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Global travel within the 2 °C climate target

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ABSTRACT

Long-term scenarios generally project a steep increase in global travel demand, leading to an rapid rise in CO_2 emissions. Major driving forces are the increasing car use in developing countries and the global growth in air travel. Meeting the 2 °C climate target, however, requires a deep cut in CO_2 emissions. In this paper, we explore how extensive emission reductions may be achieved, using a newly developed travel model. This bottom-up model covers 26 world regions, 7 travel modes and different vehicle types. In the experiments, we applied a carbon tax and looked into the model's responses in terms of overall travel demand, modal split shifts, and changes in technology and fuel choice. We introduce two main scenarios in which biofuels are assumed to be carbon neutral (not subject to taxation, scenario A) or to lead to some greenhouse gas emissions (and therefore subject to taxation, scenario B). This leads to very different outcomes. Scenario A achieves emission reductions mostly through changes in fuel use. In Scenario B efficiency improvement and model split changes also play a major role. In both scenarios total travel volume is affected only marginally.

1. Introduction

Passenger travel forms a rapidly growing source of greenhouse gas (GHG) emissions. In 2005, passenger travel was responsible for 14% of global energy-related CO_2 emissions (i.e., 0.61 t CO_2 per capita) (IEA, 2010). In high-income countries, however, the share is considerably higher. In the United States, for instance, passenger travel represents more than 21% of total energy-related CO_2 emitted (or 4 t per capita) (Schafer et al., 2010, p. 14). Scenario analysis has been used to explore developments in future travel demand and related CO_2 emissions. IEA and WBCSD (Fulton and Eads, 2004), project an increase from 3.8 Gt CO_2 in 2005 to 8.3 Gt CO_2 by 2050. Schafer et al. (2010) project future emissions to increase up to even 11–18 Gt CO_2.

Such 'baseline' emission projections from travel are clearly not consistent with emission levels required to achieve the 2 °C climate target used in the context of international climate policy (UNFCCC, 2010). Achieving the 2 °C target with a certainty of more than 50% (based on the uncertainty in climate sensitivity) requires a stabilisation of atmospheric GHG emission concentration below a radiative forcing level of 3 W/m^2 (Meinshausen et al., 2009). Emission scenarios (van Vuuren et al., 2007; van Vuuren and Riahi, 2011) show that such radiative forcing levels would require global emissions to be in the order of 20 Gt CO_2 equivalent by 2050 and close to 0 Gt CO_2 equivalent by 2100. While passenger travel forms only a part of total emissions, it is clear that this climate target cannot be met without significant emission reductions compared to the baseline projections. Therefore, in this paper we analyse whether and how direct CO_2 emissions from the passenger transport system could be reduced to be consistent with levels required to achieve the 2 °C climate target.

For this analysis, we created and applied the TRAVEL model, a global transport model with a considerable level of detail. This passenger transport model has been developed to become part of the TIMER energy model, a long-term system dynamics energy model. TIMER, in turn, forms part of the IMAGE integrated assessment model (Integrated Model to Assess the Global Environment) (Bouwman et al., 2006); a model developed to explore long-term changes in global environmental issues. The TRAVEL model includes seven travel modes (foot, bicycle, bus, rail, car, high-speed train and aeroplane), and characterises various vehicle types for their energy efficiency, fuel type and costs. The model is based on nested multinomial logit (MNL) type equations for the different transport modes and technologies, but also respects the constant travel time and money budget (Zahavi and Talvitie, 1980). The TRAVEL model can be used to determine mode split and fleet composition based on input variables, such as income, energy prices and technology costs. In our research, we used a carbon tax to force the model to reduce its emissions in a way

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that can be considered to be consistent with the RCP2.6 scenario. This scenario describes a **r**epresentative **c**oncentration **p**athway leading to radiative forcing of an additional 2.6 W/m^2 (IPCC, 2008; Moss et al., 2010; van Vuuren et al., 2011). We also looked into the possible impact of GHG emissions from biofuels.

Our study adds to existing literature in several ways: (1) it provides information, on a global scale, about mitigation pathways for passenger transportation including technological change and travel behaviour (mode split); (2) it provides scenarios with a high-tech resolution (most useful in the first decades of the scenario); and (3) it looks into the consequences of varying future performances of liquid fuel substitutes with regard to their GHG emissions.

The paper is structured as follows: Section 2 starts with the description of the baseline and mitigation scenarios. Subsequently, the applied TRAVEL model is described, focusing on the assumptions relevant for climate mitigation and the policy module added for this exercise. Section 3 presents the results, focussing on changes in travel demand suggested by the TRAVEL model to reduce direct CO_2 emissions in line with the RCP2.6 scenario. Finally, these results are discussed and conclusions are presented for researchers involved in the development of low-emission mitigation scenarios as well as decision makers concerned with long-term climate policies in line with the 2 °C target.

2. Method

2.1. Baseline projections

The baseline used for this study relies on the income and population projections from the recent OECD study (OECD, 2012). Direct CO_2 emissions of the TRAVEL baseline are shown in Fig. 1. A decrease in CO_2 emissions beyond 2065 is related to the increase in the energy price of fossil fuels and the decrease in the price of biofuels to a similar level in 2060 without additional policy measures, according to the underlying study by van Ruijven and van Vuuren (2009) (cf. Fig. 4). As a consequence, the share of biofuels in transportation increases rapidly. Up to 2050, our baseline is similar to recent transport studies (Fulton, 2009; Schafer et al., 2010). Other studies have looked into long-term projections (up to 2100), but only include emissions from cars (Kyle and Kim, 2011) or focus on mitigation scenarios only (Grahn et al., 2009). Although technology-rich models are most useful for exploring the next decades, long-term projections also are needed, given the inertia involved in climate change and associated decision-making. The fact that current models link the 2010–2050 period to the even longer time scale up to 2100 helps to understand the long-term dynamics

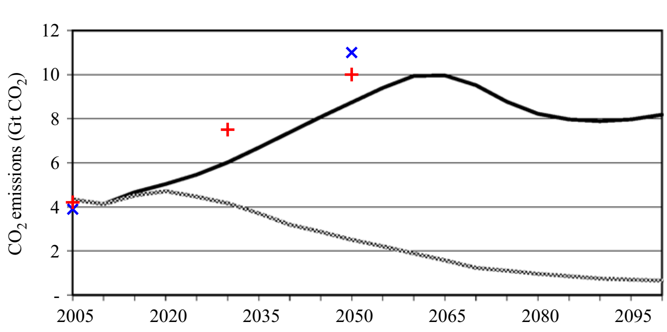

Fig. 1. Projections of future CO_2 emissions related to travel, compared to two baseline projections from literature (Fulton, 2009; Schafer et al., 2010) and emission levels connected to the 2 °C target (RCP2.6 in 2100).

(although, obviously, long-term scenarios should not be interpreted as exact forecasts). The TRAVEL model shares some important characteristics with the GCAM transport model (Kim et al., 2006; Kyle and Kim, 2011) with respect to overall structure, simulation of competition between different transport technologies and modes. However, similar to the model from Schafer et al. (Schafer, 1998; Schafer et al., 2010) the TRAVEL model is directly coupled to empirical observations of travel time and income budgets.

2.2. Mitigation scenarios

The mitigation scenarios aim to reduce CO_2 emissions in line with the 2 °C climate target. We therefore consider the IPCC emission pathway RCP2.6, which is consistent with this climate target (IPCC, 2008).

The RCP2.6 emission trajectory shows considerable emissions for the economy as a whole (Moss et al., 2010; van Vuuren et al., 2012). The share of passenger transportation in total emissions was about 10% in 2005. Since costs of mitigation are higher in the transport sector, low-emission scenarios generally include less than proportional reductions for the transport sector. For instance, the van Vuuren et al. (2007) study, upon which the RCP2.6 scenario is founded, results in an GHG emission share of 34% for transportation by the end of the 21st century. Even if we assume that about 40% of these emissions would be related to freight (Fulton, 2009), we would still end up with a share of about 20% for passenger transportation. Based on this, we looked into an emission path that follows the RCP2.6 emissions path but includes an increase in the share of GHG emissions from passenger transportation from 10% in 2000 to 20% by 2100 (see Fig. 1).

To reduce the direct CO_2 emissions from the baseline to the target path (see Fig. 1) we increased the carbon price. The model structure described below allows the TRAVEL model to respond endogenously to this price increase by changing travel demand, and vehicle and fuel selection towards lower carbon intensity.

We looked specifically into the uncertainties around GHG emissions from biofuels. Estimates of GHG emissions associated with biofuels vary over a wide range. A moderate estimate for current first-generation biofuels is in the order of 60–120 g CO_2-eq./MJ (Dornburg et al., 2010; Farrell et al., 2006) compared to 72 g CO_2/MJ for petrol. However, second-generation biofuels are expected to lead to better environmental performance (Eisentraut, 2010; Sims et al., 2010). We therefore evaluated two scenarios:

1. *Mitigation Scenario A*: This scenario does not account for GHG emissions from biofuels; hence, no carbon tax is applied to biofuels. This situation may arise from optimistic assumptions about biofuels.
2. *Mitigation Scenario B*: This scenario accounts for GHG emissions from bio-energy by assuming an emission factor of 30 g CO_2-eq./MJ, which would still be about a factor 2–4 improvement on current first-generation biofuels. Thus, the carbon tax applies also to biofuels.

In our calculations, emissions from the generation of electricity and hydrogen were not considered, as these strongly depend on model assumptions outside the scope of this paper (e.g., the use of bio-energy and carbon capture and storage (CCS) could even lead to negative emissions in the power sector (van Vuuren et al., 2007)). Section 4 discusses the possible implications of this assumption. We also omitted non-CO_2 GHG emissions from aviation (Kollmuss and Allison, 2009) since the quantification of the corresponding mitigation costs is very uncertain.

2.3. TRAVEL model

We used the TRAVEL model to identify options which would significantly reduce CO_2 emissions from transport. This section focuses on the main structure of the model and provides an extended description of vehicle costs and energy efficiencies, since these are most relevant in climate mitigation. The TRAVEL model consists of four main modules (Fig. 2): (1) the travel modes module, (2) the fleet module, (3) the vehicle module, and (4) the policy module.

