TOSCA Project Final Report:
Description of the Main S&T Results/Foregrounds

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Table of Contents

1. Introduction 1
2. Techno-Economic Analysis of Transport Systems and Fuels 1
1.1 Road Vehicles 2
1.2 Aircraft 5
1.3 Railways 7
1.4 Transportation Fuels 11
1.5 Intelligent Transportation Systems 14
3. Scenarios of European Transport Futures in a Global Context 16
4. Analysing Relevant Transport Policy 21
5. Conclusions 24
6. Acknowledgements 25

List of Figures and Tables

Figure 1 Direct and Lifecycle CO_2 Emissions in the Absence of New Policies 20
Figure 2 Direct and Lifecycle CO_2 Emissions under Full Adoption of Lowest-Emission Technologies 23

Table 1 Technological Feasibility for Road Vehicles 2
Table 2 Passenger Car Energy Use and CO_2 Emissions at Technology Readiness 3
Table 3 Truck Energy Use and CO_2 Emissions at Technology Readiness 3
Table 4 Cost Characteristics of Alternative Car Technology and Fuels at Technology Readiness 4
Table 5 Cost Characteristics of Alternative Truck Technology and Fuels at Technology Readiness 4
Table 6 Technological Feasibility for Aircraft 5
Table 7 Aircraft Energy Use and CO_2 Emissions at Technology Readiness 6
Table 8 Cost Characteristics of Aircraft Technologies at Technology Readiness 7
Table 9 Technological Feasibility for Passenger Trains 8
Table 10 Passenger Train Energy Use and CO_2 Emissions in 2050 8
Table 11 Cost Characteristics of Alternative Electric Passenger Rail Technologies 9
Table 12 Technological Feasibility for Freight Trains 10
Table 13 Freight Train Energy Use and CO_2 Emissions in 2050 10
Table 14 Cost Charcteristics of Alternative Electric Freight Rail Technologies 11
Table 15 Technological Feasibility for Transportation Fuels 12
Table 16 Lifecycle Energy Use and GHG Emissions for Transportation Fuels at Technology Readiness 13
Table 17 Cost Characteristics of Transportation Fuels at Technology Readiness 13
Table 18 Technological Feasibility for ITS 15
Table 19 Potential Changes in Infrastructure Capacity, Energy Use, and CO_2 Emissions for ITS 15
Table 20 Cost Characteristics of ITS Technologies 16
Table 21 Overview of the Key TOSCA Scenario Variables from 2009 through 2050 17
Table 22 Base Year (2010) Traffic Volume and Mode Shares and Projections for 2030 and 2050 18
Table 23 Policies Selected for Further Study in TOSCA 21
Table 24 Lowest-Emission Vehicle, Fuel and Infrastructure Technologies by Mode 22
Table 25 Absolute and per-pkm or per-tkm Lifecycle CO_2 Emissions by Major Intra-EU-27 Mode for the 'no new policies' and 'lowest-emission' Cases 24

Abbreviations

Abbreviation	Description	Abbreviation	Description
ABS	Anti-Blocking System	GTL	Gas-to-Liquid
AHS	Automated Highway System	HEV	Hybrid Electric Vehicle
bbl	barrel (oil)	HVO	Hydrogenated Vegetable Oil
BEV	Battery Electric Vehicle	ICE	Internal Combustion Engine
BTL	Biomass-to-Liquid	ITS	Intelligent Transport Systems
CNG	Compressed Natural Gas	L	Litre(s)
CVO	Commercial Vehicle Operations	LB	Lower Bound
DAS	Driver Assistance Systems	LPG	Liquified Petroleum Gas
DOC	Direct Operating Cost	km	kilometre(s)
EC	European Commission	kWh	kilowatt-hours
ERTMS	European Rail Traffic Management System	MJ	Megajoule(s)
ESC	Electronic Stability Control	OR	Open Rotor
ETCS	European Train Control System	PHEV	Plug-in Hybrid Electric Vehicle
EU	European Union	pkm	passenger-kilometre(s)
FC-HEV	Fuel Cell Hybrid Electric Vehicle	R&D	Research and Development
FT	Fischer-Tropsch	SNG	Synthetic Natural Gas
g	gram(s)	tkm	tonne-kilometre(s)
GDP	Gross Domestic Product	UB	Upper bound
GHG	Greenhouse Gas	VAT	Value Added Tax
GJ	Gigajoule(s)	WP	Work Package

1. Introduction

Intra-European transportation generated nearly 25% of all energy-related EC-wide greenhouse gas (GHG) emissions in 2010, up from 17% in 1990. With ongoing integration of the EU economy, this share is likely to continue to increase. At the same time, such growth in transportation-related GHG emissions is likely to jeopardize the EC's political goal of keeping the global average temperature rise below 2 degrees.

The main objective of the TOSCA project is to identify the most promising technology and fuel pathways that could help reduce transport related GHG emissions through 2050. To better understand the policy interventions that are necessary to push these (more expensive) technologies and fuels into the market, TOSCA tested a range of promising policy measures under various scenario conditions. The outcomes in each case were then evaluated using different metrics. This report summarizes the TOSCA project results.

It continues with assessing the techno-economic characteristics of major transport modes and fuels that are capable of reducing GHG emissions. Section 3 of this report integrates this assessment with a scenario analysis. Finally, section 4 evaluates a range of policy measures and their outcome on technology adoption and CO_2 emission mitigation along with other metrics.

Given the numerous studies that underlie this report, reference is made to the work package reports in which all results are thoroughly described and referenced.

2. Techno-Economic Analysis of Transport Systems and Fuels

In this step, a techno-economic analysis of major transport modes and fuels was conducted. The starting point is a reference technology, which represents the average new technology in place within the EU-27 states today. Against this baseline, the fuel efficiency improvement potential of alternative technologies and the associated costs are evaluated. Careful consideration is given to potential constraints and trade-offs. To fully explore the technological potential for reducing GHG emissions, the opportunities for using alternative fuels are also explored. In addition, this analysis evaluates the level of R&D required to achieve technology readiness, the expected point in time when technology readiness is achieved, and several social and user related acceptability metrics, ranging from direct negative impacts such as higher levels of noise to desired ones such as the generation of jobs within the EC. Many of the inputs into these reports are derived from expert surveys, which were conducted by the respective WP1-5 teams. The range of systems that are studied include road vehicles[1] (WP1), aircraft (WP2), railways (WP3), transportation fuels (WP4), and intelligent transportation systems (WP5). In this techno-economic assessment, all calculations are based on social costs, thus ignoring fuel taxes and using a social discount rate of 4% when annualizing investment costs. In section 3 of this study, where consumer and industry decisions are modelled, discount rates appropriate for purchase decisions are used and fuel taxes are included. The carbon intensity of electricity is assumed to be 460 gCO_2 equivalent per kWh, i.e., the average 2009 value at the end-use level. In contrast, carbon intensity of electricity is a scenario variable in sections 2 and 3 of this report.

[1] Marine vehicles were also studied in WP1 but for brevity the results are omitted here (see WP1 report: Techno-Economic Analysis of Low-GHG Emission Marine Vessels).

1.1 Road Vehicles

Two reference passenger cars (gasoline and diesel) are selected as representative new vehicles sold in the EU-27 in 2009. The reference road freight transport vehicles represent urban delivery, interregional and long distance delivery trucks covering light, medium and heavy duty transport within the EU. The low-GHG emission technology and fuel options evaluated for these modes include

Passenger cars

- Alternative fuels: bioethanol blend (E85) from wood feedstock, hydrogenated vegetable oil (HVO), biosynthetic natural gas (Bio SNG)
- Plug-in-hybrid electric vehicle (PHEV)
- Battery electric vehicle (BEV)
- Fuel cell hybrid electric vehicle, with natural gas derived hydrogen (FC-HEV)

Light duty trucks

- Hybrid electric vehicles (HEV)
- Fuel cell hybrid electric vehicle, with natural gas derived hydrogen (FC-HEV)

Medium and heavy duty trucks

- Resistance reduction (Res. Red.)
- Idling reduction (Idle Red.)
- Alternative fuel: Hydrogenated Vegetable Oils (HVO) and biomass-to-liquids (BTL)

The feasibility assessment of these technologies and fuels, which is based on expert questionnaire responses, is summarized in Table 1 (see WP1 reports for details). The advanced electric powertrain technologies for passenger cars and light trucks are estimated to achieve technological feasibility within the next 5 to 10 years under the assumption of significant to substantial R&D investments. In contrast, the technology options studied for medium and heavy duty trucks and marine vessels are generally well-established today and require insignificant R&D effort.

Table 1 Technological Feasibility for Road Vehicles

		Technology-Readiness			R&D Requirements (to achieve technology readiness)		
		Most likely	LB	UB	Insignificant	Significant (Company level)	Substantial (EU-level)
Passenger Cars	**ICE–Bioethanol blend (E85)**	2015	2015	2020	X		
	ICE–Hydrogenated vegetable oil	2010	2010	2010	X		
	ICE–Biosynthetic natural gas	2020	2020	2020	X		
	Plug-in-hybrid electric vehicle	2015	2012	2017			X
	Battery electric vehicle	2020	2010	2020			X
	Fuel cell hybrid electric vehicle	2015	2010	2015			X
Trucks	**Resistance Reduction**	2010	2010	2010	X		
	Idling Reduction	2010	2010	2015		X	
	ICE–Hydrogenated vegetable oil	2010	2010	2010	X		

Table Notes:
Upper bounds (UB) and lower bounds (LB) represent the inter-quartile range of questionnaire responses.
R&D requirements for alternative fuels only consider the engine modification aspects (excluding the fuel production process).

Table 2 reports direct and lifecycle energy use and CO_2 emissions for alternative technology and fuel options for automobiles. A plug-in-hybrid electric vehicle delivering a 40 km "electric" range would reduce the direct vehicle energy consumption by around 50%. Even greater reductions in energy consumption in the order of 70% could be achieved through full battery electric powertrains. However, the associated fuel lifecycle CO_2 emissions strongly depend on the electricity generation mix. Similarly, fuel cell hybrid electric powertrains promise a large potential for reducing vehicle energy use, whereas lifecycle CO_2 emissions greatly depend on the hydrogen production pathway.

