TOSCA

Technology Opportunities and Strategies towards Climate friendly trAnsport

Deliverable D8.2

Vehicle Stock and Emissions

University of Cambridge

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Abbreviations

Abbreviation	Description
AHS	Automated Highway Systems
BEV	Battery-electric vehicle
CVO	Commercial Vehicle Operations
ETS	Emissions Trading Scheme
EU	European Union
F-T	Fischer-Tropsch
GDP	Gross Domestic Product
GJ	Gigajoule(s)
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
HVO	Hydrogenated Vegetable Oil
LULUCF	Land Use, Land-Use Change and Forestry
km	Kilometer(s)
lt	Litre(s)
Mt	Million tonne(s)
pkm	Passenger kilometre(s)
tkm	Tonne kilometre(s)

Abstract

The TOSCA project aims to identify promising technology and fuel pathways to reduce transportation-related greenhouse gas emissions to 2050. In the first stage of the project (WP 1-5), the techno-economic characteristics of low-Greenhouse Gas (GHG) emission transportation technologies by mode were specified. The future impact of these technologies depends on how and whether they make it into the active vehicle fleet, which in turn depends on demand and the future development of key uncertain variables such as oil price and GDP. Therefore the second stage of the project looks at future scenarios for European transportation demand, how this affects the composition of the vehicle fleet and emissions, and how lower-GHG transportation outcomes could be achieved by applying policies. This report covers the second part of this process; starting from the technology specifications from WP 1-5, and scenarios of key variables and demand to 2050 (WP6), it explores how the vehicle fleet and emissions may develop to 2050 in the absence of new policy measures.

First, the composition of the existing fleet is assessed, and an estimation is made of how fleet size will develop under each scenario. Second, the factors affecting technology adoption are discussed and simple cost-based estimates of vehicle uptake are generated. Finally, the resulting emissions trajectories are calculated. We find that transport emissions will likely remain level or increase in all scenarios under the present policy environment, even under scenario conditions favourable to low-emission trajectories. This reflects a combination of several underlying trends: a strong growth in aviation demand, particularly for intercontinental aviation; low penetration of alternative technologies for road and aviation; and limited availability of technology and new infrastructure in general. Although this in part reflects the many assumptions and simplifications in this stage of the project, it is in agreement with the results of other studies. This suggests that policy intervention will be needed to reap the full benefits of the technologies investigated in TOSCA WP 1-5.

1. Introduction

1.1   Background

Transportation has become an increasingly important source of emissions in the EU27 countries since 1990. In 2007, intra-EU27 transportation accounted for around 19% of EU27 greenhouse gas (GHG) emissions[1] (EC 2010). This proportion has been growing over time, and the proportion of these emissions attributable to different modes of transport has also shifted. Figure 1 shows the change in GHG emissions in the EU27 countries by major sector since 1990, the Kyoto protocol benchmark year. Whilst most sectors show a small decline in emissions over the 1990-2007 time period, transport emissions have increased. In particular, international shipping and aviation, which are excluded from the Kyoto protocol, have shown large increases.
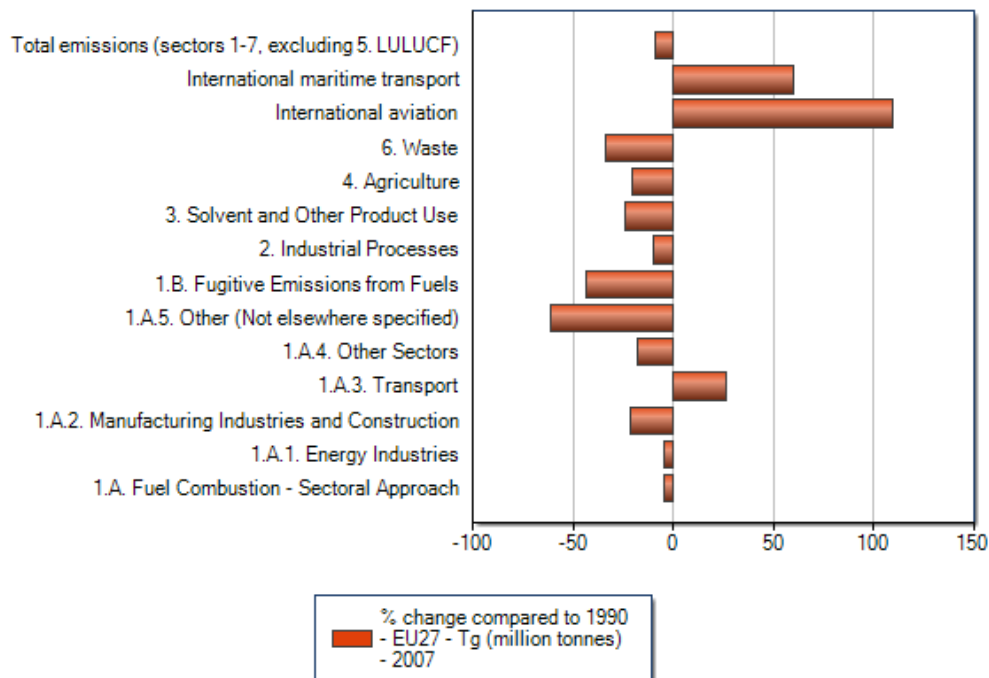
Figure 1. Change in EU27 emissions since 1990, by sector, excluding land use, land-use change and forestry (LULUCF). Source: EEA (2010).

The development by mode of EU27 CO_2 emissions since 1990 is shown in Figure 2. As discussed in the WP6.1 report, the only mode displaying a decrease in emissions over this time period is rail. Road emissions dominate, but shipping and aviation emissions have been growing at faster rates than road emissions. This past emissions data reflects relatively smooth, incremental trends in demand and underlying fleet composition. Whilst radical shifts in technology have occurred for most of the modes considered in TOSCA, most of these shifts occurred at the beginning of the automobile era (for cars) or at least 40 years ago (for other modes). For road vehicles, gasoline and diesel-powered internal combustion engines (ICEs) were dominant technologies in 1990, and remain dominant technologies throughout the EU27 today. However, there have been some incremental changes on the

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[1] CO_2 equivalent, excluding emissions from land use and land use change.

consumer side: for example, the proportion of new cars with diesel engines has increased from under 20% in 1990 to around 45% today (e.g. ACEA 2010). In addition, EU automobile manufacturers have been working towards voluntary goals for reducing tailpipe emissions, as discussed in the TOSCA WP1 final report (Safarianova et al. 2011a). These effects have contributed to around a 15% decrease in average direct CO_2 emissions per km from new passenger cars since 1995 (Eurostat 2010). Long-term commitments such as that by the ACEA mean that relatively high rates of incremental improvement in road vehicle emissions are likely to continue in future. However, greater reductions in emissions will likely require a shift to alternative power sources such as biofuels, electricity, or hydrogen.
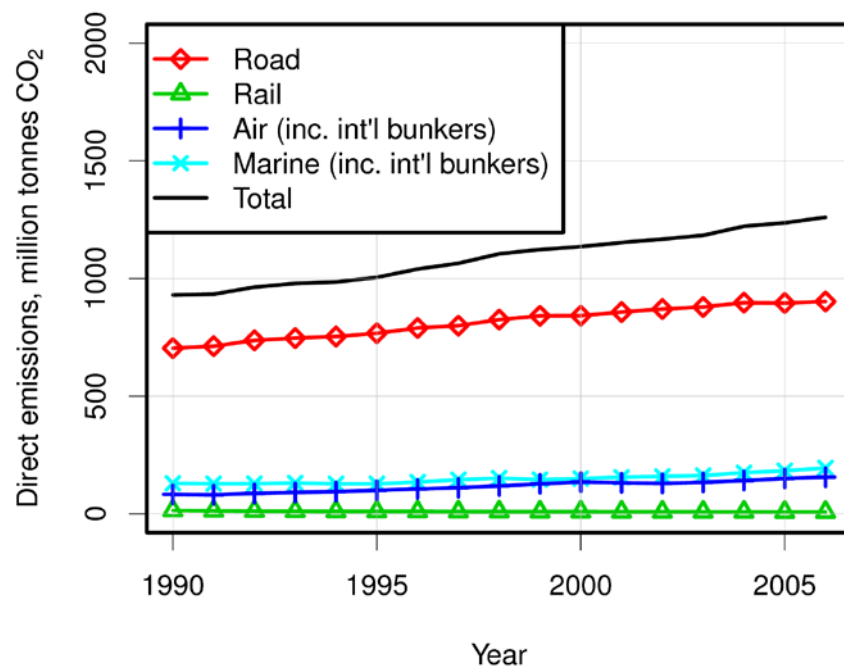

Figure 2. Development of EU27 direct CO_2 emissions by mode over the period 1990-2006. Data: EC (2010).

Rail technologies have remained broadly similar, apart from incremental improvements, since the widespread electrification of rail lines and phasing out of steam trains in the 1960s. At present 88% of the European rail network is electrified and the vast majority of the remainder is operated by diesel trains. The reduction in emissions since 1990 is partly a consequence of greater use of electric trains. However, the potential of further electrification to reduce emissions is limited, and other sources of alternative power are not anticipated to become widespread before 2050. The most important technology breakthroughs to affect (fuel lifecycle) rail emissions are likely to be in the electricity generation sector, though there remain significant gains to be made from changes to present-day technology (Andersson et al. 2011).

The main aircraft used for intra-EU aviation are narrowbody types, particularly the Airbus A320 (introduced into service in 1988) and Boeing 737 (introduced into service in 1968; OAG 2009). Although incremental changes have been made to both aircraft, they remain (similarly to road and rail vehicles) the same basic technology, using the same fuel type,

which has been in use for over 40 years. However, incremental improvements in aircraft technologies have had significant impacts on fuel use and emissions over this time period. Schäfer et al. (2009) estimate that average energy intensity of aircraft in the US fleet declined by around two-thirds between 1970 and 2005. Both Airbus and Boeing plan replacement narrowbody aircraft around the 2020-2025 time period, which may either be based wholly on existing technology, or could utilise new alternative technologies such as the open rotor engine[2]. Turboprops are an older-technology alternative to narrowbody jet aircraft for short-haul flights (e.g. Vera-Morales et al. 2011). Although turboprops have typically lower fuel burn for the same route, the superior cruise speed and passenger comfort of jet aircraft has led to a decline in the use of turboprops since the 1960s (OAG 2009). Aircraft used for intercontinental aviation have had more recent technology updates, with both the Airbus A380 and the Boeing 787 beginning entry into the fleet in the 2008-2012 period. However, the long development times of commercial aircraft mean that any replacement for these aircraft may be unlikely to see significant fleet penetration before 2050. These factors in combination mean that it is difficult to reduce aviation emissions per passenger-km travelled (pkt) faster than the rises in pkt seen since 1990 and projected to 2050 in TOSCA WP6.1. Absent the large-scale introduction of low-carbon synthetic fuels, an increase in total emissions is likely.

Estimates of shipping emissions show a considerable decrease in emissions per tonne-km since 1960 (e.g. IMO 2009). As noted by Endresen et al. (2007), this arises from multiple factors. There was a significant decline in the proportion of steam-powered ships between 1960 and 1980. The average size of ships has also increased, there have been efficiency improvements in engine technology, and in addition speeds are typically lowered to reduce fuel consumption when fuel prices are high. These factors have contributed to the relatively slow increase in emissions seen in Figure 2, despite demand growth. However, it is uncertain how much they will contribute in the future, as ship size increases are limited by existing port and canal infrastructure. In addition, the long lifetime of ships means that the technologies dominating the fleet to 2050 are likely to be those available in the market today (Safarianova et al. 2011b).

As discussed in the TOSCA WP 1-5 final reports, there are technologies which may become available in the time period to 2050 which could dramatically reduce direct and fuel lifecycle emissions from nearly all of these modes. Biofuels, electrification, infrastructure improvements and changes to vehicle mass and aerodynamics all offer significant potential. However, the principles behind many of these technologies have been known for decades (for example, electric cars existed in 1900) without coming into widespread use. Although high oil prices and climate change legislation provide a supportive environment for alternative technology adoption, significant barriers with respect to R&D, infrastructure, fuel production and traveller attitudes still remain. The question of how and whether

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[2] Since the TOSCA results were generated, more information has become available about the plans of Boeing and Airbus with regard to narrowbody replacement aircraft models. As of May 2011, Airbus plans to make available an intermediate-technology option, the Airbus A320 NEO, for fleet entry in 2016. The NEO would be a re-engined version of the existing A320 aircraft, using upgraded conventional rather than open rotor engines. Up to a 15% improvement in fuel burn over existing aircraft is anticipated (Airbus 2011). The announcement of the A320 NEO means that it is more likely that Boeing too will introduce an intermediate-technology aircraft. This in turn may delay the introduction of more radical narrowbody aircraft technology changes.

modern-day versions of these technologies will make it into the fleet to 2050 is thus not a simple one.

1.2   This report in the context of TOSCA

Within the TOSCA project, the characteristics of present-day and future technologies by major transportation mode have been estimated by Work Packages 1-5. Scenarios for future transportation demand, assuming no major changes in technology, were formulated in the first part of Work Package 6 (WP Report 6.1). This report looks at how the vehicle fleet might develop under these conditions in each scenario, and what the resulting emissions would be, including any changes from the demand baseline. A further report (WP7) describes how these emissions may be affected by policy intervention. The general structure of this part of the TOSCA project is shown in Figure 3, with the area detailed in this report highlighted.
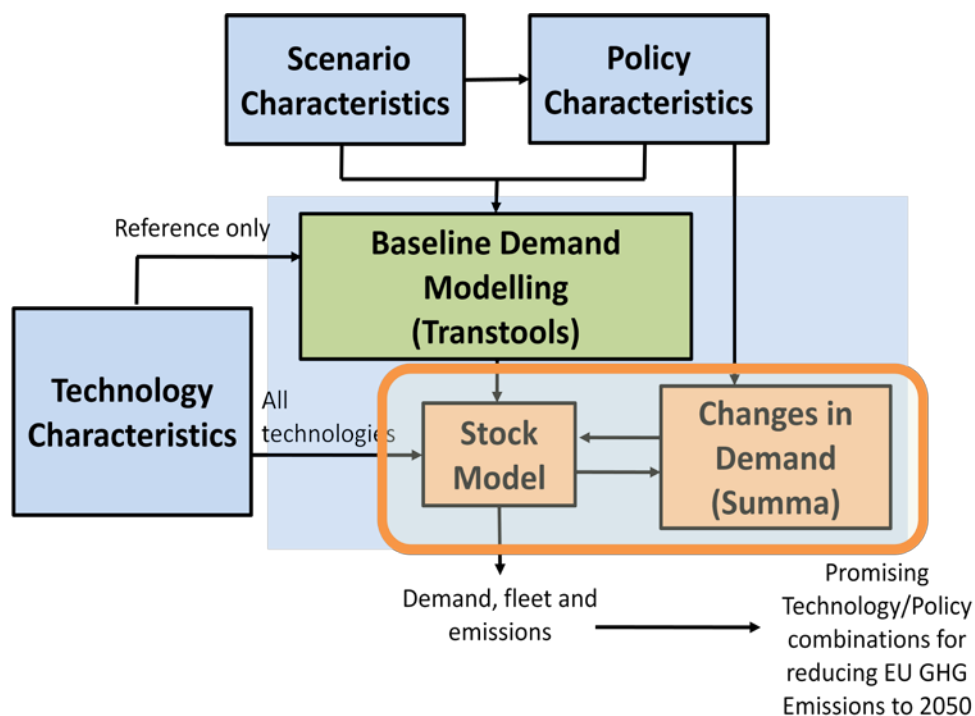

Figure 3. TOSCA project structure, highlighting the section covered in this report.

The structure of the remainder of this report is as follows. Section 2 gives an overview of the methodology, assumptions and input data used in this part of the study. Section 3 and Section 4 give results in terms of fleet size and composition, emissions and fuel use for the case that no new policies are adopted, and conclusions, respectively. Supplementary details, including a detailed discussion of fuel price and taxation assumptions, and tables of input parameters, are given in an annex.

2   Methodology

The purpose of the stock and emissions modelling stage of TOSCA is to estimate how vehicle stock size and composition, in terms of the vehicles studied in WP1-5, may change to 2050 under the scenarios generated in WP6. In this report, the focus is on methodology and results are given only for the case in which no new policies are applied. The TOSCA WP7 report considers how applying policies may affect the system equilibrium.

Broadly, the methodology may be divided into five basic steps:

1. Calculate the existing fleet size and number of vehicle retirements by year, based on base year data, vehicle age and policy variables.
2. Using scenario data on demand for passenger and freight transport (WP6), calculate how many new vehicles will need to enter the fleet to satisfy that demand.
3. Using scenario data on costs, and TOSCA data on vehicle characteristics (WP 1-5), estimate how many of these new vehicles will be of each type and technology class.
4. Estimate whether the new fleet equilibrium would change passenger or freight demand (for example, a technology which reduces journey cost may increase the number of journeys taken). If there is a significant change, steps 2-4 may be iterated.
5. Estimate the resulting emissions.

These steps are incorporated into a cross-platform java framework. Each of the steps, along with the input data and scope are discussed below. It should be noted that as TOSCA is a FP7 co-ordination and support project, we are required to use existing models where possible. A discussion of uncertainty and sensitivity, including comparisons to other studies, is given in Annex A.

2.1   Fleet Classification

To represent the present-day EU27 vehicle fleet, TOSCA uses reference vehicles for each mode and common vehicle type. A detailed description of each new year-2009 reference vehicle is provided in the final reports of WP 1-5. This classification is followed in the stock model, with some adjustments allowing for the use of external fleet datasets with different classifications. Present-day reference vehicles are divided into groups based on the mode and whether they are primarily used for freight or passengers. Marine passenger transport is neglected.

Some vehicles are readily substitutable for one another, whereas others are not. This is an important factor in technology choice, and hence forms the basis for a third level of classification. For example, a small gasoline-powered car is a viable substitute for a medium diesel-powered car (although the two vehicles may have different qualities in terms of cost, capacity, safety and comfort that affect the consumer decision). However, an electric freight train is not a straightforward substitute for a diesel freight train, because it cannot travel on non-electrified lines. Similarly, a widebody aircraft would be an unusual substitute for a narrowbody aircraft on most airline routes, because the two vehicles have very different

operating capabilities. Where future technologies are anticipated by the TOSCA WP 1-5, we have assumed that they will be able to directly substitute for one or more of the present-day reference vehicles, rather than forming a new category of their own. A full list of the TOSCA reference vehicles for the present-day fleet is given in Table 1; more detailed descriptions of the vehicles in question and their characteristics can be found in the respective work package reports for each mode.

In addition, each substitution group will be added to in the future, as new technologies become available. For example, a possible narrowbody air passenger substitution group in 2030 is depicted in Table 2 (see also the individual TOSCA Work Package reports). Airlines wishing to purchase an aircraft in 2050 would have to make a decision between these aircraft and fuel types, based on their respective characteristics and the anticipated economic environment in which they will be operated.

Table 1. Vehicle classification in the TOSCA stock modelling.

Mode	Type	Substitution Groups	Subtypes
Road	Passenger	Passenger Cars	Small (diesel, gasoline)
			Medium (diesel, gasoline)
			Large (diesel, gasoline)
	Freight	LDT	LDT (diesel, gasoline)
		MDT	MDT (diesel)
		HDT	HDT (diesel)
Rail	Passenger	High-speed train	High-speed train (electric)
		Intercity (electric)	Intercity (electric)
		Intercity (diesel)	Intercity (diesel)
		Local City	Local City (electric)
	Freight	Ordinary (electric)	Ordinary (electric)
		Ordinary (diesel)	Ordinary (diesel)
		Intermodal (electric)	Intermodal (electric)
		High-Value (electric)	High-Value (electric)
Air	Passenger	Widebody	Widebody (Jet A)
		Narrowbody	Narrowbody (Jet A)
		Regional[3]	Turboprop (Jet A)
			Regional Jet (Jet A)
	Freight	Widebody Freighter	Widebody Freighter(Jet A)
		Narrowbody Freighter	Narrowbody Freighter(Jet A)
Marine	Freight	Container	Container (Heavy fuel oil)
		Tanker	Tanker (Heavy fuel oil)
		Bulk	Bulk (Heavy fuel oil)

We also assume that existing technology types in each mode will remain available for purchase in some (incrementally improved) form throughout the TOSCA time period of 2009-2050. This means that vehicles are not deleted from the substitution groups. However,

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[3] Regional Jet aircraft are not modelled in detail in TOSCA, but as simple models for them exist in the aircraft stock model adapted for use in this project, they have been included here.

if they are sufficiently unattractive to purchase under future fleet and scenario conditions, the production rate will effectively drop to zero.

Table 2: Possible Year-2050 vehicle classification for narrowbody passenger aircraft.

Mode	Type	Substitution Groups	Subtypes
Air	Passenger	Narrowbody	Narrowbody (Jet A)
			Open Rotor (Jet A)
			Narrowbody (F-T Jet A)
			Open Rotor (F-T Jet A)

2.2 Base Year Fleet

Both emissions and vehicle retirement rates can be functions of vehicle age: therefore, it is important to have a description of the age distribution as well as the size of the present-day vehicle fleet. The data availability of information about operating fleets varies strongly. This means that fleet data in TOSCA is obtained and/or estimated from a variety of sources, as described by mode below. The resulting year-2009 age distributions by mode and vehicle subtype for the EU27 countries are shown in Figure 4 and discussed by mode below.

Road Vehicles
Road vehicle data is extracted from the TREMOVE stock model (TREMOVE 2007) and updated as appropriate using data from Eurostat (2010) on the present-day total road vehicle fleet by size, fuel and country. TREMOVE contains information about the car fleet disaggregated by vehicle type, country and age. Cars are disaggregated into 'small', 'medium' and 'large' by engine capacity (<1.4 litres, 1.4-2.0 litres, >2.0 litres) and by fuel type. Light duty trucks and vans are disaggregated by fuel type, and heavy duty trucks are disaggregated by weight (3.5-7.5t, 7.5-16t, 16-32t, >32t) and fuel type. For use in TOSCA these categories are aggregated to fit the TOSCA reference vehicle classifications. Data from TOSCA work package 1 for passenger cars is provided in the form of relationships that are dependent on vehicle size, so it is possible to directly adopt the TREMOVE classifications for passenger cars. For trucks, we aggregate TREMOVE light duty trucks and vans into the TOSCA LDT category, disaggregated by fuel type. The TOSCA HDT category (represented by a 40 tonne vehicle) is assumed to be represented by the highest TREMOVE weight category (> 32 tonnes). All other trucks are assumed to belong to the TOSCA MDT category. As TREMOVE vehicle retirement curves and fuel taxation are country-specific, we do not aggregate road vehicles to the EU27 level, but keep the TREMOVE country-specific designation.

