition also provides a common approach to facilitate the comparison of scenarios in a harmonized way. This tool has been increasingly used in recent years for climate mitigation scenarios (Ang and Goh, 2019), in particular to study and compare global passenger transport scenarios (Edelenbosch et al, 2017; Mittal et al, 2017; Yeh et al, 2017). These decomposition analyses for transport scenarios generally show that the main drivers for CO_2 emissions reductions are energy efficiency and fuel shift (see also Mathy et al, 2018; Förster et al, 2013). This prevalence of 'Improve' strategies within the 'Avoid-Shift-Improve' framework is also observed within the Nationally Determined Contributions (NDCs) for countries climate plans (SLoCaT, 2018), which mainly focus on technological drivers to decrease emissions. Transport-based and place-based models seem to put slightly more emphasis on the potentials of modal shifts (Creutzig, 2016; Yeh et al, 2017).

At the same time, there is a need to better understand the role that reduction of energy-service demand could play (Mathy et al, 2018). Thus a growing body of literature try to better include in prospective models and better quantify the potentials of energy-service demand reduction (Kesicki and Anandarajah, 2011; Anable et al, 2012; Creutzig et al, 2016; Grübler et al, 2018), as well as the spatial determinants of mobility (Waisman et al, 2013), and the potential role of lifestyle and behavior changes (Girod et al, 2013; Van Sluisveld et al, 2016; Le Gallic et al, 2017; Samadi et al, 2017).
This analysis also aims at participating in the debate about the relative potential of the Avoid-Shift-Improve mitigation strategies: here through the analysis of prospective scenarios; with a decomposition analysis into five drivers instead of three; and for the specific case of France, that should provide results that are close to other developed countries such as neighboring European countries.

A third objective of this paper is to discuss some policy implications for the implementation of the national low-carbon strategy for transport. This discussion is based on: the comparison with the potentials identified in the other French scenarios; the comparison with past trends since 1960 (Bigo, 2019) in order to inform the pace of decarbonization (Spencer et al, 2017; Gambhir et al, 2017); and the indirect effects of the expected changes.

After this introduction, the rest of the paper is organized as follows. Section 2 explains the studied scenarios and the IDA methodology conducted. Section 3 presents and discusses the main results, addressing the three research questions of scenarios comparison, relative abatement potential of the five drivers, and implications for the national strategy. Section 4 concludes.

2. Methodology and data

2.1. Studied scenarios

This paper gathers thirteen passenger and ten freight scenarios, coming from seven different institutes and eight studies (Table 1). These are all scenarios to 2050. Their reference year is mostly 2015; it is 2010 for ADEME and IDDRI; and 2013 for SNCF scenarios.
Four studies develop baseline or trend-based scenarios: MTES – AME (AME means ‘with existing measures’), négaWatt - Trend, and IEA – NPS for ‘New Policies Scenario’, which include passenger and freight transports; and the SNCF - Ultramobility scenario for passenger alone (in italic in Table 1). The other scenarios are pro-active or ambitious on the energy transition of transport, with further emissions reductions compared to baseline scenarios.
Most of the prospective scenarios only include tank-to-wheel (TTW) CO_2 emissions, at the point of use of transport vehicles. Scenarios from IEA and SNCF report well-to-wheel (WTW) emissions, so they also include emissions linked to the production of energy consumed by vehicles.
Most of the scenarios come from studies that study energy transition for the whole economy (MTES, 2019, 2020; EpE, 2019; négaWatt, 2017; ADEME, 2017); IEA transport scenarios are regularly reevaluated for their publications (as for IEA, 2019); IDDRI produced a first scenario for passengers (Briand et al, 2017), and a second scenario for freight (Briand et al, 2019); finally, SNCF published 3 contrasted scenarios for passengers in 2015 (SNCF, 2015).

Institute		**Scenario**		**Scope**		**% change CO_2**	
Name	**Type**	**Year**	**Name**	**Sector**	**Ref. year**	**Passengers**	**Freight**
MTES	French ministry	2019	*AME*	All GHG	*2015*	*-26%*	*29%*
			AMS / SNBC		2015	-99%	-100%
EpE	Federation of companies	2019	ZEN 2050	All GHG	2015	-96%	-92%
négaWatt	French NGO	2017	*Trend.*	All GHG	*2015*	*-38%*	*-19%*
			négaWatt		2015	-100%	-100%
ADEME	French public institute	2017	ADEME Vision	All GHG	2010	-91%	-88%
IEA	IEA	2019	*NPS*	Transport	*2015*	*-63%*	*-53%*
			EV30		2015	-96%	-81%
IDDRI	International think tank	2019	S1	Freight	2015		-99%
			S2		2015		-98%
		2017	MOB-First	Passengers	2010	-83%	
			TECH-First		2010	-87%	
SNCF	French rail company	2015	*Ultramobility*	Passengers	*2013*	*-47%*	
			Altermobility		2013	-64%	
			Proximobility		2013	-70%	

Table 1: Name of the studied scenarios, the institutions that produced them, perimeter and CO_2 emissions reductions from the reference year to 2050 (baseline scenarios in italic). MTES: ministry for ecological and inclusive transition; EpE: companies for the environment; ADEME: Agency for the environment and energy control; IEA: international energy agency; IDDRI: institute for sustainable development and international relations; SNCF: national railway society

2.2.The decomposition analysis into 5 factors

Index decomposition analyses (IDA) have been increasingly used since 1990, when Kaya proposed a first economy-wide identity to decompose CO_2 emissions between the four drivers of population, per capita activity, energy intensity of GDP (gross domestic product) and carbon intensity of the energy (Kaya, 1990).

These decomposition techniques have been mostly used to study the past trends in CO_2 emissions, known as the ‘retrospective IDA’, especially for the transport sector (Xu and Ang, 2013). They are also increasingly used recently for prospective analyses, such as short-term prospects known as ‘extrapolative IDA’ (Steenhof et al, 2006; Lin and Xie, 2014), or for temporal and spatial scenario analyses (Ang and Goh, 2019).

The ‘temporal analyses of scenarios’, mostly used in this paper, consider the relative changes compared to a base year, by evaluating the contribution of different drivers to emissions changes, for instance between 2015 and 2050 for most of the scenarios in this study.

The ‘spatial analyses of scenarios’ compare different prospective scenarios of a same study, for instance between baseline and mitigation scenarios (McCollum and Yang, 2009; Yang et al, 2009; IEA, 2017). It is not possible to systematically conduct this kind of analysis for the studied scenarios, because: only a few studies include baseline scenarios; these baseline scenarios show quite varied trends among studies; and methodological issues arise with carbon neutrality scenarios to conduct this kind of comparison (the whole emissions reductions appear in the carbon intensity factor). Nevertheless, the study highlights for each driver of the decomposition the difference between the average factor from baseline scenarios and the average factor from the most ambitious scenarios. This difference may be interpreted as a mitigation potential compared to the baseline trend.

