Liimatainen et al. European Journal of Futures Research (2018) 6:22
https://doi.org/10.1186/s40309-018-0151-y

European Journal of Futures Research

RESEARCH ARTICLE Open Access

CO_2 reduction costs and benefits in transport: socio-technical scenarios

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Abstract

The transport sector produces 23% of greenhouse gas (GHG) emissions globally. While the mitigation of climate change requires GHG emissions to be drastically reduced, the emissions from the transport sector are expected to grow. The purpose of this study is to produce alternative scenarios which meet the target of 80% CO_2 emission reduction by 2050 for the Finnish transport sector and to analyse the carbon abatement potentials, costs and benefits of the required behavioural and technological measures. We found that the most cost-efficient measure for the society is to support a shift from private car use to shared car use through increasing car-sharing and ride-sharing. Aiming to reach the emission reduction targets solely through technological measures would require a rapid uptake of alternative energies and the society would not receive the possible benefits, including health benefits, energy savings and fixed car cost savings.

Keywords: Transport, GHG emissions, Emission reduction, Costs, Benefits, Scenarios

Introduction

Global CO_2 emissions from transport are 9000 billion tons, which is 18% of man-made emissions and these are expected to grow by 60% until 2050 [20]. According to the Intergovernmental Panel on Climate Change [19], emissions from transport may grow faster than on any other sector without aggressive and sustained emission reduction measures. In Finland, transport emitted 12.6 Mt of CO_2equivalent, which was 21% of total greenhouse gas (GHG) emissions in 2016 [39]. As an EU member state, Finland is committed to reduce GHG emissions by at least 40% by 2030, while the long-term target is at least 80% decrease by 2050, compared to emissions in 1990 [10, 30]. The emission reduction targets for transport are even stricter, with a 50% reduction target from 2005 level by 2030 and "over the long term, transitioning into a transport system with extremely low emissions" [33]. Hence, there is an urgent need for identifying, evaluating and promoting measures with which emissions from transport can be reduced cost-efficiently.

Figure 1 shows seven components that are directly affecting the emissions from passenger transport. The population, amount of trips per day and average trip distance set the demand for transport. The mobility habits then affect the modal split and the load factor in different modes of transport. The mobility needs and habits combined create the actual vehicle kilometres. In the end, the technology and its development has an effect on how much energy is used to travel and how much emissions are caused. Each component can be thought of as a lever in a mixing table, which can be adjusted through a variety of policies and measures to achieve emission reduction targets.

All of the components in Fig. 1 can be affected through different supportive, directive and restrictive policies and they affect the result as a whole. With mitigation policies, the necessary reduction in GHG emissions from the transport sector can be achieved. According to IPCC [19], avoiding journeys, modal shift, improvements in vehicle technology, low-carbon fuels, infrastructure investments and densifying urban landscapes effectively combined enable significant emission reductions. A range of strong and mutually supportive policies are needed to support these measures in both the short and long terms. The policies promoting both behavioural change and uptake of improved technology offer together high mitigation potential [37]. The mitigation policies within the transport sector are well known and can be broadly categorised as presented in Table 1.

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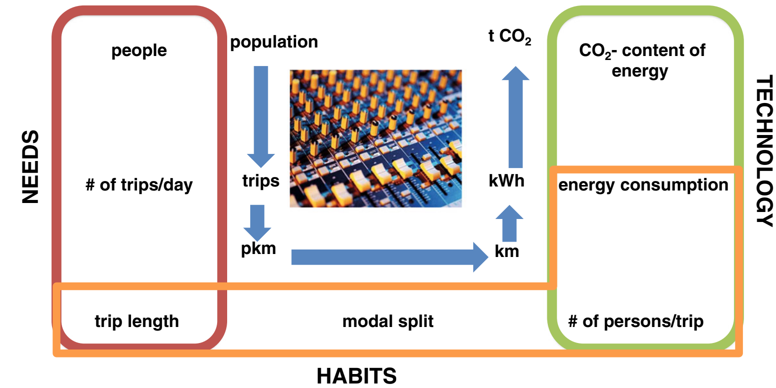

Fig. 1 The mixing table for CO_2 emission reductions in passenger transport. The mixing table in Figure 1 presents factors, which affect CO_2 emissions of passenger transport. This study discusses changes in mobility needs, habits and technology, which can provide emission reductions

Although the behavioural measures to mitigate climate change in transport are acknowledged to have significant potential, the amount of studies quantifying the effects of these measures is low. Anable et al. [3] highlight this gap of knowledge and present future scenarios, which demonstrate the potential contribution of behavioural measures towards an 80% emissions reduction target by 2050 in the UK transport sector. Bueno [6] argues that in order to meet the CO_2 reduction targets in the Basque Country, a reduction in mobility in absolute terms as well as very high occupancy rates of vehicles are required in addition to the technological measures. Banister and Hickman [5] urge researchers and policy-makers to 'think the unthinkable' by developing scenarios which look at changes to travel behaviour. Crozet and Lopez-Ruiz [7] take the analysis of behavioural measures further and model the effects of various factors affecting the modal choices of the population in France. Finally, Harvey [17] states that eliminating transport CO_2 emissions worldwide by the end of the century requires simultaneous application of all technical and behavioural measures.