Rail Vehicles
In order to have consistency with the reference vehicle types within TOSCA, rail vehicle fleet size and age distribution was directly estimated by TOSCA work package 3. As the data is provided in 10-year age bins, we assume uniform age distributions within each bin. For rail vehicles we also do not disaggregate by country.
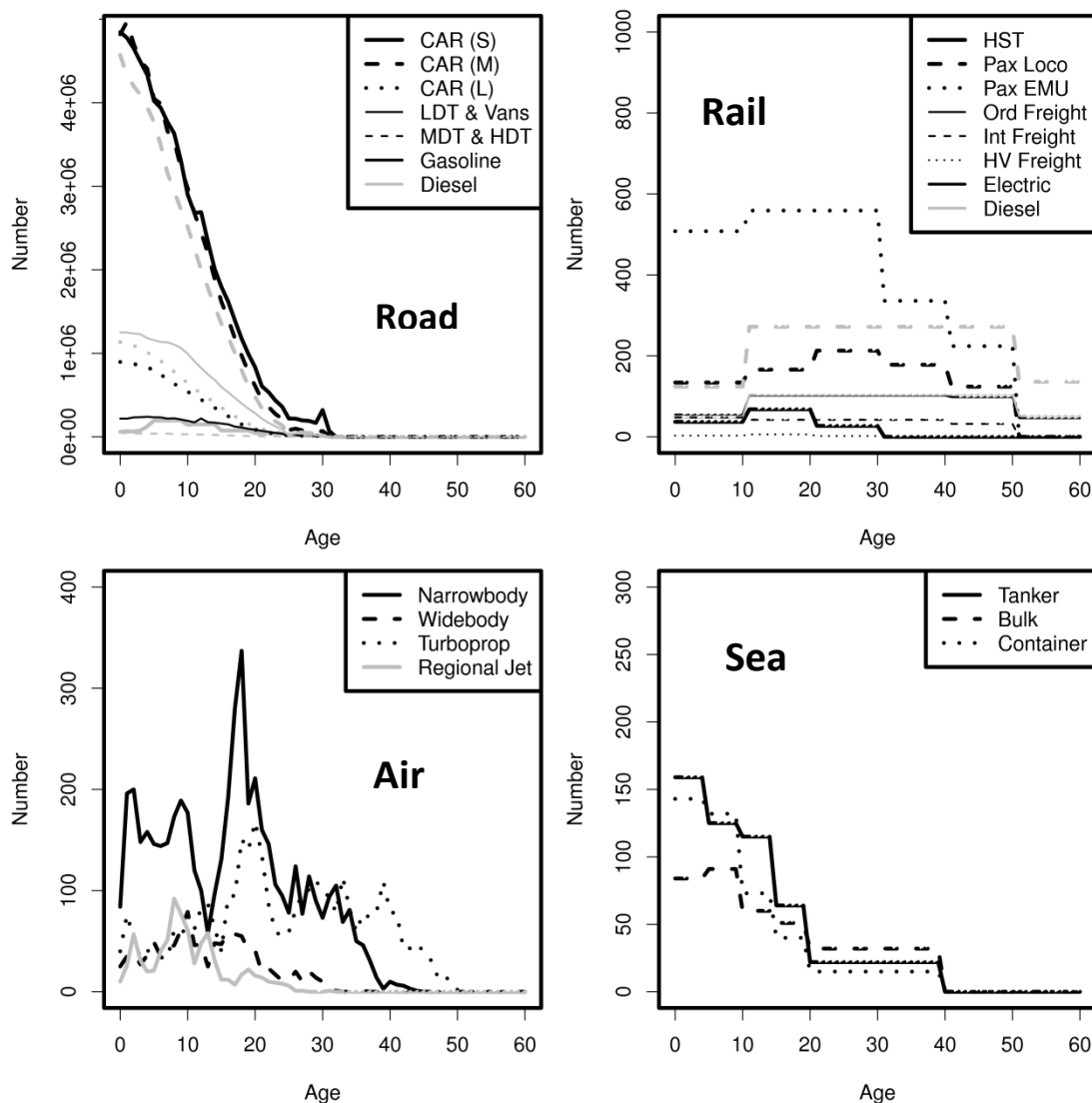
Figure 4: Present-day EU27 vehicle fleet age distributions by mode and vehicle subtype.

Aircraft

Data on aircraft age distributions is obtained from the Aviation Integrated Modelling project (e.g. Dray 2010), which derives its age distributions for European operators from the Aviation Link database of global aircraft fleets (OAG 2009). Due to the global nature of aircraft movements, it can be difficult to assign an aircraft to a particular geographical region. We assume that the EU aircraft fleet consists of those aircraft which are operated by EU-registered airlines. This means that approximately 50% of flights to and from the EU are covered (i.e. the same scope as bunker fuel totals), as well as nearly all internal flights. Aircraft are not disaggregated by country.

Marine Vehicles

For shipping, data on Europe-specific fleets is relatively sparse. We use data from TOSCA WP 1 about the size of the European fleet, in combination with age distribution data from the Ex-tremis project on European non-road emissions (Ex-tremis 2008; BIMCO 2008). Where

data is provided in 5- or 10-year age bins, we assume that vehicle ages are uniformly distributed throughout those age bins. It should be noted that, in industries where vehicle acquisition is strongly tied to economic cycles or there have been recent periods of rapid fleet growth, this assumption is questionable. As with aircraft, it is difficult to assign ships which operate globally to geographical regions. Ship numbers from TOSCA WP1 refer to the total fleet of ships over 1000 grt controlled by EU27 companies (as used in EC, 2010), rather than the flag carried. As noted in the TOSCA Scenarios report, we also concentrate on large-scale marine freight, which is responsible for the majority of shipping emissions, and neglect short-sea coastal and inland waterway freight. It should be noted that we also neglect the effect of any restrictions at EU ports which may prevent older vessels operating from them.

2.3 Vehicle Retirement

Retirement behaviour depends strongly on vehicle age for all modes. In addition, it may be influenced by fuel price, the availability of better alternative vehicles, scrappage incentive schemes, and a variety of other factors. Within TOSCA, we use retirement curves to depict what proportion of a cohort of vehicles typically remains active in the fleet at a given age by mode and for a given vehicle subtype. Sample curves are shown in Figure 5. It should be noted that the car and truck retirement curves shown are country-dependent; two sample values (Romania and the UK) are shown. Data sources and assumptions are discussed by mode below.

Road Vehicles

For consistency with the vehicle age dataset, we use retirement curves from the TREMOVE road vehicle stock module (TREMOVE 2007). Different retirement curves are used in TREMOVE for different vehicle types and countries, based on the results of the TRENDS project (TRENDS 2003). The default assumption is that retirements are dependent only on age, i.e. not on fuel price or the characteristics of replacement vehicles. The relationship of scrappage to fuel price in the literature is complicated, with some studies finding that scrappage rates decrease when fuel price is high (e.g. Lin, Chen & Niemeier 2008; Greenspan & Cohen 1999), possibly due to a reduction in vehicle utilisation. There is more information to support a relationship between scrappage and the characteristics of replacement vehicles (e.g. de Jong et al. 2001) and models exist that predict scrappage by considering, e.g. age and new car price (Steffens 2001). The decision to finally remove a vehicle from the fleet as opposed to selling second-hand may be made for a number of reasons, but most are primarily due to damage or deterioration, and hence are likely to be a function primarily of age and utilisation. For example, around 22% of car scrappage decisions in the Netherlands are the result of collisions (Ghering et al. 1989) and around 36% of scrappage decisions in the UK are due to actual or expected MOT failure (Smart 1989). In these cases, the cost of repair is also an important factor. In TOSCA, it is assumed that vehicle age is the main factor behind retirement, and other factors are neglected.

The TREMOVE retirement curves are consistent with vehicles being typically retired later in countries with lower GDP per capita. As GDP per capita is forecast to rise, it is also possible that these countries will shift to lower mean vehicle retirement ages. However, vehicle retirement curves have typically shifted to higher mean retirement ages over time, because

of greater vehicle durability (US DoE 2004). We assume in TOSCA that retirement curves will remain broadly constant over time.

Retirements may also be affected by scrappage scheme-type policies (e.g. Dill 2004). This is discussed further in the WP7 final report.
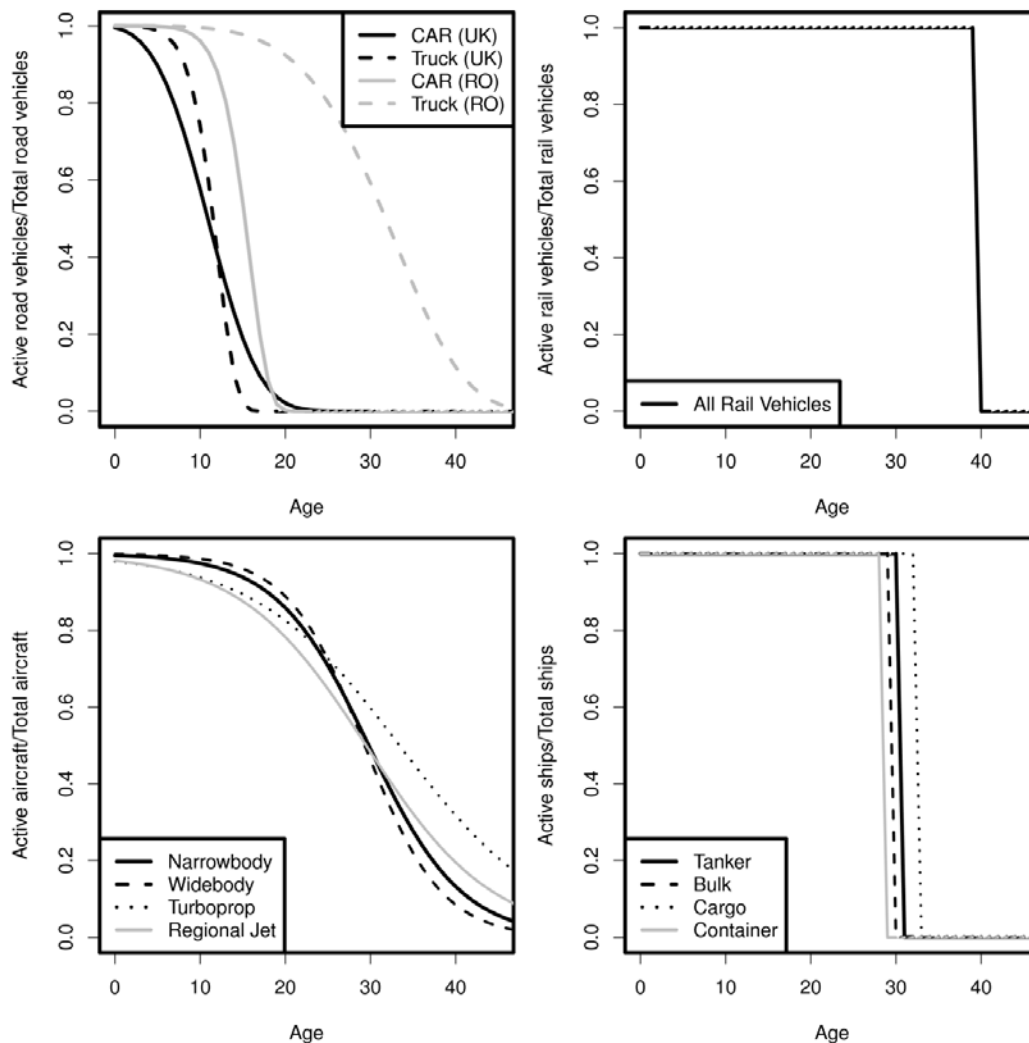

Figure 5: Retirement curves used in TOSCA by mode and vehicle subtype. For road vehicles, example by-country curves for Romania (RO) and the UK (UK) are shown separately.

Rail Vehicles

Information about rail vehicle retirements is relatively sparse. As noted by TOSCA WP 3 (Andersson et al. 2011), lifetimes for capital cost estimation are available (e.g. OECD 2001). A typical lifetime for a passenger or freight locomotive from these sources is around 25 years. However, similarly to aircraft, there can be a strong discrepancy between actual lifespan and capital cost estimation lifespan (e.g. Morrell & Dray 2009). In addition, the present-day age structure of the rail vehicle fleet in Figure 4 suggests that large numbers of vehicles have survived beyond this age. Applying retirement curves with a mean retirement age of 25 years to this age distribution results in a large and unrealistic peak of retirements

in the initial year of simulation. TREMOVE (2007) use the assumption that all trains retire at age 40. We continue this assumption in TOSCA.

Aircraft

Aircraft retirement curves by type are taken from Morrell & Dray (2009), who found that there was no significant relationship between fuel prices and aircraft scrappage, and that retirement curves have remained consistent over time for aircraft manufactured after 1965. There is possible evidence of a relationship between scrappage and new vehicle characteristics for pre-1965 aircraft, but not unambiguously. As aircraft are bought and sold globally, there is also the possibility that by using these retirement curves we are overestimating the average age of aircraft within the EU (assuming that older aircraft may be sold to world regions where regulations are less tight or capital constraints more stringent). However, historically this has not had a large effect on EU or North American fleets (Morrell & Dray 2009) because the total demand for second-hand aircraft from other regions is small compared to the number of aircraft in the EU and North America.

Marine Vehicles

We assume that all ships are scrapped at the average age for scrapping by ship type, from the UN Review of Maritime Transport (2007). This report notes that scrapping activity is negatively correlated with increases in freight rates, i.e. as with road vehicles, there is some evidence that the number of vehicles scrapped goes down as costs increase. As with road vehicles, this may result from decreased utilisation.

2.4   Demand for New Vehicles

The future demand for transportation, in terms of passenger-kilometres (pkm) and freight tonne-kilometres (tkm) by mode and country, is provided by the demand modelling within TOSCA WP 6. For a given year, the previous year's fleet and the retirement curves specified in Section 2.3 provide an estimate of the size and composition of that year's fleet before new vehicles are added.

Typical utilisation by vehicle type for new vehicles is provided for all reference vehicles in Work Packages 1-3. In addition, utilisation may be affected by a number of external factors. Utilisation typically declines as vehicle age increases. For example, Morrell & Dray (2009) find a 1.5-2.5% per year decrease in the utilisation of older narrowbody passenger aircraft[4], and US DoE (2004) data on utilisation of US passenger cars indicates a decrease in utilisation of up to 3.7% per year. Thorsen and Wigan (1998) similarly find a 3.2% decrease per year for Australian passenger cars. We assume the latter value for the European passenger car fleet. Road freight vehicles are also subject to a utilisation decline with age. Redmer (2009) estimates this to be around 2.5% per year for the Polish truck fleet. As discussed above, utilisation may also decrease as costs increase. The amount of tkm or pkm available from an individual vehicle also depends strongly on the typical load factor of that vehicle. However, load factors are also constrained by logistics (e.g. the demand for freight from A to B not being the same as that from B to A) and personal preference. We assume that load

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[4] We do not assume a decline in utilisation of freighter aircraft with age, as many freighter aircraft are converted passenger aircraft which are already 20-30 years old when they begin to be used for freight.

factors will remain roughly constant to 2050 at present-day values, apart from cases, such as CVO for trucks, where specific technologies are aimed at changing load factors. It is also assumed that the ratio of tkm of pkm performed between non-substitutable vehicle groups remains constant at base year values. This means that, for example, the ratio of HDT-suitable freight to LDT-suitable freight is assumed to remain constant.

The tkm and pkm available from this fleet at the estimated utilisation values is then compared to the scenario demand for tkm and pkm, and any shortfall is assumed to be made up by the purchase of new vehicles (at typical new-vehicle utilisation). If instead there is an oversupply of vehicles (for example, if demand is decreasing), it is assumed that the oldest vehicles in the fleet will be mothballed. This gives an estimate of the number of new vehicles required by mode, usage type, country and substitution group.

2.5   New Vehicle Choice

Substitution groups (e.g. passenger cars, see Table 1) represent groups of alternative technologies which perform similar-enough functions that they can be wholly or partially substituted for each other. Once demand for new vehicles has been estimated by substitution group, the proportions of different vehicle models which are chosen within each substitution group needs to be estimated (for example, would trucking firms choose reference technology or reduced resistance heavy trucks). These proportions will be the result of user choices, and will depend on the individual characteristics of the vehicles in the group, the users, and scenario variables which affect the costs and journey times associated with these vehicles.

Vehicle choice and diffusion into the fleet, particularly in the case where the new technology is radically different from existing technology, is a complex process which is affected by many factors. First the question of whether a vehicle which is made available to purchase will achieve significant fleet penetration at all must be considered. Although it can be argued that a firm or government will only concentrate resources on developing a technology if it has a reasonable chance of being a success, there are many cases where significant development work has gone into a technology which did not (or has not yet) go on to long-term success. For example, electric and steam-driven cars were marketed as alternatives to gasoline in the 1900s (Hård & Jameson 1997) but did not establish a long-term presence in the fleet. Second, the question of how a successful technology diffuses into the fleet needs to be considered. For cases such as passenger cars, where fleets are large, purchasers are heterogenous, a diversity of producers exists and technological change may also require refuelling infrastructure change, even a successful technology is unlikely to form a high percentage of new car purchases in its introduction year. Typically, diffusion of a successful product is considered a five-stage process (e.g. Rogers, 1962), with successive adoption by innovators, early adopters, the early and late majority, and laggards, resulting in an overall adoption trajectory which forms a distinctive S-curve (Figure 6; Bass, 1969). Specific real-life examples for cars and aircraft are given below.
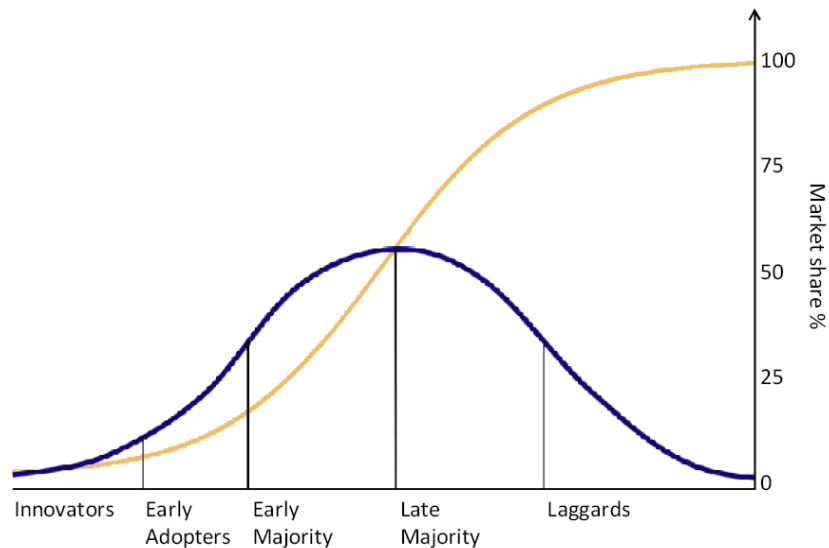
Figure 6. Stages of consumer adoption during the diffusion of a technology into the market.

We split the process of technology adoption in to two broad cases. In the first case, the decision is a largely rational one made by a large company. Such decisions are likely to apply to freight transport, and to passenger transport in cases where the vehicle is bought by an airline or rail operator. For example, for aircraft, Net Present Value (NPV) is widely recommended and used as a decision criterion (e.g. Clark 2007), where:

$$NPV = \sum_{t=1}^{T} \frac{R_t}{(1+i)^t}$$

and R_t is the total sum of cash inflows and outflows related to the vehicle purchase at time t; T is the investment horizon, and i is the discount rate. The purchase option with the highest NPV should be chosen; however, if the expected cash inflows associated with the two vehicle options are the same (for example, if they would both be used for transporting the same number of paying passengers on the same routes, over the same time period) then it is sufficient to choose the vehicle option for which total cash outflows have the least-negative NPV. This information is available in TOSCA and forms part of the estimation process in WP 1-5[5].

However, even in this case purchasers are likely in reality to base their decision on many factors about which we have relatively little knowledge. For example, new aircraft technologies which are clearly attractive to an average airline on a NPV basis according to the data available in TOSCA may not be purchased for a number of reasons. These include risk aversion, unaccounted-for passenger preferences (for example, a decrease in demand

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[5] Note that the calculation which is performed here is not the same as the technology cost-effectiveness calculation in the WP 1-5 final reports. That calculation, using a social rate of discount, looked at whether technologies were a cost-effective way for society to reduce emissions. Here, the question is: will the technology be bought by consumers? However, cash flows for individual costs associated with owning and operating a technology are also estimated at an earlier stage in WP 1-5 and can be used in this calculation.

may be anticipated if open rotor engines are adopted due to the prospect of increased cabin noise) and delivery delays caused by limits in production line capacity. Similarly, airlines may have existing relationships with manufacturers which they wish to continue, even if a competitor offers a better alternative product. These and other factors mean that even where technologies appear to offer a significant cost saving to companies, implementation is often delayed (e.g. Kar et al. 2009). Similarly, there are cases where new technology is chosen even though it appears to result in greater technology-related costs for the purchaser, because of some other benefit (e.g. company or national prestige, safety perception, ability to advertise a service as 'green').
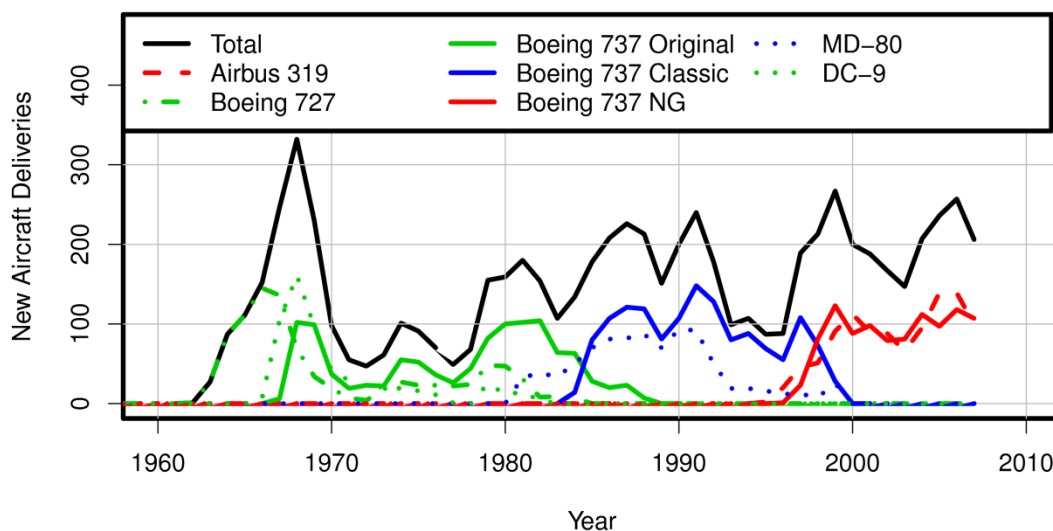
Figure 7. Global deliveries of major 100-seater jet aircraft models since 1960. Data: OAG (2009)

An example of technology diffusion for the case of 100-seater aircraft is shown in Figure 7. For aircraft, relatively few producers exist, and producers tend to synchronise new aircraft models so that similar-technology aircraft become available for purchase from multiple producers within a few years of each other. When new-technology aircraft become available, the transition between deliveries of old-technology aircraft and new-technology aircraft is relatively rapid. For example, in the late 1990s aircraft deliveries switched from almost entirely old-technology (Boeing 737 classic and MD-80; blue lines in Figure 7) to almost entirely new-technology (Boeing 737 NG and Airbus A319; red lines in Figure 7) within five years.