The decomposition analysis also serves as a mean to compare different scenarios, as in the three papers on global transport scenarios from Edelenbosch et al (2017), Mittal et al (2017) and Yeh et al (2017).
The decomposition analysis is based on the five key drivers of transport CO_2 emissions identified within the national low carbon strategy (SNBC): transport demand (TD), modal shift (MS), load factor of vehicles (LF), vehicles energy efficiency (EE), and the carbon intensity of fuels (CI). The global equation is a sum of this decomposition for each mode i:

$$CO_{2,Transport} = \sum_i D.\frac{D_i}{D}.\frac{T_i}{D_i}.\frac{E_i}{T_i}.\frac{CO_{2,i}}{E_i}$$

where D is total transport demand (in pass.km for passengers or t.km for freight) and D_i the demand for each mode; T_i the traffic of the mode i (in vehicle.km); E_i and $CO_{2,i}$ represent energy consumption (in toe, tons of oil equivalent) and CO_2 emissions (in tCO_2) of the transport mode i.
Actually, the inverse of the load factor is considered within the equation, which explains why an increase in the load factor (number of passengers by car for instance) contributes to a decrease of the (C_i/D_i) factor and then to a decrease in CO_2 emissions.
Five passenger and four freight transport modes are included (see section 2.3). The decomposition analysis requires data of transport demand (pass.km or t.km), traffic (veh.km), energy use (toe) and emissions (tCO_2) for each transport mode and each year. This data is generally not publicly available and is then obtained from scenarios producers.

The log-mean divisia index (LMDI) is used for the decomposition analyses (Ang, 2004). This method has solid theoretical foundations, is easy to use, and has been increasingly used in IDA since the beginning of the 2000 (Xu and Ang, 2013).
The results interpretation is as follows. For the multiplicative decomposition, each factor represents a relative change compared to the base year: for instance, a 0.8 factor means a 20% reduction in CO_2 emissions due to this factor. For the additive form, the result corresponds to an abatement measured in million tons of CO_2 ($MtCO_2$). A detailed example is given for the SNBC passenger scenario at the beginning of section 3.1.

2.3. Key adjustments for comparison

The three main difficulties to compare scenarios assumptions, CO_2 emissions outputs and decomposition results concern: the integration of light commercial vehicles (LCV); the considered scope for navigation and air transport; the inclusion of active modes (walking and cycling) for passenger transport; and finally the initial level of transport CO_2 emissions.
Firstly, the question of light commercial vehicles (LCV) is treated differently from one scenario to another, in particular because it is not clear which shares of their traffic serve for passenger and for freight purposes. An analysis of the two last enquiries about LCV uses in France leads to an estimation of around 60% of traffic for passenger transport, and 40% for freight (CGDD, 2012, 2014). Thus 60% of LCV traffic is added to individual road transport (with cars and motorized 2-wheelers) within the passenger decomposition, the other 40% being added as a fourth freight transport modes. It appeared to be the best choice to facilitate the interpretation of the different emissions drivers. This distribution 60%/40% was also used for the analysis of transport emissions over the period 1960-2017, which helps to compare the trends in prospective scenarios with past trends.
Secondly, the scope for aviation varies depending on the scenarios: only metropolitan traffic for MTES, EpE, IDDRI, SNCF, with estimations on oversea and international traffics for some of them; aviation separated between travels inferior or superior to 800 km for négaWatt; total aviation for IEA; not taken into account for ADEME (only some figures not sufficient to

be included here). Except for ADEME, the comparison only keeps metropolitan traffic (and inferior to 800 km for négaWatt) as it allows comparing the maximum number of scenarios on a common basis. Similarly, only domestic navigation is included. For IEA scenarios, the future domestic air and navigation figures are estimated by taking the same activity growth for domestic as for total traffic (except for metropolitan traffic which is supposed constant for the EV30 mitigation scenario), with the same efficiency and carbon intensity gains projected for domestic and total traffics.
Thirdly, active modes are considered in different manners within the scenarios: no estimation for IEA scenarios; only cycling for MTES, EpE and ADEME; both walking and cycling for négaWatt, IDDRI and SNCF scenarios. For the passenger decomposition, active modes are then considered as a fifth transport mode when they are included within the scenario.
There are generally five transport modes considered for passengers: individual road transport modes (cars, 2-wheelers, 60% of LCVs), collective road modes (buses), rail transport, aviation, and active modes. There are four modes for freight: trucks, 40% of LCVs, river freight and rail freight transport.
The last adjustment concerns additive decompositions, for which initial CO_2 emissions are changed to the national strategy levels of 90 $MtCO_2$ for passenger emissions and 33 $MtCO_2$ for freight transport, in order to make the results among scenarios more comparable.

3. Results and discussion

3.1. Decomposition results by scenario

The multiplicative and additive decomposition analyses are conducted as follow for the national low carbon strategy (SNBC) scenario, with a 5-year time interval (Figure 1).

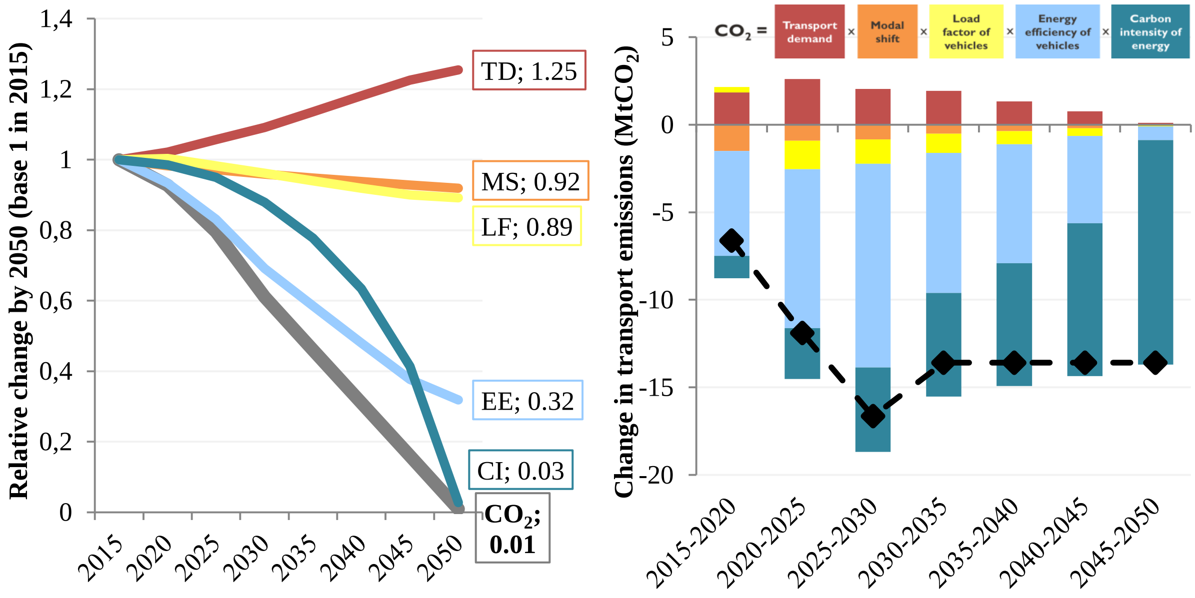
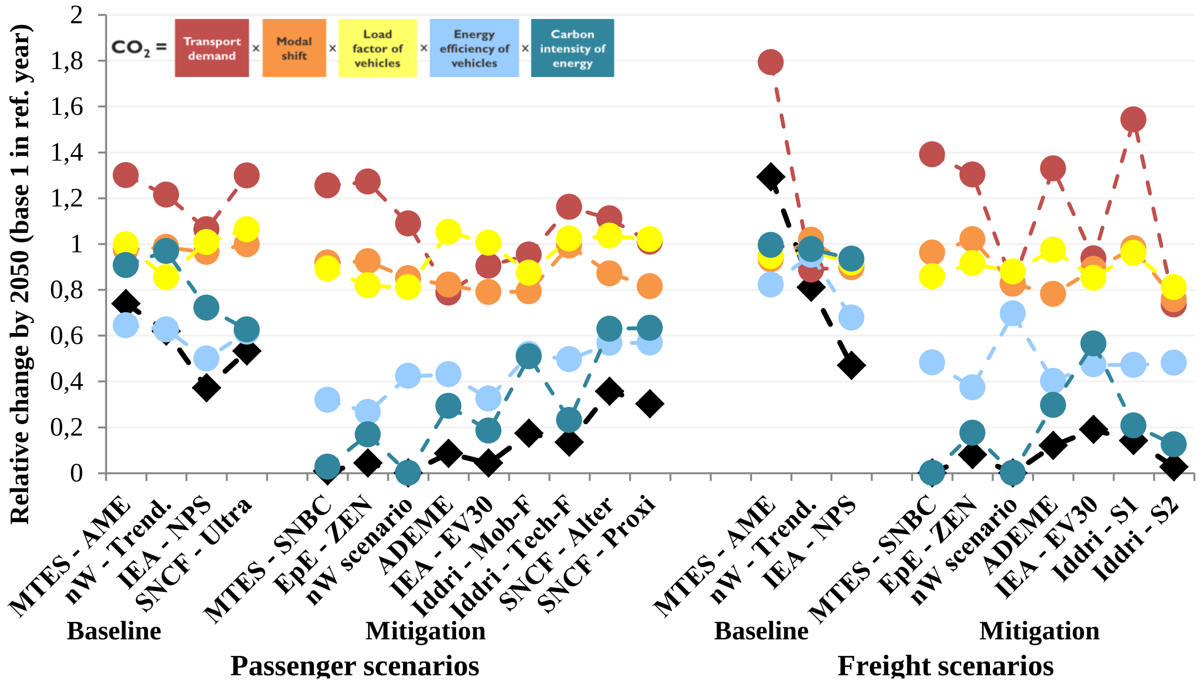