Table 2 Passenger Car Energy Use and CO_2 Emissions at Technology Readiness

	Direct (Lifecycle) Energy Use MJ/100km [1,2]			Direct (Lifecycle) CO_2 Emissions gCO_2-eq/km [3]		
	Most likely	LB	UB	Most likely	LB	UB
Reference gasoline	199.6 (235.5)			145.9 (170.9)		
ICE–Bioethanol blend (E85)	186.8 (497.1)	165.3 (439.9)	216.2 (575.4)	28.8 (66.0)	25.6 (58.6)	33.4 (76.7)
ICE–Hydrogenated vegetable oil	160.7 (289.2)	149.1 (268.4)	160.7 (289.3)	0 (79.9)	0 (73.9)	0 (79.7)
ICE–Biosynthetic natural gas	177.1 (379.0)	157.4 (336.8)	205.7 (440.2)	0 (69.2)	0 (61.1)	0 (79.8)
Plug-in-hybrid electric vehicle [4]	109.5 (202.7)	101.2 (187.3)	140.0 (59.1)	65.3 (103.9)	42.8 (99.3)	59.3 (137.4)
Battery electric vehicle [4]	51.5 (158.1)	50.0 (154.0)	90.0 (277.2)	0 (64.2)	0 (63.8)	0 (115)
Fuel cell hybrid electric vehicle [5]	70.8 (120.4)	70.0 (119.0)	120.0 (204.0)	0 (72.5)	0 (71.4)	0 (122.4)

Table Notes:
[1] Energy use is based on the New European Driving Cycle assuming vehicle kerb weight.
[2] Upper bounds (UB) and lower bounds (LB) represent the inter-quartile range of questionnaire responses.
[3] Upstream energy use and CO_2 emissions are adopted from WP4 of the TOSCA project.
[4] Plug-in-hybrid electric vehicles with 38% electric share using EU electricity mix with CO2 intensity of 460 g CO2-eq/kWh.
[5] Hydrogen produced from natural gas is considered as the fuel option for fuel cell hybrid electric vehicle.

The direct and fuel lifecycle energy use and CO_2 emissions of light-, medium- and heavy- duty vehicles with alternative technology or fuels are reported in Table 3. The fuel consumption characteristics refer to fully loaded conditions. Light-duty trucks could achieve an 8-10% reduction in fuel consumption by hybridization of the powertrain. In contrast, higher energy consumption savings up to around 55% could be gained with fuel cell hybrid electric powertrains.

Continuous reductions in aerodynamic and rolling resistances can reduce the fuel consumption of medium and heavy duty trucks by 6.5% and 5.0%, respectively. In addition, auxiliary power units can reduce idling fuel consumption in heavy-duty trucks by about 5%.

Table 3 Truck Energy Use and CO_2 Emissions at Technology Readiness

	Direct (Lifecycle) Energy Use MJ/1000 tkm	Direct (Lifecycle) CO_2 Emissions[1] gCO_2-eq/tkm
Reference light duty truck	3,425 (4,110)	256.2 (304.9)
Hybrid electric vehicle	3,131 (3,757)	234.2 (278.7)
Fuel cell hybrid electric vehicle [2]	1,538 (2,614)	0 (156.9)
Reference medium duty truck	710 (852)	53.1 (63.2)
Resistance reduction	664 (797)	49.7 (59.0)
ICE–Hydrogenated vegetable oil	710 (1,278)	0 (35.2)
Reference heavy duty truck	525[3] (630)	39.3 (46.7)
Resistance redution	490 (588)	36.7 (43.9)
Idling reduction	501 (601)	37.5 (44.5)

Table Notes:
[1] Lifecycle CO_2 emissions refer to fully loaded condition.
[2] Fuel cell vehicles are fuelled with compressed hydrogen from natural gas.
[3] Reference heavy-duty truck energy use and CO_2 emissions include an average of 8 hours idling per day.

The economic assessment of the technology and fuel options accounts for operating costs, the break-even oil price and CO_2 mitigation costs (Table 4). The estimates carried out suggest that application of alternative fuels such as bioethanol, HVO and synthetic natural gas could be cost-effective at oil prices of €94-163 per bbl. Advanced powertrain options based on batteries and fuel cells could be cost effective at higher oil prices of €220-250 per bbl. Although the CO_2 emission mitigation costs for battery and fuel cell vehicles are comparable, the mitigation costs for the former can decrease significantly once less carbon-intensive electricity is supplied. In Table 4, the carbon intensity of the average European electricity mix is considered.

Table 4 Cost Characteristics of Alternative Car Technology and Fuels at Technology Readiness

	Operating Costs (incl. Fuel) €¢/km	Break-Even Oil Price €/bbl	Mitigation Costs €/ton CO_2-eq
Reference gasoline	23.8 (26.5)		
ICE–Bioethanol blend (E85)	24.0 (29.1)	144	242
ICE–Hydrogenated vegetable oil	25.9 (29.2)	94	177
ICE–Biosynthetic natural gas	27.2 (30.3)	163	489
Plug-in-hybrid electric vehicle	27.8 (31.7)	324	767
Battery electric vehicle	29.6 (33.6)	257	653
Fuel cell hybrid electric vehicle	29.7 (32.4)	223	674

Table Notes:
Operating costs include capital costs, insurance and running costs (i.e., expenditure on maintenance, repair, replacement of parts, service labour, tires, parking and tolls) over 15,000 km annual driving distance. A discount rate of 4% was assumed. Fuel costs exclude taxes.
Break-even oil prices and mitigation costs include fuel costs (excluding gasoline and diesel tax) over 15,000 km annual driving distance.

Table 5 shows the cost characteristics of technology and fuel options for road freight transport vehicles. The studied technology options are cost effective at an oil price range of €11-138 per bbl and reflect mitigation costs between €0-171 ton of CO_2 equivalent.

Table 5 Cost Characteristics of Alternative Truck Technology and Fuels at Technology Readiness

	Operating Costs (incl. Fuel) €¢/tkm	Break-even Oil Price €/bbl	Mitigation Costs €/ton CO_2-eq
Reference light truck	22.8 (27.4)		
Hybrid electric vehicle	24.5 (28.3)	138	165
Fuel cell hybrid electric vehicle	27.0 (29.3)	85	112
Reference medium truck	2.3 (3.3)		
Resistance reduction	2.4 (3.3)	68	171
ICE – hydrogenated vegetable oil	2.3 (3.8)	94	176
Reference heavy truck	0.6 (1.4)		
Resistance reduction	0.7 (1.3)	11	<0
Idling reduction	0.7 (1.4)	67	92

Table Notes:
Operating costs include capital costs, insurance and running costs (i.e., expenditure on maintenance, repair, replacement of parts, service labour, tires, parking and tolls), over 100,000 km annual driving distance. A discount rate of 4% was assumed. Fuel costs exclude taxes.
Break-even oil prices and mitigation costs include fuel for 18,000, 45,000 and 100,000 kilometre annual driving distance for light, medium and heavy duty trucks, respectively.

The user and social acceptability of low CO_2-emission technologies for road vehicles are assessed based on literature reviews and expert opinions gathered through questionnaires (see WP1 reports). The results suggest that technology options considered for road freight vehicles are not generally faced with major social concerns. In contrast, low CO_2-emission automobiles may face challenges in gaining social and user acceptance. Electric and fuel cell powertrains may generate negative social equity impacts, due to their higher retail price and limited supporting infrastructure. The limited driving range for battery electric vehicles further affects the user acceptability of these vehicles. Plug-in-hybrid electric vehicles are likely to have higher user and social acceptance, as the internal combustion engine is used as a range extender, eliminating driving range and charging infrastructure concerns. The lack of publicly available battery charging stations may not significantly challenge the social and user acceptance of these vehicles, as the existing electricity infrastructure can be used to a great extent for home charging. In contrast, the hydrogen infrastructure existing today is quite limited and user and social acceptance of fuel cell vehicles ultimately depends on the availability of infrastructure.

1.2 Aircraft

Starting from two reference aircraft, a current-generation narrowbody and turboprop vehicle operating in today's European airspace, the following low-GHG emission technologies were evaluated:

- Replacement narrowbody aircraft
- Fast open rotor engine powered narrowbody aircraft
- Reduced speed open rotor engine powered narrowbody aircraft (unswept wings)
- Second generation drop-in biofuels
- Replacement turboprop aircraft
- Improvements in Air Traffic Management

Due to the very limited availability of existing studies investigating the techno-economic potential for reducing aircraft fuel burn, a new, simplified aircraft performance model was designed and the DAPCA IV cost model was adjusted to the investigated aircraft (see WP2 Report). Table 6 reports the technology feasibility characteristics of the considered future aircraft. All data are based on expert questionnaires (see WP2 Report). The projected aircraft are expected to be available from around 2025, with a lower and upper bound of plus/minus 5 years. The narrowbody and turboprop replacement aircraft will require significant R&D investments. In contrast, the more advanced Open Rotor (OR) aircraft would require substantial R&D for commercialization, partly due to noise mitigation measures.

Table 6 Technological Feasibility for Aircraft

	Technology-Readiness			R&D Requirements (to achieve technology-readiness)		
	Most Likely	**LB**	**UB**	**Insignificant**	**Significant (Company-Level)**	**Substantial (EU-Level)**
Narrowbody Replacement	2025	2020	2030		X	
Fast Open Rotor	2025	2020	2030			X
Reduced-Speed Open Rotor	2025	2020	2030			X
Turboprop Replacement	2025	2020	2030		X	

Table 7 reports direct and lifecycle energy use by and CO_2 emissions from all considered aircraft. All energy use and CO_2 emission figures relate to a great circle distance of 983 km, the average stage length in Intra-European passenger air transport in 2005 (the well-to-tank figures are derived from the TOSCA WP4 report). An evolutionary design narrow-body aircraft with a carbon fiber composite-intensive airframe could reduce energy use and CO_2 emissions relative to current generation vehicles by about 17-22%, depending on advances in structural weight, aerodynamic efficiency, and engine technology. Even greater reductions in the region of 31-45%, could be achieved by replacing turbofan engines with OR units, the higher values applying if lower cruising speeds can be accepted. Benefits well in excess of 13% are achievable without any technological development whatsoever if flights under 1,000 km currently made by narrow-body turbofan aircraft are carried out instead by turboprops (at comparable load factors). A replacement turboprop might increase this potential to values in excess of 43-47%, at minimal technological risk. If taking into account second generation biofuels produced from cellulosic material, fuel lifecycle CO_2 emissions would decline by some 60% for all aircraft. Finally, advanced air traffic management systems have the potential to reduce energy use and CO_2 emissions from all aircraft designs by another 5-11%.