Based on the considerations above, we assume simple maximisation of NPV as a purchase criterion for all cases where the majority of purchase decisions are likely be made by businesses. This includes all modes other than passenger cars. As discussed above, we assume that the cash inflows associated with each purchase option will be the same, i.e. all alternative vehicles are anticipated to have the same utilisation, over the same time period. A review of the treatment of fuel costs is given in Annex A, and a summary of the parameters used, including discount rates by mode and references, is given in Annex B. It is assumed in all cases that carbon prices, where they are relevant, will be applied to direct emissions only, using the TOSCA convention that the direct emissions of biomass-derived

fuels are zero. It is also assumed that product diffusion, in terms of the percentage of new vehicles with the new technology, is rapid, i.e. if a technology is economic to adopt in terms of NPV for all new vehicles in (say) Poland, then it will be adopted by all of those vehicles. This also implies an assumption that production lines will have sufficient capacity to meet demand.

As these models look into the future from the time of purchase decision, a decision must also be made as to the amount of foresight shown by consumers about future oil and carbon price trajectories. Although the assumption of perfect foresight is often used, it is inappropriate in cases where unexpected large changes in future input values are assumed. As the model sensitivity tests include a disruptive scenario with a sudden, unexpected increase in fuel price (Annex C), we assume that consumers make their purchasing decision on the basis that fuel and carbon prices will remain at their purchase year values.
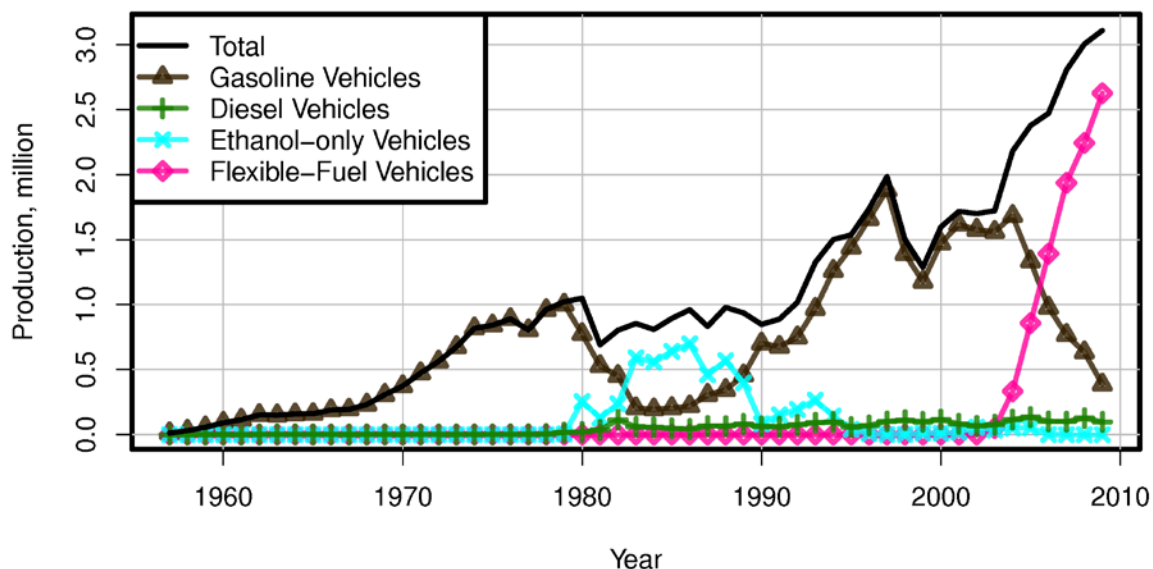

Figure 8. Vehicle production by fuel type in Brazil, 1957-2009. Data: ANFAVEA (2010)

The situation for passenger cars is more complex. An example of a new car technology entering the fleet is shown in Figure 8. Widespread use of sugarcane ethanol as fuel in Brazil was first promoted in 1975, as a response to the 1973 oil crisis. Significant government support was applied as part of the ProAlcool program (Moriera & Goldemberg 1999). This enabled ethanol-only vehicles to overtake gasoline cars as a percentage of new purchases between 1983 and 1988. After this point, falling gasoline prices, a supply shortage of ethanol and a decrease in government support via the ProAlcool program intervened, and the percentage of new vehicles which were ethanol-fuelled dropped significantly. However, ethanol refuelling infrastructure remained in place. In 2003, flex-fuel vehicles capable of running on a variable blend of ethanol and gasoline were introduced to the market and were able to take advantage of the existing infrastructure to achieve a 50% market share over 5 years. The example of Brazil suggests that large-scale switches to alternative technologies are possible, but may require significant and ongoing government support, as well as helpful scenario characteristics. It also illustrates that a change to alternative

technology can in theory take place over a relatively short timescale, if suitable infrastructure is present.

The factors affecting individual vehicle purchase decisions are more complex in the case of passenger car purchases that for commercial vehicle purchases. If all drivers chose only the lowest-cost existing vehicle (based on the data available in TOSCA) then the EU27 car fleet would be composed entirely of small, low-powered cars – a situation which is very far from reality. A review of models for car ownership and vehicle choice is given by de Jong et al. (2004). One of the most important factors from the TOSCA point of view is fuel cost myopia. As noted by, e.g., Greene et al. (2005), car purchasers do not typically place a high value on fuel saving, with multiple studies showing that car buyers prefer to be paid back in 3 or fewer years for an investment in fuel economy (e.g. Jansen & Denis 1999). In fact, Turrentine and Kurani (2007) find that in many cases car purchasers do not have an accurate idea of what their yearly fuel costs are.

Because of these complicating factors, detailed modelling of vehicle purchase decisions is often carried out using discrete choice models in which purchasers choose vehicles from a given choice set by utility maximization, and utility is a function of characteristics such as vehicle acceleration, range, price size, fuel and many other potential factors. However, estimating such models requires data on past choices or, in the case of technologies that do not yet exist, stated preference data on how consumers would choose given the new technology as an option. Therefore, models for vehicle choice and diffusion in the literature tend to concentrate on existing technology for which data is readily available (e.g. TREMOVE 2007; Hayashi et al. 2001) or existing technology compared with one alternative technology (e.g. Schwoon 2006; Collantes 2007). A further complicating factor is that the car purchase decision does not only include technology; it also includes a choice of vehicle size. One plausible response to an increase in fuel costs is to purchase an alternative technology; another is to purchase a smaller car with the same technology (e.g. Thoresen & Wigan 1988).

For the purposes of TOSCA, we adopt an extremely simplified hybrid model. The base case choice of vehicle size and gasoline/diesel is made using the TREMOVE vehicle choice model (TREMOVE 2007). This is a nested logit discrete choice model in which utility is a function of fuel and non-fuel cost per vkm, GDP per capita and acceleration time from 0 to 100km/h, as well as dummy variables which capture historical preferences for different car types in different countries. As much of the car input data is derived from TREMOVE, this model is consistent with the vehicle size categories used in TOSCA and easy to implement in the TOSCA framework. However, it does not include a detailed treatment of alternative technologies. A simple framework is included to exogenously include the effect of alternative technology penetration on the vehicle size choice, by treating each vehicle option in the choice model as an aggregate over the base case technology (e.g. small gasoline cars) and alternatives (e.g. an exogenously-imposed fraction of small LPG cars). In TREMOVE (2007) this approach is used for LPG, CNG and hybrid cars. In TOSCA, we follow this approach for alternative technologies but couple it with a version of the NPV model described above, with parameters chosen to account for consumer myopia, to determine whether some of the vehicles chosen are of an alternative technology and, if so, which technology. As noted above, the diffusion of technology into vehicle fleets typically follows

an S curve (e.g. Usha Rao & Kishore 2010) and the fraction of new vehicle demand captured by alternative technologies is likely to initially be small, even for a successful technology. This affects the proportion of new vehicles chosen. Therefore we limit adoption rates to literature values for comparable technologies (e.g. Collantes 2007; ANFAVEA 2010). It should be noted that the use of such a model set is a significant and relatively crude approximation, and that results should consequently be viewed with caution. A discussion of model sensitivity and a comparison of results with other models is given in Annex C; parameters affecting the technology adoption model are given in Annex B.

Demand for new technologies may be affected by policies aimed at reducing the costs associated with low-emission technology, increasing the costs associated with high-emission technology, or making low-emission technologies easier to obtain or operate (e.g. Greene et al. 2005, SEI 2008). Historically, 'gas guzzler' policies have prompted action both by consumers and by automobile manufacturers (e.g. McNutt 1983), with changes in the range of vehicles available for purchase accounting for a greater proportion of emissions reductions than changes in vehicle choice from amongst those available. This effect is not modelled directly here. However, it can be simulated by applying vehicle emissions standards instead of taxation. This is discussed further in the WP7 final report.

Assumptions about Technology Availability
Not every combination of technology and fuel is likely to become available in a future where no new policies are imposed. For example, Automated Highway System (AHS) vehicle technologies are designed to be used with dedicated road lanes. Changing the use of existing lanes and/or widening public roads is a policy decision, so AHS technologies are unlikely to penetrate widely in the vehicle fleet without significant government support. Similarly, car purchasers are unlikely to buy a hydrogen-powered vehicle if the nearest hydrogen fuelling station is a significant fraction of the vehicle's range away. Therefore government support for charging or refuelling infrastructure may be needed to make the use of a technology feasible for early adopters, even if in theory it is cost-effective. Other technologies may not make it to market because the research and development effort involved is too great for any one company to undertake alone.

The R&D requirements associated with each technology discussed in TOSCA WP 1-5 are graded on a 3-point scale: insignificant, significant (company-level) or substantial (EU-wide program). For this study, we assume that technologies graded as requiring 'substantial' R&D will not reach a stage of market readiness unless there is some form of policy intervention. This means that technologies such as plug-in hybrid cars and vans, battery electric vehicles, fuel cell vehicles, open rotor aircraft and wood-based diesel and Jet A substitutes are assumed to not be widely available without support from EU governments. In addition, we assume that technologies with 'significant' R&D requirements which would also require significant infrastructure investment will require some form of government support. This primarily affects vehicles fuelled with ethanol from wood feedstock.

These assumptions mean that the technologies available in the no-new-policies case examined in this report are relatively limited. As the TOSCA assessment of marine vehicles includes only existing technologies, all options are available. For cars, the primary alternative technologies are accelerated technology improvement (ATI), LPG, CNG and

hybrid electric vehicles. For trucks, resistance reduction and idling reduction technologies are available. Nearly all investigated train technologies are assumed to be available, with the exception of low mass freight trains, low drag passenger trains, and 'combination' trains. For aircraft, however, only the evolutionary replacement aircraft meets the criteria specified above.

2.6   Greenhouse Gas Emissions

Once demand for new vehicles by type has been estimated, the fleet composition and utilisation is known and fuel use can be estimated. For each technology, the WP 1-5 reports include estimates of per-pkm and per-tkm fuel use for new vehicles in their year of market readiness (or 2010, for reference vehicles). In addition, the change over time in these values is estimated by WP 1-5 as either a rate per year or as a function of cumulative production volumes, so it is possible to estimate the characteristics of a new vehicle from (e.g.) 20 years after the year of market readiness, if the cumulative production is known.

Estimating whole-fleet fuel use from these values requires knowing the fuel use of older vehicles already in the fleet in 2010. The trends in future emissions with manufacture year estimated by WP 1-5 are intended to capture incremental technology changes only. However, for many technologies these incremental trends were estimated from historical trends under the assumption that recent technology changes have been primarily incremental. Therefore we use these trends for historical vehicles too. An exception is made for aviation. Here, the long time between new aircraft models means that the WP2 estimated trends in fuel use and emissions capture the effect of system improvements only (e.g. improved air traffic management). For older vehicles, we use a value of 1%/year instead (Morrell & Dray 2009).

Fuel use may also be affected by any capacity technologies which are applied. For each capacity technology in WP5, estimates are provided for the resulting total reduction in fuel use, taking into account the proportion of journey time spent using that technology (for example, a Europe-wide AHS system would still reduce emissions on only around half of EU27 passenger-km, because AHS requires dedicated lanes; Psaraki-Kalouptsidi & Pagoni 2011). Fuel use for vehicles also using capacity technology is reduced by this amount. However, it should be noted that journey times will also decrease, and this may lead to an increase in demand and hence in emissions (23). Under most combinations of scenario and capacity technology studied here the net effect on emissions including demand effects is a reduction.

Once fuel use is estimated, direct and indirect emissions by fuel are applied using values from TOSCA WP4 (Perimenis et al. 2011). The final output is emissions by scenario, year, policy, geographic scope and vehicle type.

2.7   Changes in Demand

Demand for transportation is affected by many factors, including income, population distribution, journey cost and journey time. The last two factors in particular may be affected by new technologies and/or policies. The demand totals generated in the WP6.1

report represent a base case in which the vehicle fleet is made up of only existing technologies and incrementally improved designs based on existing technologies, and the policy environment remains the same as in the present day. However, for cases which deviate from these assumptions, it is likely that demand will change too. For example, the widespread adoption of a technology which reduces journey cost may increase demand via the 'rebound effect' (e.g. Greene 1992). Similarly, capacity technologies aimed at reducing journey time may lead to increased demand. Policies which increase the cost of fuel or of emitting carbon dioxide may result in a decrease in demand.

As discussed in the WP6.1 report, these base case demand totals are generated by complex models with high run times. This means that it is not feasible to make large grids of model runs looking at different combinations of scenario, policy and uncertain input variables. However, it is likely that in most cases the change in demand from the base case will be relatively small (e.g. Greene 1992). Therefore we follow a simple elasticity-based approach to calculate changes in demand from the base case due to these effects. For each model run, the changes in journey cost and journey time by mode, area and vehicle class compared to the base case due to new technology and policy are calculated. A consistent set of elasticities and cross-elasticities of demand[6] are then applied to these numbers to give the resulting changes in demand.

There are several potential sources for elasticities and cross-elasticities. For TOSCA, we use output generated by the SUMMA project (van Grol et al. 2007). This was an EU framework 7 project aimed at generating a meta-model from a set of individual-country EU transportation models and using it to assess potential policy interventions. It builds on and expands the EXPEDITE framework (de Jong, Gunn & Ben-Akiva 2004). The SUMMA Fast Simple Model (FSM) takes as input the change by mode in journey cost and journey time, and outputs changes in demand segregated by mode, distance band, trip purpose and country. These changes in demand are calculated using matrices of demand response derived from running a set of national transport models from EU countries. They therefore draw on the same broad framework of existing EU models as Transtools. However, it should be noted that the responsiveness of transport demand to changes in journey costs and time of Transtools and SUMMA over all modes and contexts are not necessarily the same, so results should be interpreted with caution. The relatively disaggregate output of SUMMA means that output can be aggregated to suit the requirements of TOSCA. For the purposes of this project, separate elasticities were used by mode, trip purpose or commodity (derived from transtools output) and broad geographic scope (EU interurban trips/EU long-distance/non-EU). The elasticities derived from SUMMA are given in Annex B ("Model Parameters").

SUMMA covers passenger demand for intra-EU road, rail and air travel, and intra-EU road, rail and sea freight. For other modes and geographic scopes covered within TOSCA, a selection of literature values was used. Elasticities for intercontinental shipping were derived from Oum et al (1990), Hummels, Lugovsky & Skiba (2007) and UNCTAD (2010). For

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[6] An elasticity of demand to a given quantity gives the percentage change in demand expected given a percentage change in the quantity. Cross-elasticities indicate the expected change in demand due to a change in a quantity relating to an alternative product (for example, the response in demand for road passenger transport following a doubling of train fares).

aviation, elasticities from IATA (2007) were used. For consistency with the AIM model, which was used to generate intra-EU27 demand and which also utilises IATA (2007) elasticities, these were also used for intra-EU27 aviation demand. As the main intercontinental modes considered (freight shipping and air passenger) are not substitutes, no cross-elasticities were used for intercontinental travel.

Not only does technology adoption affect demand, but demand also affects technology adoption (for example, an increase in demand may lead to more vehicles of a given sort being chosen, which may lead to a decrease in the price of that vehicle via learning effects). This means that the stock and demand change modelling are interdependent, as indicated in Figure 3. To resolve this issue, the two models are run iteratively until a stable solution is reached. As demand elasticities are typically well below 1, and changes in journey costs and time in iterations after the first typically minimal, for most runs an acceptable solution is reached after 2-5 iterations.
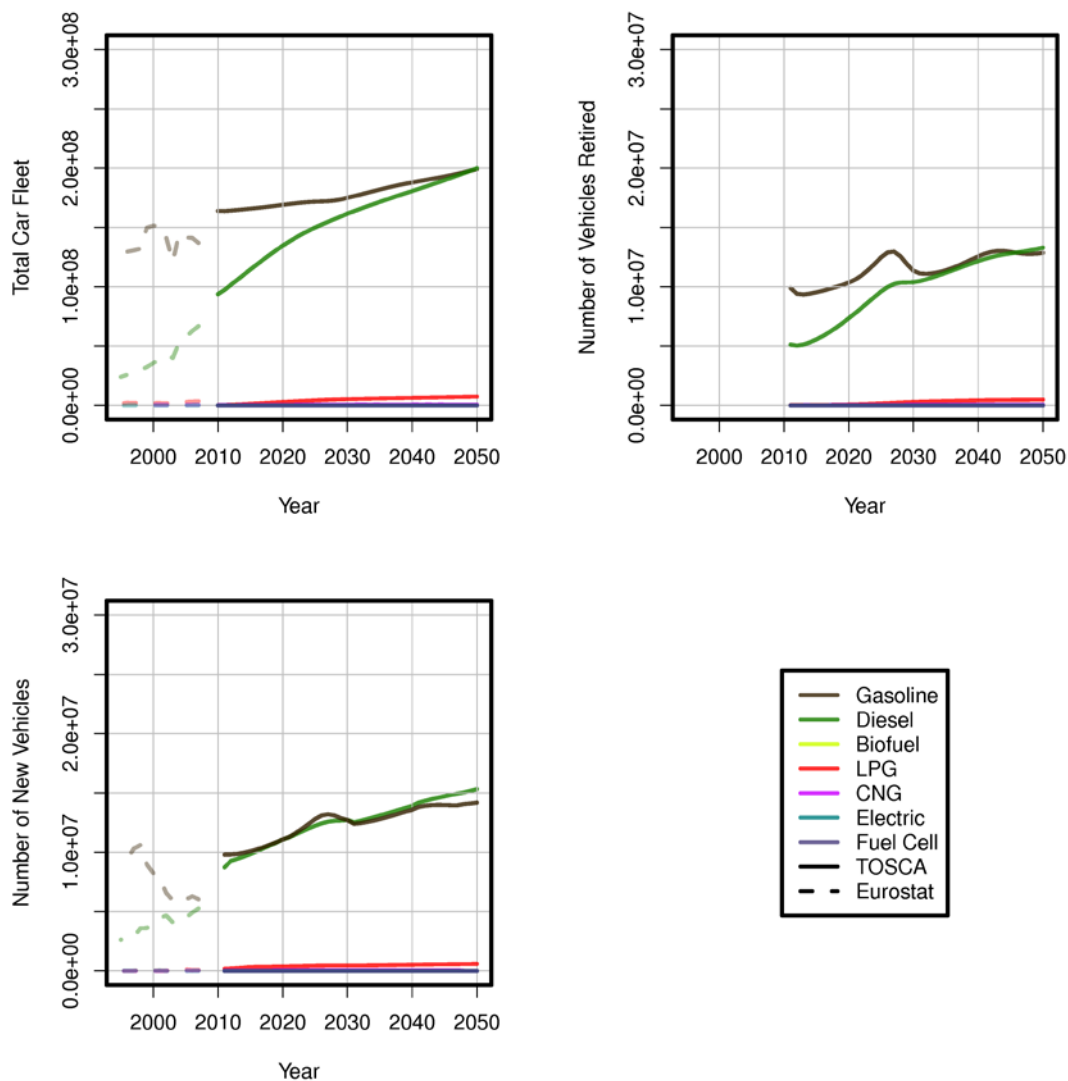
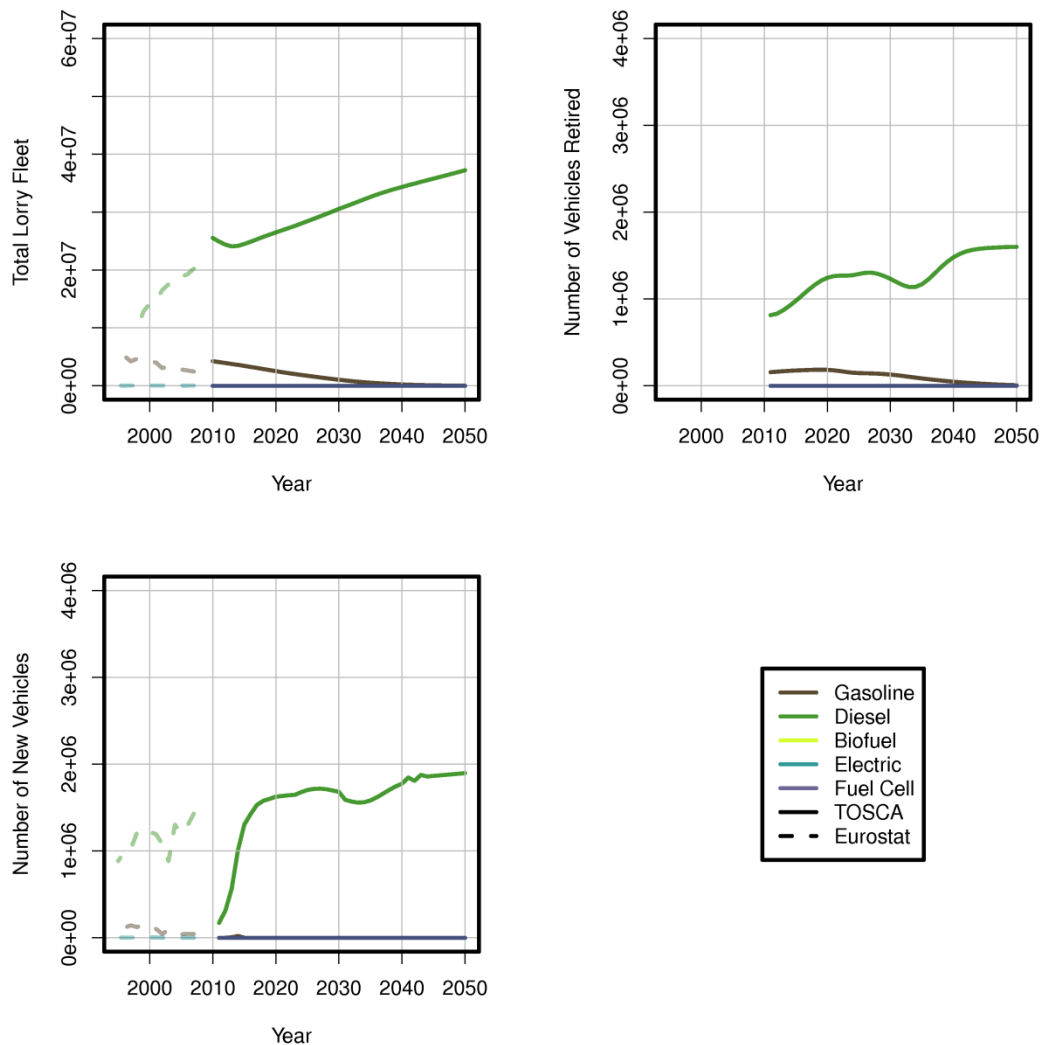**Figure 9. Development of the EU27 car fleet by major technology to 2050 in the Baseline scenario, in comparison to past data.**