Figure 1: Multiplicative (on the left) and additive (on the right) decomposition analyses of the passenger scenario of the national low carbon strategy (SNBC) from 2015 to 2050

The multiplicative decomposition results show the following contribution of each driver by 2050 compared to 2015: passenger transport demand increases by 25%; modal shifts allow decreasing CO_2 emissions by 8%, and by 11% for the load factor; energy efficiency shows a mean progress of energy use per veh.km of -68%; finally, carbon intensity almost reach zero thanks to the full decarbonization of most of the transport modes (except aviation).

So passenger transports almost reach zero emission in 2050, compared to 90 $MtCO_2$ in 2015. The impact of a multiplicative factor on the additive carbon abatement depends on when change takes place and the total volume of emissions at that time: for instance, carbon intensity improves especially at the end of the period, explaining a lower impact than if it improved at the beginning of the period when emissions were higher. Over the period 2015-2050, the addition of the 5-year interval additive decompositions gives an emissions reduction of -89.5 $MtCO_2$, explained by an increase of 10.6 $MtCO_2$ due to transport demand, and decreases by 4.4 $MtCO_2$ due to modal shift, by 5.0 due to load factor, by 47.2 due to energy efficiency, and by 43.5 $MtCO_2$ due to the carbon intensity factor.



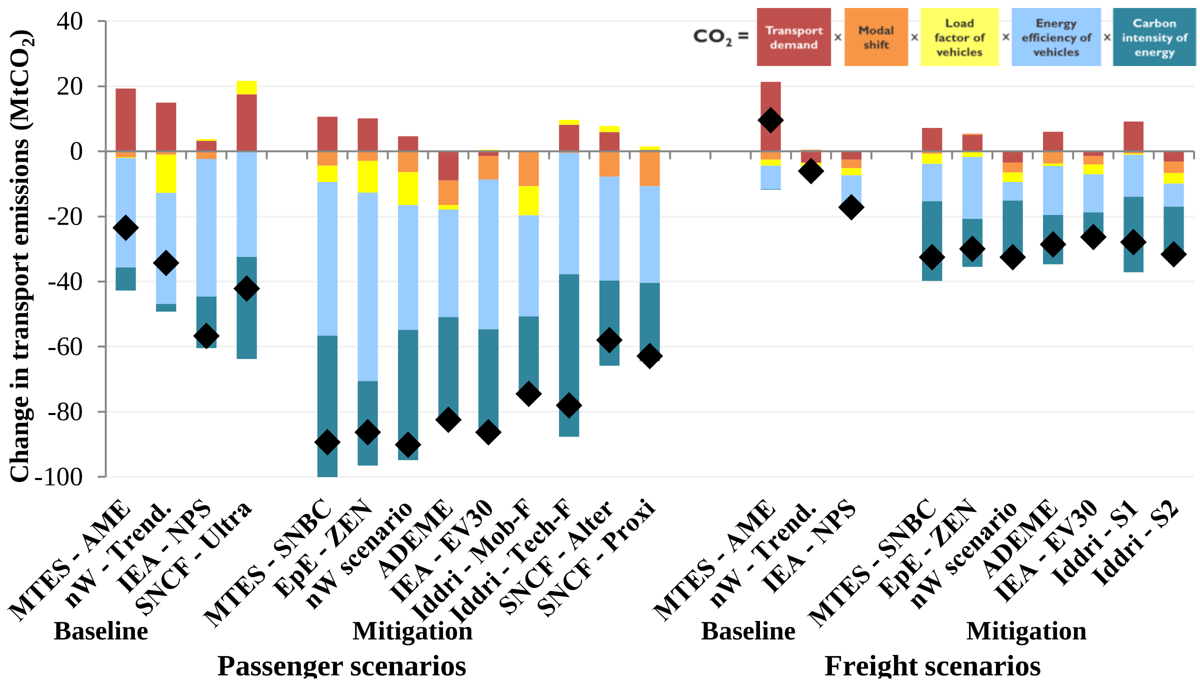


Figure 2: Results of the multiplicative (top) and additive (bottom) decomposition analyses for the 13 passenger scenarios (on the left, of which 4 baseline and 9 mitigation scenarios) and 10 freight scenarios (on the right, of which 3 baseline and 7 mitigation scenarios). The black square represents CO_2 emissions, and is explained by the multiplication or addition of the five factors respectively for multiplicative and additive decompositions by 2050

Figure 2 presents the final results of multiplicative and additive decompositions by 2050 for passenger and freight scenarios, as described above for the passenger SNBC scenario.
As common features among the scenarios, the decomposition results highlight similar trends regarding the most important drivers: energy efficiency appears as the most important driver in terms of CO_2 emissions reductions, both for baseline and mitigation scenarios, with improvements generally more important for passengers than for freight; carbon intensity also appears as an important driver, especially for mitigation scenarios, while it is only projected to decline slightly in baseline scenarios. Transport demand appears as the only factor that contributes significantly to emissions growth for some scenarios, both for passenger and freight transport. The drivers of modal shift and load factor show lower changes, generally between 0% and -20% change for modal shift and +5% and -20% for load factor, with comparable impacts on passenger and freight transports.
Besides these common features, some important differences arise, both between baseline and mitigation scenarios, but also within each of these categories. Baseline scenarios, which define trends with current policies, should in principle present similar features. In reality, they show divergent outlooks, especially for freight transport. For instance, CO_2 emissions are projected to decrease between 26% and 63% for the four passenger baseline scenarios, and are projected to increase by 29% for MTES-AME and to decrease by 53% for IEA-NPS for the freight baseline scenarios. This last important difference is due especially to transport demand forecasts, which appears as increasing by 79% for the MTES baseline scenario and decreasing for the two other baseline scenarios. This highlights the difficulty to build scenarios and plan public policies in a context of uncertain trends on drivers as important as the level of demand that the transport system should supply, even for trend-based scenarios.

Transport demand growth by 2050 also shows contrasting hypotheses among mitigation scenarios, especially for freight transport. Modal shifts and load factors contribute to emissions decreases for most of the mitigation scenarios, but remain stable for some others. The contributions of energy efficiency and carbon intensity are important for all scenarios, but with some divergences in terms of means and results that are further explained below.