The *travel mode module* describes travel volumes per region for seven different mode categories, i.e., on foot, bicycle, bus, train, car, high-speed train and aeroplane. Two fundamental rules that determine the mode split in our travel mode module are (1) the travel-time-budget (TTB) rule, and the (2) travel-money-budget (TMB) rule. The literature suggests that the TMB approaches about 12% of GDP with an increasing share of car travel (Schafer et al., 2010; Zahavi and Talvitie, 1980). For the beginning of the 21st century, the TTB is estimated at around 1.2 h per day, globally (Schafer et al., 2010; Zahavi and Talvitie, 1980). Some studies claim that TTBs are constant and are likely to remain so in the future (Schafer et al., 2010), while others indicate an annual increase of daily TTB by 2 min (Toole-Holt et al., 2005). For our study, we have taken a middle position and assumed an annual increase of daily TTB by 0.25 min. The TTB and TMB concepts have been used in earlier transport models (Schafer et al., 2010; Schafer and Victor, 2000). Compared to these studies, however, we use a more general representation and more transport modes. For instance, the model includes non-motorised modes as they account for a very relevant share of transport in developing countries, and the distinction between aeroplane and high-speed train is relevant for climate mitigation scenarios. Within the mode split module, TTB and TMB relationships play a key role in describing the transition processes within these seven main categories, considering their relative costs and speed characteristics and consumer preferences for comfort levels and specific transport modes. Within the module, the TTB and TMB criteria are combined with an MNL-type equation.

The *fleet module* describes the competition between various specific technologies within each travel mode. For instance, within the mode 'cars' the module distinguishes 22 different car types that compete for market share. The most important car types are conventional internal combustion engines (ICE), hybrid ICE electric vehicles (HEV), plug-in HEVs and fuel-cell cars; (see Appendix A). The market shares of these technologies within each travel mode are determined by using a second set of MNL-type equations for new investments and a vintage structure for the existing stock.

The *vehicle module* describes efficiency, costs and speed of the various transportation technologies.

Finally, the *policy module* describes policy in the model, such as a carbon tax. Such a tax influences the costs in the travel-mode and fleet-composition modules, generally resulting in lower emissions (less energy-intensive transport modes; more efficient technologies; low or zero carbon fuels). In this module, it is possible to specify an emission target. To achieve this, the carbon tax is set to a level whereby direct emissions are reduced to the level required for the target.

In addition to these modules, the model includes a set of exogenous assumptions on income, population, energy prices and technology. The data on income, population and energy prices are derived from the connected IMAGE-TIMER model (Bouwman et al., 2006).

2.4. Model equations and assumptions

The model described in 2.3 is driven by a set of constraints (such as the TTB, TMB and possibly an emission target) and the assumption that the lowest travel-cost technologies are used. Costs ($Cost_i$), thus, form the basis for modelling; both the vehicles shared within each travel mode ($VehicleShare_v$) and mode shares ($ModeShare_m$) are determined using a MNL-type model:

$$Share_{i,t} = \frac{\exp(\lambda \times \mathrm{Cost}_{i,t})}{\sum_i \exp(\lambda \times \mathrm{Cost}_{i,t})}\ [-] \qquad (1)$$

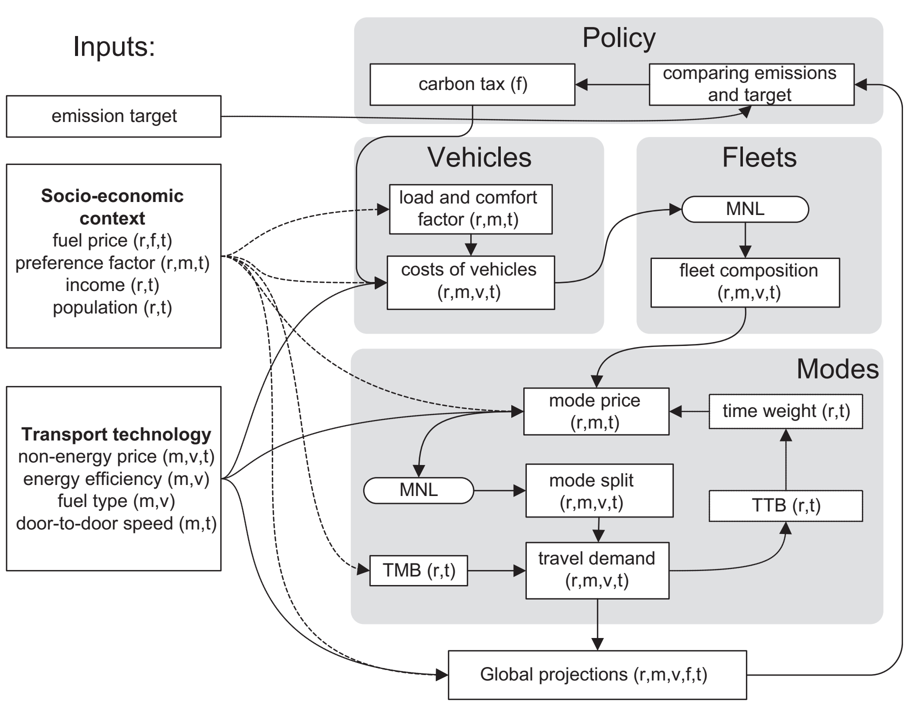

Fig. 2. Overview of the TRAVEL model. The indices *r*, *m*, *v*, *f*, *t*, respectively, denote region, travel mode, vehicle type, fuel type and time.

where λ is a calibration factor that influences the shares' sensitivity to the different costs for a mode or vehicle, *i*, which vary over time.

An MNL-type models are often used to describe discrete choices by different actors. They are often used for more data-rich situations, in which the equations can be calibrated on a large set of information, and where the model will be used to describe the choices in a time period close to calibration period. In more system-dynamics (long-term) energy models, the MNL-type equations are also used to assign market shares for different technologies based on their characteristics, such as relative costs and preferences (Edmonds and Reilly, 1985; Jaccard, 2005; van Vuuren and de Vries, 2001; de Vries et al., 2001). The MNL-type of model was also used by Kyle and Kim (2011) for global long term transport modelling. An advantage of the MNL-type model is that is able to assign market shares to several technologies (in contrast to full optimisation), a situation that is often empirically observed. For modelling the mode shares, we considered, similar to Kyle and Kim, the real costs, a constant factor and the costs related to travel time:

$$Cost_{r,m,t} = Const_{r,m,t} \cdot CostPerPkm_{r,m,t} + Timeweight_{r,m,t} \cdot TimeUse_{r,m,t} \quad [-] \tag{2}$$

Here, the constant (*Const*) corrects for non-monetary differences in preference between each mode, while the time weight (*TimeWeight*), describes the importance of time compared to monetary costs. Both values basically appreciate the value of the issue at stake (capital or humans). All variables vary over region (r), mode (m) and time (t)[1] . In the model, both terms are divided by the average value of all modes to obtain a unit-less factor. Time use is modelled based on the door-to-door speed of a certain travel mode and derived from different sources (ARE and BFS, 2005; Schafer et al., 2010). The values for the different transport modes are indicated in Appendix A. Schafer et al. (2010) projects further speed increases for the different transport modes, whereas we were more conservative and assumed that speed would remain constant, partly accounting for congestion. We assumed that the weight of the time costs is determined endogenously by the model (instead of exogenously by wage rate as in the study from Kyle and Kim (2011). Our formulation was drawn from the travel time budget criterion; if the total travel time per capita exceeds the target value of the travel time budget (1.2 h at the beginning of the 21st century), we assume that the time factor is awarded more weight. In our model, the travel volume is also determined by travel expenditure, which is related to income; therefore, time weight actually increases with income. This leads to the empirically observed trend of increasing shares of higher speed modes with increasing income levels (despite their higher costs per passenger kilometre). One of the advantages of this formulation is that implications of changing speed and prices of transportation for total demand are considered. Therefore rebound effects are also taken into account (Girod et al., 2011).

By adjusting the TMB and the constant factor, the model can reproduce the observed travel demand from 1971 to 2005 estimated by Schafer et al. (2010) with very high correlation ($R^2 = 0.99$ for global model, see Appendix B, Fig. 14). For the projections into the future, we assumed that the TMB converges with the increase in fast transport modes to 12%. We assume that the regional constant factors remain the same as estimated for 2005, except for aircraft. This is because this mode is not well represented for low-income countries in the historical data (only a marginal share). We therefore assume that the preference factor in developing regions converts to the value from industrialised regions in 2005. High-speed train is only reported for Europe and Pacific OECD. We therefore assume its constant factor to shift to the same value as for aeroplanes.

Within a travel mode (fleet composition module), a second MNL-type equation is used to determine the choice of vehicle type (*VehicleShare*). Here, it is assumed that monetary cost is the deciding factor. The cost per passenger kilometre for each vehicle, consists of three parts:

$$CostPerPkm_{r,v,t} = \frac{AddTechCosts_{v,t} + EnergyCosts_{r,v,t} + NonEnergyCost_{r,t}}{load_{r,t}} \quad [USD/pkm] \tag{3}$$

The non-energy costs (*NonEnergyCost*) include the costs related to vehicle purchase and maintenance. The additional technology costs (*AddTechCost*) describe the higher investment needed for more efficient vehicles compared to the default vehicle. The energy costs (*EnergyCost*) are a function of efficiency and energy prices (including the carbon tax). Finally, the costs per passenger kilometre also depend on the passenger load of the vehicle ($load_{r,t}$). The indices describe the different world regions (r), vehicles (v) and time (t). Infrastructure costs are included in the non-energy costs for collective transport modes and in the fuel tax. Latter is used in some regions to finance road infrastructure and explains the high fuel prices in Western Europe. However, if the infrastructure is subsidised by the government, this cost should not be considered, since only the costs paid by the passenger influence travel behaviour. The following section describes the four factors that determine the travel costs related to a vehicle, as calculated in Eq. (3) in more detail.