There seems to be very few academic research presenting monetary values of the costs and benefits associated with the behavioural measures aiming at emission reductions. Kok et al. [23] review both academic and non-academic literature and find that the cost-effectiveness of behavioural measures were analysed in only 30% of the studies, of which 4 were academic studies and 6 non-academic studies. Furthermore, if the behavioural measures are concerned, the analyses mostly focus on the effects of financial measures, such as carbon or fuel tax or feebate programs, on the demand of car transport [15, 22, 32, 35]. For instance, the review by Sims et al. [37] presents carbon abatement costs for various technological measures but provide only qualitative analysis of the behavioural measures. The research by Dedinec et al. [8] is a rare exception as it considers the CO_2 reduction potential and associated cost savings of driver behaviour and travel behaviour, i.e. using public transport on commuting trips and walking and cycling short distances. These measures were found to be highly cost effective, but Dedinec et al. [8] did not consider the infrastructure investments or increased operational costs of public transport, which are likely to be needed to promote the behavioural change. AlSabbagn et al. [2] studied the CO_2 abatement costs of public transport investment in the case of introducing light rail and bus rapid transport in Bahrain, considering

Table 1 Mitigation policies and examples of measures in passenger and freight transport (based on [23, 27, 37])

Mitigation policy	Behavioural measures	Technological measures
Reducing transport activity	Densifying urban structure Restructuring supply chains	Replacing physical transport with ICT Improving the efficiency of vehicle routing
Promoting modal shift	Mobility management Affecting the relative competitiveness of transport modes	Improving public transport, walking and cycling infrastructure Improving infrastructure for intermodal transport
Improving energy efficiency	Increasing passenger occupancy rates Improving vehicle utilisation on laden trips and level of backhaulage Eco-driving	Reducing vehicle energy consumption
Reducing carbon intensity of energy	Using vehicles exploiting alternative energy (electricity, hydrogen, biofuels)	Substituting oil-based fuels with biofuels, electricity or hydrogen

the capital as well as the maintenance costs, and found the costs high compared to the estimated CO_2 reduction.

The purpose of this study is to produce alternative scenarios, which meet the 80% CO_2 emission reduction target in 2050 for the Finnish transport sector, and to analyse the carbon abatement potentials, costs and benefits of the required behavioural and technological measures. The research question is how the CO_2 reduction targets in transport can be met cost-effectively. The analysis encompasses emissions from both passenger and goods transport. The analysis is done from governmental perspective on a national level using Finnish data and by constructing scenarios up to 2050 on the most effective and cost-efficient alternative to reach the 2050 GHG goals. The Finnish ministry of transport and communications has a tradition of using scenarios in developing GHG emission reduction policies [40], and the results of this study have also been used in developing the transport sector policy packages of the medium-term climate change plan for 2030 [28]. The emission reduction target is reached in two scenarios: one by adapting exclusively technological measures, and the other by adaption a combination of different measures. As a reference case, a business as usual (BAU) scenario is outlined.

Methods and data

Scenarios can be classified in several ways, and there are several ways to construct scenarios. In our scenario approach, one key element is the vantage point, from which the scenarios are developed. The two types of scenarios, forecasting and backcasting scenarios, differ from each other in terms of their starting point. Forecasting scenarios are exploratory and take the current situation as their starting point, whereas backcasting scenarios are normative and anticipatory or prescriptive, and start from a specific future situation [41]. In this study, we start from the current state in the BAU scenario and this scenario is a forecasting scenario by nature. As the 80% emission reduction target sets the premise for the two scenarios, which reach the target, the backcasting scenarios are implemented as we study the possibilities to arrive at the desired target with alternative measures in two scenarios.

In this study, a widely recognised framework for analysing the relationships between the economy, road freight transport demand, energy consumption and CO_2 emissions (see, e.g. [24]) was complemented and applied to analyse also passenger car transport. With the framework presented in Fig. 2, the effects of mitigation policies on both car and truck transport can be analysed. As the CO_2 emission from cars and trucks represent 80% of total transport emissions in Finland [43], the research focuses on these modes and other modes of passenger and freight transport are analysed in less detail.

The framework for analysis starts off with the amount of population for passenger transport and with gross value added (GVA) for freight transport. For these, data from Statistics Finland regarding current and forecasted population in years 2011, 2030 and 2050 and the regional accounts in 2012 as well as an economic forecast for 2030