3.2. The abatement potential of each driver

Table 2 summarizes the main results from the decompositions, with some other elements on: modal shifts, with details of additive contributions for some transport modes often gaining modal shares by 2050; and details on energy efficiency and carbon intensity within the national strategy (SNBC).

Transport demand assumptions appear very diverse within scenarios, especially for freight transport. Demand grows within most of the scenarios, with some of them projecting declines by 2050: the baseline scenarios expect the demand to rise by +22% in average for passengers and by +19% for freight transport (with important differences among scenarios in this last case); the four passenger and three freight most ambitious mitigation scenarios on this driver assume a mean decline in transport demand by 9% for passengers and by 17% for freight transport. The decrease would be even higher per capita, because the scenarios generally include a population growth close to 12%. The relatively important difference between baseline and ambitious scenarios show the importance that transport demand could play in some mitigation scenarios when compared to baseline scenarios, even if the reduction percentage is not very important. The important gaps between maximum and minimum

projections (intervals of +30% to -21% for passenger and +79% to -26% for freight demand) also highlight the risks and uncertainties associated to this driver.
Transport demand was also the main driver of past CO_2 emissions changes, and should remain a crucial contributor to emissions changes at least in the next few years and as long as the vehicles fleets and used energy are not highly decarbonized.
The main measures mentioned within scenarios to moderate transport demand growth are related to: territory and urban planning, in order to shorten daily travels and freight distances; telework and other work organizations; and sometimes, local productions and consumptions, circular economy, sufficiency behaviors, and limitation of air travels are also mentioned as causes of reduction in transport demand compared to baseline trends.

Studied change		**Relative change (% change, multi. decomp.)**				**CO_2 abatement ($MtCO_2$, addi. decomp.)**			
Driver	**Drivers & measures**	**Interval**	**Baseline**	**Ambitious**	**SNBC**	**Interval**	**Baseline**	**Ambitious**	**SNBC**
Transport Demand (TD)	**Passengers**	+30% to -21%	22%	-9%	25%	+19 to -9	14	-2.5	11
	Freight	+79% to -26%	19%	-17%	39%	+21 to -4	5.1	-3.2	7.2
Modal Shift (MS)	**Passengers**	0% to -21%	-2%	-20%	-8%	0 to -11	-1.4	-9.1	-4.4
	Passenger trains					0 to -6.7	-1.2	-5.4	-2.4
	Cycling (and walking)					0 to -6.4	-0.2	-4.3	-1.7
	Road public transit					+0.5 to -1.1	0.0	-0.4	-0.4
	Freight	+2% to -26%	-5%	-22%	-4%	+0.5 to -3.6	-1.6	-3.3	-0.8
	Rail freight					0 to -4.1	-1.0	-3.5	-0.4
	River freight					0 to -0.7	-0.3	-0.5	0.0
Load Factor (LF)	**Passengers**	+6% to -19%	-2%	-16%	-11%	+4 to -12	-1.8	-10	-5.0
	Freight	-3% to -19%	-6%	-15%	-14%	-0.2 to -3.1	-1.7	-3.0	-3.0
Energy Efficiency (EE)	**Passengers**	-36% to -73%	-40%	-64%	-68%	-30 to -58	-36	-46	-47
	EE on ICE cars								-22
	Cars electrification								-22
	Freight	-5% to -63%	-18%	-56%	-52%	-1 to -19	-5.7	-15	-12
Carbon Intensity (CI)	**Overall**								-68
	Passengers	-3% to -100%	-19%	-85%	-97%	-2 to -50	-14	-38	-44
	Freight	-1% to -100%	-3%	-100%	-100%	0 to -30	-0.8	-22	-24
	Electric								-45
	Biogas								-15
	Biofuels								-8

Table 2: Impacts of the five drivers on passenger and freight transport emissions within the studied scenarios, from the reference year to 2050. Results of the multiplicative decompositions (% changes, on the left) and additive decompositions ($MtCO_2$ changes, on the right) are presented. The table compares the maximum and minimum values (interval) from the scenarios, with the average baseline scenarios, the 4 passenger and 3 freight most ambitious scenarios for each driver and measure, and the results of the French low carbon strategy (SNBC)

The **modal shift** factor measures the impact of changes in the shares of transport modes on emissions. These modal shares are quite constant within baseline scenarios and for some mitigation scenarios that mainly focus on technological means in order to decarbonize the transportation sector. For the most ambitious scenarios, modal shift contributes to decreases in CO_2 emissions around 20%, both for passenger and freight transports.
Shifts towards low carbon transport modes especially concern rail transport, both for passenger and freight transport (potentials of -5.4 and -3.5 $MtCO_2$ respectively within the most ambitious scenarios; Table 2). For passenger transport, shifts towards active modes and especially cycling also reveal large room for improvement with similar abatement potential (of -4.3 $MtCO_2$), well above shifts to road public transit (-0.4 MtCO2 for the four most ambitious scenarios). For freight transport, some scenarios also show slight shifts towards navigation river freight (potential around -0.5 $MtCO_2$), while shifts towards LCV (light

commercial vehicles) for a few scenarios tend to limit the contribution of freight modal shifts, due to their higher emissions per ton.km transported.
Figure 3 indicates the changes in terms of modal shares in each scenario. Modal shares for the reference year are generally: around 80% of pass.km for individual road transport, 6-7% for road public transit, 10% for rail, 1-2% for aviation and 1-2% for active modes for passengers; around 88% of t.km for road freight transport (of which 5-7% for LCV), 10% for rail freight and 2% for river freight transports. A modal shift of 1% from a carbon-intensive mode (as cars, trucks, or aviation) to a low carbon transport mode (as rail or active modes) generally leads to a decrease in CO_2 emissions close to 1%.
It is important to note that modal shift is closely related to the transport demand factor, as a fewer demand growth facilitates the possibility for low carbon modes to increase their modal share. For instance, passenger rail traffic increases by 79% for SNBC and 89% for ADEME, and this leads respectively to modal shifts of 4% and 13% (while the modal share of rail transport is 10% in reference year), because the overall transport demand increases by 25% for SNBC and decreases by 21% for ADEME. Thus similar traffic growths for one mode may cause varied modal shifts depending on the level of total transport demand growth.
According to the scenarios narratives, the measures favoring modal shifts generally include: developments of infrastructures and services for low carbon modes, fiscal incentives (subsidies, carbon tax, heavy vehicles fee, tax on air travels, etc.), and sometimes information tools and behaviors changes.