Table 7 Aircraft Energy Use and CO_2 Emissions at Technology Readiness

	Direct (Lifecycle) Energy Use, MJ/pkm			Direct (Lifecycle) CO_2 Emissions, gCO_2/pkm		
	Most Likely	**LB**	**UB**	**Most Likely**	**LB**	**UB**
Narrowbody Reference	1.04 (1.26)			76.0 (92.0)		
Narrowbody Replacement	0.81 (0.98)	0.81 (0.98)	0.87 (1.05)	59.2 (71.6)	59.2 (71.6)	62.9 (76.1)
Fast Open Rotor	0.67 (0.81)	0.67 (0.81)	0.71 (0.86)	48.8 (59.0)	48.8 (48.8)	51.8 (62.7)
Reduced-Speed Open Rotor	0.58 (0.70)	0.58 (0.70)	0.61 (0.74)	41.9 (50.7)	41.9 (50.7)	44.5 (53.8)
Turboprop Reference	0.90 (1.09)			51.5 (62.3)		
Turboprop Replacement	0.55 (0.67)	0.55 (0.67)	0.59 (0.71)	40.1 (48.5)	40.1 (48.5)	42.5 (51.4)

Table Notes:
No flight inefficiencies are considered.
All flights have great circle distance of 983km and a passenger load factor 80%.

From an economic perspective, most of these reductions seem to be manageable. Our rough cost analysis suggests that the Narrowbody Replacement Aircraft would be cost-effective, relative to the Reference Narrowbody, at current oil prices and below. The Fast OR Aircraft may be cost-effective at oil prices starting at €31 per bbl, but the upper bound of our uncertainty range would require an oil price of €147 to achieve cost-effectiveness. The lower fuel burn of the Reduced-Speed OR is offset by its slightly higher DOC figure, so its oil price range for cost-effectiveness is comparable. The Turboprop Replacement Aircraft has an estimated break-even oil price of €55 per bbl, although this figure would be lowered (via reduced acquisition costs) if the type's market share were to increase in future. See Table 8 for details.

Table 8 Cost Characteristics of Aircraft Technologies at Technology Readiness

	Operating Costs (incl. Fuel), €¢(2009)/pkm			Break-Even Oil Price, €(2009)/bbl			Mitigation Costs, €(2009)/ton CO_2		
	Most Likely	LB	UB	Most Likely	LB	UB	Most Likely	LB	UB
Narrowbody Reference	8.5 (9.7)			Ref			Ref		
Narrowbody Replacement	8.8 (9.7)	8.6 (9.5)	9.0 (9.9)	37	< 0	78	< 0	< 0	132
Fast Open Rotor	9.3 (10.0)	8.9 (9.6)	9.7 (10.5)	88	31	147	171	< 0	369
Reduced-Speed OR	9.5 (10.1)	9.0 (9.7)	9.9 (10.6)	85	37	132	158	< 0	319
Turboprop Reference	15.9 (16.9)			Ref			Ref		
Turboprop Replacement	16.1 (16.7)			55			< 0		

Table Notes:
Operating costs consist of direct operating costs (DOC) and indirect operating costs (assumed to be €0.025 per pkm). DOC includes aircraft standing charges, flying costs, and maintenance costs.
Aircraft standing charges: Depreciation costs are based on an economic lifetime of 15 years with a 10% residual value. The financing rate is 4% and the insurance 0.5% of the original aircraft cost per year.
Flying costs: Landing fees are €300 per flight, navigation charges are €320-340 per flight depending on aircraft weight, ground handling charges are €2,240 per flight, and the crew cost per block hour is €1,230. The uniform landing fees of €300 per flight are optimistic for the OR aircraft, as they will almost certainly be noisier than the turbofan aircraft.
Maintenance costs: Labour and materials for engines depend on engine thrust and are €51 for the reference aircraft, €48 for the replacement aircraft, and €53-72 for the OR aircraft (the interquartile range of expert questionnaire responses). Maintenance costs for the airframe depend on empty weight and are €500 per hour for the reference aircraft and €330 for all alternative aircraft, assuming a roughly one-third reduction due to the higher share of carbon fiber composites.
CO_2 Emission Mitigation Costs: Reference oil price of €(2009) 54/bbl (US$75/bbl)

The user acceptability and a range of societal concerns based on expert responses to questionnaires were also studied. Among the latter, only the potentially increased noise levels of the OR engine aircraft are seen as problematic by expert respondents. In practice, such aircraft will have to meet noise regulations, so the issue translates to one of technical risk (accounted for in our development cost estimates). Under user acceptability, cabin noise is a factor for both the OR aircraft and the turboprop; the Reduced-Speed OR and the turboprop are also disadvantaged by longer flight times. These factors suggest that policy interventions are likely to be necessary to encourage uptake of the most promising CO_2-reducing technologies. However, such interventions could have the effect of raising air fares in general, which might lead to social equity concerns.

1.3 Railways

Six individual technologies aiming at reducing energy use and GHG emissions over the period 2010-2050 were analyzed. In addition, the combination of these technologies under increased operating speeds for most future electric rail operations was considered. The energy-saving and low-GHG emission technologies include

- Low aerodynamic drag
- Low train mass
- Energy recovery at braking
- Space efficiency (passenger) and heavy trains (freight)
- Eco-driving (driving advice)
- Energy efficiency (train equipment and supply systems)

- Combination of measures above + higher speed
- Low-carbon electric power + combination as above

Passenger Trains

Four reference trains are defined, with representative top speeds, load factors, market shares (EU-27), and GHG emissions per passenger-kilometre (pkm). These include high-speed trains (20% market share), an electric intercity train (43%), a diesel-fueled intercity motor coach (12%), and an electric city train (25%). Table 9 reports the technological feasibility and characteristics of the considered future passenger train technologies and measures.

Table 9 Technological Feasibility for Passenger Trains

	Technology-Readiness			R&D Requirements (to achieve technology-readiness)		
	Most Likely	LB	UB	Insignificant	Significant (Company-Level)	Substantial (EU-Level)
Low drag	2025	2020	2030		X	
Low mass	2025	2020	2030			X
Energy recovery	2025	2020	2030		X	
Space efficiency	2025	2020	2030		X	
Eco driving	2015	2012	2020		X	
Energy efficiency	Continuous				X	
Low-carbon electric power	2025	2020	2030			X

Table 10 reports energy use (at public grid) and lifecycle CO_2-eq emissions as a weighted average of all considered passenger trains, with market share and load factors as in 2009.

Table 10 Passenger Train Energy Use and CO_2 Emissions in 2050

	Energy Use MJ/pkm			Lifecycle GHG Emissions [3] gCO_2-eq/pkm		
	Most Likely	LB	UB	Most Likely	LB	UB
Reference average electric train	0.34			**44**		
Low drag	0.31	0.29	0.32	39	37	41
Low mass	0.32	0.31	0.33	41	39	43
Energy recovery	0.30	0.28	0.32	38	36	40
Space efficiency	0.29	0.28	0.31	37	35	39
Eco-driving	0.29	0.27	0.31	37	35	39
Energy efficiency	0.31	0.30	0.32	39	37	41
Combination + higher speed [2]	**0.18**	0.16	0.22	**24**	20	28
Low-carbon el power [1] + combination	0.18	0.16	0.22	**5**	**4**	**11**
Reference diesel train	0.75			**66**		
Combination of six measures [2]	0.37	0.34	0.43	**33**	30	38

Table Notes:

Energy use at public electric grid or train fuel tank.

[1] Carbon content of electricity tentatively reduced by 80% compared to 2009 levels. Lower bound of GHG corresponds to 80% reduction, while upper bound corresponds to 60%.

[2] High-speed trains are assumed to increase representative top speed from 300 to 370 km/h; intercity trains from 160 to 230 km/h; city trains from 140 to 165 km/h; diesel trains no change.

[3] Note: GHG emissions are estimated as fuel lifecycle emissions. For diesel-fuelled trains fuel lifecycle emissions are approximately 20% higher than direct emissions.

Table 11 reports cost characteristics of the studied technologies and measures as an average of all considered electric passenger trains.

Table 11 Cost Characteristics of Alternative Electric Passenger Rail Technologies

	Operating Costs (incl. Fuel)[1], €¢(2009)/pkm			Break-Even Electr. Price €¢/kWh
	Most likely	LB	UB	Most Likely
Low drag	9.2 (10.0)	8.1 (8.9)	10.3 (11.1)	10
Low mass	9.2 (10.1)	8.1 (8.9)	10.3 (11.1)	5
Energy recovery	8.9 (9.7)	7.9 (8.6)	10.0 (10.8)	<0 [2]
Space efficiency	8.3 (9.0)	7.2 (7.9)	9.4 (10.1)	<0 [2]
Eco-driving	9.0 (9.7)	7.9 (8.7)	10.1 (10.8)	<0 [2]
Combination + higher speed	8.1 (8.6)	7.0 (7.5)	9.2 (9.6)	<0 [2]
Reference average electric train	9.1 (10.0)	8.1 (8.9)	10.2 (11.0)	9.1

Table Notes:
Operating cost includes capital cost, maintenance, crew, charges for track+stations+dispatch, train formation, sales and administration. The 2009 cost structure is assumed, i.e., no improvement of load factors, crew utilization, train maintenance, etc. Long-term capital cost is 4% per year of initial investment. Tonnage-dependent track charges are €0.003 per gross tkm. Train crew cost is €100 per time-tabled hour for drivers and €70 per hour for others.

[1] Electricity price excludes taxes.