3   Results

3.1   Fleet Development

The size and composition of the EU27 vehicle fleet plays a vital role in determining transportation emissions, and is a function both of demand for pkm and tkm, and of technology uptake. In this section we discuss fleet development for aggregate groups of technologies primarily with respect to the Baseline scenario. However, as noted below, differences between scenarios in terms of technology uptake are typically small in comparison to the differences in demand between scenarios.

Figure 10. Development of the EU27 truck and van fleet by major technology to 2050 in the Baseline scenario, in comparison to past data.

Figure 9 shows the development of the EU27 passenger car fleet to 2050 in the Baseline scenario, in comparison to data from Eurostat (2010). It should be noted that the Eurostat tables include data gaps for several countries, and thus represent an underestimate of the true fleet size and number of vehicle registrations per year. The bumpy variation seen in the

numbers of retirements and new vehicles required is because both are dependent on the age structure of the existing fleet (e.g. Figure 4.) and retirement curves, both of which also differ by country. In general, the fleet development follows past trends without large-scale radical technology change. There is a small increase in the adoption of LPG and CNG vehicles, and the existing trend towards a larger share of diesel vehicles in the fleet continues. Although this outcome depends somewhat on the many assumptions and simplifications made in this study, it is in line with the conclusions of other studies looking at future technology penetration (e.g. Christidis, Hidalgo & Soria 2003).

The fleet outcome is not substantially different between scenarios; although scenarios with higher fuel prices have slightly more CNG-fuelled vehicles and slightly fewer LPG-fuelled vehicles (due to the higher purchase price, but lower fuel costs, of CNG vehicles), the penetration of alternative technologies and fuels remains low in all cases. In particular, the option of accelerated improvements to existing technology (ATI) is not adopted in any scenario.
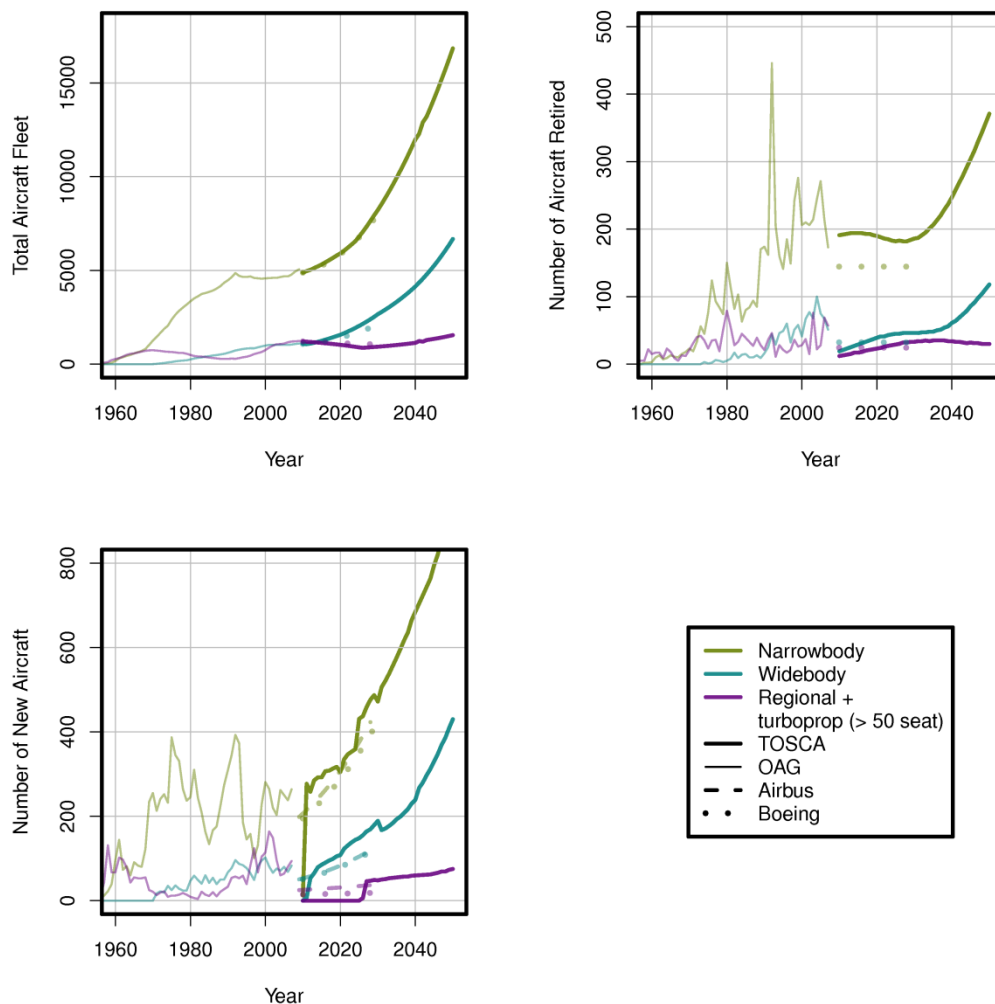
Figure 11. EU27 Aircraft fleet to 2050 in the Baseline scenario, in comparison with past data and industry projections.

A similar plot for road freight vehicles is shown in Figure 10. Here the model predicts an oversupply of trucks in the base year, leading to initially low sales which then increase back to historical levels. This oversupply represents a real effect: the recent global financial crisis has led to a decrease in total freight shipped and oversupplies of freight vehicles in general, particularly ships. As with cars, no major technological shift takes place. Reduced drag and rolling resistance technologies are widely adopted, but there are no major changes in fuel or drivetrain technologies. This partially reflects the lack of alternative options which do not require extensive R&D programs, particularly for heavy trucks.
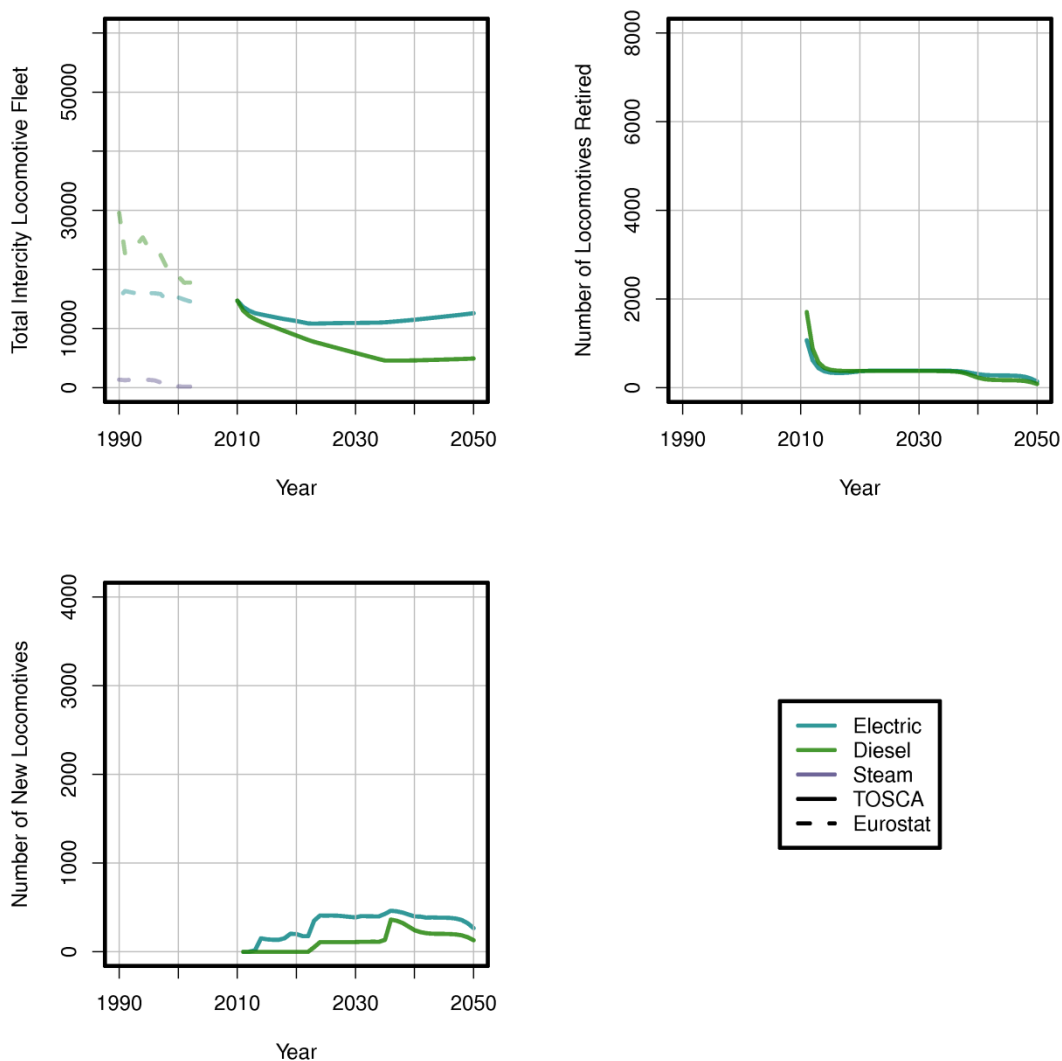
Figure 12. EU27 intercity locomotive fleet to 2050 in the Baseline scenario, in comparison with past data.

Figure 11 shows the development of the aircraft fleet to 2050 in the Baseline scenario, in comparison with past data on the fleets operated by EU airlines from OAG (2009), and projections for future aircraft orders from Boeing (2010) and Airbus (2009). Note that aircraft used by non-EU airlines to fly to and from the EU are not included. Although growth in all aircraft fleets is large, values from the Baseline scenario match closely to industry

forecasts, indicating that these growth levels are not unrealistic. Growth rates are typically higher for larger aircraft types, reflecting a stronger increase in demand for long-haul travel and relatively flat growth for short, domestic flights. The initial oversupply of regional aircraft reflects an existing oversupply primarily of older turboprop aircraft. Although usage of turboprops on short-haul flights has increased over the recent recession as a response to high fuel prices (e.g. OAG 2009; Vera-Morales et al. 2011), it is unsure whether this trend will continue, as there are significant disadvantages associated with turboprop use (e.g. cabin noise; safety perception) which are not captured in this model. Therefore this result should be viewed with caution.

As for trucks, there is no major penetration of new technologies. For aircraft, the alternative technologies and fuels considered in TOSCA are all judged to require EU-wide R&D before they can become market-ready. Therefore the only technology improvements available in this no-new-policy case are incremental, in the form of the narrowbody and turboprop evolutionary replacement aircraft. These aircraft are, as expected, widely adopted (e.g. Figure 7).
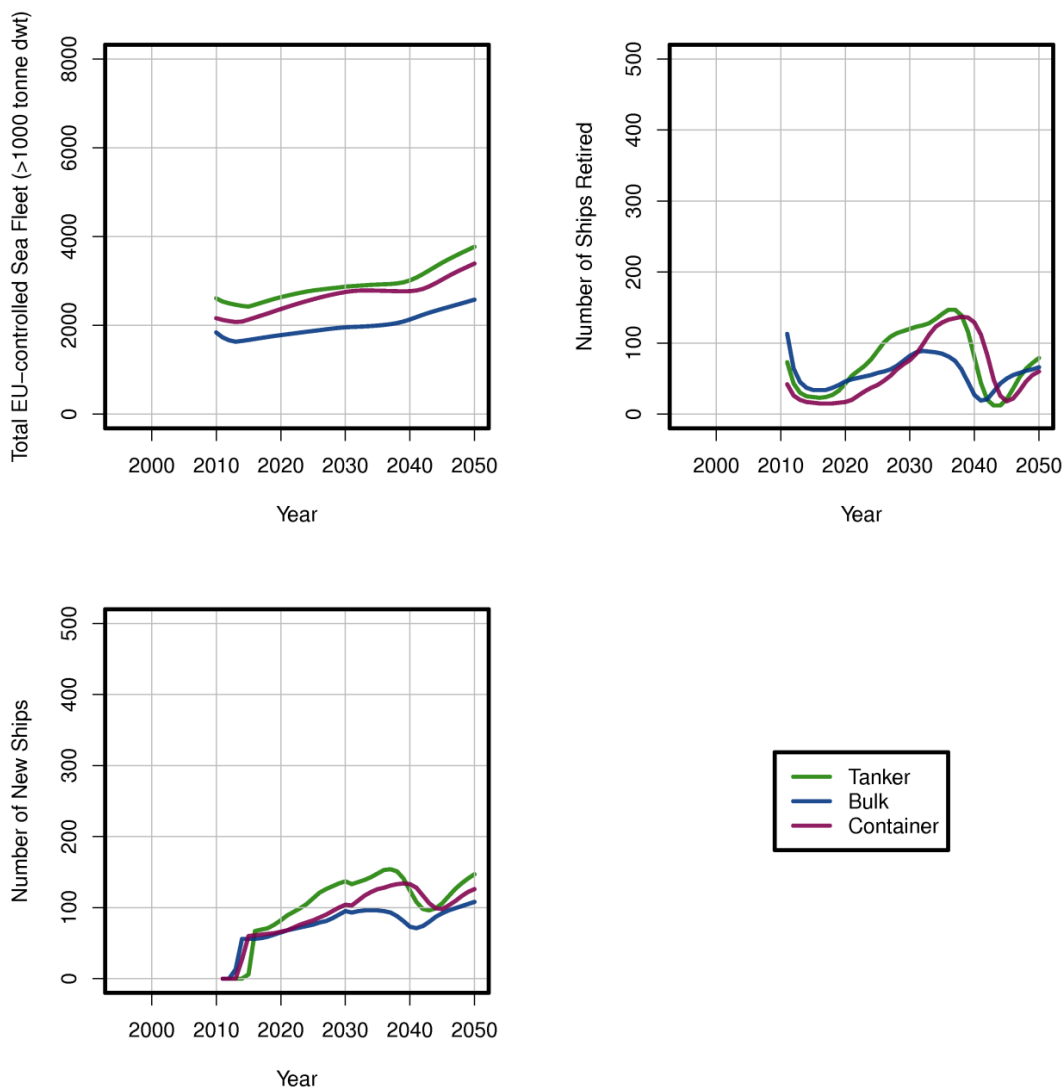
Figure 13. EU27 shipping fleet (> 1000 tonne dwt) to 2050 in the Baseline scenario, in comparison with past data.

Figure 12 shows similar data for trains, by major technology type. As for cars, present-day trends are expected to continue. These include a decreasing fleet of diesel trains and a relatively flat fleet of electric trains. The initial peak in retirements is primarily a function of the rail initial fleet and retirement assumptions, and reflects the long tail of trains over 40 years old in the initial age distribution. In addition, there is an initial oversupply of diesel trains. This is a result of the historical switch from diesel to electric trains and is observed in the real world; however, it is likely that the older diesel trains have low utilisation, and this is the assumption used in TOSCA. A range of new technologies are available for purchase, as detailed in the TOSCA WP3 final reports (Andersson et al. 2011). As these are based on present-day diesel and electric trains, they are included in the diesel and electric totals above. In the runs used here, it is assumed that the 'combination' train technology is not available, but other technologies, in particular space-efficient trains, are widely adopted.

Figure 13 shows equivalent data for ships. As noted above, the recent recession has resulted in an oversupply of ships, leading to initially low demand for new ships under the assumptions used here. The new shipping technologies considered in TOSCA WP1 are presently-available adaptations of existing ship designs, so are included in the totals shown above. However, the Air Cavity System technology is widely adopted, as in Engine Energy Recovery (depending on ship type).