2.4.1. Cost of technologies

Fig. 3 illustrates the energy use and non-energy costs per passenger kilometre for the various vehicles considered in the TRAVEL model for the United States, for 2005. We assumed that the additional technology costs and the energy use per vehicle kilometre (vkm) would be the same globally, based on the fact that these technologies tend to be traded worldwide. This assumption is obviously not fully correct, but given the purpose of the model to explore long-term trends, it seems appropriate. Global technology costs were combined with regional fuel prices,

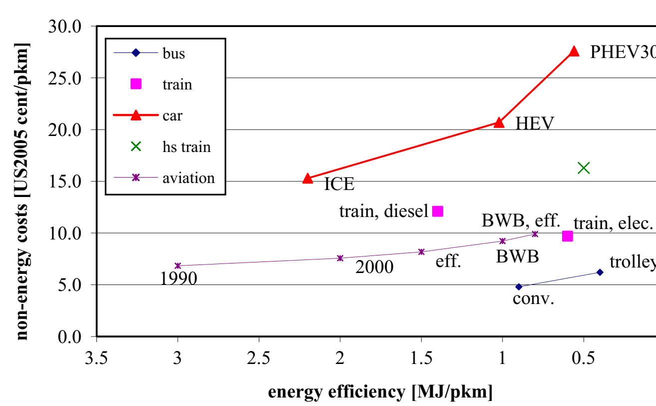

Fig. 3. Increasing non-energy costs (including additional technology costs) for higher energy efficiency. Data for the United States in 2005. Note: Not all vehicles used in the TRAVEL model are displayed (see Appendix A); data sources are indicated in the main text. Abbreviations: ICE — Internal Combustion Engine, HEV — Hybrid Electric Vehicle, PHEV30 — Plug-in HEV with 30 miles full electric, BWB — blended wing body. 1990 and 2000 indicate efficiency of new aeroplanes in that year.

[1] The 26 regions are: Canada, USA, Mexico, Rest Central America, Brazil, Rest South America, Northern Africa, Western Africa, Eastern Africa, South Africa, OECD Europe, Eastern Europe, Turkey, Ukraine +, Asia-Stan, Russia +, Middle East, India, Korea, China +, South East Asia, Indonesia +, Japan, Oceania, Rest of South Asia, Rest of South Africa.

non-energy costs and energy use. These would vary on a regional scale, because of different regional load factors and luxury levels (see Eq. (3)). For all calculations, purchasing-power-parity-corrected income levels were used.

Calculations show that car use is more expensive than other transport modes. This illustrates that travel choices are not only influenced by monetary costs. In Eq. (2), this translates into different factors. First, travel time costs are considered. With increasing incomes this leads to a higher preference for faster transport modes. Second, the various factors influencing the choice of transport mode are considered by the aggregated value of the perceived prices, which accounts for the higher preference for cars. Within the travel modes, more energy efficient vehicles carry higher investment costs than less efficient vehicles (due to the additional technology costs).

The model also deals with energy efficiency. This is captured by the model in three ways:

- Price-induced efficiency improvement: In the fleet-composition module, different car types are specified with different efficiency levels and costs. An increasing energy price thus influences the fleet composition, as efficient vehicles will become more competitive.
- Autonomous: In the model it is assumed that the additional technology costs of efficient technologies decline over time because of technological learning. Thus, efficient vehicles become more competitive within the same energy price range, leading to an autonomous energy efficiency improvement.
- Mode shift: An increasing energy price may also cause a shift towards more efficient transport modes and thus increase the overall energy efficiency of passenger travel.

To determine the additional costs for the different technologies, we used various studies:

Bus & rail: For buses and trains, we did not consider technological learning, as these modes cover only a small share of total CO_2 emissions, and they are already considerably more efficient than cars. The current energy efficiency and additional costs of these modes were based on estimates from the transport model by Kyle and Kim (2011).

Cars: For cars, we used the technologies in accordance with Ogden et al. (2004), but added plug-in and full electric vehicle technologies as in the study from Kromer and Heywood (2007). The cost estimates were updated by using those from Bandivadekar et al. (2008), and technological learning trends for 2050 were adjusted to projections by Plotkin and Singh (2009). For the very long term, we assumed costs to decrease to mass production level as indicated by Ogden et al. (2004).

High-speed train: Here, we only considered one vehicle type (electric) using data taken from Kyle and Kim (2011).

Aeroplanes: Historically, a sharp decline in energy intensity (MJ/pkm) can be observed (Lee, 2000; Schafer and Victor, 2000). Although the pace of improvement is expected to decrease, a further reduction in energy intensity is possible. The IEA estimates average energy intensity in 2005 at 2.5 MJ/pkm and projects 1.5–2 MJ/pkm for 2050 (2009, Figure 7.3). Schafer et al. (2010) make a more optimistic assumption, estimating the intensity for new aeroplanes in 2020–2020 to be 0.8–1.4 MJ/pkm. Based on this literature, the model includes aeroplane types with historical energy efficiencies and types with improved energy efficiency (1.5 MJ/pkm). The latter are assumed to enter the market after 2020. We also assume that after 2040, a new more efficient concept of blended wing body is commercially available (BWB, 1 MJ/pkm) (Liebeck, 2004). Beyond 2050, we assume that slightly improved BWB aeroplanes (0.8 MJ/pkm) are feasible (based on the data from Schafer et al., 2010). For additional technology costs we consider investment costs from the technology–cost relationship estimated by Lee et al. (2001). Finally, hydrogen fuelled aeroplanes (cryoplanes) are assumed to be only feasible in the second half of the century. Its costs and energy efficiency are roughly estimated starting from the improved BWB design and correcting for higher costs and lower energy efficiency, because of the lower vehicle load due to the volume lost to the large hydrogen tank required (Krijnen and Astaburuaga, 2002; Westenberger, 2008).

A detailed technology description (energy use, non-energy price, speed) is provided in Appendix A (Tables 2–5).

2.4.2. Energy costs

The energy costs (Eq. (3)) are calculated as follows:

$$EnergyCosts_{v,t} = NetPresentValue_{r,t} \cdot Efficiency_{r,fl,v} \cdot EnergyPrice_{r,fl,t} \quad [\text{USD/vkm}] \tag{4}$$

where the indices concern the different world regions (r), vehicles (v), fuels (fl) and time (t). The expected lifetime costs are used, considering the net present value to account for depreciation. The net present value (*NetPresentValue*) is calculated as follows:

$$NetPresentValue_{r,t} = \frac{(1+DiscRate_{m,r,t})^{lifetime}-1}{(1+DiscRate_{m,r,t})^{lifetime} \cdot DiscRate_{m,r,t}} \quad [-] \tag{5}$$

where *lifetime* represents the period of time during which a vehicle can be used, and the discount rate (*DiscRate*) concerns the decrease from the present value for future energy costs. In the model we used discount rates of 4% for all vehicles except cars. For cars, household discount rates were applied, which although considerably higher, decrease with income. According to a literature review (Train, 1985) of cars, discount rates reduce from 20% for an income of USD 10,000 per capita to 5% for an income of USD 55,000.

In addition to the energy efficiency assumptions on the vehicles described above, we also applied regional energy efficiency factors. These account for regional differences in energy efficiency that are not explained by energy price and income. For instance, the US preference for sport utility vehicles (SUV) leads to lower efficiency. These correction factors were determined by calibration with data from the IEA (Fulton and Eads, 2004). However, the model considers the most important regional factors endogenously. For instance, the higher energy efficiency in Europe is a direct consequence of higher energy prices. The less efficient vehicles in poor countries are a consequence of high discount rates. Energy prices were derived from the medium fossil-fuel price projections from van Ruijven and van Vuuren (2009), which project increasing prices for fossil fuels and decreasing prices for biofuels and hydrogen up to the end of this century (see Fig. 4). For this study, detailed regional energy prices were used, which took into account political aspects (e.g., taxes) as well as availability of the various energy carriers (e.g., lower price for OPEC countries). Note that the price changes in Fig. 4 are also influenced by the regional distribution of the energy use. For instance, the decreasing share of biofuels in Western Europe, where secondary energy prices are high, contributes to a decrease in the global average energy price.

2.4.3. Non-energy costs

Basic costs of travel modes were derived from US values (Schafer et al., 2010). The lower costs paid by low-income countries as well as the increasing expenditure for luxury is considered by the

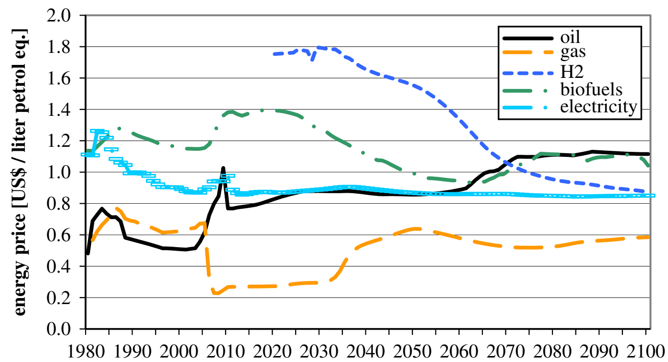

Fig. 4. Global secondary energy prices in the transport sector for oil, modern biofuels, hydrogen and electricity. Note: 35 MJ/l petrol equivalent used for unit conversion. Weighted mean of the price in the 26 world regions used to derive global average prices.

introduction of a comfort factor:

$$NonEnergyCost_{v,t} = NonEnergyCost_{v,t} \cdot \underbrace{a \cdot Income_r^{ComfElast}}_{ComfortFactor} \quad [\mathrm{USD/vkm}] \tag{6}$$

We assumed that the comfort factor would increase with constant income elasticity of demand. Only a few studies have evaluated the influence of an increasing comfort level on travel costs and its future development. We introduced this factor, since our model approach directly links income budget with travel demand through the travel money budget. An introduced comfort elasticity of 0.5 was confirmed by calibration of the model and comparison with historical travel demand. A comfort elasticity of 0.5 implies that prices double when incomes quadruple. This is in line with a Swiss study, which estimated that the income elasticity of expenditure for higher quality (higher price paid for the same physical consumption unit, e.g., passenger kilometre) is about 0.5 (Girod and de Haan, 2010). Also, the increase in car prices in the United States between 1950 and 2005 (Schafer et al., 2010) can be modelled using this income elasticity.