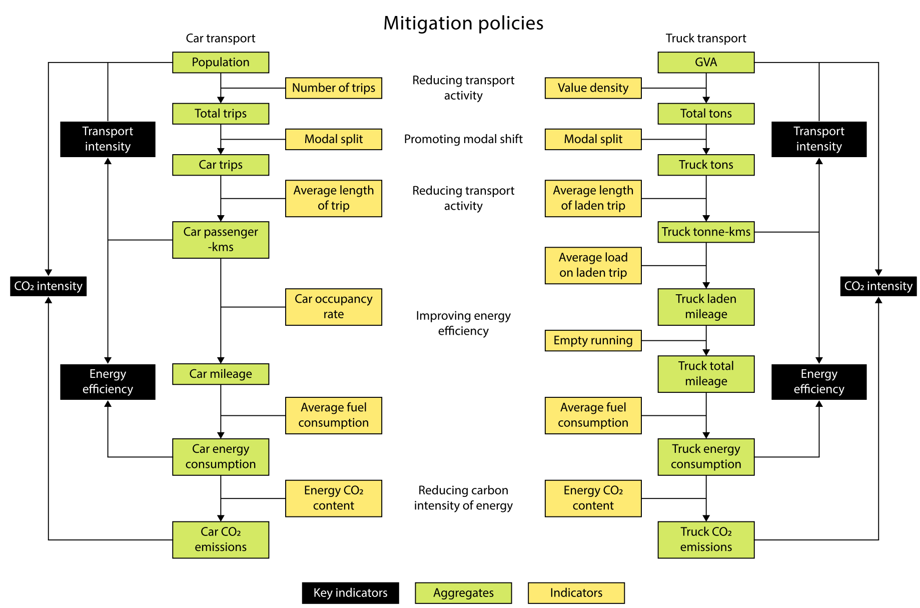

Fig. 2 Framework for analysing the effects of CO_2 mitigation policies on passenger car and freight truck transport. The framework in Figure 2 presents mitigation policies of CO_2 emissions and their connection to different key indicators, aggregates and indicators of CO_2 emissions of car and truck transport. In this study, the framework is used to calculate the CO_2 emissions in different scenarios

and 2050 from VATT [42] were adopted. The next level in the framework analyses the total number of trips made in passenger transport and by car and the total amount of tons transported by trucks. For these, data from national travel survey data from Finnish Transport Agency and road freight transport from Statistics Finland was applied. The passenger transport data consists of the Finnish National Travel Survey (FNTS) data from 2010 to 2011 in which there are about 46,600 trips covering all modes. The road freight transport data consists of the continuous Goods Transport by Road survey (GTRS) data from 2013 in which there are about 11,500 trips reported with only trucks covered. Other modes of transport are analysed using aggregate data based on the official statistics for each mode.

The next levels of the framework analyse the amount of passenger kilometres and tonne kilometres, car mileage and truck mileage (both laden and total; total including also the unladen kilometres). This analysis utilises the aforementioned FNTS and GTRS data. The last part of the framework focuses on issues related to the energy consumption and CO_2 emissions. For these, energy (i.e. mostly fuel) consumption and vehicles' emission data was adopted from VTT [44]. For freight transport, also unit emission data from Network of Transport Measures NTM was used, following the methodology presented by Liimatainen & Pöllänen [25]. Based on the unit emission data from these sources, each trip in the FNTS and GTRS data is given an energy consumption and emission factor, which enable detailed analysis of all indicators in the framework.

Scenario tool

Based on the framework, a model for constructing scenarios on the future CO_2 emissions of transport was created. The model was implemented in Microsoft Excel. Due to the available data, the base year of the model is 2011 for passenger transport and 2013 for freight transport. The effects of policy measures are analysed from year 2015 onwards. The scenario tool integrates different data inputs, development prospects and different measures, which affect the issues depicted in Fig. 2, e.g. in passenger transport the developments related to population and urban structure, and the transport demand. For passenger car fleet, future prospects of great interest include the amount of new registered vehicles, medium lifetime for a car, distribution of motive powers, energy use and emissions. For car use, inputs for the scenarios include, e.g. changes in average load (persons per car trip) and for energy issues, e.g. the share of biofuels in petrol and diesel fuels. For other modes of transport, the development of energy efficiency and CO_2 content of the energy (kg/kWh) are included in the model. As outputs, the scenario tool produces annual data, e.g. on trips, transport and traffic volumes in different modes, the car fleet, energy consumption and CO_2 emissions up to year 2050.

In order to make the model able to consider the current situation and future development prospects in adequate resolution, the modal shares and average trip lengths are considered within four different regional categories in Finland as well as in inter-regional transport. The four different regions are (1) Helsinki metropolitan region, (2) large city regions with population of more than 100,000, (3) medium-sized city regions with population of 40,000–100,000 and (4) other regions. In addition, international transport and its future development can be considered in the model, but is not included in the cost-efficiency assessment.

For road freight transport with trucks, the scenario tool includes the variables related to GVA (€) and value density (€/t) for different industries, average trip length (km), load (t), energy use (kWh/km) and the CO_2 content of the energy (kg/kWh). Additionally, the share of unladen trips of the transport volume is one variable in the model. As the variables for road freight transport with vans, the scenario tool includes energy use and the CO_2 content of the energy whereas for waterborne freight transport only the CO_2 content of the energy is included.

To be able to analyse the effects and costs of different measures aiming at CO_2 emission reductions, a literature study was carried out. In the cases where there was no information available based on previous research, the researchers deployed own estimates. The costs and benefits are assessed holistically, without making detailed distinction between households', companies', and the public sector's cost effects, but some discussion on the distribution of costs and benefits are presented in the "Discussion and conclusions" section. The costs and benefits are considered within the transport sector, thus the possible benefits related to, e.g. biofuels and their production, such as domestic employment and business opportunities for companies, are not considered. In the scenario tool, we assume invariable energy prices and thus the prices of alternative energies remain unchanged as we choose not to be hypothetical on these or other technological breakthroughs.