[2] Negative break-even prices should be interpreted as a beneficial technology with respect to operating cost, also if energy cost is excluded.

According to Tables 10 and 11, the most promising technologies are 'Eco-driving' and 'Energy recovery' (electricity regeneration when braking), as these measures are relatively inexpensive to implement. 'Space efficiency' (more seats per meter of train) is very efficient both in terms of GHG emissions and operating cost (8-10% non-energy cost reduction). 'Low drag' will likely be introduced in most passenger trains. 'Low mass' is important in stopping trains (commuter and metro), but may require additional incentives to be introduced on a large scale. 'City trains' with tight stops have the highest potential for improvement, if increased energy recovery at braking and eco-driving techniques are systematically applied. High-speed trains are expected to have the lowest cost, energy use and GHG emissions per pkm, due to their high average load factor and superior aerodynamics.

The combination of the six technologies results in average energy and GHG emission reductions of 45-50%, assuming a constant load factor and the same GHG content of electricity (or liquid fuels) as in 2009. If GHG emissions are reduced by 60-80% for future average European electricity, rail GHG emissions are estimated to reach 4-11 gCO_2-eq per pkm in electric passenger trains. All electric passenger trains are assumed to have 20-40% higher top speeds by 2050 than year-2009 values, while those of diesel trains remain unchanged.

The evaluated technologies are expected to be generally well accepted. However, space efficiency must be improved in a careful way in order not to be detrimental to passenger comfort. A considerable mode shift to rail - and thus realizing the benefit of low GHG emissions for rail in comparison to other modes - would need investment, in particular in rail infrastructure.

Freight Trains

Four reference trains are defined, with representative train mass, load factor, market share (EU-27) as well as GHG emissions per net tonne-kilometre (tkm). These trains consist of an electrically propelled ordinary freight train (65% market share), diesel-fueled ordinary freight train (15%), an intermodal electric freight train (19%), and a high value freight train (1%). Table 12 reports the technological feasibility and characteristics of the considered future freight train technologies and measures.

Table 12 Technological Feasibility for Freight Trains

	Technology-readiness			R&D requirements (to achieve technology-readiness)		
	Most Likely	LB	UB	Insignificant	Significant (Company-Level)	Substantial (EU-Level)
Low drag	2020	2017	2025			X
Low mass	2020	2017	2025		X	
Energy recovery	2015	2013	2020		X	
Heavy freight	2025	2020	2030		X	
Eco driving	2014	2011	2018		X	
Energy efficiency	Continuous				X	
Low-carbon electric power	2025	2020	2030			X

Table 13 reports energy use (at public grid) and lifecycle CO_2-eq emissions as a weighted average of all considered freight trains, with market share and load factors as in 2009.

Table 13 Freight Train Energy Use and CO_2 Emissions in 2050

	Energy Use MJ/net-tkm			Lifecycle GHG Emissions [1,3] gCO_2-eq/net-tkm		
	Most Likely	LB	UB	Most Likely	LB	UB
Reference average electric train	0.140			**18**		
Low drag	0.129	0.12	0.14	17	16	18
Low mass	0.130	0.12	0.14	17	16	18
Energy recovery	0.123	0.11	0.13	16	15	17
Heavy freight	0.117	0.11	0.13	15	14	17
Eco-driving	0.123	0.12	0.13	16	15	17
Energy efficiency	0.124	0.12	0.13	16	15	17
Combination + higher speed [2]	**0.083**	0.07	0.10	**11**	8	13
Low-carbon el power [a] + combination	0.083	0.07	0.10	**2**	**1.5**	**5**
Reference diesel train	0.365			**32**		
Combination of six measures [2]	0.21	0.18	0.25	**19**	15	23

Table Notes:

Energy use at public electric grid or train fuel tank.

[1] Carbon content of electricity tentatively reduced by 80% compared to 2009 levels. Lower bound of GHG corresponds to 80% reduction, while upper bound corresponds to 60%.

[2] Ordinary electric freight trains are assumed to increase representative top speed from 90 to 105 km/h; intermodal trains from 100 to 120 km/h; diesel trains and high-value freight trains are assumed to maintain present top speeds.

[3] GHG emissions are estimated as lifecycle emissions. For diesel fuelled trains, lifecycle emissions are approximately 20% higher than direct emissions.

Table 14 reports the cost characteristics of the studied technologies and measures as an average of all considered electric freight trains.

Table 14 Cost Charcteristics of Alternative Electric Freight Rail Technologies

	Operating Costs, (incl. Energy)[1], €¢/net-tkm			Break-Even Electricity Price €¢/kWh
	Most likely	LB	UB	Most Likely
Low drag	2.70 (3.03)	2.20 (2.55)	3.10 (3.43)	33
Energy recovery	2.55 (2.86)	2.15 (2.46)	2.95 (3.26)	<0 [2]
Heavy freight	2.30 (2.60)	1.90 (2.20)	2.70 (3.00)	<0 [2]
Energy efficiency	2.65 (2.96)	2.25 (2.56)	3.05 (3.36)	11
Eco-driving	2.55 (2.86)	2.15 (2.46)	2.95 (3.26)	<0 [2]
Combination + higher speed	2.20 (2.41)	1.80 (2.01)	2.60 (2.81)	<0 [2]
Reference average electric train	2.60 (2.95)	2.20 (2.55)	3.00 (3.35)	

Table Notes:
Operating cost includes capital cost, maintenance, crew, charges for track+stations+dispatch, train formation, sales and administration. The 2009 cost structure is assumed, i.e., no improvement of load factors, crew utilization, train maintenance, etc. Long-term capital cost is 4% per year of initial investment. Tonnage-dependent track charges is €0.003 per gross tkm. Train crew cost is €100 per time-tabled hour for drivers and €70 per hour for others.
[1] Electricity price excludes taxes.
[2] Negative break-even prices reflect beneficial technology with respect to operating cost.

According to Tables 13 and 14, the most promising technologies are 'Eco-driving' and 'Energy recovery' (electricity regeneration when braking), as these measures are relatively inexpensive to implement. 'Heavy freight trains' (heavier and more compact) are very efficient both in terms of GHG emissions and operating cost (10-14% non-energy cost reduction). Improved 'Energy efficiency' is likely to be introduced continuously. 'Low drag' (in particular due to tighter loadings of containers, trailers etc) will also likely be introduced to some extent, but may require further external economic incentives for large-scale introduction. The operating cost increase of this technology is estimated to be around 1-4%, neglecting reduced energy cost.

The combination of the six technologies results in energy and GHG emission reductions of 40-45%, assuming a constant load factor and the same GHG content of electricity as in 2009. If GHG emissions are reduced by 60-80% for future average European electricity, the indirect specific GHG emissions are estimated to be 1.5-5 g CO_2-eq per net-tkm in electric freight trains.

The evaluated technologies are expected to be generally well accepted. A considerable mode shift to rail, realizing the benefit of low GHG emissions for rail in comparison to other modes, would require investment, in particular in rail infrastructure.

1.4 Transportation Fuels

Compared to transportation technologies, alternative fuels bear the potential advantage of decoupling GHG emissions from transportation demand. In addition, alternative liquid fuels that are compatible with the vehicle and fuel infrastructure can cut the time to impact short, whereas it typically takes several decades for low GHG emission technologies to impact the vehicle fleet characteristics. Starting from a set of

reference petroleum-based fuel systems (gasoline, diesel, and jet fuel), the following (mostly) low CO_2-emission fuels were evaluated:

- **Gasoline replacement:** bioethanol (sugarcane, wheat, and wood feedstocks), Compressed Natural Gas (CNG), Liquefied Petroleum Gas (LPG), Bio-SNG (wood feedstock), hydrogen (natural gas feedstock), hydrogen (wood feedstock)
- **Diesel replacement:** Biodiesel (rapeseed feedstock), Fischer Tropsch (FT) Diesel via Gas-to-Liquids (GTL), FT Diesel via biomass-to-liquids (BTL) using short rotation coppice as feedstock, Hydrogenated Vegetable Oil (HVO) using palm oil feedstock
- **Jet A1 replacement:** FT Diesel via GTL, FT Diesel via BTL using short rotation coppice as feedstock, HVO) using palm oil feedstock
- **Heavy fuel oil replacement:** FT Diesel via GTL, FT Diesel via BTL using short rotation coppice as feedstock

The ultimate selection of alternative fuel options in this study is based primarily on their GHG mitigation potential. An important concern for biofuels is the production potential, which depends on the availability of land for growing biomass for energy purposes. There is significant uncertainty underlying such estimates due to their dependence on population growth and food consumption, agricultural productivity, land allocation and trade balances. With the help of an agronomic model (Global Agro Production Potential, GAPP) and a series of assumptions on the aforementioned factors, a total of 30 million hectares of surplus agricultural area in Europe could be available for the production of energy crops by 2050. Another uncertainty associated with biofuels is the release of soil carbon associated with the conversion of non energy-crop related land, which has not been considered here.

Table 15 reports the technological feasibility of the most promising fuel options. This indicator assesses whether a particular fuel can be produced on a large, commercial scale from the technological point of view only. As can be seen, the most promising fuels, bioethanol and BTL from lignocellulosic feedstocks still require significant and substantial R&D investments to become available at large commercial scale in 2015 and 2025, respectively.

Table 15 Technological Feasibility for Transportation Fuels

	Reference Fuel	Technology-readiness			R&D requirements (to achieve technology-readiness)		
		Most Likely	LB	UB	Insignificant	Significant (Company-Level)	Substantial (EU-Level)
Bioethanol (wood)	Gasoline	2015	2015	2020		X	
Bio-SNG (wood)	Gasoline	2020	2020	2020			X
BTL (wood)	Diesel	2025	-	-			X
CNG	Gasoline	Ready	Ready	Ready			
HVO	Diesel	Ready	Ready	Ready			

Table 16 summarizes typical values for lifecycle energy use and GHG emissions associated with the most promising fuels under consideration, split into the upstream and direct components. All numbers include the amount of energy and carbon contained in the used feedstock, which is transferred to the final

fuel. As can be seen, the most promising fuels are wood-based ethanol and BTL. Hydrogen is not shown in this table because of the challenges associated with fuel distribution and storage.