2.4.4. Vehicle passenger load

Another important factor for calculating future emissions per transport mode is the load factor, which describes the number of passengers per vehicle. The passenger load factor decreases with increasing income. In the model, changes in load factor are therefore modelled as a power function of income with a constant elasticity. For the transport modes of bus, train, high-speed train and car, we calibrated the function with the estimates from IEA/WBSCD (Fulton and Eads, 2004) for the year 2000. The derived income–load factor relationship is used for projecting future change in load. Lee (2000), Figure 6.3 projects a slow increase in load for the aeroplane transport mode. This projection is based on the observed historical increase in load, which was achieved through operational optimisation by the airlines. Increasing the comfort level might lead to an increase in the space used per passenger, which in turn would translate into a decrease in passenger load. However, no studies on the possible influence of increasing comfort levels were found. Nevertheless, Hinninghofen and Enck (2006) suggest increasing the space per business-class passenger. In view of the above, we assumed no further increase in the load factor for aeroplanes.

2.4.5. Inertia

It should be noted that the influence of energy prices on mode split or fleet share is diminished by the system's inertia. We accounted for the inertia that is caused by the lifetime of certain technologies by using a vintage formulation in a simple stock model that only introduces new technology after old technology has expired. Other factors also lead to inertia, such as infrastructure, travel habits, limited flexibility of vehicle manufacturers and consumers' reaction to changing prices. For the latter we used an additional equation, introducing an inertia factor α, which can be described as follows:

$$\frac{da_m}{dt} = \alpha \times (a\_old_m - a\_optimal_m) \quad [-] \tag{7}$$

where *a_old* represents the modal share of the previous time step and *a_optimal* is the share based on actual aggregated prices and income. Including this inertia leads to a gradual shift in shares for the main transport modes as well as for the fleet composition. The inertia of the main transport mode depends on infrastructure and travel habits and was set at 5 years for non-motorised transport, 10 years for bus, train and car, and 20 years for high speed modes. Inertia in vehicle purchase behaviour, which represents delayed responses of vehicle producers and consumers, was set at 10 years. Vehicle lifetimes for the stock flow model were set at 15 years for cars and at 20 years for bus and rail. For aeroplanes, successful production runs and aeroplane lifetimes span about 40 years (IPCC, 1999).

3. Results

3.1. Carbon emissions

The TRAVEL model is able to present a strict climate mitigation scenario for the transport system. Fig. 5 shows direct CO_2 emissions from the passenger transport sector, for the baseline and both mitigation variants: (A) taxation on fossil fuels only, (B) taxation also on biofuels.

Both mitigation scenarios achieve emission reductions in line with the RCP2.6 scenario. By 2050, Mitigation Scenario A, which only accounts for fossil–fuel emissions, will have reduced direct emissions by 72%, compared to those in the baseline scenario, and by 2100 this will be more than 90%. Scenario B results in even higher emission reductions (above 76% by 2050 and above 99% by 2100). However, if the upstream emissions of biofuels are accounted for, with an emission factor of 30 g CO_2/MJ, Scenario A would not reach the RCP2.6 target; instead, it would reduce emissions only by about 55% in 2050 due to the increasing use of biofuels. Since in Scenario B emissions from biofuels also are taxed, the scenario would still meet the emission target and reduce emissions by 66% by 2050 and 91% by 2100.

3.2. Travel system changes

This section evaluates the achievement of emission reductions shown in the previous section, starting with the evaluation of

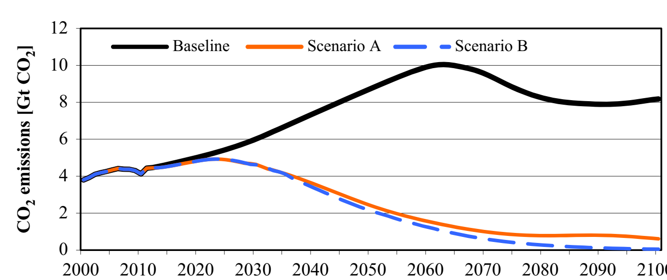

Fig. 5. Global CO_2 emission projections for the baseline and two mitigation scenarios.

changes in aggregated energy use of the passenger transport system. Subsequently, the underlying actual consumption (in passenger kilometres (pkm)) and its distribution over the different transport modes is explored. Finally, an analysis of the changes within travel modes (the technological composition of fleets) is provided.

Changing fuel use: Model calculations have shown that, in Mitigation Scenario A, energy consumption initially decreases by 33% and then levels out to 7% below the baseline (Fig. 6). In contrast, in Mitigation Scenario B, the reduction in energy consumption in the transport sector is more pronounced (47% by 2050).

A deeper understanding of the results can be obtained if changes in fuel mix are also considered. In the baseline scenario, fossil energy carriers still account for more than 50% of total fuel use by the end of the 21st century. By the end of this century, the use of petrol will partly be replaced by natural gas as a result of rising oil prices. The share of biofuels will also be considerable by that time. In Mitigation Scenario A (which only accounts for fossil–fuel emissions) the trends towards biofuels is amplified, and the share of electricity use is also slightly increased. Mitigation Scenario B, which accounts for biofuel emissions, is initially similar to the first mitigation scenario, however electricity use

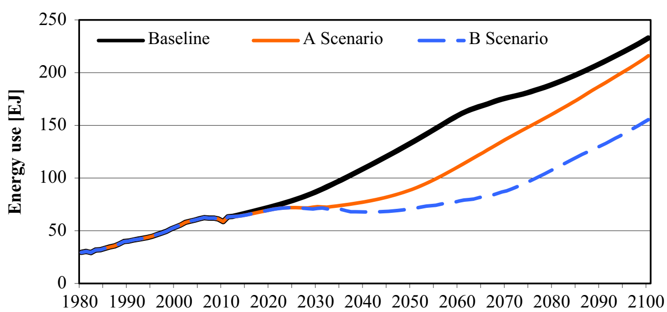

Fig. 6. Global energy consumption in the baseline and the two mitigation scenarios.

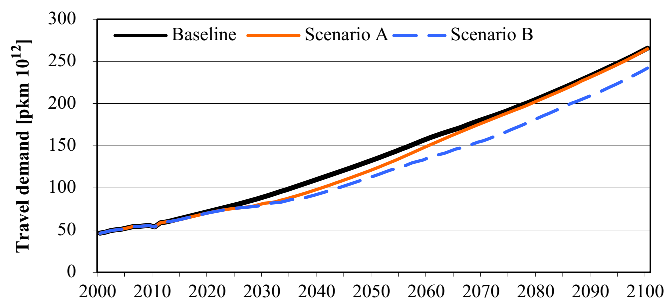

Fig. 8. Global travel demand [tera pkm] in the baseline and the two mitigation scenarios.

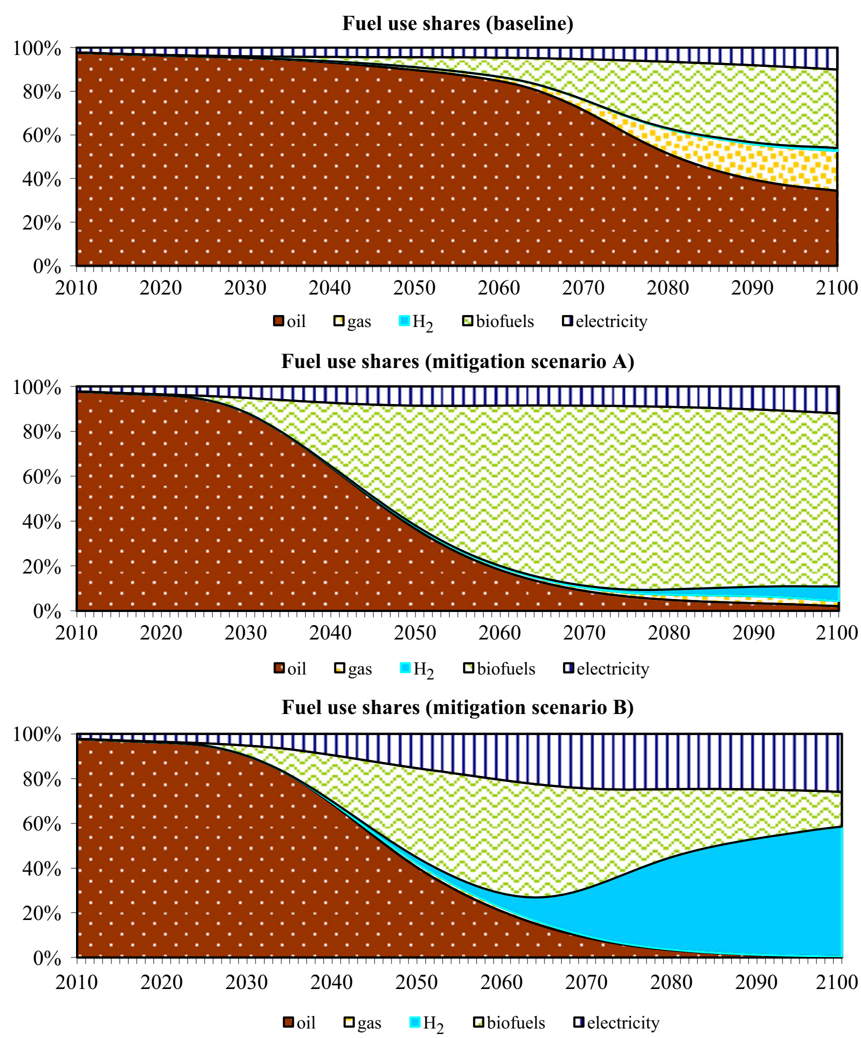

Fig. 7. Global fuel consumption in the baseline (top) and the two mitigation scenarios.

increases faster, and, by 2060, hydrogen will replace biofuels. (Fig. 7)

Impact on travel demand: Fig. 8 illustrates that in Mitigation Scenario A, global travel demand drops only slightly compared to the baseline scenario, and rejoins it towards 2100 (8% by 2050, 0.3% by 2100). In Mitigation Scenario B (which accounts for biofuel GHG emissions) travel demand is reduced by 15% from that in the baseline by 2050 (9% by 2100).

Changing mode split: Similar to total travel demand, the mode split in Mitigation Scenario A changes only slightly (Fig. 9). In Mitigation Scenario B, shifts in transport modes are more pronounced. Here, initial increases are in the use of bicycles, trains and also cars (with air travel decreasing); by 2100, high-speed train uses take a larger share. The Scenario B mode split changes are mainly due to the increasing air travel prices and the overall reduction in travel demand.