Main assumptions in the scenarios

With the scenario tool, three scenarios to years 2030 and 2050 are generated with a business as usual as the reference scenario and two scenarios, in which the emission reductions target is met. In the two scenarios, which meet the target, the target is met with exclusively technological measures (technology scenario), and in the other with a combination of behavioural and technological measures (recommendation scenario). The following key assumptions related to passenger transport are made in the scenarios:

- All scenarios share the same assumption on regional population in 2030 and 2050.
- The number of trips per person and average trip length for each mode are assumed to remain at the 2011 level in 2030 and 2050 in all scenarios.
- The modal split is assumed to remain at the 2011 level in the reference and technology scenarios, but this is one of the key changes in the recommendation scenario (Fig. 3).
- The average vehicle occupancy for passenger cars is assumed to remain at the 2011 level (1.84 persons) in the reference and technology scenarios. This is one of the key changes in the recommendation scenario with a 5% increase in 2030 and 30% increase in 2050 due to ride-sharing.
- The average energy consumption of new passenger cars is assumed in all scenarios to be reduced from the 2013 level of 0.54 kWh/km (CO_2 emissions about 132 g/km) to 0.36 kWh/km (CO_2 emissions 95 g/km) by 2021 in accordance to the EU norms. After 2021, the energy consumption is assumed to remain stable in the reference scenario, but decrease considerably due to technological improvements and changes in the amount of cars of different motive powers in the technology and recommendation scenarios. The number of new cars with different motive powers in the reference scenario were estimated based on references [1, 21, 29, 31] and are presented in Table 2.
- The CO_2 content of the energy is assumed to decrease to 193 g/kWh for gasoline and 231 g/kWh for diesel by 2020 in accordance with the Finnish regulation, which mandates a 20% share of transport energy to be coming from biofuels. This level remains after 2020 in the reference scenario, but in technology scenario and recommendation scenario, the level decreases further. Biofuels, electricity and hydrogen are assumed to have zero CO_2 content within the transport sector, but some calculations on the well-to-tank (WTT) emissions are presented based on the assumed WTT emissions of 80 g/kWh for biogas, 50 g/kWh for ethanol, 100 g/kWh for renewable diesel, 160 g/kWh for electricity and 400 g/kWh for hydrogen ([9, 34, 36]).
- Regarding the other transport modes, it is assumed in the reference scenario that the energy efficiency (pkm/kWh) will increase 10% by 2030 and 20% by 2050. Rail transport is assumed to have zero CO_2 content of energy. In aviation, the CO_2 content of energy is assumed to be 0.25 kg/kWh in 2030 and 0.24 kg/kWh in 2050, and for waterway transport 0.26 kg/kWh in 2030 and 0.25 kg/kWh in 2050.

Two scenarios were made for freight transport, the reference (BAU) scenario and the recommendation scenario. In the two scenarios, the GVA, value density and average length of haul are assumed to be the same. Hence, the total haulage is the same in both scenarios and in line with the national traffic forecast [13]. In the reference scenario, the share of empty running, average load on laden trips and average fuel consumption are assumed to develop until 2030 as forecasted in a previous study [24] and then level off, with some slight changes due to relative importance of different types of commodities transported. In the recommendation scenario, these indicator values are assumed to further improve after 2030. The CO_2 content of energy is assumed to be the same as in passenger transport.

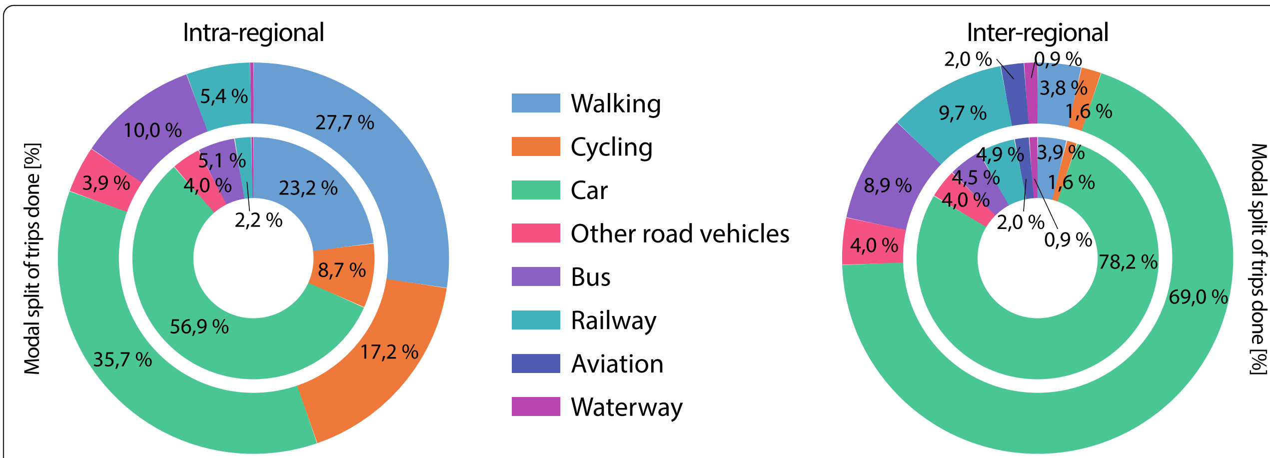

Fig. 3 Modal split in intra- and inter-regional travel in reference and technology scenarios (inner circle) and recommendation scenario (outer circle) in 2050. Modal splits in Figure 3 present the share of trips done with different modes of transport in 2050 according to the different scenarios in this study. Intra-regional travel refers to urban mobility and inter-regional to intercity and long-distance travel