Table 16 Lifecycle Energy Use and GHG Emissions for Transportation Fuels at Technology Readiness

Fuel	Energy use (MJ/MJ_{fuel})				GHG emissions ($gCO_{2\text{-eq.}}/MJ_{fuel}$)				
	Total	LB	UB	Renewable	Upstream	LB	UB	Direct	Lifecycle
Gasoline	1.18	-	-	0.00	12.5	-	-	73.0	85.5
Diesel	1.20	-	-	0.00	14.2	-	-	74.8	89.0
Jet A1	1.21	-	-	0.00	14.2	-	-	74.3	88.5
Electricity mix (Europe, 2009)	3.07	-	-	2.88	0.46 *	-	-	-	-
Heavy fuel oil	1.22	-	-	0.00	6.7	-	-	80.6	87.3
Bioethanol (wood)	3.06	2.4	3.3	2.85	22.0	17.5	43.7	0	22.0
Bio-SNG (wood)	2.14	1.2	2.3	1.88	38.8	17.0	36.0	0	38.8
BTL (wood) #	2.24	2.2	2.2	1.50	35.0	6.9	39.0	0	35.0
CNG	1.40	1.1	1.8	0.01	14.5	8.7	22.0	56.2	70.7
HVO	1.80	1.5	2.2	1.20	49.6	24.9	60.3	0	49.6

Table Notes:
Biofuels have by definition zero direct CO_2 emissions, as they will be absorbed by the next generation of energy crops; * per kWh (estimate based on 2007 figures); # UB and LB based on literature estimates. GHG emissions include CO_2, methane (CH_4) and nitrous oxides (N_2O).

Table 17 reports the various cost elements associated with the production and distribution of the alternative fuels shown in Table 16. Also shown are mitigation costs compared to the respective reference fuel and the feedstock break-even costs. GHG mitigation costs include lifecycle emissions. Negative values mean that the alternative option provides GHG emission reductions at a lower cost than the reference fuel.

Table 17 Cost Characteristics of Transportation Fuels at Technology Readiness

Fuel	Production Costs €(2009)/GJ_{fuel}			Distribution Costs €(2009)/GJ_{fuel}			Mitigation Costs €(2009)/$tonCO_{2\text{-eq}}$	Break-Even Costs €(2009)/$ton_{feedstock}$
	Most likely	UB	LB	Most likely	UB	LB	Most likely	Most likely
Gasoline [1]	13.2	-	-	0.4	-	-	-	-
Diesel [1]	13.2	-	-	0.4	-	-	-	-
Jet A1	13.2	-	-	0.4	-	-	-	-
Electricity Mix (Europe, 2009)	4.8 [4]	-	-	4.3 [4]	-	-	-	-
Heavy fuel oil	8.1 [5]	-	-	0.4	-	-	-	-
Bioethanol (Wood)	29.6	35	18	1.1	7.5	0.8	269	31
Bio-SNG (Wood)	16.5	32	12	0.9 [2]	12.6	0.2	80 (130 [3])	1
BTL (Wood)	30.6	-	-	0.4	-	-	325	19
CNG	8.1	19	7.5	0.9 [2]	12.6	0.2	< 0 (< 0 [3])	-
HVO	19.6	30	19	0.9	4.7	1.8	176	279

Table Notes:
[1] Underlying oil price = US$75/bbl.
[2] Excluding refuelling costs (approx. €2.3/GJ).
[3] Including refuelling costs.
[4] €(2009)/100kWh.
[5] Based on historical trend.

GHG emission reduction costs include lifecycle GHG emissions. Table 17 also presents a "breakeven" feedstock price for biofuels, i.e., a threshold feedstock price below which the production costs of the alternative biofuel option are less than the ones of the reference fuel (assuming a reference oil price of US$75/bbl). Although the feedstock is the same for lignocellulosic biofuels, the capital costs of BTL and Bio-SNG plants are higher compared to bioethanol; this extra cost has to be offset by lower feedstock costs.

1.5 Intelligent Transportation Systems

In addition to quantifying the existing transportation infrastructure (which is reported in the Annexes of the WP5 final reports), WP5 examines Intelligent Transportation Systems (ITS) technologies for two infrastructures, road and railways. ITS technologies for air transport are considered in WP2.

The reference technology for road transport corresponds to the average new vehicle (passenger car or heavy truck) operating within the EU-27 road network with regard to fuel consumption, CO_2 emissions, and costs for the year 2009 (see Tables 2-5). Reference ITS equipment includes Anti Blocking System (ABS) and Electronic Stability Control (ESC) for passenger cars, while Electronic Screening and Clearance is installed in the reference heavy truck. Relevant infrastructure capacity levels were also considered. Under reference traffic and geometric conditions, highway capacities can be as high as 2,400 vehicles per hour per lane (veh/h/l). In practice, lower capacities of about 1,800 veh/h/l are observed.

The reference system for railways consists of the Trans-European (TEN-T) high-speed railway network for passenger transport which is equipped with modern conventional signaling systems, and the six major freight corridors with mixed freight and passenger traffic equipped with conventional signaling systems of various standards. Energy use characteristics, costs, and capacity issues were examined. The capacity range was 12-15 trains/h for high-speed railway network and 12-20 trains/h for freight corridors. The following ITS technologies and capacity-enhancing measures were assessed:

- **Driver Assistance Systems (DAS):** These include a whole range of information and communication technology in-vehicle systems which support drivers in maintaining a safe speed and distance, driving within a given lane and avoid overtaking in critical situations.
- **Automated Highway System (AHS):** These involve computer-controlled wireless communications between vehicles and infrastructure. Vehicles can organize themselves into platoons and be linked together by communication networks, which allow the continuous exchange of information regarding speed, acceleration, braking and obstacles.
- **Commercial Vehicle Operations (CVO for freight transport):** These ITS applications require roadside equipment, databases, and in-vehicle transponders or other tags for: Electronic Credentialing, Electronic Screening and Clearance and Fleet Management.
- **European Rail Traffic Management System (ERTMS)-(ETCS/Level 3):** This European system is designed to replace the existing partly incompatible safety and signaling systems throughout Europe and to enable interoperability throughout the European rail network.
- **Operation of Heavier/Faster freight trains:** This means both increased axle load and loading gauge as well as longer freight trains and reduced effective transport time.

Table 18 presents the technological feasibility of the most promising selected ITS technologies for cars, trucks and railways. The vision of "driverless" cars operating within an AHS is not expected to

materialize before 2030, as several challenges associated with interoperability, standardization and social acceptability issues need to be resolved for a wide implementation. In freight traffic, some CVO applications have already been deployed in several European countries but are not fully integrated on a European scale. Thus, CVO is expected to enter the European market only after 2020. ERTMS has already been implemented in some European lines in the form of the preliminary ETCS levels (ETCS/Level 1 and 2). However, ETCS/Level 3 is still in a conceptual phase and is considered to experience large-scale implementation only after 2030. The ETCS/Level 3 deployment will most likely start from the six major freight corridors and then continue on the European high-speed lines. AHS and ERTMS (ETCS/Level 3) will still require substantial R&D to resolve interoperability and standardization issues.

Table 18 Technological Feasibility for ITS

	Technology-Readiness			R&D Requirements		
	Most Likely	LB	UB	Insignificant	Significant (company-level)	Substantial (EU-wide program)
AHS	2030	2025	2050			**X**
CVO	2020	2015	2030		**X**	
ERTMS (ETCS/Level 3)	2030	2025	2040			**X**

Table 19 summarizes the benefits offered by ITS technologies in terms of capacity improvement, energy use mitigation, and CO_2 emissions reduction. AHS offers the greatest benefits for capacity, showing an increase of road capacity by 2.4 to 2.7 times, resulting in capacities of up to 6,400 veh/h/l. This is achieved by reducing distances between fully automated vehicles and by avoiding stop-and-go operations in the AHS. Due to the reduction of aerodynamic drag and acceleration resistance, energy use and CO_2 emissions from "intelligent" cars are expected to be about 20% lower than those of similar-sized conventional cars. Similarly, a 16% reduction in CO_2 emissions generated by trucks is expected after CVO deployment, which, however, is not accompanied by a direct increase in road capacity. Finally, for ETCS/Level 3, a 35% increase in line capacity may be achieved.

Table 19 Potential Changes in Infrastructure Capacity, Energy Use, and CO_2 Emissions for ITS

	Capacity Improvement			Energy Use Reduction			CO_2 Emissions Reduction		
	Most Likely	LB	UB	Most Likely	LB	UB	Most Likely	LB	UB
AHS	140%	140%	170%	20%	15%	25%	20%	15%	25%
CVO	No direct effects			16%	6%	26%	16%	6%	26%
ERTMS (ETCS/Level 3)	35%	15%	60%	1%	0%	5%	1%	0%	5%

Table Notes:
AHS: The level of capacity improvement strongly depends on the platoon size, the inter-vehicle and inter-platoon separations, the vehicle mix, the length of the trip operated in the platoons and the frequency with which vehicles enter and exit platoons.
ETCS/Level 3: The potential for capacity improvements depends on the system previously employed. Other uncertainties are the mixes of different train types and the line layouts which affect the capacity. The numbers describing the CO_2 emissions reductions are mainly based on the expert questionnaires (see WP5 report).

The need for additional ITS technology is projected to increase the retail price and operating costs of new vehicles. On the other hand, some operating costs (especially fuel costs) may be reduced due to the ITS technology. Cost estimates for each technology are shown in Table 20. The cost effectiveness of each

technology is assessed by calculating the break-even energy costs and the CO_2 mitigation costs for each technology. Our study suggests that CVO is a cost-effective technology, due to the low costs for implementing this technology in light of the expected fuel efficiency gains. Furthermore, the negative break-even energy costs for ERTMS (ETCS/Level 3) mean that the technology is cost-effective at very low energy costs, due to the simultaneous reduction of operating costs and energy use after its deployment.