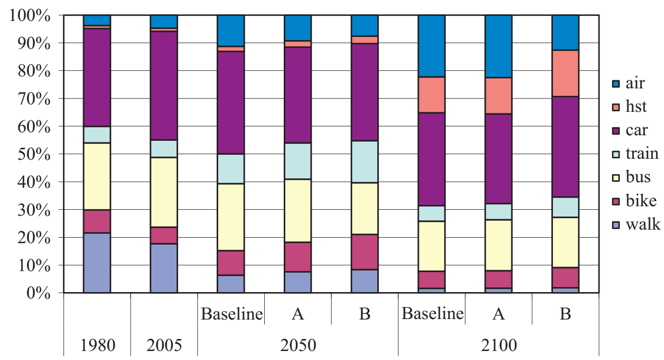

Fig. 9. Global mode split in the baseline and the two mitigation scenarios.

Changing fleet composition: Fig. 10 shows the change in fleet composition. The 22 car types described in Appendix A are aggregated into 12 groups with cars of similar type. In the baseline scenario cars, with conventional and improved internal combustion engines (ICE) will dominate the global market up to 2070. Only in the second half of the century do hybrid vehicles (HEV) penetrate the global market. In the baseline scenario, by the middle of this century, the HEV and Plug-in HEV (PHEV) will have a global market share of about 10%. In Scenario A this vehicle type is projected to start to dominate the market in 2040 due to an increasing fossil–fuel price. In Scenario B the PHEV will enter the market even more rapidly. However, after peaking in 2050 it is replaced by the hydrogen fuel-cell car. This is due to the fact that PHEV cars still use biofuel, while fuel-cell cars are considered to be zero-emission vehicles.

In the other travel modes similar shifts occur. Buses switch to biofuels in Scenario A, and to electricity in Scenario B. For trains, the electric variant is more competitive in all scenarios. For high-speed trains, the model only considers electric trains. Finally, in air travel, aeroplanes are successively replaced by more efficient vehicle types. In 2050 half of the aeroplanes have an efficiency of 2 MJ/pkm, while only at the end of the century will aeroplanes with improved efficiency (1.5 MJ/pkm) reach a global market share of 80%. In scenario A the efficiency is similar but aeroplanes

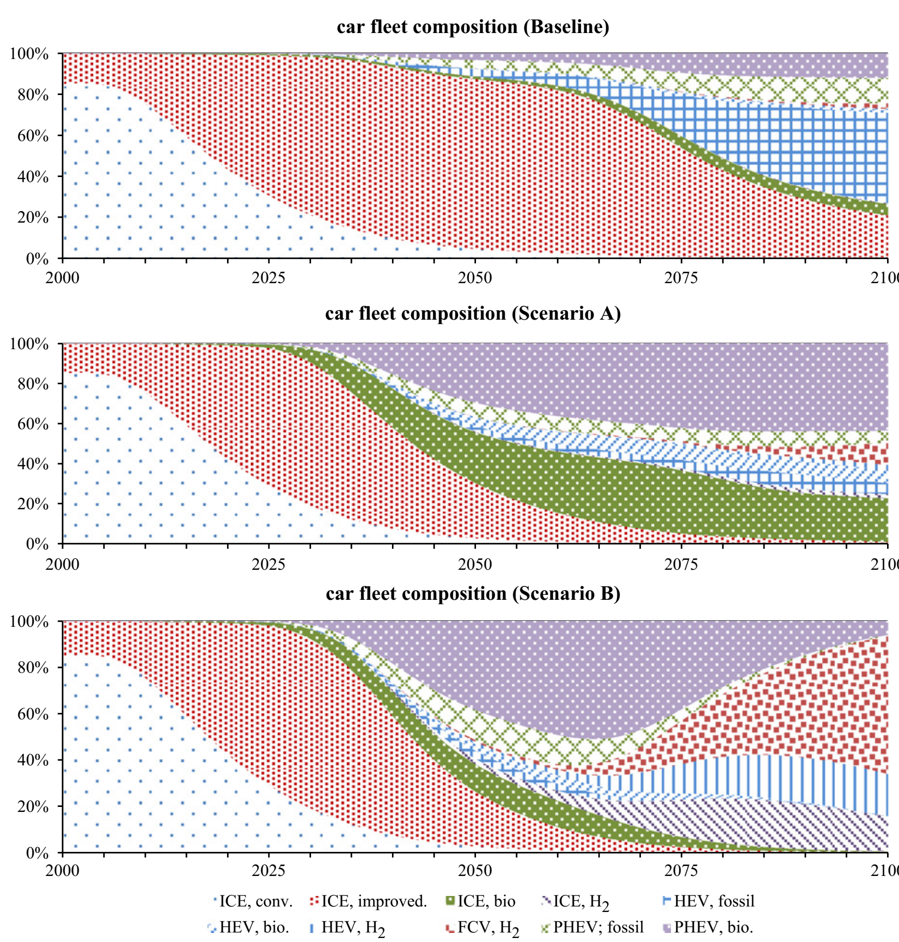

Fig. 10. Global car fleet composition in the baseline (top) and the two mitigation scenarios. ICE: Internal combustion engine, conv.: default car up to 2010, ICE improved: ICE car with improved energy efficiency, HEV: Hybrid electric vehicle, PHEV: Plug-in HEV, FCV: Fuel cell vehicle, Bio, Oil., H_2: Secondary energy carrier used (biofuels, fossil fuels, hydrogen). *Note*: PHEV in addition to the indicated energy carrier also use electricity.

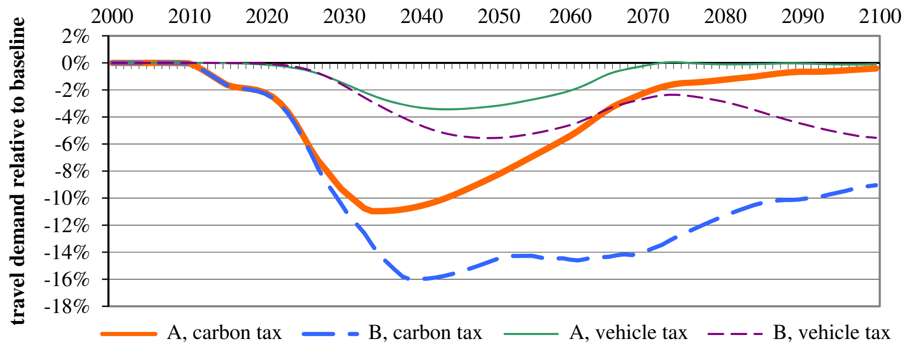

Fig. 11. Change in global travel demand relative to the baseline, in the two mitigation scenarios using carbon tax (default case) and only increasing the purchase price of high CO_2 emitting vehicles.

Table 1
Carbon tax (USD2005/t $CO_2-eq.$) estimates for base run and lower costs for plugin hybrid vehicles and H_2-aeroplanes.

	Mitigation scenario A	Mitigation scenario B	
	2050	2050	2080
Base run	289	486	1713
Lower cost	241	544	1428

switch to biofuels. In the scenario B, blended wing body (BWB) aeroplanes (1 and 0.8 MJ/pkm) start penetrating the market in 2050 and dominate towards the end of the century.

3.3. Mitigation costs

We used two indicators for the costs in the mitigation scenarios compared to those in the baseline scenario. First, we considered the decrease in consumption level (travel demand), followed by an evaluation of the level of the required carbon tax.

Travel demand: Fig. 8 shows that the decrease in total travel volume is quite low in both mitigation scenarios across the century. As an alternative variant for both scenarios, we looked into regulation of vehicle CO_2 emissions instead of a general carbon tax on transport. We modelled this by increasing the carbon tax within the vehicle/fleet-module only, instead of increasing the overall price level. This is similar to the European Union's incentive for reducing CO_2 emissions from passenger cars (European Parliament and the Council of the European Union, 2009). This scheme implies that the average car price still increases because more advanced technologies are used, but not because of higher fuel price. Fig. 11 shows that for this variant the decrease in travel demand is even lower. However, since such a tax does not trigger a mode shift or demand reduction, more radical changes in the car fleet are required.

Carbon tax: Table 1 shows the carbon tax estimated for 2050 and 2100 in our model calculations. For Scenario A the key technology by 2050 will be the plug-in hybrid using biofuel (10 mile range). If its additional non-energy costs (see Appendix A) are reduced by 25%, the tax for 2050 decreases accordingly. The much higher tax in Scenario B is caused by the more radical changes required. The high carbon tax by the end of the century is mainly caused by aviation, where the cryoplane is the only transport vehicle without fossil–fuel or biofuel GHG emissions. A sensitivity run illustrated the implications of 25% lower costs for hydrogen aeroplanes (cryoplane).. This evaluation showed how sensitive the required level of the carbon tax is to the costs of some key technologies. However, fossil–fuel prices and baseline projections also have a strong influence.

4. Discussion

The discussion in this section is structured as follows: First, it focuses on the feasibility of the RCP2.6 targets to be achieved by the mobility sector. Second, the costs of reaching these targets are discussed. Third, we examine the relevance of the indirect GHG emissions. Fourth, three transition stages are identified in the passenger transport system on the path to a low-emission future.

4.1. Feasibility

According to our calculations, emission reductions achieved by 2050 are in line with the 'BLUE Map' scenario of the International Energy Agency (Fulton, 2009). For the time beyond 2050 however, few studies are available for comparison. The technological feasibility of the low-emission scenarios should be regarded as a robust result, since the model is explicit about the technology that allows travelling at such low emission levels. If second-generation biofuels become zero-emission fuels, the RCP2.6 emission level can be reached by merely switching fuel type. Since the future performance of biofuels is uncertain, we also evaluated a scenario which assumes that biofuels will lead to GHG emission cuts of only about 60%, compared to fossil fuels emission levels (Mitigation Scenario B). In this scenario, other technological options were chosen by the TRAVEL model to reach the RCP2.6 emission level. In the model, bus and rail transport switch to electric, cars first to plug-in HEVs and then to hydrogen fuel-cell cars. For aviation, no switch to electricity or hydrogen fuel occurs because electric aeroplanes are not feasible, and the cost of hydrogen aeroplanes is too high. Strong efficiency improvements and a large shift towards high-speed trains would still allow a reduction sufficient to achieve RCP2.6 emission levels. Despite the already strong cut in CO_2 emissions and steep increases in energy efficiency, other studies using a bottom-up approach result in even higher efficiency potentials (Graus et al., 2010; Teske et al., 2010).