Table 2 New car sales by motive power in the reference scenario

Motive power	Year 2013		Year 2030		Year 2050	
	Cars	Share	Cars	Share	Cars	Share
Gasoline	64,129	62.0%	46,560	38.8%	33,600	28.0%
Flex-fuel (gasoline and ethanol)	414	0.4%	6000	5.0%	12,000	10.0%
Diesel	38,587	37.3%	42,000	35.0%	30,000	25.0%
CNG (compressed natural gas)	103	0.1%	10,800	9.0%	12,000	10.0%
Plug-in hybrid: electric and gasoline	103	0.1%	6000	5.0%	12,000	10.0%
Plug-in hybrid: electric and diesel	62	0.06%	6000	5.0%	12,000	10.0%
Electric	52	0.05%	2400	2.0%	6000	5.0%
Hydrogen	0	0.00%	240	0.2%	2400	2.0%
Total	103,450	100%	120,000	100%	120,000	100%

Assumptions on costs and benefits

Atkins and University of Aberdeen [4] and Schade et al. [36] have carried out emission reduction cost analysis in Scotland and in the EU, respectively. These findings were used to benchmark the calculations made in this study, but also several other references were used to justify the following main assumptions on costs and benefits of the measure packages deployed in the scenarios:

- In the urban form, walking, cycling and public transport package, the costs are estimated to be 510 M€ annually. This cost is in addition to the current infrastructure and public transport operation costs of the national and regional governments. The amount is about 50% of the current annual public transport funding by the national and regional governments in Finland [14] and would allow increasing the service level of public transport, infrastructure projects and mobility management activities. This package induces also significant health benefits due to direct health benefits of increased walking and cycling, estimated at 0.27€/pkm for walking and 0.11€/pkm for cycling. These values are based on Litman [26] and give a rather moderate value of health benefits compared to some estimations using the Health Economic Assessment Tool, see, e.g. Fishman et al. [12]. Health benefits of reduced car transport are estimated at 0.002€/pkm. The calculation is based on the emission costs of cars estimated by Gynther et al. [16] and passenger kilometres travelled by cars as reported by FTA [14].
- In the car-sharing and ride-sharing measure package, the costs are estimated at 1000€ per shared car. This estimate is higher than the investment currently needed to enable car-sharing, but it is set at a high level to allow some of the shared vehicles to be automated vehicles towards the end of the estimation period as according to EY [11] the estimated price for AV technology is about $3000 after 2035. The benefits of car sharing are due to decreased car ownership and hence decrease in the fixed costs of cars, which are assumed at 1000€/car/year and estimated based on Statistics Finland [38].
- In the measure packages related to the changes in the car fleet, the additional costs are estimated based on Nylund et al. [34] and AEA [1]. Additional costs are estimated at 16,500€ for plug-in hybrid and battery electric and 35,000€ for hydrogen cars in 2015, 10,000 € and 15,000€ respectively in 2030 and 2500€ and 4000€ respectively in 2050. Also conventional cars are estimated to have an additional cost which reaches 4300€ by 2030 due to light-weight materials and hybrid engines. For trucks, the additional cost of improved fuel efficiency is estimated to be 15,000€ in 2030 and 30,000€ in 2050 and for vans 5000€ in 2030 and 10,000€ in 2050.
- The energy costs (price without tax) used in all scenarios are 0.5€/l for fossil gasoline and diesel, 0.8€/l for renewable diesel and ethanol, 1€/kg for biogas, 5€/kg for hydrogen and 0.1€/kWh for electricity. There are also infrastructure costs for electricity (private charging station for each electric or plug-in hybrid car at 2000€ per station and one public charging station for every 10 cars at 5000€ per public charging station), hydrogen (1 M€ per station and one station for every 100 cars) and biogas (0.5 M€ per station and one station for every 250 cars). These assumptions are made based on Nylund et al. [34] and Schade et al. [36].
- Additionally, it is estimated that liquefied biogas (LBG) for maritime transport needs one fuelling terminal every 6 years at 70 M€ per terminal and one smaller bunkering facility every 3 years at 25 M€. These prices and capacities are estimate based on MINTC [29].

Results of the scenarios for 2030 and 2050

Table 3 presents the detailed results related to passenger car transport in the three scenarios in 2011, 2030 and 2050. As it can be seen, the recommendation scenario emphasises the large-scale modal shift from cars to other transport modes and a significant increase in car occupancy, resulting in a 45% decrease in car mileage in 2050 compared to the other two scenarios. Even with such decrease in mileage, significant reductions in the average energy consumption of cars and CO_2 content of energy are required to meet the CO_2 reduction target. In the technology scenario, on the other hand, reductions in the average energy consumption and CO_2 content of energy have to be even larger to meet the target.

Table 4 presents the detailed results of truck transport in the two scenarios in 2013, 2030 and 2050. It can be seen that the emission reductions in the recommendation scenario rely heavily on the reduction of energy CO_2 content through the use of biodiesel, as the difference between the two scenarios is just 26% in terms of energy consumption, but 67% in terms of CO_2 emissions.

Reference scenario

The reference scenario results in a 27% decrease in CO_2 emissions in the period 2011–2030 and a 36% reduction in 2011–2050. The emission decrease is mainly reached through reduction in passenger cars' average energy consumption and increased utilisation of biofuels. It is notable that the emission reduction target of 80% is very far from the results in the BAU scenario, and in fact, the emissions from freight transport alone exceed the amount of targeted CO_2 emissions of transport in 2050. The emissions decrease even though the passenger and freight transport volumes increase by 12% and 41%, respectively. However, the reference scenario assumes a very low increase in passenger transport volume, due to people moving to larger cities and adopting the modal split and average trip length of the current residents of those regions.