Table 20 Cost Characteristics of ITS Technologies

	Operating Costs (incl. Energy)	Break-even Energy Price	CO_2 Mitigation Costs, €(2009)/ton CO_2
Reference Car	3,570 (3,977) €/year	-	-
AHS	3,785 (4,155) €/year	400 €/bbl	755
Reference Truck	16,395 (31,845) €/year	-	-
CVO	16,830 (29,805) €/year	< 0 (-9 €/bbl)	27
Reference High-Speed Train	0.063 (0.069) €/pkm	-	-
ERTMS (ETCS/Level 3)	0.047 (0.053) €/pkm	< 0 (~8 €/MJ)	-

Table Notes:
Road Vehicles: Operating costs include capital and depreciation costs, maintenance costs, parking and tolls and insurance. For passenger cars, the annual driving distance is 15,000 km, discount rate 4%, and the lifetime 10 years. For heavy trucks, the average annual distance is 100,000 km, while discount rate and vehicle lifetime are 4% and 10 years, respectively.
AHS: 50% of the annual mileage is assumed to occur on roads over which AHS will be implemented (see WP5 report).
Railways: Operating costs include capital costs, maintenance, labour, track and terminal and dispatch charges and sales cost.
Fuel/Energy Costs (excluding taxes): Gasoline: €13.6/GJ = €0.44/L, Diesel: €13.6/GJ = €0.48€/L, Electricity: €0.091/kWh.

Social acceptability issues are critical to the uptake of ITS applications. Issues considered include social equity implications, generation of jobs within the EC, passenger and driver safety and comfort, and privacy and liability issues. Following expert responses to questionnaires, privacy and liability issues are seen as most critical for the uptake of the AHS. Passenger and driver safety is expected to increase after the adoption of the considered ITS applications.

3. Scenarios of European Transport Futures in a Global Context

TOSCA WP6 integrates the technology, fuel, and infrastructure studies carried out in WP1-5 through a scenario and modelling analysis. The first step in the scenario analysis consisted of a systematic review of existing European transport scenarios. Consequently, a set of scenario variables that affect future passenger and freight transport demand were determined. These were used to formulate four distinct scenarios (three detailed scenarios which are reported here and one sensitivity case that is only reported in the WP6 report) that describe future trends in the drivers of passenger and freight transport demand. This was followed by a modelling stage in which transport demand for each scenario was projected under the assumption of no new policies. This part of the modelling stage was carried out with the EU demand model Transtools. Due to the limitations of that model, Transtools was complemented with other models such as the Aviation Integrated Model (AIM). To obtain the required size and composition of the vehicle fleet along

with the resulting emission levels, the derived transportation demand (in pkm and tkm) was translated into vehicle-km using vehicle stock models, and the market penetration of new technologies and fuels was estimated based on their cost-effectiveness and other scenario conditions. Finally, the resulting EU-27 transport emissions were estimated. Sensitivity tests assessed the robustness of these results.

The review of existing transport scenarios indicated that scenario timeframes, the exact geographical scope, the investigated scope of the transport sector, the scope of the energy system, the definition of a scenario, key scenario drivers, and the nature of scenarios (continuous, disruptive) often vary across scenario studies. Within TOSCA, scenarios include exogenous variables which are both uncertain and relevant for reducing GHG emissions. TOSCA scenarios include a set of consistent assumptions about the future development of these variables. The TOSCA scenarios are not forecasts, but represent a range of plausible futures and are intended to describe uncertainty about the future via a collection of consistent assumptions.

We consider three main scenario variables with high relevance and large uncertainty. The most important driver of transport demand is growth in the economy or GDP. Over much of the history of motorized transportation, passenger travel has grown at an income elasticity of about unity, that is, every percentage increase in GDP has translated into a similar percentage increase in pkm. Due to the strong dependence of transportation on oil products, another key variable is the price of oil and its substitute fuels. Oil prices depend on mainly geopolitical factors, which are difficult to predict. High oil prices depress transportation demand and improve the economics of low carbon alternative technologies and fuels. The third key variable is the CO_2 intensity of electricity, measured in grams of CO_2 per kWh produced. This variable will become increasingly relevant to transport as electricity becomes a more and more important energy carrier for transportation applications, e.g., through plug-in hybrid electric vehicles, battery electric vehicles, or a mode shift to rail. If transportation becomes highly electrified, but the CO_2 intensity of electricity does not decline significantly, EU transport may not be able to significantly reduce its emissions. The three scenarios, evaluated over a time horizon from 2009 through 2050, are defined as follows:

- A reference case for the evolution of exogenous factors (**Baseline**)
- Challenging evolution of exogenous factors in terms of GHG emissions (**Challenging**)
- Favourable evolution of exogenous factors in terms of GHG emissions (**Favourable**)

Table 21 summarizes the key scenario variables. The absolute change in oil price over the scenario time horizon is also given in parenthesis.

Table 21 Overview of the Key TOSCA Scenario Variables from 2009 through 2050

Scenario assumptions:	**GDP**	**Oil Price**	**CO_2 Intensity of Electricity**
	%/yr	**%/yr (€(2009)/bbl)**	**%/yr**
Scenario 0: 'Baseline'	+1.7	+1.8 (54 – 113)	-1.7
Scenario 1: 'Challenging'	+2.5	± 0 (54 – 54)	-0.5
Scenario 2: 'Favourable'	+0.7	+2.5 (54 – 144)	-3.0

In addition to growth in GDP, oil price, and the CO_2 intensity of electricity, other important inputs into the Transtools model include a detailed database of transport policy-relevant European variables, as appropriate for a 2005 base year (based on the European Transport Policy Information System (ETIS) data).

These 2005 data (population, urbanisation, fuel prices, and values dependent on the techno-economic characteristics of reference technologies) were updated to the TOSCA 2010 base year using scenario and WP 1-5 output.

Table 22 reports model outputs for passenger and freight transport in billion pkm and tkm by major mode of transport. In addition, the percentage share of passenger cars, aircraft, and public surface transport modes are shown. Road and Rail results were computed with the Transtools model, while aviation demand was projected with the AIM model. Simple literature estimations were used for air freight and maritime transport (see WP6 report). The results exclude inland navigation.

In the Baseline scenario, demand for transport would increase by about 70% (passenger) and 50% (freight) by 2050 over the year-2010 level. In the Challenging scenario with high GDP growth and stable 2009 oil prices, these transportation levels would reach 130% and 80% above the year-2010 level, respectively. In contrast, in the Favourable scenario with low GDP growth and high oil prices, transportation demand would grow by only 30% (passenger) and 10% (freight). The variation around the 2050 baseline demand (passenger, freight) in the Challenging scenario (+33%, +16%) and Favourable scenario (-26%, -29%) scenarios offers a sufficiently wide range of transportation activity to account for future uncertainty in examining the opportunities for reducing GHG emissions through changes in technologies and fuels.

Common to all scenarios is the increase in the relative importance of air transportation. This is especially the case in passenger travel, where revenue pkm growth ranges from 50% over 2010 levels in the Favourable scenario to 160% in the Challenging scenario. In contrast, mode shares in freight transportation remain largely unchanged over the scenario time horizon. This can be attributed to the relatively insensitive behaviour of Transtools with regard to changes in the input assumptions, and the relative lack of importance of air freight.

Table 22 Base Year (2010) Traffic Volume and Mode Shares and Projections for 2030 and 2050

		Baseline			Challenging			Favourable		
	2010	**2030**	**2050**	**'50/'10**	**2030**	**2050**	**'50/'10**	**2030**	**2050**	**'50/'10**
Total Intra-EU pkm, bln.	**5,692**	7,670	9,766	1.7	8,742	12,960	2.3	6,456	7,273	1.3
% Passenger Cars	**83**	81	76	0.9	79	70	0.8	82	79	0.9
% Air	**10**	13	18	1.9	16	26	2.6	11	15	1.5
% Public Surface	**7**	6	6	0.8	6	4	0.6	7	6	0.9
Total Intra-EU tkm, bln.	**2,322**	2,996	3,514	1.5	3,207	4,078	1.8	2,383	2,500	1.1
% Trucks	**81**	82	82	1.0	81	82	1.0	84	82	1.0
% Air	**0.1**	0.1	0.1	1.6	0.1	0.1	1.9	0.1	0.1	1.3
% Rail	**19**	18	18	0.9	19	18	1.0	16	18	0.9

Table Notes:
Percentages may not add up to 100% due to rounding.

To estimate emissions and technology uptake from the demand projections summarized in Table 22, a five-step framework was constructed, using data from WP 1-5, other EU project results, and existing stock modelling frameworks. To enable sensitivity testing and the use of uncertain inputs, this framework was designed to have a rapid run time (around a minute per run) and the ability to be run with randomised input values for Monte Carlo modelling. The steps followed were:

- Calculate the existing fleet size and number of vehicle retirements by year, based on base year data, vehicle age and policy variables.
- Using scenario data on demand for passenger and freight transport, calculate how many new vehicles will need to enter the fleet to satisfy that demand.
- Using scenario and WP4 data on fuel prices, and TOSCA data on vehicle characteristics (WP 1-5), estimate how many of these new vehicles will be of each type and technology class.
- 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.
- Estimate the resulting emissions.

These steps were carried out for all modes and, in the case of road vehicles, by country. A principal geographic scope of intra-EU-27 transport plus half of intercontinental transport to and from the EU-27 countries was considered for aircraft and marine vessels. Existing fleet composition data and retirement curves by mode and vehicle type were obtained from a number of literature sources, most notably stock models from TREMOVE (2007) and Morrell & Dray (2009). Available pkm, tkm and vehicle-km from the existing fleet were estimated using utilisation estimates from WP 1-3 in combination with literature data on how utilisation varies with vehicle age and size.

The total demand for new vehicles was then estimated by comparing available pkm and tkm from the existing fleet with demand estimates for the different TOSCA scenarios. Purchaser technology choice for these new vehicles was assessed on a cost-effectiveness basis using Net Present Value as a decision criterion, with parameters chosen to take account of factors such as consumer myopia with regard to fuel cost savings[2]. The costs associated with owning and operating each vehicle were taken from WP 1-5 outputs, including cost trends over time and with increased technology production. In the case that policies, new infrastructure or vehicle choice changed the average journey times or costs, the resulting change in demand from the base scenario values was estimated using a set of elasticities and cross-elasticities of demand estimated from the SUMMA project outputs and the fleet calculation was re-run with these new values. This approach was chosen to keep individual model runs to a short run time.