The feasibility of achieving RCP2.6 emission levels of course also depends on the baseline travel demand projections. Here the evaluated model comparison with past observations resulted in a good overall fit (Appendix B). However, uncertainties remain as to how the income, population, energy prices and constant factors (preferences for different modes) will evolve in the future. Latter is especially true for air travel, which has only a small and steeply rising share in the different world regions. Hence, it is difficult to project how it will evolve in the different countries and whether the constant factors for air travel raise above, or remain below the US level.

4.2. Decreasing travel demand

Fig. 8 shows that the decrease in total travel volume is quite low in both scenarios across the century. This can be explained by fossil-fuel costs being a low share of total transport costs in the distant future, and the ability of the transport system to adapt by changing the vehicle fleet. Because of the high comfort levels, especially in high-income countries, the additional technology costs for less CO_2 emitting vehicles are only a few per cent of total vehicle costs. Therefore total travel costs increase only little.

The response to the carbon tax is comparable to that found in the literature. From an extensive review on transport elasticity, Litman (2011) summarises a fuel price elasticity of passenger transport between 0.1 and 0.3. The implicit fuel price elasticity in the TRAVEL model can be derived from the comparison of fuel price and travel demand in the different Scenarios. The implicit global fuel price elasticity for travel demand is around 0.2 in 2020 and raises to 0.3. Towards the end of the century the elasticity decreases because of the increasing share of non-fossil fuels.

An additional evaluation of the alternative policy scheme showed that travel demand could be further reduced if the purchase price of carbon-intensive vehicles was raised, instead of the carbon tax raising the costs for the whole vehicle fleet. This result supports the policy scheme considered by the European Union (European Parliament and the Council of the European Union, 2009).

4.3. Carbon tax

Obviously, the carbon tax as calculated in this study is subject to uncertainty, certainly for long-term calculations. This is not only due to uncertainties in technological learning and fuel prices, but also due to the baseline development and inertia of the travel system having an influence on the required carbon tax. Table 1 shows how the costs of a few key technologies influence the required carbon tax (biofuels, plug-in hybrids in Scenario A, cryoplanes in Scenario B). Given these uncertainties, it is difficult to compare our results with those of other studies. Considering the magnitude of the carbon tax, the original RCP2.6 modelling group (van Vuuren et al., 2007) has projected carbon tax levels (permit price) of around USD 220/tCO_2 by 2100 in a scenario with similar GDP and population growth. With this tax, global direct CO_2 emissions from the transport sector will be reduced to nearly zero, while emissions from land-use change increase. This is very similar to Scenario A and the resulting shift towards biofuels, according to our model calculations. van Vuuren et al. (2007) assume that hydrogen fuel cells start entering the market in 2050, allowing for steep reductions of direct CO_2 emissions in the transport sector. This development is projected to occur only in the scenario where biofuels are also taxed (Scenario B). Kim et al. (2006) evaluate only the US transport sector. They conclude that a carbon tax of 100USD/tCO_2 will not be sufficient to reduce demands for passenger light-duty services or to induce a major shift from ICE vehicles to more efficient hybrid electric and fuel-cell vehicles. Furthermore, they state that a carbon tax is not likely to have significant leverage in either affecting aggregate demand for transportation services or the choice of passenger vehicle unless the tax is stringent. This is in keeping with our findings. We found that even a very high tax (increasing to USD 2000/tCO_2 by 2100) would reduce travel demand only by 8%, because the travel system would switch to electric and hydrogen alternatives. The IEA 'BLUE Map' scenario assumes technologies with costs of up to USD 200/tCO_2 (Fulton, 2009) and reaches similar emission cuts by 2050.

4.4. Indirect emissions

Many studies on transportation consider not only direct GHG emissions (tank-to-wheel) but also indirect emissions (well-to-tank or upstream emissions) (Fulton, 2009; Kim et al., 2006). However, future indirect emissions depend heavily on changes outside the transport sector, namely the technological change and mitigation efforts in the energy production sector for electricity and hydrogen. Therefore we deliberately focused on direct GHG emissions (except for the indirect GHG emissions of biofuels in Scenario B), which consist of fossil CO_2 emissions. It is not very likely that including the GHG emissions from electricity and hydrogen generation would alter the conclusions much. For the GHG emissions associated with electricity and hydrogen production, it has been shown by various publications that climate mitigation is possible at much lower costs here than in the transport sector (van Vuuren et al., 2007, 2012). This can be evaluated by applying the transport sector carbon tax from Scenario A to the electricity production in TIMER model calculations. Fig. 12 shows CO_2 emissions from electricity production in the baseline scenario and those when the carbon tax from Scenario A is applied, with and without allowing for the combination of bio-energy and CCS (BECCS). It reveals that with such a carbon price, the CO_2 emissions in the energy sector are reduced steeply and are even projected to be negative if BECCS are allowed. A similar picture occurs for hydrogen. Therefore, the increasing share of electricity and hydrogen is not so likely to increase the well-to-wheel emissions, if similar climate mitigation efforts are applied in the energy sector. If the tax level in Scenario B was applied in the energy sector, the emission reduction would of course be even more pronounced.

4.5. Transition options

Using our model, we identified three options that contribute towards lowering CO_2 emissions from passenger transportation systems:

Changing fuel use of vehicles: The first and most cost-efficient measure is that of changing the fuel mix. If zero- or very low-emission biofuels become available in the future, this option would account for the main contribution. In other situations, a switch to electricity or hydrogen would be needed to reduce CO_2 emissions. This is easily feasible for buses and trains. For cars, considerably higher costs are involved in a switch to the corresponding technologies (FCV, BEV). For aeroplanes, switching to

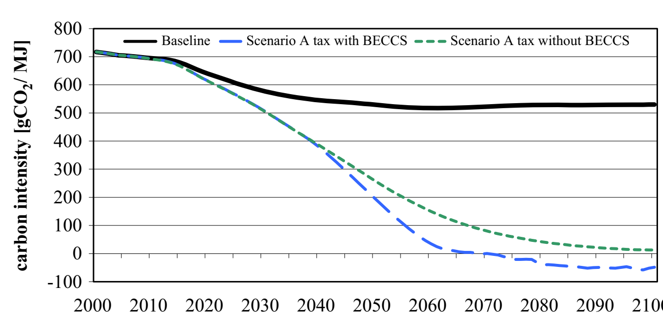

Fig. 12. CO_2 emissions from electricity production (g C/MJ). Scenarios: Baseline (black), carbon tax from transport mitigation Scenario A with BECCS (green) and without BECCS (blue).

electricity is not possible and switching to hydrogen carries very high costs.

Increasing efficiency of fleets: An alternative option is energy efficiency improvements. There is a consistent further decrease in energy use if biofuels also are taxed. In that case, the increase in energy efficiency is projected to contribute significantly to the required reduction in GHG emissions needed to reach the RCP2.6 targets.

Changing mode split: Different studies suggest that mode split could contribute significantly to climate mitigation (Chapman, 2007; Fulton, 2009). Our model allows for such changes in mode split. Our results show that this third option contributes little to the low-emission scenarios. The switch from aeroplanes to high-speed trains is essential to reach the RCP2.6 targets if no solutions for zero-emission aeroplanes are found. The proposed switches from car to bus and train (Chapman, 2007) are projected to contribute only marginally in our projections. The difference can be explained by the fact that Chapman makes exogenous assumptions about changing modal split, while we used carbon tax to drive the changes in the transport system. Our model's calculations also suggest that the share of transport mode is less sensitive to price, compared to other mitigation measures (e.g., changing fuel type or increasing energy efficiency). Of course if only monetary costs would be considered, mode shift would allow for cost-effective climate mitigation. However, such a calculation does not consider the time costs. Hence, a shift in passenger travel towards slower modes can only be realised if people fundamentally change their travel behaviour (e.g., spend more time but less money on transportation).

5. Conclusion

The results show that direct CO_2 emissions from passenger transportation can be reduced to the level required by the RCP2.6 (2 °C climate target), even if greenhouse gas emissions of biofuels are considered. The TRAVEL model indicates that direct CO_2 emissions could be reduced by 45% by 2050 and by 85% by 2100, compared to the 2010 level. The optimal reduction pathway depends on various assumptions, including those on emissions from bio-energy.

A high carbon tax would lead to only a small reduction in total travel demand (7% to 15% by 2050). This is because of the low share of the carbon tax in total transportation costs. Emission reduction occurs via other mechanisms than through the reduction in total travel volume. It also implies that even if mitigation options are not very expensive, sometimes relatively high carbon taxes are required to make them competitive. Therefore, depending on the targeted outcome, emission or energy efficiency standards might be effective alternatives to taxes. Such measures could trigger technological learning and include the mitigation costs into the purchase of new vehicles. In addition, our evaluation shows that the latter approach would even further reduce travel demand (3% to 6% by 2050).

The main contribution to CO_2 emission reductions is achieved by fuel switches, but efficiency improvement and modal split changes also play a role. If only emissions from fossil fuels are taxed, the major change compared to the baseline is the energy supply switch to modern biofuels. If upstream emissions of biofuels are also taxed (50% of the tax on fossil fuels), the transport system would start switching to electric and, after 2050, towards hydrogen. For this scenario, the share of high-speed trains doubles towards the end of the century, as costs in the aviation sector also increase. The technological feasibility of low emission transport systems is in line with the literature (Graus et al., 2010). The potential climate mitigation through switching to non-motorised travel modes (Chapman, 2007) was not found in the TRAVEL model calculations, as the monetary costs did not outweigh the high costs in time.

A climate tax in the order of USD 280/tCO_2 will be required by 2050 to reach the emission level required by the RCP2.6. The tax levels found in this study are similar to those in other mitigation studies (Fulton, 2009; van Vuuren et al., 2007). The key technology for reducing these costs is projected to be the plug-in ICE HEV with a 10 mile full electric range. The greenhouse gas tax required in the scenario where emissions from bio-energy are accounted for is high (USD 480/tCO_2 by 2050) and increases steeply. The latter effect is caused by high mitigation costs for aviation.