A sensitivity analysis was carried out to estimate emissions with a higher increase of 36% in passenger-kilometres in accordance with FTA [13]. This would result in a CO_2 reduction of 22% by 2030 and 30% by 2050. Furthermore, the emission reduction in the reference scenario relies heavily on the decrease in average energy consumption of cars, which are uncertain, especially given the mismatch between actual CO_2 emissions and test data [18]. If the average energy consumption would actually be 20% higher than the nominal test consumption (e.g. CO_2 emissions of 114 g/km instead of 95 g/km in 2021), the emission reductions would be less than 20% in 2030. Even without the sensitivities, the emission reductions would not be enough

Table 3 Values of framework indicators for passenger cars in three scenarios in 2011, 2030 and 2050

	2011	2030			2050		
		BAU	Recommendation	Technology	BAU	Recommendation	Technology
Population (> 6 years old, million)	5.0	5.5	5.5	5.5	5.7	5.7	5.7
Number of trips (per year per person)	1031	1029	1029	1029	1027	1027	1027
Total trips (billion)	5.2	5.6	5.6	5.6	5.9	5.9	5.9
Modal share of car (% of trips)	59%	59%	51%	59%	58%	38%	58%
Car trips (billion)	3.1	3.3	2.9	3.3	3.4	2.2	3.4
Avg. length of car trip (km)	17	17	18	17	17	19	17
Car transport volume (billion pkm)	53.0	56.9	51.0	56.9	58.8	42.9	58.8
Avg. occupancy (persons)	1.8	1.8	1.9	1.8	1.8	2.4	1.8
Car mileage (billion km)	38.7	41.5	35.5	41.5	42.9	23.6	42.9
Avg. energy consumption (kWh/km)	0.61	0.40	0.36	0.36	0.34	0.21	0.19
Car energy consumption (TWh)	23.9	16.5	13.0	15.0	14.8	4.9	8.3
Energy CO_2 content (kg/kWh)	0.24	0.22	0.21	0.19	0.20	0.10	0.06
Car CO_2 emissions (Mt)	5.8	3.7	2.7	2.8	3.0	0.5	0.5
Transport intensity (km/person/year)	13,717	13,608	13,425	13,608	13,528	13,354	13,528
of which by car	10,553	10,413	9338	10,413	10,317	7519	10,317
Energy efficiency (pkm/kWh)	2.4	3.6	4.3	3.9	4.1	8.2	6.3
Car energy efficiency (pkm/kWh)	2.2	3.5	3.9	3.8	4.0	8.8	7.1
CO_2 intensity (kg/person/year)	1362	833	655	656	665	181	168
of which by car	1155	670	498	511	525	85	94

Table 4 Values of framework indicators for truck transport in BAU and recommendation scenarios in 2013, 2030 and 2050

	2013	2030		2050	
		BAU	Recommendation	BAU	Recommendation
Gross value added (billion €)	172	240	240	343	343
Value density (€/t)	637	710	710	856	856
Goods transported (million t)	269	339	339	401	401
Avg. length of haul (km)	78	76	76	74	74
Truck haulage (billion tkm)	21	26	26	30	30
Avg. load (t)	10.8	12.6	12.8	12.3	14.9
Truck laden mileage (million km)	1431	1617	1602	1934	1686
Empty running (% total mileage)	26%	21%	20%	20%	15%
Total mileage (million km)	1936	2044	2002	2416	1984
Avg. energy consumption (kWh/km)	3.6	3.2	3.1	2.7	2.5
Total energy consumption (TWh)	7.0	6.5	6.3	6.6	4.9
CO_2 content (kg/kWh)	0.25	0.23	0.22	0.23	0.10
CO_2 emissions (Mt)	1.7	1.5	1.4	1.5	0.5
Transport intensity (tkm/€)	0.12	0.11	0.11	0.09	0.09
Energy efficiency (tkm/kWh)	3.0	3.9	4.1	4.5	6.0
CO_2 intensity (kg/€)	0.010	0.006	0.006	0.004	0.001

to meet the emission target set for 2030, let alone the target for 2050. Hence, there is a clear need for policy measures to meet the targets.

Technology scenario

This scenario studied the possibilities to reach the 80% reduction in CO_2 emissions by 2050 solely through technological development and the adaption of advanced technologies. To reach the reduction target, the vehicle fleet should be drastically altered of what it is today and the share of biofuels highly increased. In 2050, 60% of the cars sold should be plug-in hybrids, 30% electric cars and 10% hydrogen powered. Furthermore, 75% of the fuel used should be renewably produced diesel and ethanol or synthetic gasoline. These shares of vehicles and renewable fuels are one example of a multitude of alternative combinations that could result in the necessary emission reduction. This combination was chosen based on people's current preference of plug-in hybrids over electric cars, which necessitates the high level of renewable fuels. The cost optimum combination of the types of cars and level of renewable fuels changes depending on the advancement of technology, especially battery technology and further research should be carried out to determine the optimum combination. The combined costs for the emission reduction in this scenario would be 19,000 million euros until 2050, while monetary benefits through lower energy consumption would total 3700 million euros until 2050, which would result in unit costs of 225 euros per ton of CO_2 emissions reduced.