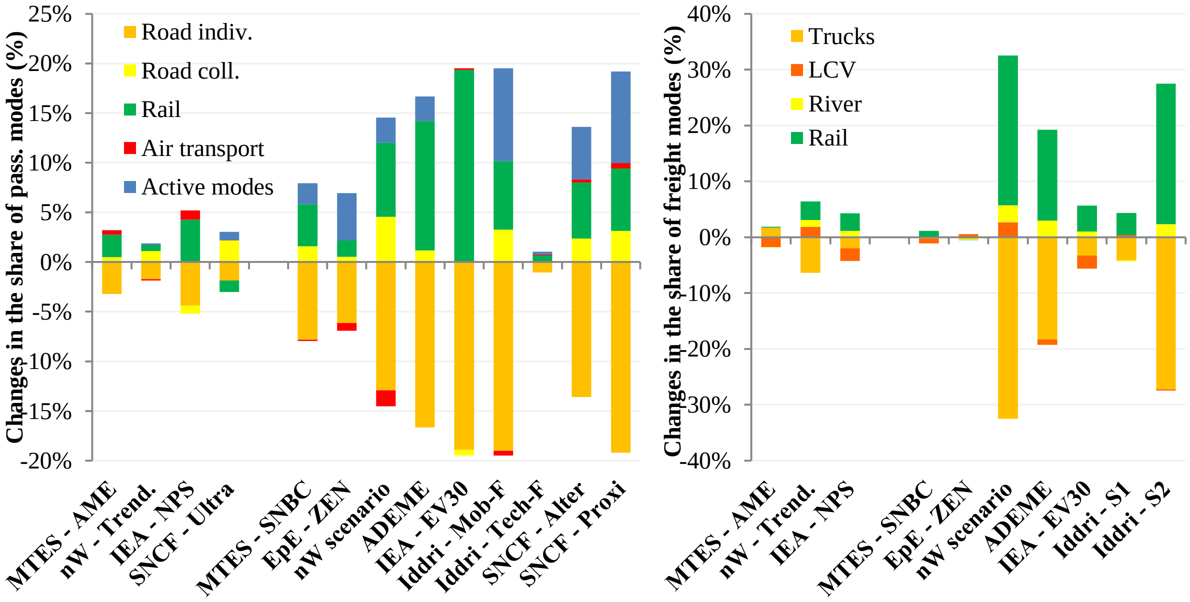


Figure 3: Changes in the modal shares of passenger (left) and freight (right) transport modes by 2050

Most of the scenarios suppose rising **load factors**, both for passenger cars and freight trucks, with generally constant loads for the other transport modes. They lead to moderate CO_2 emissions reduction, in the same range as modal shift, up to -20% CO_2 emissions. Rising load factors mean developing ridesharing for passenger vehicles, which only developed for long-distance travels in France, with rebound effects on transport demand and modal shifts from rail transport. The most important potential should be for home-work trips, especially in low density areas where alternatives to car mobility are scarce, then limiting the potential rebound effects. For freight, the mean load factor increased in the past through larger trucks. However, indirect effects on the other drivers, such as higher vehicle fuel consumptions and induced road freight demand (through lower costs), partly offset the direct expected gains. The other possibility may be to better fill in the trucks via logistic changes, but with limited potentials.

Energy efficiency appears to be an important driver to reduce emissions, both for baseline and mitigation scenarios and both for passenger and freight scenarios. The expected gains are already high for baseline scenarios with -40% energy use per veh.km for passengers and -18% for freight. These improvements further increase to -64% for passenger and -56% for freight within the most ambitious scenarios. Due to important improvements in baseline scenarios, efficiency potentials appear lower when mitigation scenarios are compared to baseline trends (spatial analysis, compared to temporal analysis, see 2.2), unlike the transport demand factor.
Efficiency improvements come from different kind of technologies and changes, whose relative importance varies among scenarios. Firstly, efficiency of new internal combustion engines (ICE) vehicles represents most of the short-term energy savings. However, some of the expected improvements seem very ambitious even for some baseline scenarios, when compared to current trends. Indeed, we observe stable CO_2 emissions for new cars in France since 2015 (around 111 gCO_2/km between 2015 and 2019), because of the rising share of SUVs (sport utility vehicles) and the decrease in diesel cars in favor of gasoline cars, and despite the growing share of electric cars (almost 2% in 2019; MTES-SDES, 2020).
The second important efficiency gains relate to the deployment of electric vehicles, which present lower energy consumptions in terms of final energy demand. This second contribution represents a growing share of efficiency gains over time: a specific decomposition of car energy efficiency for the SNBC scenario shows that this electrification effect represents around one fifth of efficiency gains for 2015-2020, and half of the gains over the period 2015-2050. Both efficiency gains on ICE cars and through electrification contribute to a decline of 22 $MtCO_2$ for the SNBC passenger scenario. As electrification is less developed for some other passenger scenarios and for freight transport, it partly explains their lower efficiency improvements compared to the high efficiency (-68%) of the SNBC passenger scenario.
A third kind of measures impacting efficiency is more related to sufficiency in vehicle use rather than technical advances. These efficiency gains include: the development of lighter vehicles, from cars of one or two places to a decrease of the mean weight of cars; speed limitations, especially for national roads and highways, allowing short-term benefits for some scenarios; finally, ecodriving has also the potential to save energy for the same distance travelled.

Changes in the **carbon intensity** of energy are presented in Figure 4 for some scenarios that both include passenger and freight transports. Due to different data sources and scope, the reference year value varies among scenarios. The carbon intensity of the transport energy mix is close to 3 tCO_2/toe, due to the high share of oil fuels (91%), while biofuels (7%) and electricity (2%) represents the remaining consumptions (ADEME, 2019).
Data of energy mixes is not available for all scenarios, but there is generally an important diffusion of electric vehicles and (bio)gas vehicles for road transport. Electricity dominates especially the light-duty vehicles segment with electric cars, 2-wheelers and LCVs, while bio(gas) mostly applies to heavy vehicles as trucks or river freight vessels. Biofuels are sometimes present for road transport, and is usually the preferred fuel to decarbonize aviation.
An important feature about the carbon intensity factor is that substantial emissions reductions generally appear after the development of new drivetrain vehicles and energy decarbonization. So the mean carbon intensity of transport decreases sharply only after 2030, and presents lower potentials for short term carbon budgets objectives. By 2050, it is the only factor that allows reaching direct emissions close to zero, making the transition to electric vehicles, biogas and/or biofuels a necessary condition to reach the transport target of the national low-carbon strategy.

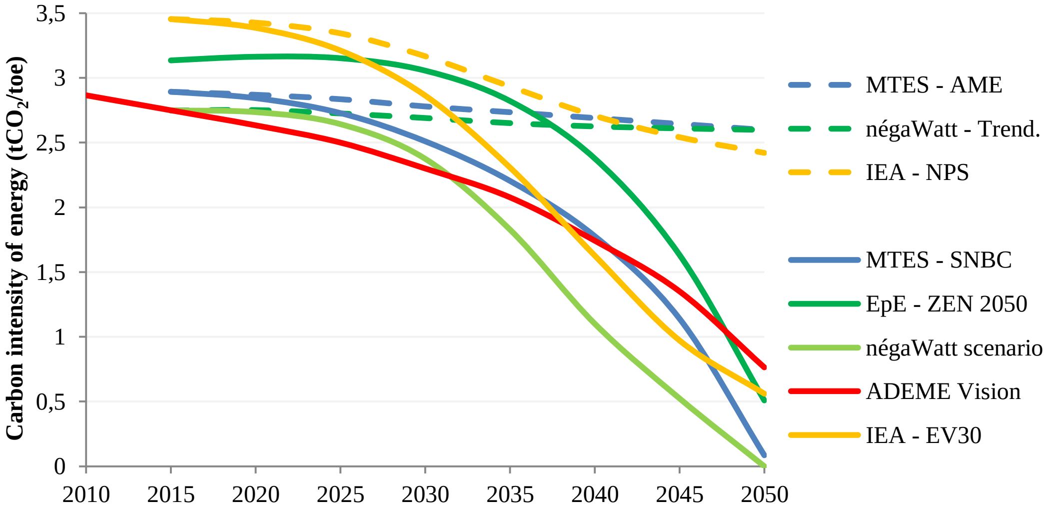


Figure 4: Changes in the mean carbon intensity of the energy mix for transport scenarios (passenger and freight)

3.3. Discussion on the national strategy

The SNBC scenario aims at reaching almost zero direct emission in 2050 for transport, a very ambitious and challenging goal when compared to recent emissions trends. Decomposition results highlight that the national strategy relies mostly on the energy efficiency and carbon intensity drivers, being among the most ambitious scenarios on these two drivers (see Figure 2, Table 2, and Figure 5 below). Ambition on the three other drivers of transport demand, modal shift and load factor appears to be lower compared to the other studied mitigation scenarios. Transport demand growth hypotheses are among the most important (+25% and +39% for passengers and freight), and are even higher than the average baseline scenarios (+22% and +19%) and far from the most ambitious scenarios that plan a decrease in the total passenger and freight transport demands. Modal shifts are also limited (allowing -8% emissions for passengers and -4% for freight), while potentials of -20% are identified by the most ambitious scenarios. While the growth in rail transport and cycling traffics are important in the SNBC, the low shifts can be explained by the important transport demand growths that limit the potentials of gaining modal shares for low carbon transport modes. Finally, the SNBC ambition is close to the most ambitious scenarios for passenger and freight load factors (contributions of -11% and -14% for the SNBC scenario).
The most ambitious scenarios on these three drivers show an additional potential of -32% to reduce passenger energy demand compared to SNBC scenario, and -50% for freight (average of the four passenger and three freight most ambitious scenarios on these three drivers combined).