Aviation plays a critical role in long-term climate mitigation. In the baseline scenario the energy efficiency reduces from 2.5 MJ/pkm in 2010 to 1.3 MJ/pkm at the end of the century. If biofuels provide a solution for low emission fuels (Scenario A), the emission target is achieved mainly through switching fuel type. If not, considerably more energy efficient aeroplanes (0.8 MJ/pkm) and a shift to high-speed train are required (Scenario B). High carbon taxes are needed in the model to ensure such a change. Deepening understanding of this conflict between air travel and climate change mitigation requires further research on air travel demand and resulting CO_2 emission projections, costs, feasibility of technological options such as low emission fuels and new more efficient aeroplane designs.

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Appendix A. Transport technology characteristics

Speed and non-energy costs of travel modes for the USA in 2005 are described in Table 2. The energy efficiency, fuel use and additional costs for the different vehicle types are shown in Tables 3–5 for buses and trains, cars and aeroplanes.

Table 2
Assumed speed and non-energy costs of travel modes.

Mode	Speed (km/h)		Non-energy costs [cents (2005USD)/pkm]	
	Rural	Urban	2005	2100
On foot	5	4	7.4	7.4
Bicycle	11	11	10.0	10.0
Bus	26	35	4.8	4.8
Train	36	38	9.7	9.7
Car	60	78	15.3	15.3
High-speed train	150	150	16.3	8.2
Aeroplane	270	270	6.6	6.6

Note: US (2005) load factor assumed for non-energy costs.
Data source: The speed is derived from different sources (ARE and BFS, 2005; Schafer et al., 2010). The speed from non-motorised travel modes and the rural–urban differences are slightly adjusted with regional per capita travel demand in 2005 such that the empirically observed travel time budget of 1.2 h per capita and day results.

Appendix B. Travel demand model setting

Calibration of different travel modes

The model described in the main text, determines long-term trends in transport modes in different world regions. The three key dynamic elements of the model which allow this are (1) the travel-money-budget (TMB) and travel-time-budget (TTB) constraints, (2) the multinomial logit type of equation to describe the selection for different transport modes based on prices, preferences and the TMB/TTB constraints and (3) the stock model describing inertia. Because of our attempt to describe long-term trends, the quality of the data (see further) and the time dependent model formulation of adjusting for TMB and TTB over time, a simple regression analysis has not been applied. Instead

Table 3
Bus and train types, energy efficiency, fuel use and additional costs.

Vehicle description	Fuel type	Energy efficiency (MJ/pkm)	Additional costs [cents (2005USD)/pkm]
Bus			
Conv.	Oil	0.9	0.0
Conv.	Bio	0.9	0.0
CNG	Gas	1.7	0.4
Trolley	Elec.	0.4	1.4
Train			
Diesel	Oil	1.4	2.4
Diesel	Bio	1.4	2.4
Electric	Elec.	0.6	0.0
High-speed train			
HS train	Elec.	0.5	0.0

Note: US (2005) load factor assumed for efficiency and costs.
Abbreviations: Conv.: conventional vehicles; CNG: Compressed natural gas.
Data source: Energy efficiency and additional costs of these modes were based on estimates from the transport model of Kyle and Kim (2011).

Table 5
Aeroplane types, energy efficiency, fuel use and additional costs.

Vehicle description	Fuel type	Year of introduction	Energy efficiency (MJ/pkm)	Additional costs [cents (2005USD)/pkm]
Air, before 1980	Oil	–	3.5	0
Air, 1980	Oil	1980	3.0	0.2
Air, 2000	Oil	2000	2.0	1.0
Air, 2000	Bio	2015	2.0	1.0
Air, improved eff.	Oil	2020	1.5	1.6
Air, improved eff.	Bio	2020	1.5	1.6
BWB	Oil	2040	1.0	2.6
BWB	Bio	2040	1.0	2.6
BWB, improved eff.	Oil	2050	0.8	3.3
BWB, improved eff.	Bio	2050	0.8	3.3
Cryoplane	H_2	2050	1.6	5.3

Note: US (2005) load factor assumed for efficiency and costs.
Abbreviations: Conv.: conventional vehicles; CNG: compressed natural gas.
Data source: energy efficiency and additional costs of these modes were based on estimates from the transport model of Kyle and Kim (2011).
Abbreviation: BWB: blended wing body. Cryoplane: H_2 fuelled airplane.
Data source: Historic efficiencies (Lee, 2000). The efficiency of the "improved efficiency" variant correspond to the efficiency of the IEA Bluemap scenario (Fulton, 2009). The BWB efficiency is within the lower range projected by Schafer et al. (2010) for new vehicles in 2020 to 2030 (Schafer et al., 2010). The costs are derived from the technology–cost relationship for aeroplanes proposed by Lee et al. (2001). The lower efficiency of the cryoplane and higher non-energy costs compared to the efficient BWB are rough estimates based on the description of the cryoplane (Krijnen and Astaburuaga, 2002; Westenberger, 2008).

Table 4
Car types, energy efficiency, fuel use and additional costs.

Vehicle description	Fuel type 1	Fuel type 2 (for hybrid)	Energy efficiency 1 (MJ/pkm)	Energy efficiency 2 (MJ/pkm)	Additional costs [cents (2005USD)/pkm]			
					2000	2010	2035	2100
Conv. ICE (2000)	Oil	–	2.20	–	0.0	0.0	0.0	0.0
Conv. ICE (2010)	Oil	–	1.62	–	1.6	1.0	0.7	0.7
Adv. ICE	Oil	–	1.30	–	2.8	2.0	1.8	1.2
Adv. ICE H_2	H_2	–	1.13	–	20.4	15.5	3.1	2.5
Turbo-petrol ICE	Oil	–	1.04	–	3.4	2.4	2.1	1.4
Diesel ICE	Oil	–	1.00	–	3.8	2.7	2.7	1.6
Diesel ICE	Bio	–	1.00	–	3.8	2.7	2.7	1.6
ICE-HEV-gasoline	Oil	–	1.02	–	6.2	4.6	3.1	1.9
ICE-HEV-diesel	Oil	–	0.96	–	6.4	4.8	3.2	2.0
ICE-HEV-H_2	H_2	–	0.94	–	21.3	16.2	3.8	2.7
ICE-HEV-CNG	Gas	–	0.88	–	18.2	13.9	3.3	2.2
ICE-HEV-diesel	Bio	–	0.88	–	25.8	19.7	3.3	2.2
FCV	Oil	–	1.56	–	88.9	68.2	5.9	3.9
FCV	Bio	–	1.06	–	69.9	53.6	4.9	2.9
FCV	H_2	–	0.72	–	62.2	47.7	4.5	2.5
PEV-10	Oil	Elec.	0.50	0.06	7.5	5.6	3.3	2.4
PEV-30	Oil	Elec.	0.35	0.13	14.0	10.6	3.9	3.0
PEV-60	Oil	Elec.	0.25	0.17	23.6	18.0	4.8	3.9
PEV-10	Bio	Elec.	0.53	0.06	7.5	5.6	3.3	2.4
PEV-30	Bio	Elec.	0.35	0.13	14.0	10.6	3.9	3.0
PEV-60	Bio	Elec.	0.25	0.17	23.6	18.0	4.8	3.9
BEV	Elec.	–	0.39	–	51.5	39.5	9.2	6.0

Note: US (2005) load factor assumed for efficiency and costs.
Abbreviations: Conv.: conventional vehicles (sold before 2000/2010 in USA); CNG: Compressed natural gas; ICE: internal combustion engine; ICE Adv: Improved ICE car, HEV: hybrid electric vehicle, PHEV10: Plug-in HEV with a 10 mile full-electric range, FCV: fuel-cell vehicle; BEV: battery electric vehicle.
Data source: The cost and efficiency are derived from Ogden et al. (2004), adding of the PHEV and BEV from Kromer and Heywood (2007). The cost estimates are updated to those from Bandivadekar et al. (2008), and technological learning trends for 2050 by Plotkin and Singh (2009). For 2100 cost are assumed to decrease to mass production level described by Ogden et al. (2004).

we adjust the model's parameters in order to reduce the difference between observed and modelled data, focussing on 5 year time steps and getting the historical trends best represented. In this procedure, we first derive the regional deviation from the general TMB formulation using the modelled prices and observed per capita travel demand. The general TMB formulation describes, according to the data from Schafer et al. (2010), an increase from 3% of income used for travel for regions with nearly no share of car and faster transport modes towards 12% for regions where people mainly travel by car and faster modes. Next, the sensitivity

Table 6
Constant factors for the different transport modes in 1971 and 2005.

	Walk	Bicycle	Bus	Train	Car	Hs train	Air
North America	1.6; 1.6	2.9; 2.8	2.8; 4.5	2.4; 3.6	0.7; 0.6	1.4; 2.2	1.4; 2.2
Pacifc OECD	2.0; 2.6	2.4; 2.8	1.7; 3.0	1.1; 2.0	0.8; 0.8	0.5; 1.1	0.8; 1.7
Western Europe	2.3; 1.9	2.6; 2.3	1.6; 2.9	1.5; 2.4	0.6; 0.7	0.8; 1.3	0.7; 1.7
Eastern Europe	2.0; 2.0	1.9; 1.6	1.5; 2.9	1.2; 1.8	0.9; 0.8	1.3; 2.1	0.9; 1.2
Former Soviet Union	1.4; 1.8	2.0; 1.5	1.3; 3.0	1.0; 1.7	1.0; 0.8	1.5; 2.1	0.6; 2.2
Sub-Saharan Africa	0.8; 1.1	0.9; 1.1	1.4; 2.0	1.9; 2.0	0.8; 0.8	1.2; 1.7	0.4; 0.6
Centrally Planned Asia	0.5; 1.1	0.8; 1.0	2.2; 2.0	1.7; 1.3	3.6; 0.6	2.4; 1.6	0.4; 0.4
Latin America	0.9; 0.9	1.3; 1.4	1.4; 1.9	1.9; 2.6	0.5; 0.5	1.6; 2.2	0.7; 1.1
Middle East & North Africa	0.7; 1.2	1.4; 1.5	1.6; 2.7	2.5; 3.2	0.6; 0.7	1.4; 1.9	0.7; 1.1
Other Pacific Asia	1.2; 2.1	1.1; 1.7	1.3; 3.2	1.0; 2.3	0.8; 0.9	1.7; 1.7	0.2; 0.9
South Asia	1.4; 1.4	1.4; 1.2	1.6; 2.3	1.3; 1.7	1.3; 0.8	1.2; 1.7	0.2; 0.5