3.2 Fuel use

Once the fleet is known, fuel use and emissions can be estimated. Figure 14 shows total fuel use over all modes, and emissions by fuel, in the Baseline scenario. Past data from Eurostat (2010) and EUROPIA (2009) is also shown. As for fleet totals, TOSCA projections in the no new policy case primarily continue existing trends. Demand for gasoline shows a small decrease, demand for diesel continues to increase, and demand for jet fuel increases rapidly. Note that TOSCA underestimates the base year demand for diesel; this is because diesel use from all transport sources is shown, but buses are not modelled here. These trends result from the fleet trends discussed above. Similarly, transportation electricity use is relatively flat; this results from the mild increase in the electric train fleet, in combination with a decrease in per-train electricity use because of technology adoption. However, electrification does not occur in other modes in this case. Emissions follow fuel use trends, and direct and fuel lifecycle emissions behave similarly. This is because there is no large-scale switch to alternative fuels with lower direct emissions, or which trade off direct for lifecycle emissions (e.g. hydrogen from gas feedstock). While only the Baseline scenario is shown, other scenarios behave broadly similarly. Although fuel use and emissions totals are different because demand varies strongly between scenarios, the same general trends (increases in diesel, jet fuel and HFO use; relatively flat electricity and gasoline and use; some increase in LPG and CNG but not to widespread fleet penetration) are seen. A direct comparison of emissions by mode between scenarios is given in the next section.
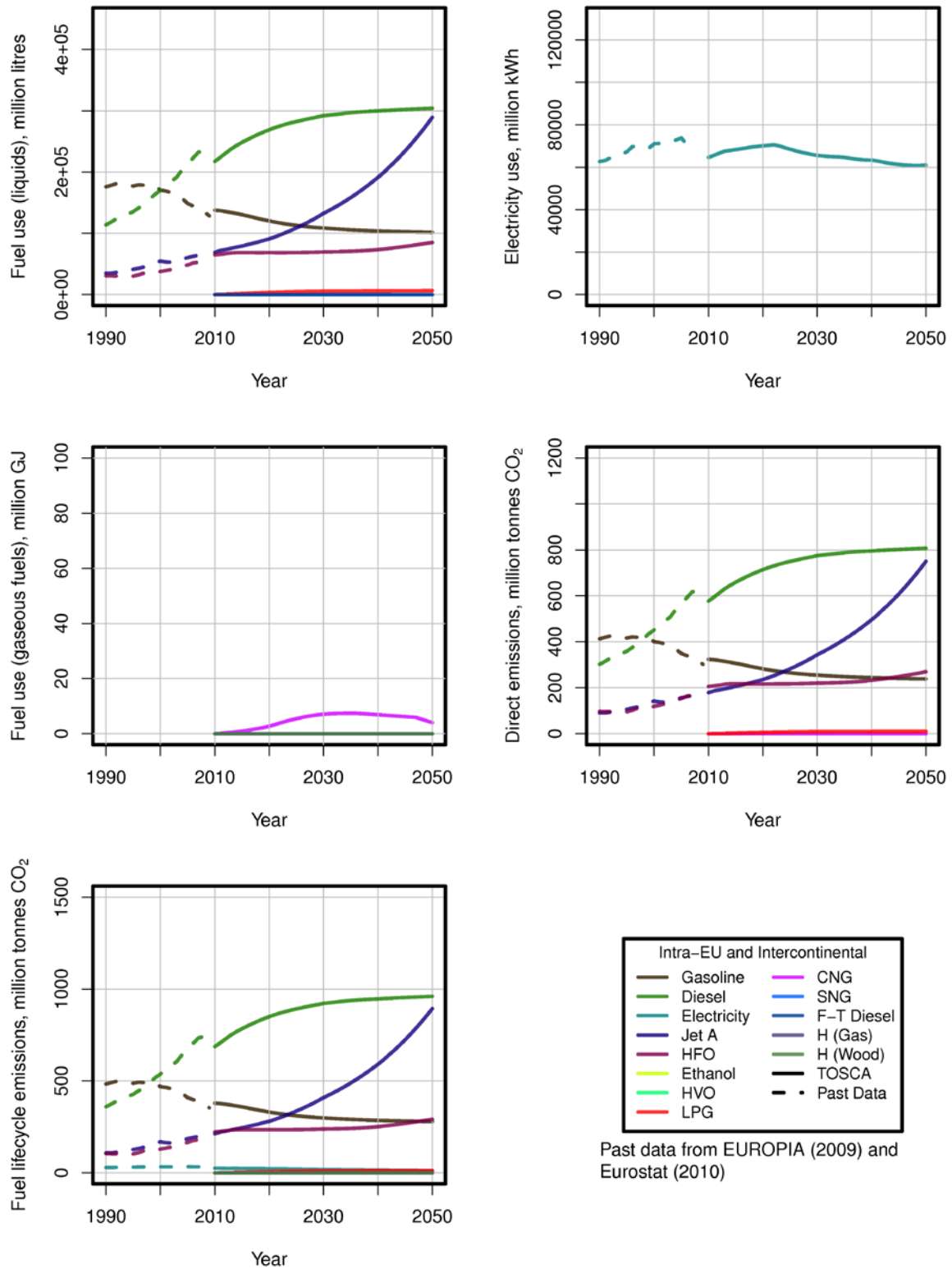
Figure 14. Fuel use by type, and emissions by fuel, in the baseline scenario to 2050, in comparison to past data.
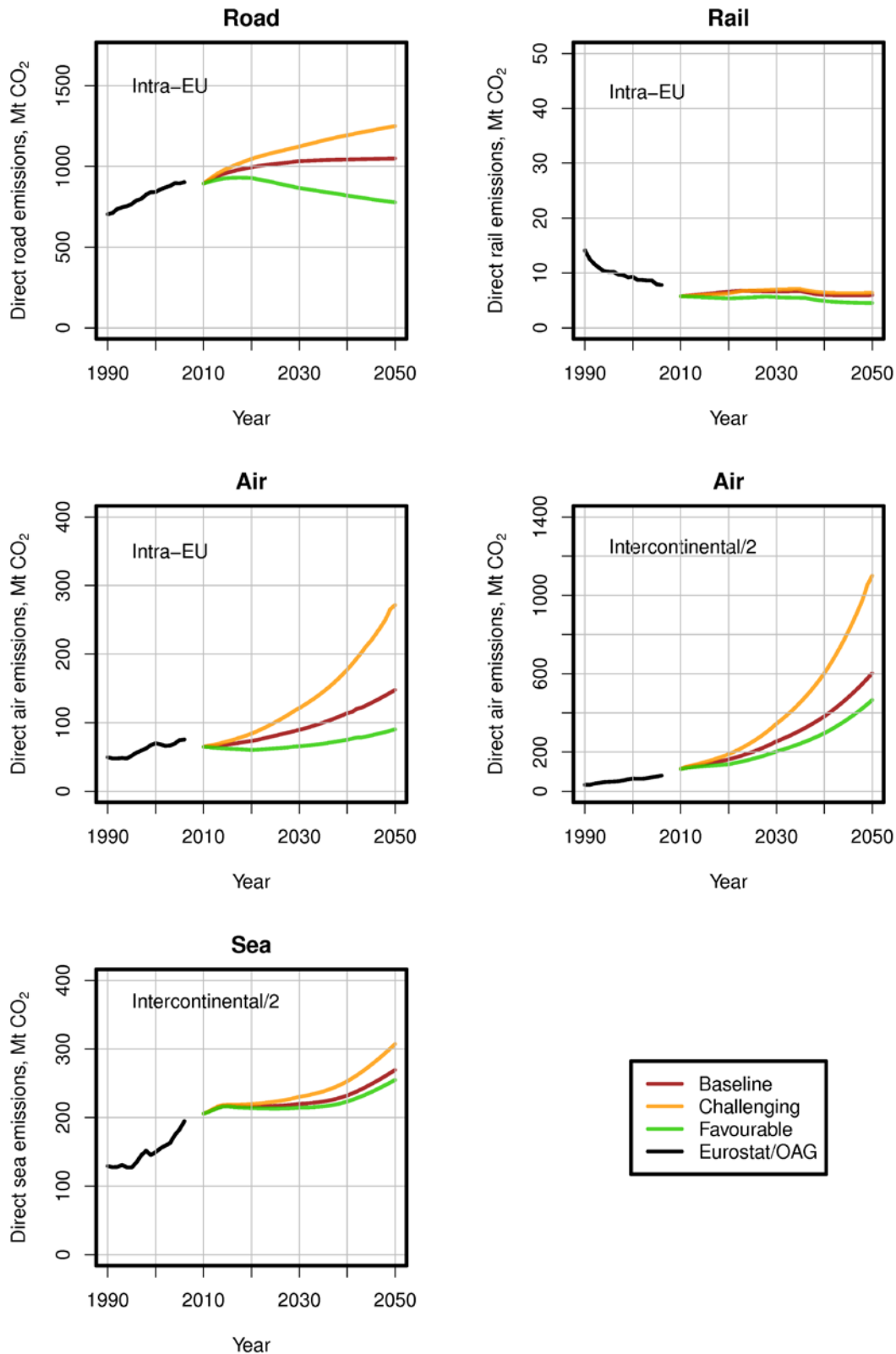
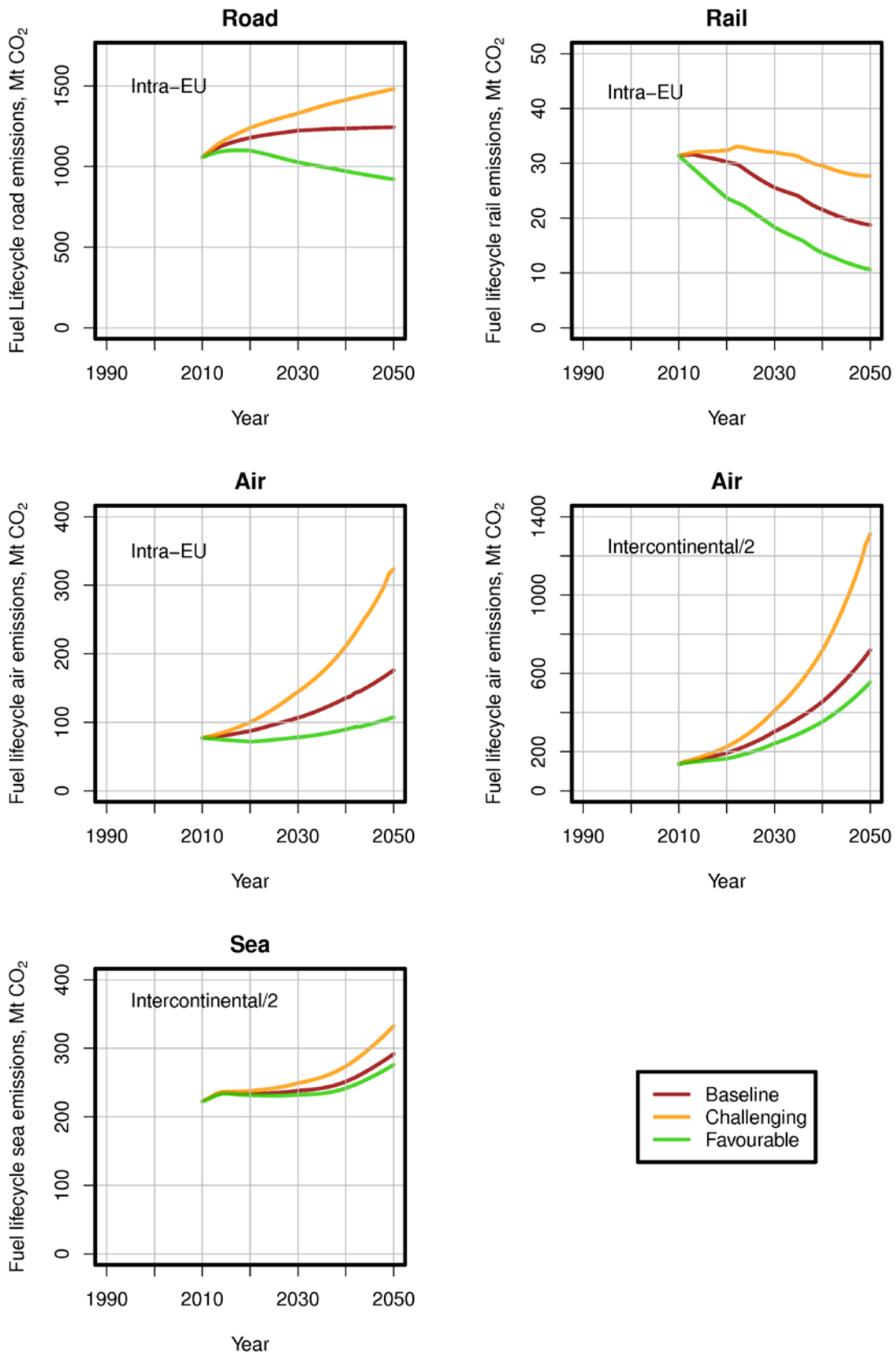**Figure 15. EU27 direct transport emissions to 2050 by mode and scenario, in comparison with past data.**

Figure 16. EU27 fuel Lifecycle transportation emissions to 2050 by scenario and mode.

3.3 Carbon Dioxide Emissions

Figure 15 shows direct CO_2 emissions, by mode, for the no-new-policy case to 2050. Corresponding charts for fuel lifecycle emissions, which include emissions associated with fuel production and distribution, are shown in Figure 16, and an overview of total emissions including current and suggested future EU emissions targets is given in Figure 17. A few general features are notable. First, total transport emissions grow in all scenarios. This is even the case for the Favourable scenario in which GDP growth is low, fuel prices are high and the carbon intensity of electricity generation strongly decreases. A comparison of the emissions-by-mode plots confirms that this growth is primarily due to the rapid projected growth of aviation emissions. As noted above, this results from a combination of strong growth in demand for air travel and a relative lack of technology options for reducing per-plane emissions. It is also notable that the geographic location of emissions is projected to change. In the Favourable scenario, emissions from road and rail sources decrease, and emissions from intra-EU aviation remain relatively flat. Therefore a small decrease in total intra-EU emissions is observed. However, intercontinental emissions, primarily from intercontinental air passenger and marine freight transport, continue to increase. This results from projected GDP increases in regions outside Europe. Even conservative projections of growth in countries such as China, India and Brazil are significantly higher than optimistic growth projections for Europe (e.g. Duval & de la Maissoneuve 2010). This effect is most notable in the Challenging scenario, in which the growth in aviation is strongest.
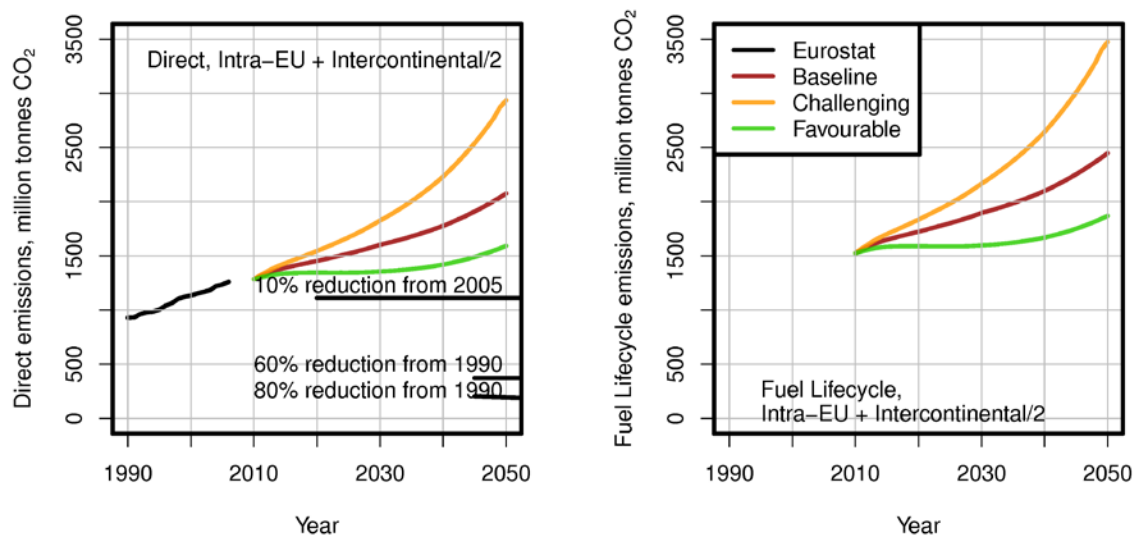

Figure 17. Total direct and fuel lifecycle emissions from all transport sources modelled in TOSCA, by scenario, in comparison to suggested EU emissions targets.

CO_2 emissions trajectories also show the influence of the timescales of technology availability. This is most notable for shipping, for which an initial increase in emissions flattens out, but then increases again in the 2030-2050 period. This arises because the shipping technologies considered are all available from 2010. An oversupply of ships means that demand for new ships is initially low, so new technology penetration is low for the first

few years and emissions increase. Thereafter, emissions flatten out as fleet growth is balanced by fuel use reductions per tkm from technology adoption. After 2035, new technology is widespread in the fleet. This means that further per-tkm emissions reductions from utilising more of that technology are limited. However, demand is still increasing. Therefore emissions start to rise again.

Finally, it is notable that none of these scenarios meets EU current or suggested future emissions targets (Figure 17). These targets are discussed further in the WP7 final report on policies. All the technologies in TOSCA WP 1-5 are associated with a date of market readiness. Most of the technologies which could produce a significant reduction in emissions have dates of market readiness close to or after 2020. This means that any year-2020 target is very difficult to meet using these technologies, because even if they are adopted by 100% of new vehicles, they will only have a widespread impact on emissions over fleet turnover timescales of potentially 10-20 years. However, none of the scenarios meet the year-2020 goal of a 10% reduction in emissions from year-2005 values in 2050, either. In the most extreme case, year-2050 emissions are more than ten times as large as the emissions total that would be required for an 80% reduction in emissions compared to year-1990 levels. However, such a level of reduction in emissions may be required to meet EU climate goals of limiting global temperature increase to 2°C (EC 2011). This suggests that significant additional policy intervention will be needed to meet these goals.

3.4   Public finance implications

The no-new-policy case looked at in this report assumes that governments will apply no new taxes or subsidies above those in place at the moment. However, this does not mean that revenues from taxation will remain constant. Figure 18 shows EU27 fuel tax revenues at a percentage of GDP (left-hand panel). This value is currently around 1.4% (Eurostat 2009). Although fuel taxation is not reported separately from energy taxation by Eurostat prior to 2007, total EU27 energy taxation receipts (of which fuel taxation is the main component) have moderately decreased over the period since 1995, from around 2.1% of GDP to around 1.8% of GDP. For comparison, transport infrastructure spending in the EU-15 countries is around 1% of GDP (EEA 2002), or which 62% is on road infrastructure and 29% on rail infrastructure; car registration taxes amount to around 0.1% of EU27 GDP, and total EU27 tax receipts (including social contributions) have remained relatively constant at around 40% of GDP over the 1995-2010 period (Eurostat 2011). The relative constancy of tax receipts as a proportion of GDP implies that any shortfall from decreased fuel tax income would probably be compensated for by increased taxation elsewhere.

Despite the lack of new policy interventions, fuel tax revenue in the simulations carried out for this report decreases to around 0.7 – 0.9 percent of GDP over the period to 2050, depending on scenario. This effect arises from several factors. First, there is some increase in the use of CNG and LPG as transport fuels. These fuels are typically taxed at a lower rate (Annex A). Second, all modes are becoming more fuel-efficient, so the same amount of transportation results in lower fuel burn and hence lower tax revenues. This is particularly important for road vehicles, which make up the majority of the emissions. Although the reference technologies still dominate the fleet in 2050, it has been assumed that reference

technology new-vehicle fuel use per vkm will decrease by 0.9% per year, due to incremental improvements. Third, many of the fastest-growing emissions sources attract low or zero rates of tax currently. For example, fuel taxation on international flights is prohibited by the Chicago Convention. Finally, although total fuel use is still increasing, it is doing so at a slower rate than the assumed rate of increase of GDP. This is the reason that the Favourable scenario, with its low GDP growth, has the highest fuel tax revenue as a percentage of GDP of the three scenarios. This decrease – of up to 0.7% of GDP – in tax revenues is significant, and suggests that in reality taxation regimes would be altered to maintain revenue, either by increasing excise duty, imposing carbon taxation, or increasing taxation outside the transportation sector.
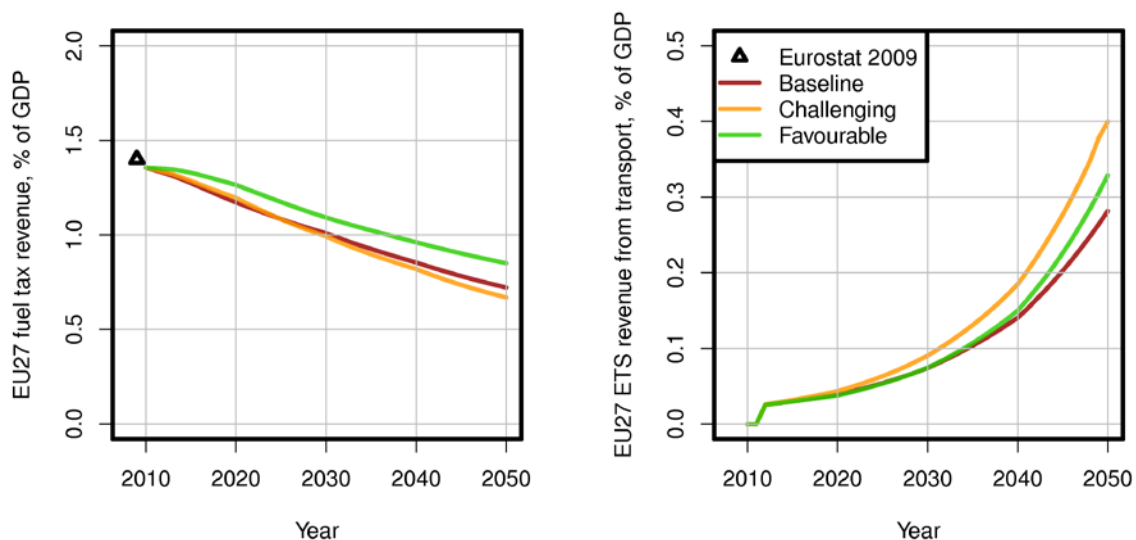
Figure 18. EU27 total transportation fuel tax revenue, and net payments from transport to other sectors in the EU ETS, by scenario to 2050.

In the right-hand panel of Figure 18 we show the total payments from transportation modelled by TOSCA into the EU emissions trading scheme. In the case detailed in this report, only aviation is directly included in the EU ETS (from 2012). Note that TOSCA models half of intercontinental aviation demand only, whereas the ETS applies to all flights to or from the EU. Therefore the total revenue from all applicable flights will be greater than that shown here. The effects of transportation on other ETS sectors, such as the electricity generation sector, are also neglected here. Total ETS payments from aviation are smaller than fuel tax revenues, but still amount to several tenths of a percent of GDP by 2050. However, unlike the fuel tax revenue discussed above, emissions trading payments will go directly to other sectors to fund emissions reductions which are achievable at lower cost than those available in transportation. This represents an extra source of emissions reduction which is not modelled in detail here.

4   Conclusions

This report investigates EU27 transportation emissions trajectories to 2010 over a range of future scenarios for factors affecting transportation demand, in the case that no new

policies are put in place. It builds on estimates of current and future technology characteristics by TOSCA WP1-5 and scenarios developed by TOSCA WP6. The model set developed here will be further used to look at system effects of policy in the TOSCA WP7 report.

Under the assumptions detailed in this report, total (intra-EU plus intercontinental bunker fuel) transport emissions will continue to grow to 2050 in all scenarios, even when economic conditions favour slow growth in transportation, fuel prices are high, and the carbon intensity of electricity generation is low. The majority of this emissions growth comes from air and to some extent sea transportation. In particular, intercontinental air emissions grow strongly in all scenarios, a result which is in line with industry forecasts for aviation growth. In contrast, road and rail emissions may see small decreases to 2050 under scenario conditions favourable to low emissions. The spread in emissions outcomes is large, with emissions potentially double those of the Favourable scenario when conditions are more challenging for emissions reduction. Because much of the emissions growth is in intercontinental passenger and freight travel, a decrease in emissions in the no-new-policy case is also possible if only intra-EU emissions are considered. As there is no widespread adoption of alternative fuels, direct and fuel lifecycle emissions display similar behavior.

These results reflect a distribution of underlying technology which does not change significantly from the present day to 2050. Widely-adopted technologies, such as reduced rolling resistance for heavy trucks, are not radically different to existing ones and, although the balance of fuels used changes, no new fuel makes a significant impact on the EU27 transport system. However, many technologies and fuels are absent from the runs carried out in this report because the R&D required to produce a version of the technology that could have significant market impact would require additional government intervention in the form of new policies. The underlying technology distributions are also not strongly sensitive to scenario (apart from there being more vehicles in total in scenarios with higher demand). This in part reflects the effect that current levels of excise duty have in reducing the variability of fuel price with respect to variability in feedstock prices; it also reflects the influence of costs which do not depend on scenario variables (e.g. capital cost or maintenance). Although these technology adoption results are dependent on a large number of assumptions, they are in line with other projections which exclude new policies.

These results suggest that policy intervention is vital if EU27 transport emissions are to be reduced. In particular, they suggest that policies aimed at supporting technology R&D may have a vital role to play in lowering EU27 transport emissions, although such policies on their own may not be sufficient. These issues are explored further in the TOSCA WP7 report on Policies.

Acknowledgments

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Annex A. Fuel prices and availability

A1. Fuel Prices

Many of the promising technology options identified in TOSCA rely on the use of new, low-carbon transportation fuels. In addition, present-day fuels make up a varying proportion of European transport costs by mode. For example, for rail transport, fuel costs are typically only around 10% of total operating costs (Andersson et al. 2010), whereas for air transport fuel currently makes up about a third of total operating costs (Vera-Morales et al. 2010). Future changes in fuel costs and availability, both for existing and for new fuels, could have a strong effect on the uptake of new technology and hence on total EU27 transport emissions. This section describes the treatment of fuel costs in TOSCA and, for fuels whose availability is likely to be limited, the treatment of those limitations.