Thus, the national strategy relies mainly on the technological advances drivers, while ambition is weaker on the first drivers of the decomposition, that imply societal, organizational and behaviors changes. If these drivers of transport demand, modal shift or ridesharing pose important transformation challenges, they also present important co-benefits on transport externalities (evaluated by SNCF, 2015; Briand et al, 2019), such as road congestion, road traffic accidents, noise or physical inactivity. On the contrary, the developed decarbonization technologies pose some risks in terms of environmental impacts and available resources, such as sustainable biomass resources for biogas and liquid biofuels, or metal resources and chemical pollutions related to batteries production for electric vehicles. Some of these alternative fuels are also more expensive than current oil-based fuels and will need important economic incentives to be competitive and to deploy rapidly in the coming years.

Further ambition of the SNBC scenario and policies on the first drivers, and especially on the moderation of transport demand for the most carbon-intensive transport modes such as cars, trucks and aviation, could then provide important co-benefits by the reduction of negative transport externalities, environmental and resources pressures, and transition costs.

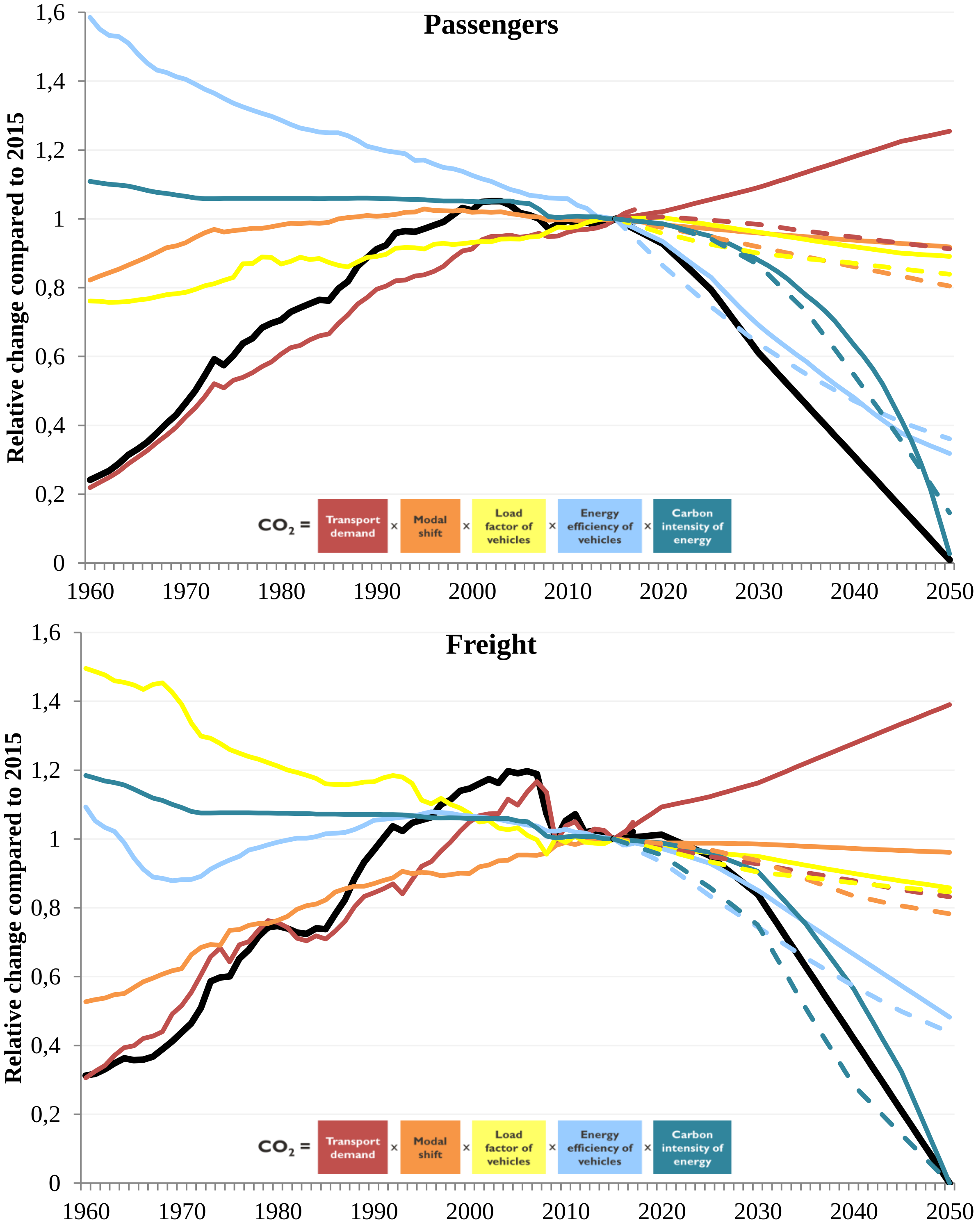


Figure 5: Comparison of past trends from 1960 to 2017 with the trends identified within the SNBC (solid lines from 2015), and the average of the other most ambitious scenarios on each driver (dashed lines). Trends are compared for CO_2 emissions (in black, for past trends and SNBC) and for the 5 drivers of passenger (top) and freight (bottom) transport emissions.

The comparison with past trends also informs the need for important transformations compared to past trends, concerning some drivers of the decompositions (Figure 5). The sharp decrease in CO_2 emissions in the next few decades appears as an important break compared to the growth of the end of the 20th century, and even compared to the stable trend in recent years. Past trends especially show a close relation between transport demand and CO_2 emissions, as there is almost no decoupling over the period 1960-2017, both for passenger and freight transports. Modal shifts towards road transports and decreasing occupancy rate for cars offset most of the efficiency, trucks load factor and carbon intensity improvements. The effects of past environmental policies were low, due to limited impacts on the drivers trends, and partly due to the potential rebound or indirect effects, such as rebound effects of efficiency gains on transport demand and modal shift, or the low climate value of biofuels when measuring their lifecycle carbon impact. These interactions of some public policies with various drivers of the decomposition call for a coordinated action on the five drivers. New policies and technologies should also be evaluated through climate and environmental lifecycle analyses to avoid indirect negative impacts.

As the SNBC scenario plans a continued growth in transport demands as well as an ambitious climate goal, there is an important challenge in accelerating the decoupling of transport emissions from demand (measured by the decrease in CO_2 emissions per pass.km and t.km). If the past trends show a yearly mean improvement rate of -0.8% per kilometer travelled for passengers and -0.9% per ton.km for freight since the beginning of the 90s (and only -0.5% and -0.6%/year when considering emissions related to biofuel combustion or production, which appear similar to oil-based fuels), these rates need to be respectively -3.8% for passengers and -2.2% each year in average between 2015 and 2030 within the SNBC. The pace of decline then needs to be multiplied at least by 4.7 for passengers and by 2.7 for freight within the SNBC scenario.