Fuel use was calculated using the estimated values by technology from TOSCA WP1-3 and WP5, including trends over time. The direct and fuel lifecycle CO_2 emissions associated with this fuel use were the estimated using the fuel characteristics generated by TOSCA WP4. For comparison, at least a 60% decrease in EU-27 transportation GHG emissions with respect to year-1990 levels is judged necessary by 2050 to meet EU climate goals. In the case of alternative fuels, a limit on total biomass supply was set using WP4 literature estimates of EU-27 production capacity to 2050.

Direct and fuel lifecycle emissions by scenario in the case that no new policies are adopted are shown in Figure 1. The assumptions in this case are as follows. Technologies judged to require a ‘substantial’ (EU-wide) R&D effort to attain market-readiness, or which require substantial infrastructure investment, are assumed not to be available in the no-new-policy case. Fuel excise duty and VAT are assumed to remain at present-day levels to 2050. Existing major policies, such as the entry of aviation into

[2] Note that this means the calculation here is not the same as the cost-effectiveness calculation carried out by WP1-5, although it uses cost data from WP1-5 as inputs. In particular, higher discount rates (8-10%) are used. Further details are given in the WP6.2 Final Report.

the EU Emissions Trading Scheme in 2012, are assumed to be carried out, but it is not assumed that emissions targets are necessarily met.

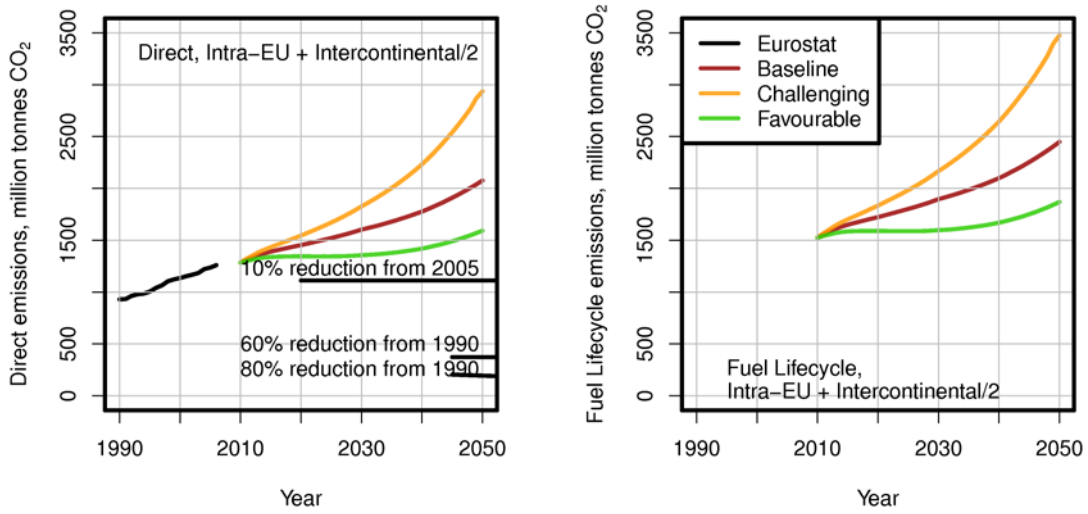

Figure 1 Direct and Lifecycle CO_2 Emissions in the Absence of New Policies

The differences in emissions between scenarios are primarily due to the differences in demand between those scenarios. Technology trajectories are similar in each case. For passenger cars, present-day 'reference' gasoline and diesel internal combustion engine technologies remain dominant in the fleet, due to the high R&D requirements and high costs associated with alternative technologies. For trucks, diesel remains the dominant fuel but reduced resistance technology is widespread by 2050. For trains, several technologies are adopted, including space-efficient carriages. For aircraft, the evolutionary replacement narrowbody aircraft takes over from the existing reference aircraft, but no other technologies are adopted.

CO_2 emissions from transport increase to 2050 in all scenarios under the assumptions used here. In the Favourable scenario, road and rail emissions decrease slightly to 2050, whilst shipping and particularly aviation emissions increase. In the Baseline and Challenging scenarios, emissions increase to 2050 for all modes apart from rail. In no scenario do emissions meet, or even approach, suggested EU targets for year-2020 or year-2050 transportation emissions, as shown in Figure 1. These scenarios are also not neutral in terms of their public finance implications. In particular, fuel tax revenue as a proportion of EU-27 GDP declines from 1.4% in 2010 to 0.7-0.9% in 2050.

Two forms of sensitivity testing were carried out. In the first, the model sensitivity to uncertainty in the technology characteristics estimated by WP1-5 was tested by running Monte Carlo simulations using the technology characteristic uncertainty bounds from WP1-5. This analysis revealed that the impact of different scenario variables on emissions is much greater than that of uncertainty in technology characteristics, under the assumptions used here. In the second sensitivity test we looked at how sensitive the results are to changes in the assumption that scenario variables follow smooth trends, by running a hypothetical 'disruptive event' scenario[3]. Over the long term, the disruptive scenario used did not produce an emissions outcome outside the range of those covered by the three main TOSCA scenarios. Although there are many forms of variability in input scenario values possible, this suggests that long-term emissions outcomes are little-affected by at least some forms of input variability.

[3] This scenario is described in the WP6 Final Report.

4. Analysing Relevant Transport Policy

Following the projection of GHG emissions in a no new policy case in section 3, this section looks at composing a set of transport policy measures that aim to mitigate these emissions. Based on the policy discussion carried out at the third TOSCA Workshop in Athens on the 22nd-24th September 2010, a literature review into transportation policies and their impacts was carried out, including literature and expert-based assessments of policy effectiveness, acceptability and other key dimensions. This review was used to select policies to run within the TOSCA framework. Policies were divided into broad types based on their primary point of impact. Representative policies were chosen from each of these groups (Table 23), based on their applicability to TOSCA, effectiveness and the likely applicability of results to other policy types. As policies are likely to be applied in combination, a selection of policy combinations was then chosen from this table. In each policy case, the dominant technology/fuel pathways from section 2, and the resulting emissions were identified. The feasibility, affordability and acceptability and likelihood of realization of each policy case were assessed, and sensitivity tests to assess pathway robustness were carried out.

Table 23 Policies Selected for Further Study in TOSCA

Policy Type	TOSCA Implementation	Cost Estimation	Results also broadly applicable to:
Economic policy affecting operating costs	Carbon tax	Direct impacts (e.g. change in total taxation revenue) – not infrastructure	Fuel tax/subsidy, emissions trading, road pricing
Economic Policy affecting fuel consumption	Vehicle purchase subsidy (by type)	Direct impacts (e.g. amount paid in subsidies)	Gas-guzzler tax, feebate, vehicle purchase penalty
Regulation	Emissions Standard	Equivalent subsidy	Fuel economy standard
Infrastructure Investment	AHS lanes, ERTMS-ETCS/Level 3	Infrastructure costs estimated in WP5	-
R&D and Information	Government-sponsored R&D	Some estimated by WP1-5	-

Based on the information available in TOSCA, indicators were given for assessed policies including the total amount of direct and fuel lifecycle CO_2 emissions released through 2050; direct costs or revenues to government; and the impact of the average vehicle in the fleet on the acceptability metrics defined by WP 1-5.

Five policy-combination cases were chosen for detailed modelling in the TOSCA policy modelling stage. These were: no new policies; R&D and infrastructure policies; carbon taxation at €100/tCO_2; carbon taxation at €100/tCO_2 plus R&D and infrastructure policies; and vehicle purchase subsidies at €3,000/vehicle plus R&D and infrastructure policies. In addition, R&D policies for road vehicles were divided into those focussing on electricity as a fuel, those focussing on hydrogen, and those focussing on biofuels. The input assumptions to, and results from this analysis were as follows.

R&D and infrastructure policies were assumed to make available technologies judged by WP 1-5 to need a 'substantial' research effort (for example, battery electric vehicles, fuel cell vehicles, open rotor aircraft and a number of alternative fuels from wood feedstock). These policies resulted in a decrease of transportation fuel lifecycle CO_2 emissions in 2050 of 8-10% compared to the 'no new policies' case, depending on scenario. This resulted primarily from use of alternative fuels by trucks and aircraft (BTL fuels from wood feedstock), as well as 'combination' train technology. Little emissions impact was seen for

passenger cars, due to the high costs associated with alternative vehicle technologies and consumer myopia with regard to fuel cost savings.

In the case of carbon taxation without R&D, technologies requiring a 'substantial' R&D effort were assumed not to be available, but a €100/tCO_2 carbon tax based on direct emissions was applied to all modes of transport. For this level of tax, fuel lifecycle CO_2 emissions were again reduced by around 10%, but relatively little impact was seen on technology uptake. Instead, emissions reductions resulted primarily from decreases in demand due to higher journey costs.

Carbon taxation in combination with R&D produced a decrease of transportation fuel lifecycle CO_2 emissions in 2050 of 16-19% compared to the 'no new policies' case. This was primarily due to a combination of demand reduction and increased use of alternative fuels over the R&D-only case, although in the fuel cell road vehicle R&D case some uptake of fuel cell light trucks was also projected. Sensitivity tests suggested that substantial changes in vehicle technology use, rather than fuel use, would require taxation levels closer to €300/tCO_2 under the assumptions used here. This would result in substantial increases in fuel price (€0.7/L gasoline). One exception is the case of road biofuel-focused R&D and infrastructure policies plus carbon taxation. Here uptake of ethanol-fuelled road vehicles using ethanol from wood feedstock was projected at €100/tCO_2. However, uptake of this vehicle/fuel combination was strongly limited by the assumed EU-27 biomass production capacity, as discussed by WP4 above. This implies that substantial biofuel imports would likely be needed in such a case. Government revenues from carbon taxation were estimated at 0.5-0.8% of EU-27 GDP in 2050 for the R&D plus €100/tCO_2 carbon tax cases. This value is similar to the amount of projected decrease in fuel tax revenues (excise duty and VAT).