In this study, we concentrate our analysis mainly on those future fuels identified as 'promising' by TOSCA Work Package 4 (Perimenis et al. 2010). A summary of the fuels we consider for this stage of TOSCA is given in Table 3.

Table 3. Reference and future fuel options considered in this stage of TOSCA

Fuel	Feedstock	Used by	Possible blend with	Assumed Limits
Gasoline	Oil	Cars, Light Trucks	Ethanol (E85, E10)	No
Diesel	Oil	Cars, Trucks, Trains	FT diesel (B5)	No
Electricity	-[7]	Cars, Trains	-	No
Jet A	Oil	Aircraft	HVO, FT Jet A	No
Heavy Fuel Oil	Oil	Ships	-	No
Ethanol	Wood	Cars	Gasoline (E85, E10)	Yes
Bio-SNG	Wood	Cars	CNG	Yes
CNG	Natural Gas	Cars	Bio-SNG	No
LPG	Oil, Natural Gas	Cars	-	No
HVO	Palm Oil	Aircraft	Jet A, FT Jet A	Yes
FT diesel	Wood	Cars, Trucks	Diesel	Yes
FT Jet A	Wood	Aircraft	Jet A, HVO	Yes
Hydrogen	Natural Gas	Cars, Light Trucks	-	No
Hydrogen	Wood	Cars, Light Trucks	-	Yes

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[7] The electricity price and carbon intensity of electricity generation are TOSCA scenario variables. However we do not directly model in detail which energy sources are used to generate electricity.

Many future alternative fuels will (at least initially) primarily be available as blends with existing fuels. The specific blends we consider are E10 (10% ethanol, 90% gasoline; usable in existing gasoline vehicles), E85 (85% ethanol, 15% gasoline; requires specially adapted vehicle) and B5 (95% Diesel, 5% biodiesel; usable in existing diesel vehicles).
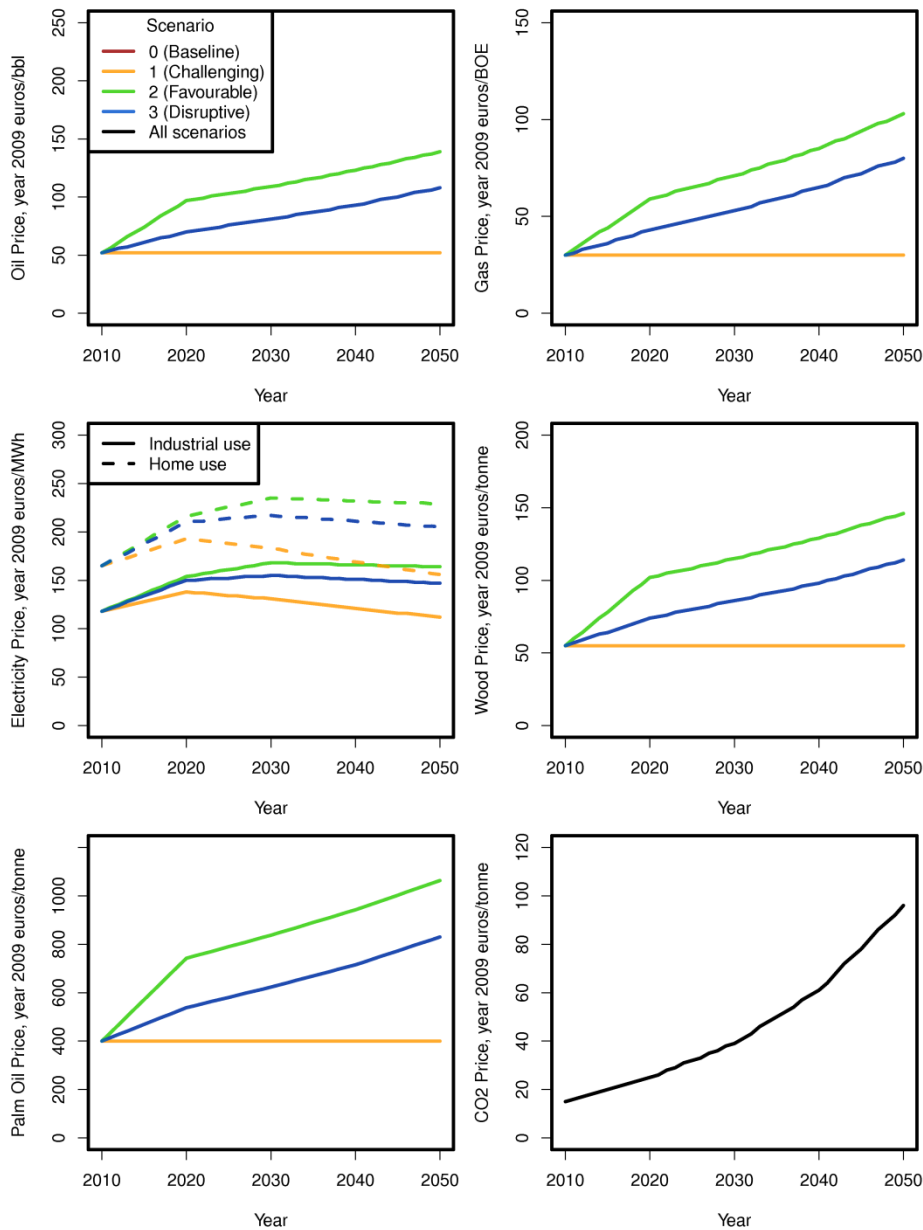
Figure 19. Scenario variables which affect fuel price, including for the disruptive scenario (Annex C). Where the baseline scenario is not shown, it is identical to the disruptive scenario.

Estimates of the production and distribution costs, and the associated uncertainty bounds, for these fuels were made in TOSCA Work Package 4 for a specific set of scenario parameters (Perimenis at el. 2010). However, the final fuel price as seen by transport users will be a function of scenario variables such as oil and gas price, and policy variables such as excise duty, the rate of VAT charged on fuel, and the carbon price. In addition, fuels based

on agricultural feedstocks such as wood or palm oil are likely to face limitations in their production capacity based on factors such as land availability and food security. The treatment of these factors and limitations is described below.

Scenario Inputs

The costs associated with refining and distributing a fuel, or in manufacturing a vehicle which uses that fuel, are likely to be relatively independent of scenario. However, fuel prices will vary strongly by scenario because of different assumptions about feedstock prices. The main scenario variables which affect fuel price are shown in Figure 19. Oil and gas prices directly affect the price of gasoline, diesel, Jet A, HFO, CNG and LPG. Wood prices affect the price of ethanol, SNG and biodiesel. Palm oil prices affect the price of HVO. In addition, carbon prices may affect the effective price of fuel for transportation modes affected by the EU Emissions Trading Scheme (ETS). Our assumption about the growth of palm oil and wood feedstock prices to 2050 is that they will follow oil price growth.

For brevity, we will show results from the baseline scenario in the remainder of this section.

Production, Distribution and Taxation

The final fuel price as experienced by transport users is a function of the feedstock price, the extra costs to refine and distribute the fuel, and taxation:

$$Fuel\ Price = (Production\ Cost + Distribution\ Cost + Excise\ Duty) * (1 + VAT\ rate).$$

The estimated production (including feedstock) and distribution costs used in TOSCA are given in Perimenis et al. (2010). For alternative fuels, production costs are given as functions of feedstock price and technology maturity (e.g. Perimenis et al. 2010, Figure 18). These relationships are used to estimate production costs in TOSCA by year and scenario. For reference fuels, we assume that only the feedstock costs will change, and other production costs will remain constant.

Taxation levels differ by country and by fuel. For road fuels, the final fuel price is often more than 70% tax at present-day levels. In contrast, for Jet A for international flights, fuel taxation is directly prohibited by the Chicago Convention (ICAO 1944). This means that the responsiveness of fuel price to a change in feedstock costs can vary dramatically. If 70% of the price of a fuel is components which do not vary with feedstock costs (e.g. excise duty), then a doubling in feedstock costs would result in only a 30% increase in fuel price.

For runs in which no new policies are assumed, we assume that existing policies, including excise duty on fuel and VAT rates, remain unchanged from present-day values. These values are taken from published tables of by-country taxation (EC 2010). For biofuels we use the present-day taxation values from Kutas et al. (2007). In scenarios run with no extra policies, we assume excise duty and VAT rates will remain constant to 2050, even if biofuel use becomes much greater. A summary of the values used in TOSCA is given in Table 4.

In the case of fuels whose availability is likely to be limited, the fuel cost will also be a function of the amount of fuel available. However, this is potentially complex to model, as it requires a set of assumptions about how prices will vary in response to fuel scarcity. For simplicity, we do not model this effect. However, we do impose limits on fuel availability, as further discussed below.

Table 4. Excise Duty and VAT for selected fuels.

Country	Excise Duty per litre fuel, year 2009 euros						VAT rate[8]
	Gasoline	Diesel	CNG	LPG	BioEthanol	BioDiesel	
Austria	0.442	0.375	0.0000684	0.141	0.000	0.000	20.00
Belgium	0.613	0.352	0.000	0.000	0.000	0.000	21.00
Bulgaria	0.350	0.306	0.000	0.094	0.000	0.000	20.00
Cyprus	0.298	0.245	0.000107	0.068	0.000	0.000	15.00
Czech Republic	0.505	0.431	0.000	0.084	0.000	0.000	20.00
Germany	0.654	0.470	0.000160	0.097	0.470	0.470	19.00
Denmark	0.570	0.386	0.000445	0.264	0.000	0.000	25.00
Estonia	0.423	0.393	0.000	0.068	0.000	0.000	20.00
Spain	0.456	0.331	0.0000475	0.031	0.000	0.000	16.00
Finland	0.627	0.364	0.0000240	0.000	0.319	0.319	22.00
France	0.543	0.446	0.000	0.058	0.330	0.330	19.60
Greece	0.410	0.428	0.000	0.068	0.302	0.302	19.00
Hungary	0.444	0.360	0.000	0.096	0.000	0.000	25.00
Ireland	0.543	0.449	0.000	0.068	0.000	0.000	21.00
Italy	0.564	0.423	0.00000322	0.123	0.275	0.275	20.00
Lithuania	0.434	0.274	0.000262	0.164	0.000	0.000	21.00
Luxembourg	0.462	0.310	0.000	0.055	0.442	0.442	15.00
Latvia	0.379	0.330	0.000110	0.069	0.000	0.000	21.00
Malta	0.459	0.352	0.000	0.000	0.000	0.000	18.00
Netherlands	0.714	0.421	0.00019	0.083	0.668	0.668	19.00
Poland	0.391	0.302	0.000	0.104	0.390	0.390	22.00
Portugal	0.583	0.364	0.000115	0.059	0.364	0.364	20.00
Romania	0.348	0.293	0.000107	0.069	0.000	0.000	19.00
Sweden	0.374	0.425	0.000140	0.090	0.000	0.000	25.00
Slovenia	0.489	0.432	0.0000362	0.068	0.000	0.000	20.00
Slovakia	0.514	0.368	0.000152	0.140	0.000	0.000	19.00
United Kingdom	0.617	0.617	0.000230	0.167	0.289	0.289	17.50

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[8] Note that some alternative fuels in some countries attract a lower rate of VAT. The VAT rate shown is the one which applies to gasoline.

Gasoline and Diesel

Figure 20 shows historical gasoline and diesel prices for the UK (DECC 2010) with and without tax, oil prices, and TOSCA projections to 2050. In the UK, excise duty is a high proportion of fossil fuel prices. This means that fuel price changes are often not very sensitive to oil price changes, as shown in the lower panel of Figure 20. Although the oil price increases to a level that is just over double that in 2010, gasoline and diesel prices do not increase more than 40% above the year-2010 level.
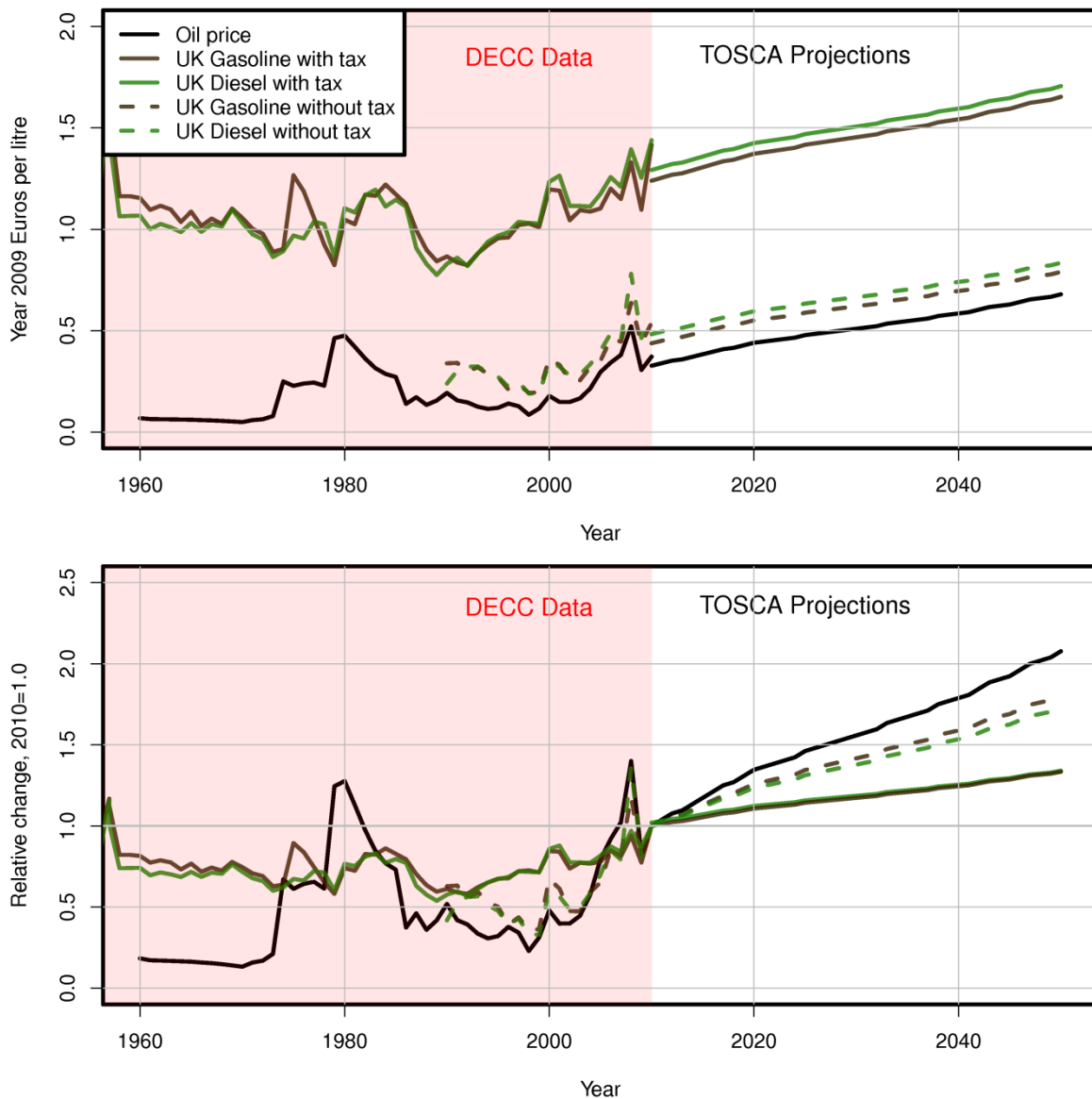
Figure 20. Gasoline and Diesel prices for the UK, past values from DECC (2010) and TOSCA estimates for the baseline scenario to 2050.

Jet A, HVO and HFO

TOSCA projections for the price of Jet A, HFO and HVO are shown in Figure 21. As for Figure 20, the upper panel shows absolute prices, and the lower panel the change relative to 2010. As Jet A for international flights is assumed to be untaxed, the Jet A price is much more sensitive to changes in oil price than gasoline is. HVO from palm oil is one alternative to Jet A considered in

TOSCA; the other is Fischer-Tropsch Jet A from wood feedstock, which is assumed to be priced similarly to untaxed Fischer-Tropsch diesel from wood feedstock (Figure 23). As the distribution and production costs of HVO are uncertain variables, the green band shows the range of final output HVO prices for 1000 runs. The solid green line shows the price at TOSCA estimate 'most likely' values for all input variables. As the most likely values of production and distribution costs for HVO are close to the low end of the range between the upper and lower bounds given (Perimenis et al. 2010), this price is at the bottom end of the range of output prices[i]. For the input assumptions used here, the price of HVO remains above that of Jet A, even when aviation's inclusion into the EU ETS is included. The price of HFO remains close to or below the oil price, as it has done historically.
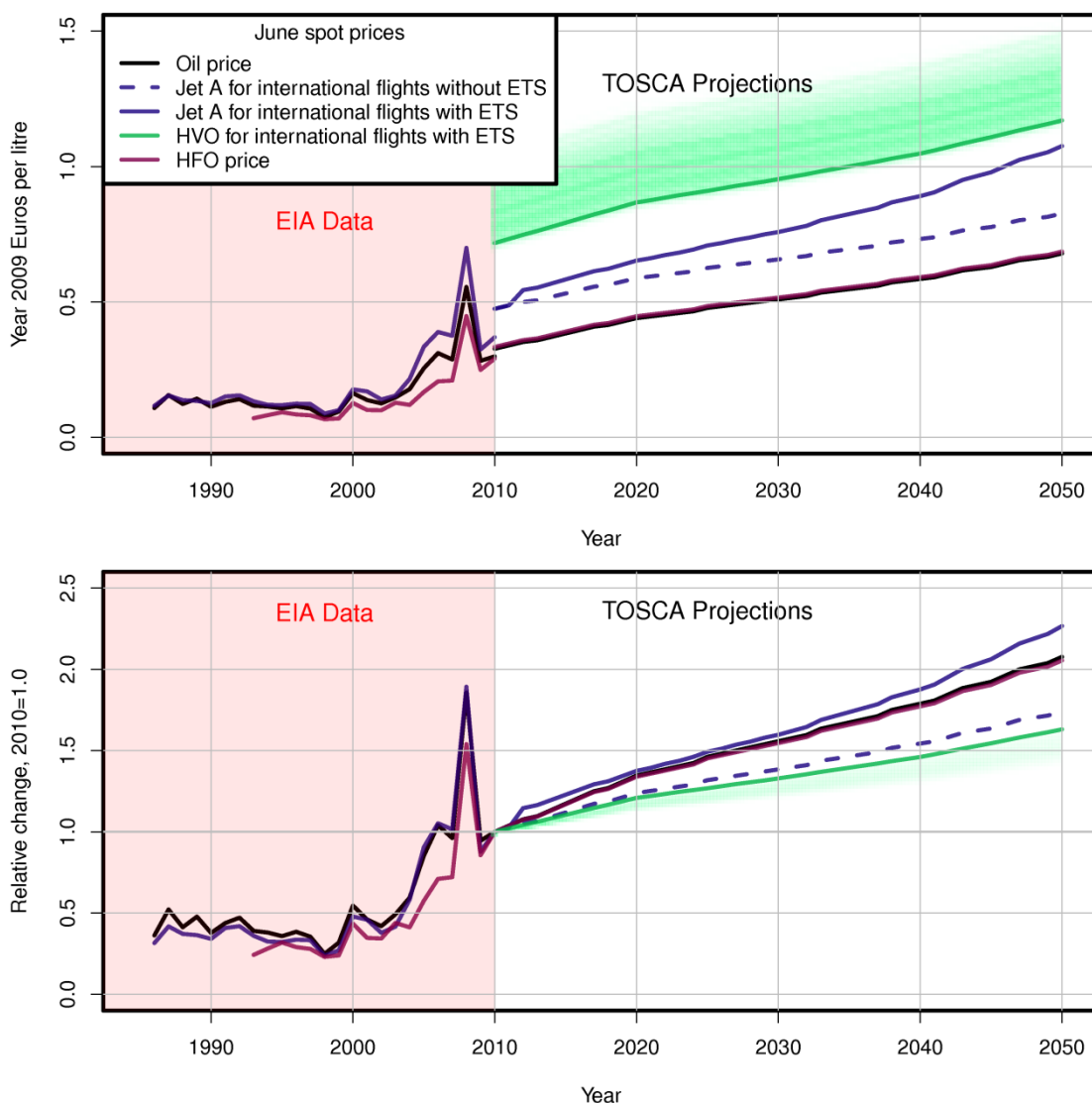

Figure 21.TOSCA projections of the price of Jet A for international flights, HFO and HVO, compared with past data for Europe from EIA (2010).

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[i] This is because the upper and lower bounds were derived from the TOSCA expert questionnaires, rather than being direct estimates made by TOSCA WP4.