Recommendation scenario

This scenario included also behavioural adaptation and changes in mobility practices to reach the emission reduction target of 80% in 2050. In the scenario, well-balanced and cost-efficient mix of measures to reach the target was deployed. The measures include affecting the transport needs, practices, technologies, and economic rationale. In this scenario, the mobility of people is not restricted, but through urban planning the passenger transport need somewhat diminishes. Urban planning also supports people walking, cycling and using public transport to a greater extent. As a result of this development, which should be supported by a vast set of policy measures, car mileage is 27% lower compared to the reference scenario in 2050. Because of this, the required car fleet is 550,000 cars smaller than in the reference scenario in 2050. Further reduction in car mileage and required car fleet can also be acquired through increasing the car occupancy, which is supported by car-sharing and ride-sharing, which in turn may be enabled by automated vehicles. Shared car use also increases the use of individual cars, resulting to lower average age of cars and again to newer technologies implemented faster into the car fleet. This scenario includes also technological measures, but these are not as large scale as in the technology scenario. Purely economic measures have rather limited emission reduction potentials as such, but they can be seen as supportive measures, which should be combined with other measures.

In this scenario, the shares of total CO_2 emissions from different transport modes and in passenger and freight transport change significantly. Cars are currently responsible for 58% of the CO_2 emissions, but only for 23% in 2050 in this scenario. The share of bus transport increases from 2 to 9% as the use public transport increases. As the share of aviation increases, aviation's emissions decrease only slightly. The share of emissions from freight transport increases from 31 to 50%. As depicted in Table 5, the combined emission reduction costs in this scenario are 21,200 million euros until 2050, while monetary benefits total 24,700 million euros until 2050 and unit costs for emission reduction would thus be – 52 euros per ton of CO_2 emissions reduced, indicating greater benefits (and cost savings) than costs. These results are elaborated in more detail in the next section.

Discussion and conclusions

For the society, the most cost-efficient measure for CO_2 emission reductions from transport is to support a shift from private car use to shared car use through increasing car-sharing and ride-sharing. Ride-sharing increases the energy efficiency of car use with barely any additional costs and car-sharing decreases the size of the car fleet thus reducing the purchase costs and fixed costs of cars. Both direct costs and benefits of this measure package apply to households, while companies offering shared mobility services will benefit and car shops may encounter adverse effects due to decreasing car sales and maintenance volumes. Enabling such transformation towards mobility services requires both technological innovations and changes to legislation and market regulation. However, the behavioural change is vital to fulfil this scenario and may require very unpopular policy decisions, such as limiting parking spaces of private cars.

Measures affecting the development of urban form are also very cost efficient as costs are mostly only caused by disseminating best practices. Developing walking and cycling infrastructure affecting the modal split may also be very cost efficient because of the achievable health benefits. Rail infrastructure projects dominate the development of public transport and while they are expensive, they also improve transport safety. Urban planning is closely related to infrastructure projects and the changes take time, thus political guidance must be proactive and persevering. Political perseverance is needed as the infrastructure investment costs affect national and regional budgets in the short term, but health and safety benefits

Table 5 Costs and benefits from the different measure packages in the recommendation scenario

Measure package	Total costs; specifications	Total monetary benefits; specifications	CO_2 emission reductions and unit costs
Urban form, walking, cycling and public transport	11,100 M€; 510 M€ annually to infrastructure projects, mobility management, increasing service level of public transport and uptake of buses using alternative energy	14,300 M€; 3900 M€ health benefits + 4000 M€ reduction in new vehicle purchase costs + 3900 M€ reduction in fixed costs of cars, approx. 1000 €/car/year + 2500 M€ energy savings	18.6 Mt, – 172 €/t
Car-sharing and ride-sharing	1000 M€; Systems required for car-sharing and ride-sharing, later automated cars, approx. 1000 €/car/year	9300 M€; 4000 M€ reduction in new vehicle purchase costs + 3900 M€ reduction in fixed costs of cars, approx. 1000 €/car/year + 1400 M€ energy savings	8.7 Mt, – 954 €/t
Cars with reduced energy consumption	3500 M€; Increased purchase costs of energy efficient cars, cost increase from 0 € to 5000 € during 2022–2050	1100 M€; Energy savings	7.1 Mt, 338 €/t
Cars exploiting alternative energy	800 M€; 600 M€ increased purchase costs of plug-in hybrid, battery electric and hydrogen cars + 200 M€ investments in energy infrastructure	–	4.5 Mt, 178 €/t emissions increase in the energy sector because of biogas, electricity and hydrogen production 3.6 Mt (BAU: 4.6 Mt)
Alternative fuels	400 M€; Higher price of alternative fuels	–	7.1 Mt, 56 €/t emissions increase in the energy sector because of ethanol and renewable diesel production 5.9 Mt (BAU: 5.7 Mt)
Energy efficiency in road freight vehicles	2500 M€; Energy efficient trucks and vans	1000 M€; Energy savings	9.3 Mt, 161 €/t
Alternative energy in freight transport	1900 M€; 600 M€ higher price of renewable diesel + 1300 M€ LBG and infrastructure for marine freight transport	–	12.2 Mt, 156 €/t emissions increase in the energy sector because of renewable diesel production 9.0 Mt (BAU: 4.2 Mt)
Total	21,200 M€	24,700 M€	68 Mt, −52 €/t

accumulate slowly and are seen indirectly as avoided health care costs.