R&D/infrastructure policies were also considered in conjunction with a €3,000/vehicle purchase subsidy for electric or fuel cell road vehicles. Here, alternative road vehicle technologies formed around 50% of the fleet by 2050. Year-2050 transportation fuel lifecycle emissions were reduced by 14-17% (in the case of R&D and subsidies for plug-in hybrid and battery electric road vehicles), and 12-17% (in the case of R&D and subsidies for fuel cell vehicles using hydrogen from natural gas feedstock). The total amount paid in subsidies in both cases in 2050 was around 0.5-0.8% of EU-27 GDP, depending on the scenario.

As a final test of the overall potential of the technology interventions assessed in TOSCA, model runs were carried out assuming that sufficient subsidies are offered for full adoption of all alternative technologies offering the lowest emissions in their vehicle class, as well as full R&D and infrastructure development funding for these technologies, regardless of any negative impacts. Subsidies were chosen as a policy lever in this case because they do not have a direct impact on demand for transportation (the rebound effect will likely be small with further growing income and value of time). A summary of the technology, fuel and infrastructure options used in this case is given in Table 24.

Table 24 Lowest-Emission Vehicle, Fuel and Infrastructure Technologies by Mode

Mode	Major Technology	Fuel (feedstock)	Capacity Technology
Road Passenger	Fuel cell vehicle	Hydrogen (Wood)	AHS
Road Freight (MDT, HDT)	Reduced Resistance Truck	F-T Diesel (Wood)	CVO
Road Freight (LDT)	Fuel cell vehicle	Hydrogen (Wood)	CVO
Air Passenger	Optimised Open Rotor	F-T Jet A (Wood)	SESAR
Air Freight	Optimised Open Rotor	F-T Jet A (Wood)	SESAR
Rail Passenger	Combination Passenger Train	Electricity/Diesel (Fossil)	ERTMS/ETCS- Level 3
Rail Freight	Combination Freight Train	Electricity/Diesel (Fossil)	ERTMS/ETCS- Level 3
Marine Freight	Air Cavity System	HFO (Fossil)	-

Such a scheme would require government funding of at least 2% of GDP, excluding R&D and infrastructure costs. It includes many options, including AHS for road vehicles, and would have a significant

negative impact on a number of acceptability metrics for some modes, most notably privacy, noise and equity. These problems, along with the extensive R&D needed into exotic technology options such as hydrogen fuel from wood feedstock, mean that this policy case may not be easily realizable. However, it provides an upper bound on emission reductions from the technologies studied in TOSCA.

A further constraint is biomass availability. Alternative fuel from wood feedstock is required by multiple modes in this case. In Figure 2 we show the most optimistic case for biomass availability, in which the limit for biofuel supply is set at the projected global production capacity. In this case, direct emissions from EU-27 transport could be reduced by 40-50% from year-1990 levels in the Baseline and Favourable scenarios, but not in the Challenging scenario.

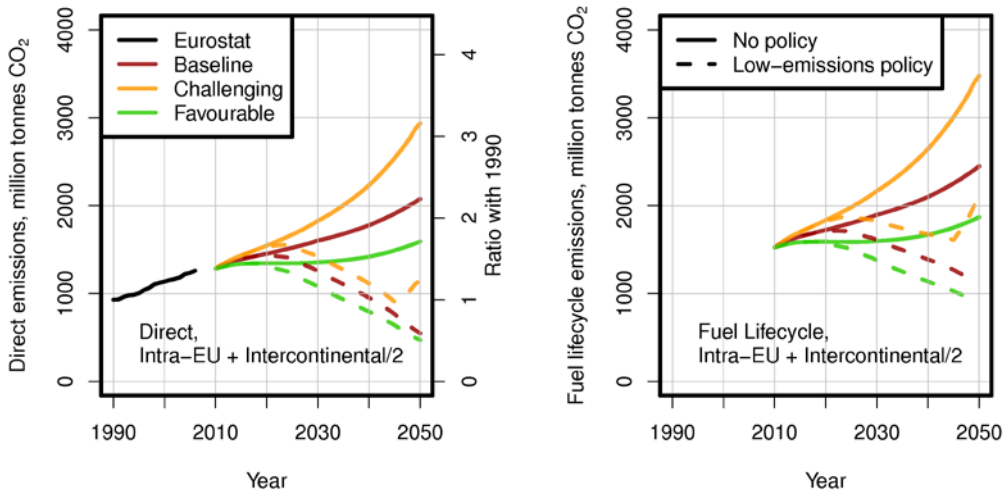

Figure 2 Direct and Lifecycle CO_2 Emissions under Full Adoption of Lowest-Emission Technologies

This case illustrates that it may not be feasible to reduce year-2050 EU-27 transport emissions by 60% from year-1990 levels (the amount judged necessary to meet EU climate goals by EU 2011) by transportation technology-related measures alone[4]. Table 25 gives a numerical comparison for major intra-EU-27 modes, analogously to Table 22 for WP6.

Model runs were carried out using Monte Carlo modelling and a disruptive scenario to test the model sensitivity to uncertain input and scenario assumptions. The Monte Carlo results were similar to those found for the no new policies case: uncertainty in projected emissions due to scenario variables is typically greater than that due to uncertainty in technology characteristics, for the assumptions used here. Similarly, results using the disruptive scenario were typically within the range covered by the three main TOSCA scenarios. However, one exception may arise from the interaction of oil price peaks with learning effects: if conditions during a temporary peak in oil prices are sufficient to promote increased adoption and production of alternative technology, the decrease in purchase price resulting from increased cumulative production may lead to increased uptake after the oil price peak has passed.

[4] Note, however, that the TOSCA project did not look in detail into electricity-generation technologies, but instead treats the carbon intensity of electricity generation as a scenario variable. The combination of vehicle electrification and very low GHG electricity would help towards meeting EU emissions goals.

Table 25 Absolute and per-pkm or per-tkm Lifecycle CO_2 Emissions by Major Intra-EU-27 Mode for the 'no new policies' and 'lowest-emission' Cases

	Fuel Lifecycle emissions, $MtCO_2$; fuel lifecycle emissions per pkm or tkm, gCO_2						
No new policies		**Baseline**		**Challenging**		**Favourable**	
	2010	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Road Passenger	602; 132	690; 115	698; 98	765; 115	854; 97	586; 114	530; 96
Rail Passenger	20; 48	17; 36	12; 21	21; 43	17; 29	13; 29	7; 15
Air Passenger	76; 139	105; 101	174; 82	143; 106	321; 83	77; 103	107; 83
Road Freight	456; 246	533; 218	545; 190	577; 217	642; 189	436; 220	391; 191
Rail Freight	11; 26	9; 16	7; 16	11; 18	11; 18	6; 14	4; 14
Lowest-emissions							
Road Passenger	602; 132	662; 110	274; 32	735; 111	455; 45	563; 110	214; 32
Rail Passenger	20; 48	16; 35	9; 14	20; 42	13; 21	13; 29	5; 10
Air Passenger	76; 139	85; 81	74; 30	109; 77	164; 38	64; 83	47; 30
Road Freight	456; 246	373; 157	130; 41	488; 161	225; 64	307; 156	94; 42
Rail Freight	11; 26	9; 14	7; 8	11; 16	11; 10	6; 13	4; 6

Table Notes:
Figures are for whole-fleet emissions, taking into account past trends over time in new vehicle emissions, typical utilisation, system inefficiencies, biofuel supply limitations and fleet turnover effects.

5. Conclusions

Based on the TOSCA project, the following conclusions can be drawn.

1. **In the absence of new policy intervention, EU-27 transport sector lifecycle greenhouse gas emissions are likely to increase above current (2010) levels by 2050.** Intra-EU-27 transport sector-related lifecycle carbon dioxide (CO2) emissions increased from around 900 million tons in 1990 to nearly 1,200 million tons in 2010, a growth by about 30%. The TOSCA scenarios suggest that these emissions may continue to rise by up to nearly 60% by 2050 in the absence of new policy intervention. If also including half of intercontinental air transportation, the EU-27 transport sector lifecycle CO_2 emissions could more than double by 2050.

2. **Promising technologies and fuel options exist, but they incur significant extra costs and require government intervention such as R&D investment, regulatory measures, subsidies, or taxation.** TOSCA's techno-economic assessment suggests that energy use per unit pkm or tkm can be reduced by 30-50% for most transport modes using technologies that could become available during the 2020s, compared to the average new technology in place today; natural fleet turnover would then translate these new vehicle-based reductions into the entire fleet by midcentury. And these reductions in CO_2 emissions can be further complemented by second generation biofuels and electricity from low carbon sources. A more electricity-based transport system also offers ancillary benefits in terms of reduced energy import dependence. However, exploiting the potential of these opportunities requires policy intervention. Many of the critical automobile, narrowbody aircraft, and (some) ITS technologies and second generation biofuels rely on substantial (EU-wide) R&D investments in order to be produced at large, commercial scale. In addition, a carbon price of around €150 per ton of CO_2 would be required for the proposed narrowbody aircraft technologies

to become cost-effective and this price would need to be more than twice for advanced automobile technologies, unless the new technologies are regulated into the market. Moreover, industry would need to be encouraged to make the capital-intensive investments to manufacture these technologies and fuels. Realizing these opportunities thus requires predictable market conditions that need to be ensured by technology and climate policy. Realizing these opportunities also requires society to prioritize climate change mitigation over other needs, as these policy interventions will lead to additional public expenditures (and thus to higher taxes or cuts in other government budgets at times of a public finance crisis) and/or to higher prices and thus decreased mobility.

3. **However, even assuming very optimistic levels of adoption of promising technologies and fuels, it is unlikely that EC-27 transport sector lifecycle greenhouse gas emissions can be reduced to significantly below 2010 levels by 2050, unless affordable and vast amounts of low-carbon biofuels and electricity can be supplied.** Hence, it appears that technological measures alone cannot produce large enough reductions in transport GHG emissions to be compatible with EU climate goals, at least by 2050. The question then is better understanding the potential for behavioural measures to mitigate transport sector GHG emissions, which include reducing the need for transport and shifts toward low-emission modes.

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