Following feedback from workshop participants at the TOSCA scenarios workshop about emissions from land-use change when producing HVO from palm oil, we exclude HVO from the cases presented in this report; Fischer-Tropsch Jet A from wood feedstock, as mentioned above, is used as the main alternative fuel for aviation.
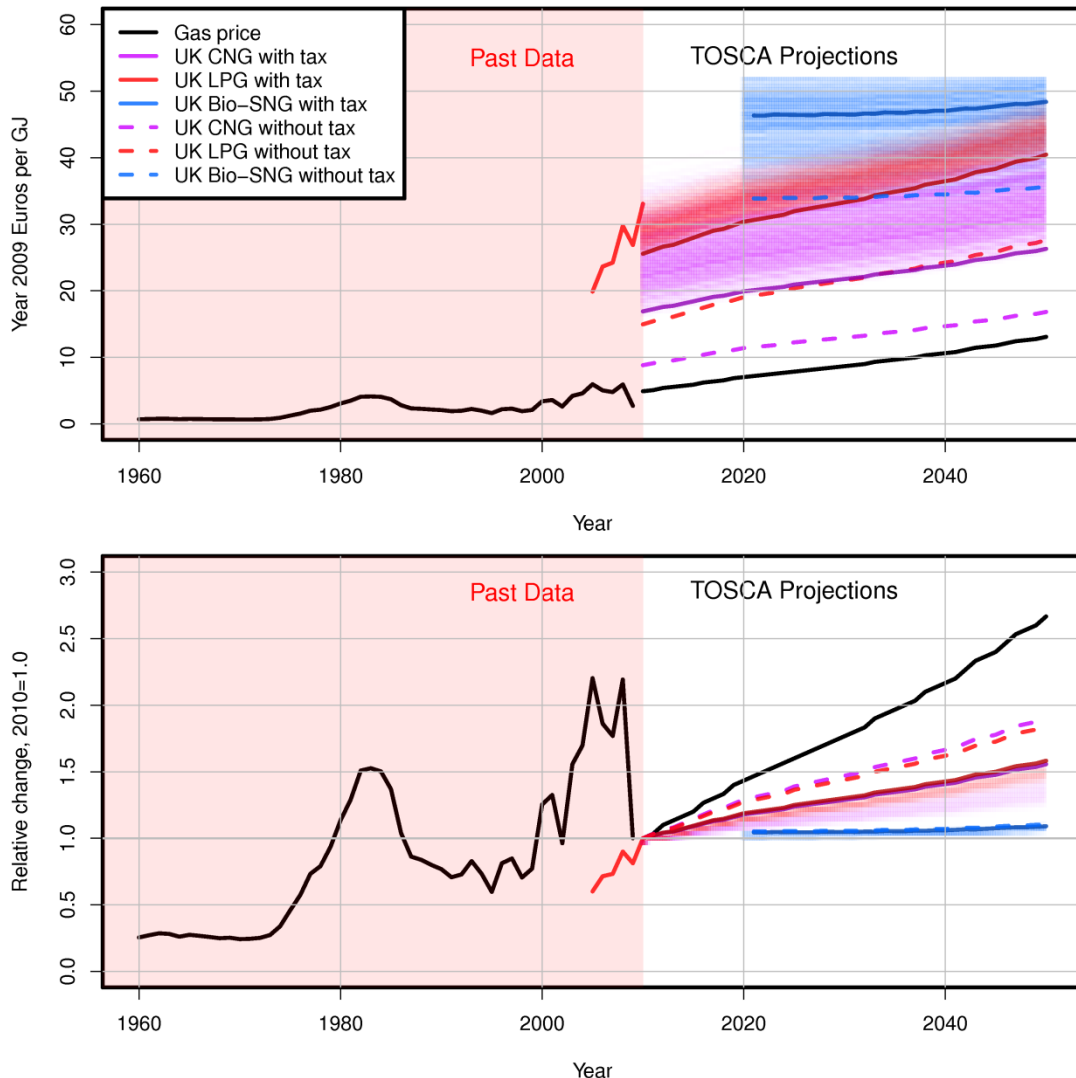
Figure 22. TOSCA projections of the baseline scenario UK price of CNG, LPG and Bio-SNG from wood feedstock, compared with historical data (whatgas.com 2010).

CNG, LPG and Bio-SNG

Figure 22 shows TOSCA projections of the UK prices of CNG, LPG and Bio-SNG (from 2020). As for HVO, the production and distribution costs of CNG, LPG and SNG are considered uncertain variables, so the ranges of output costs are shown. Although the prices without tax are also subject to uncertainty, only the uncertainty ranges for the values with tax are shown, for clarity. No direct substitute for LPG is assumed, but Bio-SNG is assumed to be a direct substitute for CNG. Initially, the Bio-SNG price is significantly above that of CNG. By 2050, there is some overlap in the distributions, primarily due to the assumed learning rate applied to CNG costs (Perimenis et al. 2010). This could mean that in some runs CNG vehicles will start using Bio-SNG by 2050, if it is available.

Other Fuels

Figure 23 shows the TOSCA baseline scenario projected UK price of ethanol from wood feedstock and Fischer-Tropsch diesel from wood feedstock, compared to past data (DECC 2010) and TOSCA projections for diesel from oil. Note that only the central values are shown for F-T Diesel, as no expert estimates were made of the uncertainty distribution. F-T Diesel is assumed to be a direct substitute for fossil fuel diesel. Under the assumptions made in TOSCA, it is expected to be less expensive than UK fossil fuel diesel from its introduction in 2025, and will therefore be an attractive option. This is due primarily to the lower rate of tax currently charged on biodiesel, as without tax fossil fuel diesel is the less expensive fuel to 2050. A similar plot for hydrogen is shown in Figure 24. Note that expert estimates were not obtained for hydrogen from wood feedstock, so no uncertainty distribution is shown. However, for model runs it was assumed that the uncertainty was similar to that for hydrogen from natural gas.
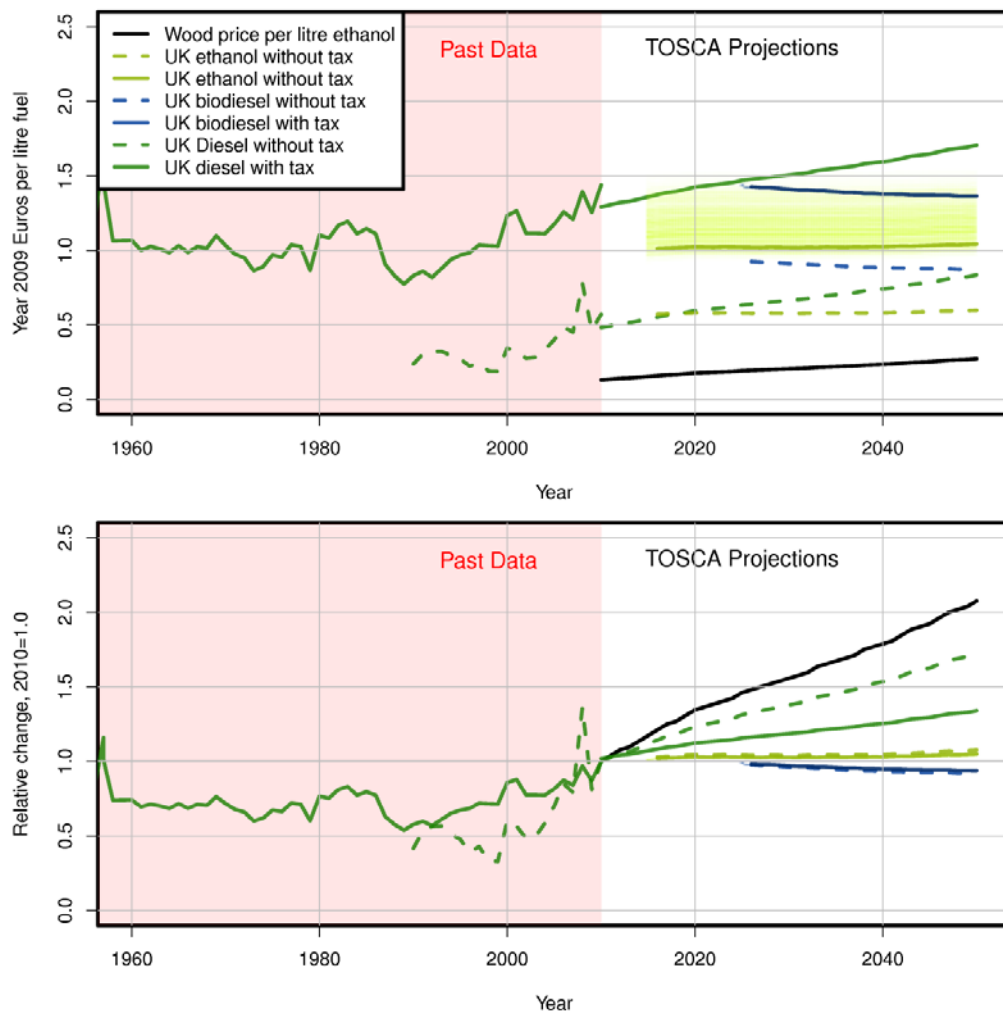
Figure 23. TOSCA projections of the price of biodiesel and bioethanol from wood, compared to past data (DECC 2010) and future TOSCA projections for diesel from oil.
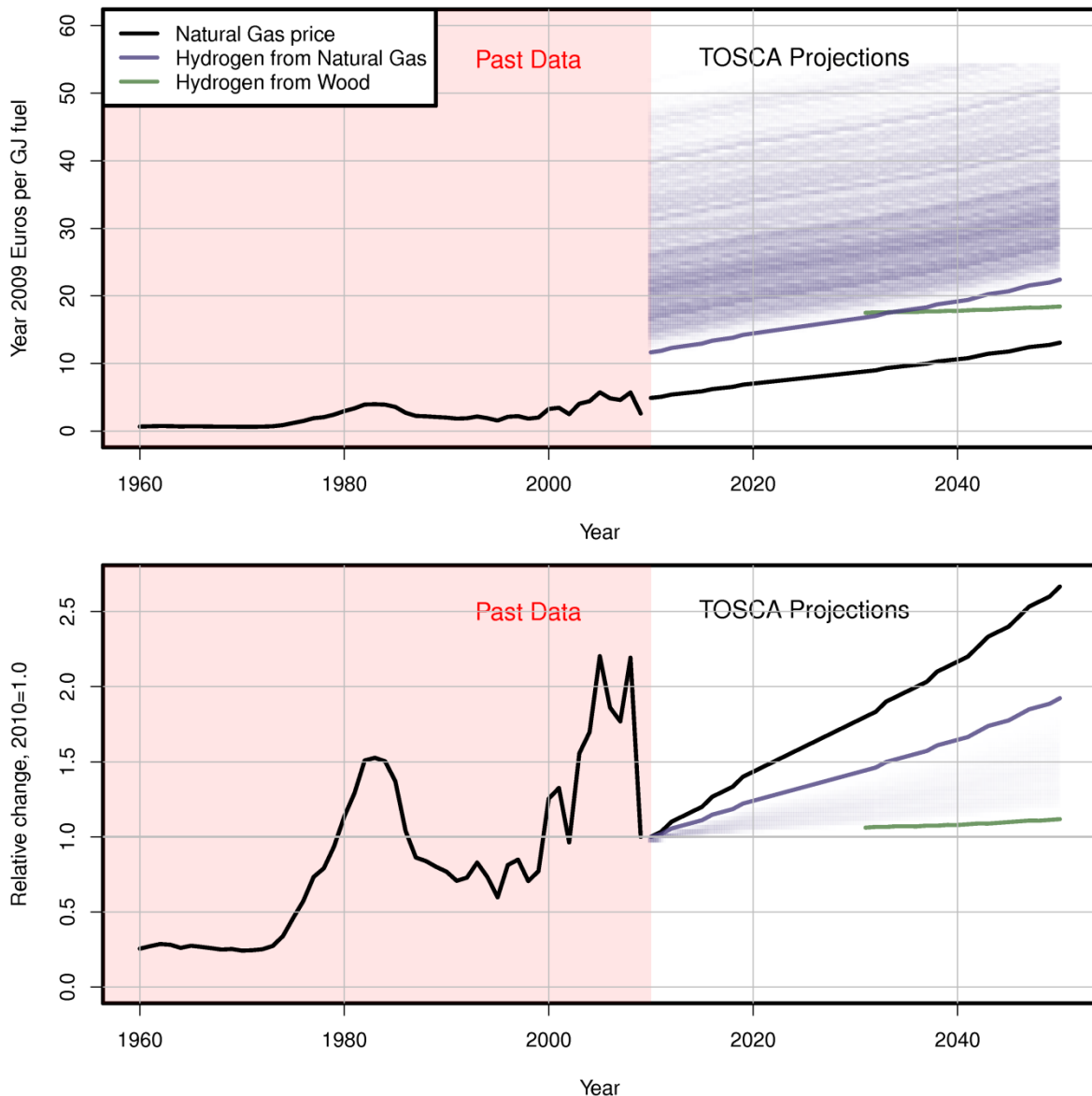
Figure 24. As Figure 23, but for hydrogen in comparison to natural gas prices.

A2. Fuel Limits

Estimates vary widely as to the achievable production capacity for biofuels in the EU27 over the next 40 years. The availability of biofuels depends on the amount of agricultural land available (which may be affected by fuel vs. food considerations), whether importing biofuel into the EU27 is considered, the amount of biomass that is used for non-transportation processes, agricultural yields and the efficiency of the biomass to biofuel conversion process. Studies of the future biofuel production capacity have come to widely differing conclusions, depending on their assumptions about these factors. For example, Skinner et al. (2010) assume a biofuel share in transportation fuels of almost 100% by 2050, whereas OFID (2009) assume a 7.2% biofuel share in 2050 in their WEO scenario. A summary of existing studies and their implications for biofuel limitations, carried out by TOSCA WP4, is given below.

BIOFRAC(2006)

By 2030, domestic biomass availability will range between 243 and 316 Mtoe in the BIOFRAC Scenarios. Considering the lower bound and assuming a mean conversion factor of 40%, this would yield around 97 Mtoe of biofuels. Considering the upper bound and assuming an optimised conversion factor of 55%, this would yield around 174 Mtoe biofuels. Road transport energy demand in EU is projected to be around 360 Mtoe by 2030 (437 Mtoe including kerosene). If all biomass was dedicated to biofuel production, biofuels would then hold the technical potential of covering 27% up to 48% of the fuel demand. However, significant cost reductions would be needed to transform this technical potential to economic. BIOFRAC (2006) suggest that a cost reduction of 20% to 30% could be achieved by future technologies. Under these assumptions, covering 25% of EU road transport fuel needs in 2030 with biofuels is a realistic assumption. 50% of this supply would come from domestic production and 50% from imports. A biofuel production of 174 Mtoe is also adopted by Skinner et al. (2010)**.** It is however considered for 2050 and not 2030**.** According to the report this would result in an almost 100% replacement of combustion fuels by 2050.

REFUEL (2007, 2008)

In the REFUEL (2008) *baseline*, the share of biofuels in gasoline and diesel supply equals the shares in the PRIMES EE scenario until 2030. This scenario is roughly based on implementation of current policies, without any additional efforts. In the *moderate case*, a pathway is analysed with minimal implementation of the new ambitions in the EU Energy Package and EU 2007 Spring Council. That is, it is assumed that the 2010 target of 5.75% biofuel use in transport is not met, and a 10% target for biofuels in 2020 is implemented. In a linear extrapolation, a 2030 target of 15% is assumed. In the *high case*, a pathway is analysed in which the 2010 target is met. The 2020 target is based on what is considered an ambitious level in the Biofuels progress report and its accompanying working document, viz. 14%. For 2030, a 25% target is used, derived from the ambition level of the Biofuels Research Advisory Council (BIOFRAC, 2006).

Table 5. Biofuel target percentages from REFUEL (2009).

Case	2010	2015	2020	2025	2030
Baseline	4.0	5.7	7.4	8.4	9.1
Moderate	5.0	7.5	10.0	12.5	15.0
High	5.8	9.9	14.0	19.5	25.0

For the EU27+ the analysis in REFUEL (2007) shows that if all the agricultural land potentially available for biofuels could be used for cultivation of the most energy-efficient bio-fuel feedstock, then by 2030 up to 50% of projected transport fuel consumption could be produced within the EU.

iTREN-2030 (2010)

The share of biofuels in transportation energy demand is shown in table 4. For 2030, 10-16% of total transportation energy demand is projected to be supplied by biofuel.

Table 6. Share of biofuels in transport energy demand in iTREN-2030 (2010).

(in Mtoe)	2020		2030	
	Reference	Integrated scen.	Reference	Integrated scen.
% share	6.6	9.8	9.9	16 (or 15)

IEA (2009a)

Biofuels represent 5% of *world* transport fuel in 2020 and 9.3% in 2030, according to the IEA's World Energy outlook (IEA 2009a). A summary of the development of biofuel use in the EU is given in Table 5.

Table 7. Biofuel share in the *EU* transport sector (p. 336, Table 9.8)

(in Mtoe)	2007	2020		2030	
		Reference	450 Scenario	Reference	450 Scenario
Energy demand	335	346	313	350	302
Biofuels	8	25	25	26	42
% share	2.4	7.2	8.0	7.4	13.9

OFID (2009)

Table 6 shows the development of transportation biofuel use in Europe and Russia to 2050 by scenario from OFID (2009).

Table 8. Final consumption of transport fuels (*Europe + Russia*)

(in Mtoe)		2000	2020	2030	2050
	Total	519	658	652	609
Scenario WEO	Biofuels	-	20 (2015	31	44
	% Share	-	-	4.7	7.2
Scenario TAR	Biofuels	-	35 (2015)	67	85
	% Share	-	-	10.3	14

IEA (2009c)

Biofuels reach about 33% of total transport fuel (worldwide) use in BLUE Map in 2050, according to IEA (2009b)/ This includes about 30% of truck, aircraft and shipping fuel use and 40% of LDV fuel. Additionally, the BLUE Map scenario in Europe (OECD Europe + Eastern Europe) suggests around 25% biofuels in the total transport fuel demand.

Shell (2008)

According to Shell (2008), biofuels will constitute around 30% of liquid fuels (worldwide) by 2050.

IEA (2009c)

Energy demand from global transportation, estimated at 2,140 Mtoe in 2005, was projected to exceed 4,700 Mtoe in 2050 in the IEA (2009c) baseline scenario. In the baseline, biofuels stay below 100 Mtoe in 2050, and are mostly composed of first generation biofuels.

IEA (2009c) also explore an ACT Map scenario, which targets the reduction of year-2050 emissions to year-2005 levels. For this scenario, they estimate worldwide biofuel use of 570Mtoe (around 82% second-generation) in 2050, or 17% of total global transportation fuel demand (3,273 Mtoe). Their BLUE scenario estimates usage of biofuels at 700 Mtoe (around 87% second-generation), or 26% of global transportation fuel demand in 2050 (2,656 Mtoe).

TOSCA Assumptions

Based on the studies detailed above, for the TOSCA scenarios we assume the following limits for maximum biofuel production:

Table 9. Assumed maximum biofuel production (in Mtoe) by TOSCA scenario and year.

Scenario	2010	2020	2030	2040	2050
Baseline	8	25	67	76	85
Challenging	8	25	67	76	85
Favourable	8	25	67	76	85
Disruptive	8	25	67	76	85

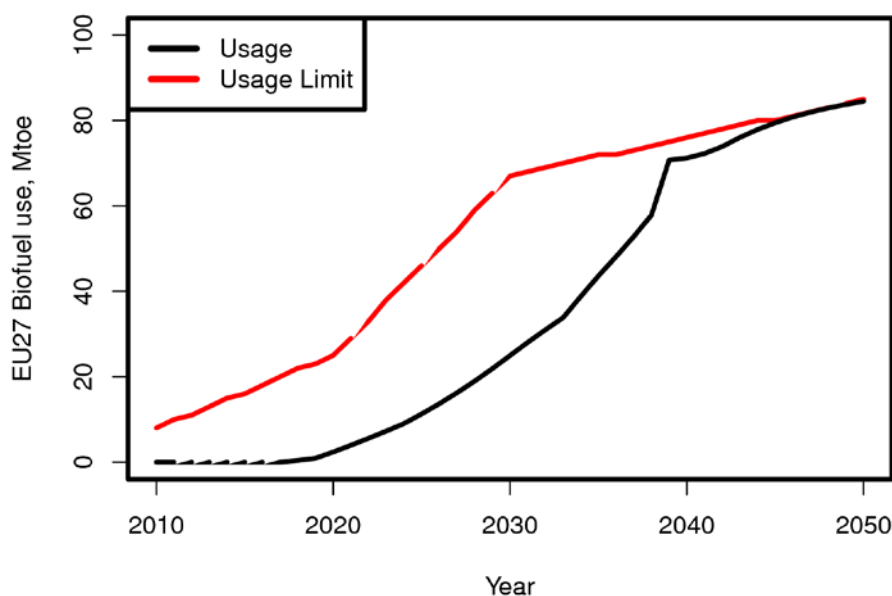**Figure 25. TOSCA baseline scenario biofuel use compared to model limits, assuming all technology options are available (i.e. R&D policies and infrastructure are in place) and all uncertain parameters are set to their most likely values.**

Whether or not these limits are reached depends on multiple factors. In particular, the TOSCA stock model can include uncertainty in input parameters, including biofuel production and

distribution costs (Annex C). This means that the outcome in terms of whether alternative fuels become a lower-cost option than the reference fuel set can in some cases vary between individual model runs. When the baseline scenario is run with all uncertain input variables set to the most likely value, and all technologies and fuels available, the limit on biofuel production would be met in 2039 without constraints on biofuel use (Figure 25).

In reality, as the limit of biofuel production is approached, the price of individual biofuels is likely to increase. However, this effect is not straightforward to model within the scope of the TOSCA project. Therefore, we simply assume that there is a hard limit on the availability of fuel independent of the price. As the limit is approached, a proportion of the demand for new biofuel-using vehicles is substituted for the lowest-cost non-biofuel option. If the limit is reached, no new vehicles which depend solely on biofuels are purchased, and the utilisation of older biofuel-using vehicles is lowered.

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Annex B. Model Parameters

B1. Elasticities derived from SUMMA

Many of the elasticities and cross-elasticities of demand used in this report were derived from runs using the SUMMA project's Fast Simple Model, as described in Section 3. A summary of the SUMMA-derived values used by mode, trip purpose and scope is given in tables B1 and B2 below.

Table B1: SUMMA-derived elasticities and cross-elasticities of demand for passenger transportation: summary

Quantity	Elasticity with respect to:			
	Change in car journey cost	Change in car journey time	Change in rail journey cost	Change in rail journey time
Car business pkm	-0.307	-0.668	0.053	0.069
Car leisure pkm	-0.336	-0.752	0.013	0.021
Train business pkm	0.238	0.914	-0.661	-1.61
Train leisure pkm	0.208	0.432	-0.273	-0.599

Table B2: SUMMA-derived elasticities and cross-elasticities of demand for freight transportation: summary

Quantity	Elasticity with respect to:			
	Change in lorry journey cost	Change in lorry journey time	Change in rail journey cost	Change in rail journey time
Lorry tkm (general freight)	-0.587	-0.611	0.329	0.279
Lorry tkm (bulk)	-0.754	-0.751	0.267	0.225
Lorry tkm (petroleum products)	-0.760	-0.887	0.228	0.272
Lorry tkm (urban, all commodities)[10]	-0.302	-0.135	0.019	0.017
Rail tkm (general freight)	1.27	1.34	-2.57	-2.01
Rail tkm (bulk freight)	0.853	0.932	-2.77	-1.29
Rail tkm (petroleum products)	1.08	1.14	-1.53	-3.86
Rail tkm (urban, all commodities)	0.351	0.818	-0.320	-0.64

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[10] Note that light duty trucks are assumed to be primarily used for urban freight transportation.