As for now, this acceleration is not observed. For passengers, given that the main improvements are expected through energy efficiency and carbon intensity gains for cars, average emissions of new cars is a good indicator to track the consistency of recent trends with SNBC goals. While the scenario expected gains of -2.4% each year between 2015 and 2020, in order to reach the European goal of 95 gCO_2/km in 2021, emissions are stable around 111 gCO_2/km since 2015, illustrating the current delay on the major abatement potential identified within the passenger strategy.
Energy efficiency and carbon intensity then need significant accelerations compared to past and current trends for SNBC, especially for carbon intensity that did not improve significantly in past decades (Figure 5). Past trends should also be reversed for freight modal shift and passenger load factor (through ridesharing). Finally, the trends identified by the SNBC scenario for future transport demand growths may be overestimated, especially for freight transport.
Besides the SNBC scenario, some other ambitious mitigation scenarios also involve high challenges in reversing past trends, especially concerning transport demand and freight modal shifts.

4. Conclusion

The present paper has compared 13 passenger and 10 freight transport scenarios to 2050 for France, in order to inform the relative potential of five drivers of transport CO_2 emissions to achieve the target of almost zero direct emission by 2050: transport demand, modal shift, load factor of vehicles, energy efficiency, and the decarbonization of the energy mix (carbon intensity). Based on the results and discussion section, the study leads to the following conclusions concerning the three research questions of scenarios comparison, potentials of the five drivers and implications concerning the national strategy.

As a main common feature of the ambitious scenarios, energy efficiency and carbon intensity of the energy appear as the most important drivers of CO_2 emissions reductions by 2050, especially through efficiency gains of new sold vehicles for short-term trends and the diffusion of electric vehicles and biomass-based energies especially after 2030. Final decarbonization of the energy mix highly depends on the scenario ambition, and should necessary be close to zero for carbon neutrality targets. Modal shifts and load factors appear more contrasted among scenarios, from low changes to reductions up to 20% for the most ambitious scenarios. Finally, the main differences among scenarios concerns transport demand, especially for freight transport: passenger scenarios plan transport demand growths from +30% to -21%, and from +79% to -26% for freight transport demand. These discrepancies are also present among baseline scenarios, showing the difficulty for decision on transport and climate issues with such uncertain futures on the level of demand.

When ambitious mitigation scenarios are compared to baseline scenarios, transport demand then appears as an important driver for policies to reduce emissions, while energy efficiency gains appear lower due already important (but possibly overestimated) gains within baseline scenarios.

The national low-carbon strategy (SNBC) shows little ambition especially on this driver of transport demand, and on modal shifts and load factors to a lesser extent. On the contrary, the strategy is particularly ambitious on the technological drivers of energy efficiency and carbon intensity of energy. However, it seems that both drivers are evolving too slowly to be consistent with the current short-term targets. Reaching these targets would require substantial acceleration in the average rate of emissions improvements for new vehicles sold, a trend that is not observed for now at least for cars, while it is more difficult to track for heavier vehicles. The delay that is already identified for these two structuring drivers provides another reason for the SNBC to be much more ambitious on the other drivers of transport emissions. Some other scenarios identify further potential of -32% passenger energy demand and -50% freight energy demand with ambitious changes on the modal shift, load factor and especially transport demand drivers.

The analysis suggests that the new ambition of reaching carbon neutrality by 2050 needs much more ambitious policies and changes from all transport stakeholders on the five emissions drivers, in order to have a chance to achieve the short and long term targets. Further work would be also useful on the evaluation of externalities, resource needs (biomass, materials, etc.) and environmental impacts (not only carbon emissions) in lifecycle analyses, in order to better inform the overall costs and benefits of the different drivers. The study also highlights the need to better understand the necessary policy instruments and possible societal changes to be consistent with the rapid and important technological and organizational transformations described within the scenarios.

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References

ADEME, 2017. Actualisation du scénario énergie-climat ADEME 2035-2050. Available at: http://presse.ademe.fr/2017/10/lademe-actualise-son-scenario-energie-climat.html

ADEME, 2019. Climat air et énergie, Chiffres clés - édition 2018. Available at: https://www.ademe.fr/climat-air-energie

Agnolucci, P., Ekins, P., Iacopini, G., Anderson, K., Bows, A., Mander, S., Shackley, S., 2009. Different scenarios for achieving radical reduction in carbon emissions: A decomposition analysis. Ecological Economics 68 (6), 1652-1666. https://doi.org/10.1016/j.ecolecon.2007.09.005

Anable, J., Brand, C., Tran, M., Eyre, N., 2012. Modelling transport energy demand: A socio-technical approach. Energy Policy 41, 125-138. https://doi.org/10.1016/j.enpol.2010.08.020

Ang, B. W., 2004. Decomposition analysis for policymaking in energy: which is the preferred method? Energy Policy 32 (9), 1131-1139. https://doi.org/10.1016/S0301-4215(03)00076-4

Ang, B.W., Goh, T., 2019. Index decomposition analysis for comparing emission scenarios: Applications and challenges. Energy Economics 83, 74-87. https://doi.org/10.1016/j.eneco.2019.06.013

Bigo, A., 2016. Comment atteindre le facteur 4 dans les transports ? Analyse comparée de scénarios de prospectives à 2050. Mémoire de Master 2 EDDEE. Available at: http://www.chair-energy-prosperity.org/publications/working-papers/atteindre-facteur-4-transports/

Bigo, A., 2019. How to explain the past trends in transport CO_2 emissions in France? A decomposition analysis for the 1960-2017 period. Working Paper. Available at: http://www.chair-energy-prosperity.org/publications/expliquer-tendances-passees-1960-2017-emissions-de-co2-transports-france/

Briand, Y., Lefevre, J., Cayla, J.-M., 2017. *Pathways to deep decarbonization of the passenger transport sector in France*. IDDRI, UMR 8568 CIRED, EDF R&D. https://hal.archives-ouvertes.fr/hal-01688931

Briand, Y., Svensson, J., Koning, M., Combes, F., Lamy, G., Pourouchottamin, P., Cayla, J.-M., Lefevre, J., 2019. *Trajectoires de décarbonation profonde du transport de marchandises en France*. Rapport descriptif. IDDRI. Available at: https://www.iddri.org/fr/publications-et-evenements/rapport/trajectoires-de-decarbonation-profonde-du-transport-de

CGDD, 2012. Les Véhicules utilitaires légers au 01-01-2011. Available at: https://www.statistiques.developpement-durable.gouv.fr/les-vehicules-utilitaires-legers-au-1er-janvier-2011

CGDD, 2014. Les véhicules utilitaires légers : une bonne complémentarité avec les poids lourds. Available at: https://www.statistiques.developpement-durable.gouv.fr/les-vehicules-utilitaires-legers-une-bonne-complementarite-avec-les-poids-lourds