Technological measures induce costs to society because reducing the energy consumption of cars and the uptake of alternative fuels and vehicles both require high investments by car and fuel industries in research and development of new technology. Households then carry the costs in increased fuel and car prices, although government may decide to subsidise new technologies in order to speed up the uptake. However, great emission reductions may be achieved through technology and the emission reduction target can be achieved through solely technological measures. This would require a rapid uptake of alternative energy vehicles, but the society would not receive the great benefits, such as health benefits, energy savings and fixed car cost savings, associated with measures affecting urban form, modal split and social car use. In addition, the technological measures shift emissions from the transport sector to the energy sector. Hence, the emissions caused by transport in the energy sector may almost double due to the vehicles using alternative energy sources.

Figure 4 presents the cost efficiency of different CO_2 reduction measures in the recommendation scenario. The height of the column indicates the costs of the measure as euros per tonne. Negative values denote that the measure will generate net benefits as there are larger monetary benefits than costs. The width of the column indicates the maximum cumulative CO_2 reduction as megatons available from that measure during 2011–2050. Both changing car use towards sharing services and promoting modal shift through urban planning are measures that also have monetary benefits due to health benefits and savings from car purchases and fixed costs. The use of alternative energy sources and alternative fuels in transport can also reduce the CO_2 emissions, but these measures are more costly because of purchase costs of new cars, higher prices of alternative fuels and investments in infrastructure of electricity and alternative fuels.

The aim of this study was to explore the cost effectiveness of achieving the 80% emission decrease target by 2050. However, the target may be greater than this in the transport sector because emission reductions may be even more difficult to achieve in other sectors, e.g. in the agriculture sector. Hence, there is a need to explore the measures, costs and benefits of even greater emission reduction in the transport sector. Furthermore, there is a need to constantly update the analysis, because transport emissions seem to remain at a high level in Finland and the policy packages analysed in this study may not be enough anymore to meet the emission reductions. The resources of this study did not enable assessing the effects of individual measures, but the methodology developed in this study enables such analyses in the future. More detailed analysis should also include sensitivity analyses related to the large number of assumptions that were made in this study, for example on the health benefits, required level of cycling and public transport infrastructure investments, costs of new vehicle technologies, energy costs and the timing of measures.

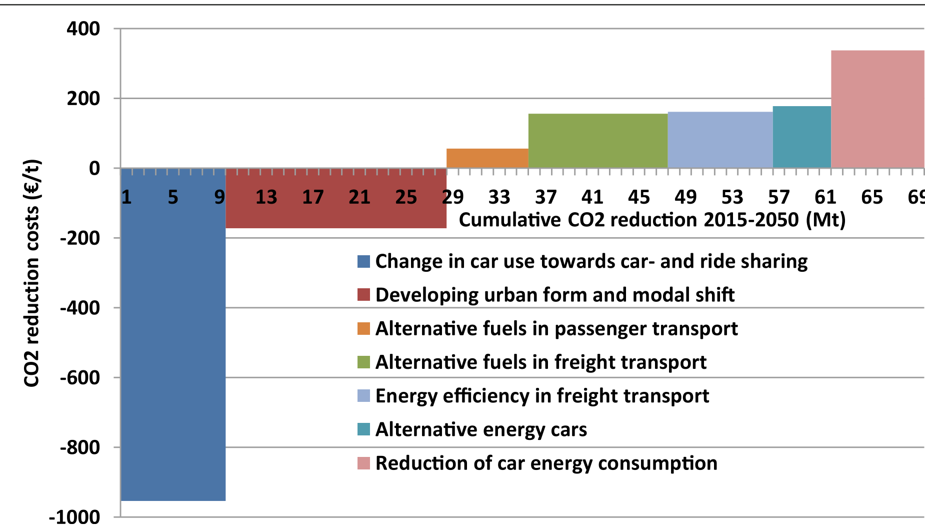

Fig. 4 Cost efficiency and CO_2 emission reduction of different emission reduction measures in the recommendation scenario. The cost efficiency of seven CO_2 emission reduction measures in terms of costs (€) per tonnes of reduced CO_2 is presented in the *y*-axis. Negative values denote that the measure will generate net benefits as there are larger monetary benefits than costs. The cumulative CO_2 reduction with each measure is presented in the *x*-axis. The figures are based on the measures implemented in 2015–2050 in the recommendation scenario

Acknowledgements
The authors would like to thank the team of researchers who were involved in the larger project this paper draws results from. Thanks Lasse Nykänen, Tuuli Rantala, Antti Rehunen, Mika Ristimäki, Anna Strandell, Jyri Seppälä, Matti Kytö, Samuli Puroila and Markku Ollikainen!

Funding
The larger research project from which this paper draws results from was financed by the Finnish Ministry of the Environment through the Finnish Climate Panel. Writing the article was supported by the Kone Foundation (grant number b4b919).

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Authors' contributions
All authors jointly shaped the manuscript and participated in the literature review and the analysis of the results. HL managed the data and the scenario model, while MP assessed the quality of the results and finalised the manuscript, and RV visualised the results and fine-tuned the figures. All authors contributed to manuscript revision based on the reviewing comments and have read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 10 August 2018 Accepted: 29 November 2018
Published online: 21 December 2018

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