B2. Parameters related to technology adoption

Mode	Discount Rate	Scalability Limitations	Econ. lifetime, years	Sources
Marine Freight	8%	None	15	Same values as for aviation used
Road Passenger[11]	10%	LPG, CNG, HVO and battery electric	3	Greene et al. (2005) and references therein
Road Freight	10%	None	5	Brodrick et al. (2002); OECD (2001)
Air Passenger	8%	HVO	15	Morrell & Dray (2009); OECD (2001)
Air Freight	8%	HVO	15	Morrell & Dray (2009); OECD (2001)
Rail Passenger	8%	As in WP3 Passenger Report	15	OECD (2001); Andersson et al. (2011)
Rail Freight	8%	As in WP3 Freight Report	15	OECD (2001); Andersson et al. (2011)

The limitations specified above are as follows. LPG and CNG are existing fuels which in theory represent a cost saving in some cases today, but are not widely adopted

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[11] Light duty trucks are assumed to behave similarly to cars. Note that the values chosen differ strongly from those used in TOSCA WP1 as they are intended to simulate consumer myopia in purchasing decisions rather than the benefit to society of purchasing the technology.

because of complicating factors such as a lack of infrastructure, safety concerns, and consumer preference for established technologies. We apply limitations to the maximum share of vehicles using these fuels to represent these constraints. LPG is a refinery byproduct, and it is unlikely that production will increase above the fraction obtainable from current refining processes (around 10%). Therefore we limit LPG penetration to this value. Similarly, aggressive policy promotion and infrastructure for CNG vehicles in Argentina has resulted in only a 25% market share (e.g. Schäfer at al. 2009), likely due to the specific constraints involved in terms of vehicle range, fitting a suitable tank, and safety concerns. We take this value as an upper limit for European CNG vehicle market penetration.

For future technologies, similar factors may apply (for example, hydrogen fuel may be subject to safety concerns); however, they are difficult to estimate and we therefore do not apply specific limits. However, battery electric vehicles are limited to small and medium-sized vehicle types only, due to current constraints on their power and range. In addition, HVO penetration is assumed to be minimal in all cases, due to concerns raised during the TOSCA workshop series about land use change-related emissions from palm oil plantations.

B3. References

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Annex C. Sensitivities and Uncertainty

Projecting future quantities is inherently uncertain. There are at least three major sources of uncertainty in the TOSCA projections shown in this report. The first relates to the technology-related quantities estimated by WP 1-5. Here, uncertainty bounds were estimated as part of the WP 1-5 process. It is possible to propagate these uncertainties through the stock modelling framework to gain an idea of how much they affect the final results. A discussion of this process and some sample results for the no-new-policy case discussed here is given in Section C1 below. The second relates to uncertainty in scenario quantities, such as GDP growth or oil price. For this reason, a range of scenarios covering widely differing futures were chosen. However, all the main TOSCA scenarios include smooth growth in these quantities. In reality, factors such as oil price can be highly volatile and it is possible that this may affect emissions and policy outcomes. For this reason, a disruptive scenario including non-smooth trends was also generated during the scenario process. The outcome of running this disruptive scenario through the stock and emissions modelling is given in Section C2 below. The third relates to the models and assumptions used at each stage in the process, which in many cases included significant simplifications. Here it is useful to compare model outputs to those of alternative models based on different levels of complexity and different assumption sets. A comparison is included in Section C3 below.

C1. Uncertainty in Technology Characteristics

The output of TOSCA WP 1-5 involved estimates of quantities and values which are relevant but highly uncertain. These include the likely introduction dates of new technologies between now and 2050, the cost, fuel use and emissions characteristics of those technologies, and their likely impact in terms of user acceptability. They also include changes over time for existing technologies, for example incremental changes to current-technology internal combustion engine cars that reduce future fuel burn, or learning rates that represent changes in future production costs. Within WP 1-5, each uncertain quantity is accompanied by an estimate of the uncertainty bounds associated with it. In this section, we deal with these uncertainties by explicitly including them in TOSCA modelling via Monte Carlo analysis.

The uncertainty of technology characteristics is expressed in several ways within WP 1-5. Some uncertain quantities are given by a range (e.g. 5000-10000). Most are given as upper bound, lower bound and most likely values. For others, an explicit uncertainty distribution based on expert questionnaire responses is given. To utilise these numbers within TOSCA, we need to assign probability distributions in all cases based on the information available. Following the process used in Allaire (2010) we use the maximum entropy probability distribution for each type of information given. For values given as ranges, this is a uniform distribution between the bounds supplied. For values given as upper bound, lower bound and most likely value, this is a beta distribution (e.g. Ayyub & Klir, 2006). As the beta distribution has complexities

associated with its interpretation and computational use, we approximate it with a triangular distribution (e.g. Johnson 1997). Each uncertain TOSCA variable is then stored as a java object which contains information about the most likely value and upper and lower limits of that variable, along with the appropriate distribution to use and methods for initialising and storing randomly-distributed instances of that variable.
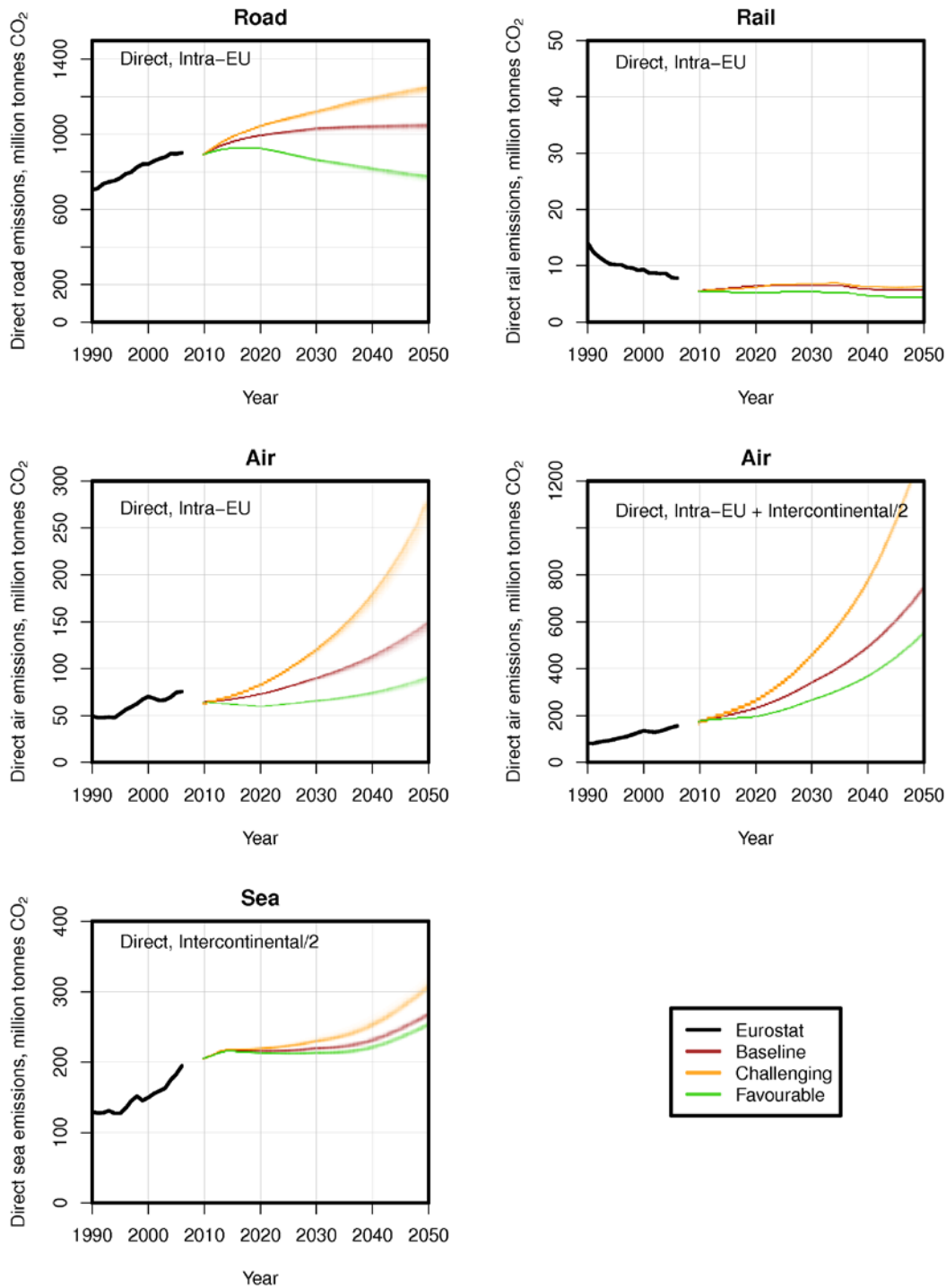

Figure 26. As Figure 15, but displaying the outcome emissions distributions of 2000 runs using uncertainty in technology characteristics.

As noted in the body of this report, the fleet and emissions modelling in TOSCA was assembled with the aim of achieving a low run time per individual run (around 1 minute). This means that Monte Carlo modelling over multiple sets of runs using instances of each uncertain variable selected from the appropriate probability distribution is possible. Although there are a large number of potentially-uncertain inputs to the TOSCA stock model, the focus of TOSCA is on the characteristics of present-day and future technologies. We therefore explicitly consider uncertainty only in these variables when carrying out Monte Carlo modelling. Uncertainty in base year fleet age distributions and retirement curves is not considered. Similarly, explicit uncertainty in future scenario variables such as oil or electricity prices is neglected; however, a range of possible futures is covered by the different future scenarios considered in TOSCA. We also assume that all uncertain variables are uncorrelated. This means that, for example, if an open rotor engine aircraft is estimated to become available sometime between 2020 and 2030, with an energy use of between 0.82 and 0.93 MJ/RPK, we assume that an 0.82 MJ/RPK open rotor is equally likely in 2020 as in 2030, rather than being more likely in 2030 due to increased development time.

Figure 26 shows the distribution of emissions outcomes in the no-new-policy case. Darker colours indicate more likely outcomes. As can be seen, the uncertainty associated with the difference between scenarios is much greater than the uncertainty associated with technology characteristics in this case. This reflects several factors. First, new technology uptake is relatively low. This means that the small uncertainties associated with existing technology, and how it develops into the future, are more influential here than the larger uncertainties associated with radical new technology. Second, many technologies which are adopted result in only small reductions in emissions. Although the difference between a 1% and a 2% reduction in emissions for one technology is important for that technology, in terms of total reduction in transport emissions it is relatively unimportant. Third, relatively few of the technologies investigated here represent a cost saving to consumers at one end of the uncertainty range but not the other. The nature of the decision criterion used (deterministic NPV) means that only the existence of a possible cost saving, not the amount of cost saving, changes the decision to adopt a technology. Therefore if the NPV of one technology is greater than the reference technology across the entire range of uncertain values, under the assumptions used here the decision is not affected by that uncertainty. Finally, the difference between scenarios is very large – over a factor of two in emissions in some cases. Typically, the uncertainty in individual technology characteristics is much less than this. These factors in combination mean that we would expect in the vast majority of scenario/policy combinations that variation between scenarios will be greater than the variation due to uncertain technology characteristics. Therefore we do not include distributions on the other plots in this report, although they are included in the other sections of this annex.

C2. Disruptive Scenario

The scenarios used in the body of this report represent a wide range of possible outcomes for variables that affect transport demand and emissions. However, they all assume smooth variation in input values. As described in Annex A of the TOSCA Scenarios report, a disruptive scenario was generated to test whether a disruptive event causing discontinuities in input values would produce different results from a scenario with smooth trends.
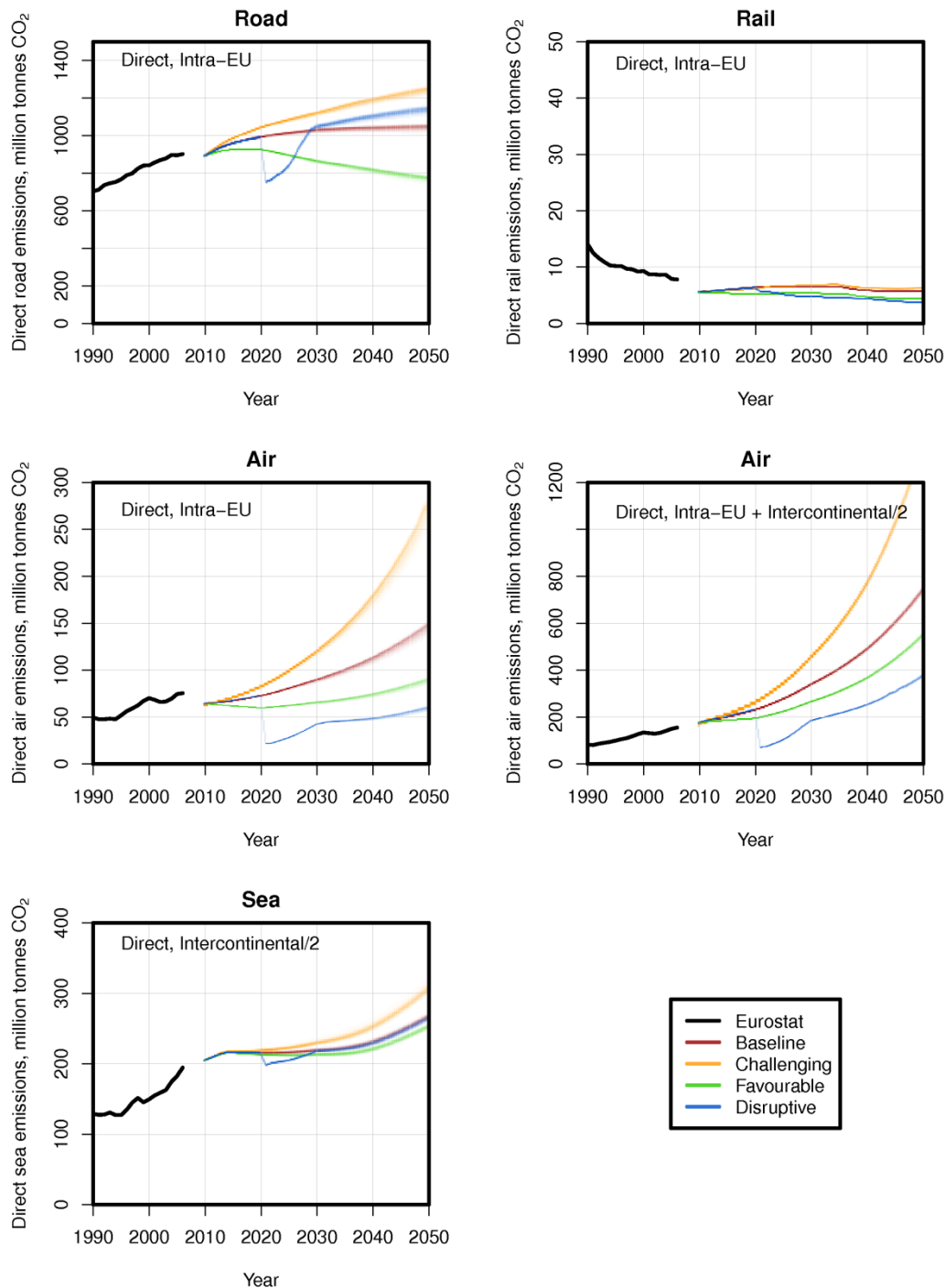

Figure 27. As Figure 15, but including the disruptive scenario as well.

The disruptive scenario chosen was based in the Baseline scenario, but involved a three-fold increase in oil prices in 2021 (decreasing back to Baseline values by 2030), a dip in GDP, increases in air and rail ticket prices and journey times, and de-urbanisation, simulating the effect of a disease outbreak or terrorist attack affecting city centres and public transportation.

As noted in Annex A of the TOSCA Scenarios report, existing models are not well-equipped to deal with this kind of input, and the results will depend on the exact disruptive event chosen, which is arbitrary. Therefore scenario results should be viewed with caution, and as sensitivity tests only. However, it is plausible that discontinuity in scenario input values may have an effect on the fleet and emissions. For example, the TOSCA disruptive scenario includes a drop in passenger and freight demand for all modes. When demand for transport is decreasing, there may be an oversupply of existing vehicles, vehicle utilisation may decrease, and demand for new vehicles is likely to be low. This makes it difficult to get new technologies into the fleet, so the full impact of new technology may be delayed until recovery occurs. Alternatively, high oil prices may help make fuel-saving technology more attractive, increasing adoption and production rates, and decreasing retail price via learning effects to provide a long-term boost for that technology once oil prices have decreased again.

For the case run in this report, the long-term impact of the disruptive event on fleet and emissions is minor. Figure 14 shows output emissions distributions including the disruptive scenario. A comparison with the demand outcomes for the disruptive scenario (Annex A of the WP6 Scenarios Report) demonstrates that that the differences in emissions between the disruptive and baseline scenarios arise primarily from differences between demand in these scenarios, i.e. the year-2050 emissions outcomes in this case are not strongly sensitive to this particular disruptive event outside of its effects on demand.

C3. Comparison with Other Scenarios

As noted above, the models assembled for this part of TOSCA contain many assumptions and simplifications, some of them quite crude. Although care has been taken to standardise model inputs and outputs between the different models used, there is also a danger when using multiple models that they may have different levels of responsiveness. These factors form an additional level of uncertainty. One way of testing that the model outputs are at least reasonable is to test them against the output of other, unrelated models using similar inputs but different methods, assumptions and simplifications.
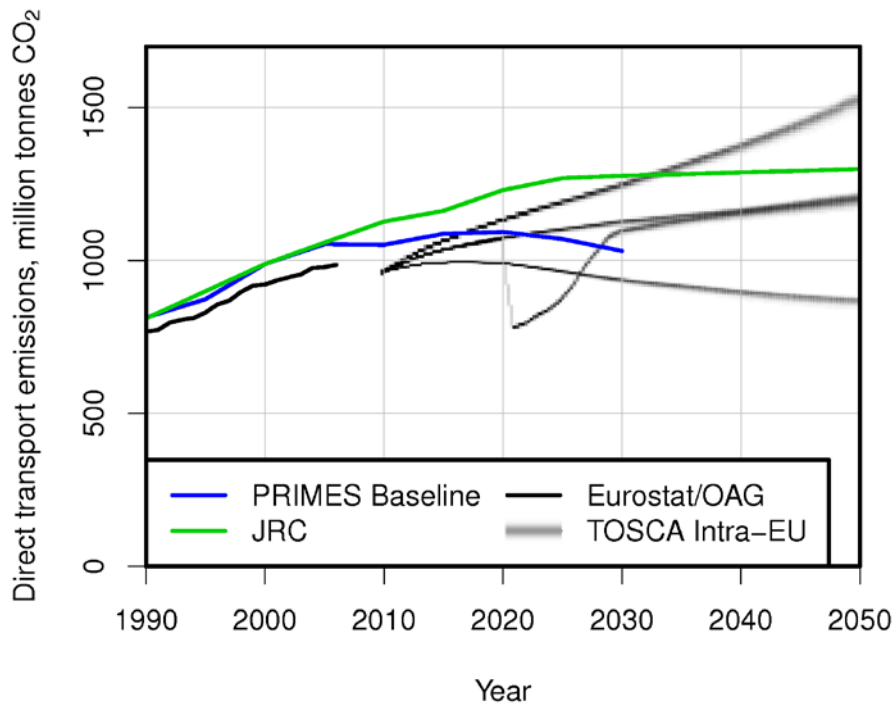
Figure 28. Direct, intra-EU emissions, in comparison with PRIMES (2009) and JRC (2007).
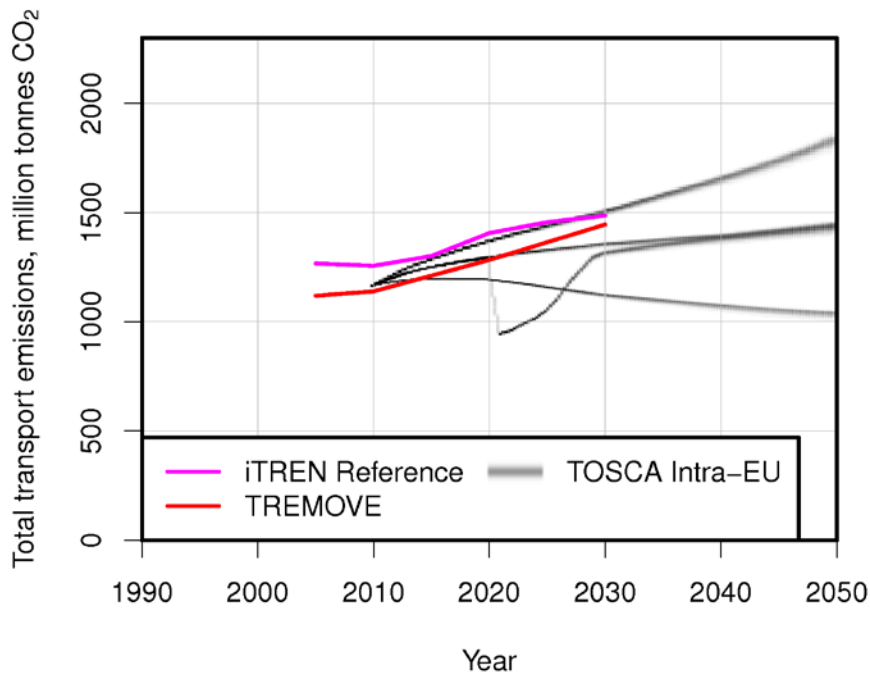

Figure 29. Total fuel lifecycle emissions, in comparison with iTREN (2010) and TREMOVE (2007).

Section 2 of the the TOSCA WP6 Scenarios report details the emissions projections of a range of alternative models for European emissions. These models cover a wide range

of complexity and scope. In Figure 28 and Figure 29, the range of TOSCA projections for direct and fuel lifecycle intra-EU emissions is shown in comparison with a set of key existing projections. This scope was chosen to be most directly comparable to existing projections. However, it should be noted that there are still some scope and coverage differences (for example, some projections include fuel lifecycle emissions from electric trains but no other indirect emissions). Allowing for these scope differences, the range in growth rates of emissions from these alternative projections is very similar to that projected in TOSCA. A description of the assumptions, geographical scope and emissions covered in these models is given in the TOSCA WP2 Scenarios report.

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