CGDD, 2019. Les comptes des transports en 2018. 56e rapport de la Commission des comptes des transports de la Nation. Disponible sur : https://www.statistiques.developpement-

durable.gouv.fr/les-comptes-des-transports-en-2018-56e-rapport-de-la-commission-des-comptes-des-transports-de-la
Creutzig, F., 2016. Evolving Narratives of Low-Carbon Futures in Transportation. Transport Reviews 36 (3), 341–360. http://dx.doi.org/10.1080/01441647.2015.1079277
Creutzig, F., Fernandez, B., Haberl, H., Khosla, R., Mulugetta, Y., Seto, K. C., 2016. Beyond Technology: Demand-Side Solutions for Climate Change Mitigation. Annual Review of Environment and Resources 41, 173–198. https://doi.org/10.1146/annurev-environ-110615-085428
Edelenbosch, O.Y., McCollum, D.L., van Vuurena, D.P., Bertram, C., Carrara, S., Daly, H., Fujimori, S., Kitous, A., Kyle, P., Broin, E.Ó., Karkatsoulis, P., Sanol, F., 2017. Decomposing passenger transport futures: Comparing results of global integrated assessment models. Transport. Res. Part D: Trans. Environment. 55, 281-293. https://doi.org/10.1016/j.trd.2016.07.003
EpE, 2019. ZEN 2050 – Imagining and building a carbon-neutral France. Available at: http://www.epe-asso.org/en/zen-2050-imagining-and-building-a-carbon-neutral-france-july-2019/
Förster, H., Schumacher, K., De Cian, E., Huebler, M., Keppo, I., Mima, S., Sands, R., 2013. European energy efficiency and decarbonization strategies beyond 2030 - a sectoral multi-model decomposition. Clim. Change Econ. 4, 134004–134029. https://doi.org/10.1142/S2010007813400046
Gambhir A, Drouet L, McCollum D, Napp T, Bernie D, Hawkes A, Fricko O , Havlik P, Riahi, K., Bosetti, V., Lowe, J., 2017. Assessing the Feasibility of Global Long-Term Mitigation Scenarios. Energies 10 (1): e89. https://doi.org/10.3390/en10010089
Girod, B., van Vuuren, D.P., de Vries, B.J.M., 2013. Influence of travel behavior on global CO2 emissions. Transport. Res. Part A: Policy and Practice 50, 183-197. https://doi.org/10.1016/j.tra.2013.01.046
Grübler, A., Wilson, C., Bento, N. et al, 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy 3, 515–527. https://doi.org/10.1038/s41560-018-0172-6
IEA 2017. The Future of Trucks. Implications for Energy and the Environment. Available at: https://webstore.iea.org/the-future-of-trucks
IEA, 2019. Global EV Outlook 2019. Scaling up the transition to electric mobility. Available at: https://www.iea.org/gevo2019/
Kaya, Y., 1990. Impact of carbon dioxide emission control on GNP growth: Interpretation of proposed scenarios. Paper presented at the IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris, France.
Kesicki, F., Anandarajah, G., 2011. The role of energy-service demand reduction in global climate change mitigation: Combining energy modelling and decomposition analysis. Energy Policy 39 (11), 7224-7233. https://doi.org/10.1016/j.enpol.2011.08.043
Le Gallic, T., Assoumou, E., Maïzi, N., 2017. Future demand for energy services through a quantitative approach of lifestyles. Energy 141, 2613-2627. https://doi.org/10.1016/j.energy.2017.07.065
Lin, B., Xie, C., 2014. Reduction potential of CO_2 emissions in China's transport industry. Renewable and Sustainable Energy Reviews, Volume 33, May 2014, Pages 689-700. https://doi.org/10.1016/j.rser.2014.02.017
Mathy, S., Menanteau, P., Criqui, P., 2018. After the Paris Agreement: Measuring the Global Decarbonization Wedges From National Energy Scenarios. Ecological Economics 150, 273-289. https://doi.org/10.1016/j.ecolecon.2018.04.012

McCollum, D., Yang, C., 2009. Achieving deep reductions in US transport greenhouse gas emissions: Scenario analysis and policy implications. Energy Policy 37 (12), 5580-5596. https://doi.org/10.1016/j.enpol.2009.08.038
Mittal, S., Dai, H., Fujimori, S., Hanaoka, T., Zhang, R., 2017. Key factors influencing the global passenger transport dynamics using the AIM/transport model. Transport. Res. Part D: Trans. Environment. 55, 373-388. https://doi.org/10.1016/j.trd.2016.10.006
MTES, 2019. Hypothèses du scénario transports. Stratégie Nationale Bas Carbone. Avril 2019, 48 p.
MTES, 2020. Projet de Stratégie Nationale Bas-Carbone (SNBC). Available at: https://www.ecologique-solidaire.gouv.fr/strategie-nationale-bas-carbone-snbc
MTES-SDES, 2020. Motorisations des véhicules légers neufs - Émissions de CO_2 et bonus écologique - Février 2020. Publié le 04/03/2020. Available at: https://www.statistiques.developpement-durable.gouv.fr/motorisations-des-vehicules-legers-neufs-emissions-de-co2-et-bonus-ecologique-fevrier-2020
négaWatt, 2017. Scénario négaWatt 2017-2050. Dossier de synthèse. Available at: https://negawatt.org/Scenario-negaWatt-2017-2050
Samadi, S., Gröne, M.-C., Schneidewind, U., Luhmann, H.-J., Venjakob, J., Best, B., 2017. Sufficiency in energy scenario studies: Taking the potential benefits of lifestyle changes into account. Technological Forecasting and Social Change 124, 126-134. https://doi.org/10.1016/j.techfore.2016.09.013
SLoCaT, 2018. Transport Knowledge Base (TraKB). Available at: http://www.slocat.net/trakb
SNCF, 2015. Vers une mobilité sobre en CO_2 : Une opportunité pour vivre mieux ? Regards croisés pour éclairer les choix de société en matière de mobilité des voyageurs. Available at: https://www.sncf.com/fr/groupe/newsroom/etude-facteur4
Spencer, T., Pierfederici, R., Sartor, O., Berghmans, N., Samadi, S., Fischedick, M., Knoop, K., Pye, S., Criqui, P., Mathy, S., Capros, P., Fragkos, P., Bukowski, M., Śniegocki, A., Virdis, M. R., Gaeta, M., Pollier, K., Cassisa, C., 2017. Tracking sectoral progress in the deep decarbonisation of energy systems in Europe. Energy Policy 110, 509-517. https://doi.org/10.1016/j.enpol.2017.08.053
Steenhof, P., Woudsma, C., Sparling, E., 2006. Greenhouse gas emissions and the surface transport of freight in Canada. Transport. Res. Part D: Trans. Environment. 11 (5), 369-376. https://doi.org/10.1016/j.trd.2006.07.003
van Sluisveld M.A., Martínez S.H., Daioglou V., van Vuuren D.P., 2016. Exploring the implications of lifestyle change in 2 °C mitigation scenarios using the IMAGE integrated assessment model. Technological Forecasting and Social Change 102, 309-319. https://doi.org/10.1016/j.techfore.2015.08.013
Waisman, H., Guivarch, C., Lecocq, F., 2013. The transportation sector and low-carbon growth pathways: modelling urban, infrastructure, and spatial determinants of mobility. Climate Policy 13, 106-129. https://doi.org/10.1080/14693062.2012.735916
Xu. X.Y.. Ang.. B.W.. 2013. Index decomposition analysis applied to CO_2 emission studies. Ecological Economics 93, 313-329. https://doi.org/10.1016/j.ecolecon.2013.06.007
Yang, C., McCollum, D., McCarthy, R., Leighty, W., 2009. Meeting an 80% reduction in greenhouse gas emissions from transportation by 2050: A case study in California. Transport. Res. Part D: Trans. Environment. 14 (3), 147-156. https://doi.org/10.1016/j.trd.2008.11.010
Yeh, S., Mishra, G.S., Fulton, L., Kyle, P., McCollum, D.L., Miller, J., Cazzola, P., Teter, J., 2017. Detailed assessment of global transport-energy models' structures and projections. Transport. Res. Part D: Trans. Environment. 55, 294-309. https://doi.org/10.1016/j.trd.2016.11.001