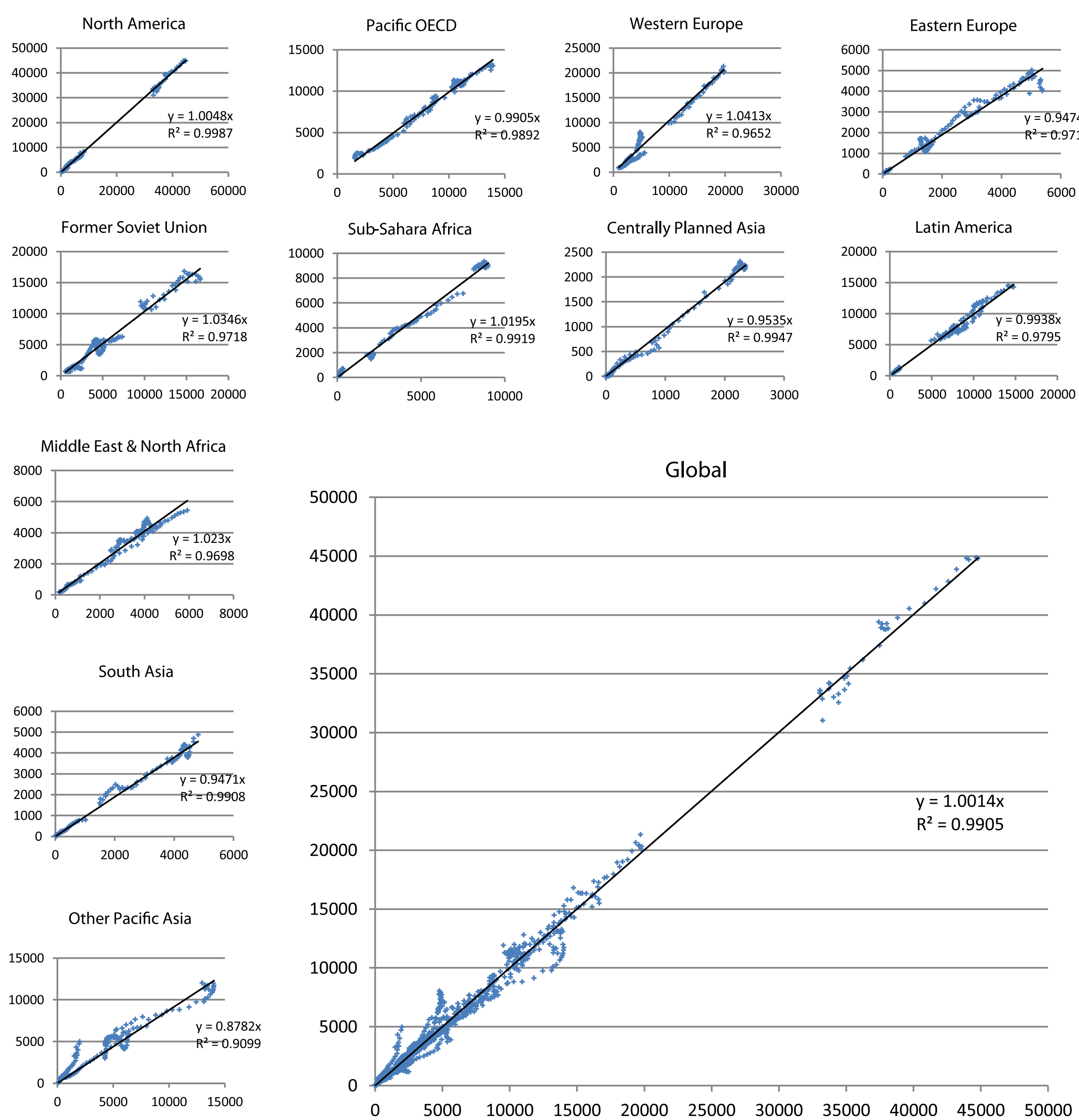

Fig. 13. Modelled (*x*-axis) versus observed (*y*-axis) travel demand from Schafer et al. (2010) for 11 world regions and three motorised transport modes (public transport (bus and train), car, high-speed travel (train and aeroplane)) from 1971 to 2005.

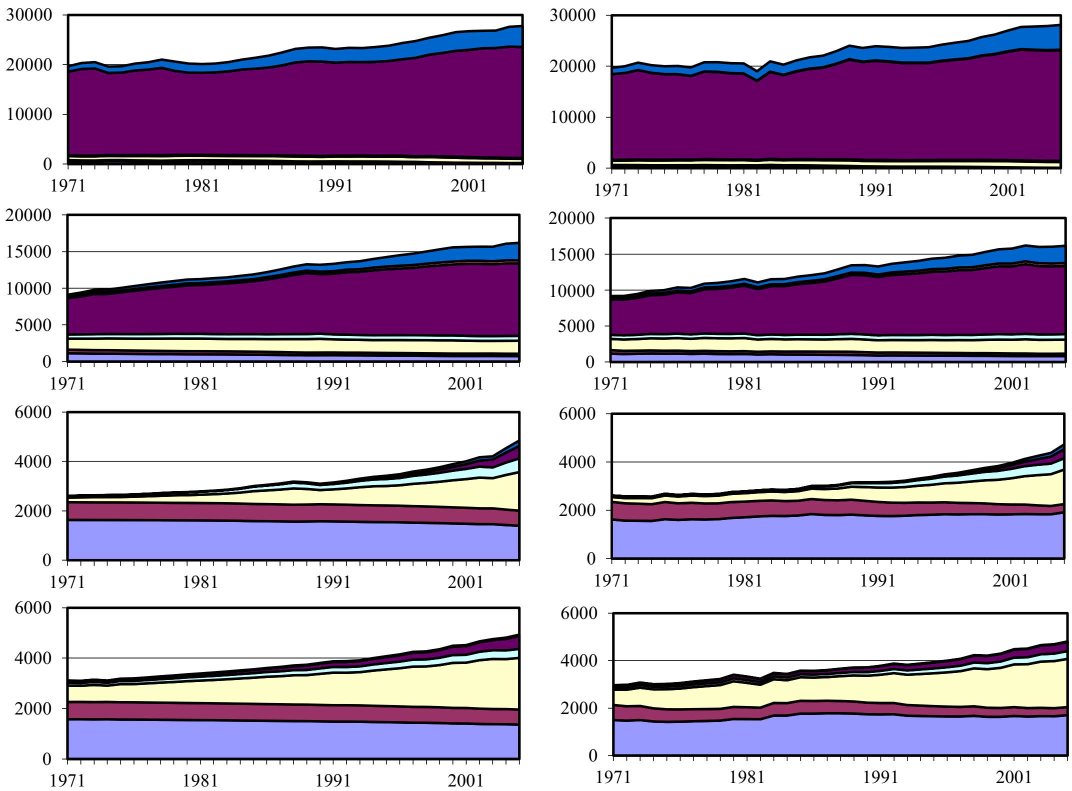

Fig. 14. Observed (left) and modelled (right) travel demand (in pkm per capita and year) for North America (top), Western Europe, China and India and seven transport modes (walk, bike, bus, train, car, high-speed train and air) from 1971 to 2005.

of the MNL-type model, lambda (see Eq. (2)), is set in order to reduce the deviation from the observed data (lambda=3.3). Then the travel system inertia is determined for the different travel modes (see Eqs. (7) and 5 years for non-motorised modes, 10 years for bus, train and car, 20 years for high speed modes). Finally, the constant factors in 1971 and 2005 are determined, allowing a further reduction of the difference between modelled and observed travel data (Table 6).

Empirical data on transport modes

To evaluate the quality and improve the model fit of the travel model we use travel demand per capita, as observed in 11 world regions between 1971 and 2005 (Schafer et al., 2010). These time series provide travel distance per capita for three modes (bus/train, car, high-speed). We separated the data for bus and train as well as high-speed train and aeroplane using the indicated shares from Schafer and Victor (2000). The share of the non-motorised modes (walk and bike) is determined by the remaining travel time per capita after subtracting the time use for the motorised travel modes from the TTB (1.2 h/day). The ratio of walk to bike is kept constant in the different world regions. To match the regions, we aggregate the 26 regions from the TRAVEL model to the 11 regions from Schafer et al. (2010) (Fig. 13).

Results

Fig. 13 shows that the model allows a good reproduction of the observed total travel demand, especially for the regions with higher incomes. As further illustration, Fig. 14 provides the historical ‘empirical’ trends for some selected regions (based on their relevance given the region’s size), and the model outcome (USA, China, Western Europe and India). From the perceived prices (Table 6) it can be observed that cars have lower constant factors (<1) than other travel modes, indicating higher preference for this transport mode in all world regions except for China in 1978 (but here it should be noted that statistics are poor and moreover, there was a lack of a real car market). In 2005, China shows a constant factor for cars that was similar to the other world regions. Bus and train data show larger variances, but all vary around 2 or higher again, except China where public transportation is more popular – or more strongly subsidised. For high-speed train, only two world regions show relevant shares in 2005 (Pacific OECD and Western Europe). For the other regions the preference was set such that no share for high-speed train results from the model. For aeroplane travel, a difference between poor countries and high-income countries as well as an increase from 1971 to 2005 can be observed.

For the long-term projections up to 2100, assumptions about the future behaviour of the different parameters were required. First, the TMB of the different regions is assumed to converge to the general TMB formulation. For the slow modes (bus, train and car), the baseline scenario assumes that the 2005 preferences will be maintained in the future, since they were also quite constant between 1971 and 2005. For high-speed train, the constant factors of the different regions are assumed to converge to the value of the Pacific OECD in 2005 which is the most mature market for high-speed train at this time. For aeroplane we assume for the baseline scenario that values in the non-OECD countries increase to the level of the OECD countries (around 2).

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