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Bouwman, ME; Moll, HC

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Energy use reduction potential of passenger transport in Europe

M. E. BOUWMAN† and H. C. MOLL

Center for Energy and Environmental Studies IVEM, Groningen University, Nijenborgh 4,
9747 AG Groningen, The Netherlands

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To contribute to a sustainable society, considerable reduction in energy use and CO₂ emissions should be achieved. This paper presents the results of calculations exploring the energy use reduction potential of passenger transport for Western Europe (OECD Europe minus Turkey). For these calculations, three types of options are defined emphasizing technological, infrastructural and behavioural change. By 2050, technological improvements may reduce energy use per passenger-km by ~30%. Adding infrastructural options, an energy reduction of > 50% by 2050 can be realised. To achieve further energy reductions, options with a large behavioural impact should also be implemented. This results in an 80% energy reduction potential in the transport sector by 2050. To calculate the reduction potential on OECD Europe level, one should factor in expectations concerning mobility growth. Two mobility development scenarios are used. Both scenarios foresee a net decrease in total energy use of 20% with the introduction of the technological and infrastructural improvement options. Adding options emphasizing behavioural change results in a net reduction potential of ~60% by 2050.

1. Introduction

The present use of energy and materials and the emission of greenhouse gases in Western Europe contribute substantially to global resource depletion and global climate change. To contribute to global sustainability, i.e. stabilization at the 1990 emission level by 2050 (Houghton *et al.* 1995), while leaving room for development outside the Western world, considerable reductions in the use of energy and materials are required, resulting in the required reduction of greenhouse gases (mainly CO₂).

There is a variety of reduction options such as technological improvements, infrastructure modifications and behavioural change. Technological improvements aim at increasing the energy and material efficiency and at providing substitutions, resulting in lower overall energy and material consumption. Some options demand large behavioural adaptations such as shifting from private to public transport. Some consequential substitutions also require a new or a heavily modified infrastructure such as, for example, distributing a new energy carrier or providing the infrastructure for increased use of public transport. All such options can be evaluated individually on their potential to reduce CO₂ emissions.

Transport—passenger and freight moved by road and railways—contributes about one-quarter (OECD/IEA 1997) [14×10^{18} Joules per annum] of the total

†e-mail: M.Bouwman@fwn.rug.nl

energy consumption in OECD Europe. This share justifies a specific assessment of reduction options in the transport sector. Moreover, substantial growth (RIVM 1992) is foreseen for transport performance—expressed in passenger-km and ton-km—with possible related growth in energy requirements and CO₂ emissions.

To stabilize transport's energy requirement and emissions, the impact per unit of performance has to be at least halved from 2000 to 2050. An equitable distribution of CO₂ emissions on a globally sustainable level in 2050 requires an absolute reduction to one-fifth of the current energy consumption and emission levels for OECD Europe (cf. Mulder and Biesiot 1998). Combined with the expected growth of transport, this long-term reduction objective implies a reduction of the impact per unit of performance to 10% of the present one.

This paper calculates the reduction potential of passenger transport in energy terms in OECD Europe. The general aim is to achieve a 50% reduction by 2020 and a 90% reduction by 2050 per unit of performance. Technological improvements, infrastructure modifications and behavioural change are all considered, regardless of their implementation problems. This approach yields an indication of the reduction potential. The reduction potential is calculated for each individual category of options, as well as for the combined total.

The results described are part of the MATTER project. This multi-institutional project uses the MARKAL model to optimize cost-efficient CO₂ reductions. MARKAL (acronym for MARKET ALlocation) is a flexible linear programming model of a generalized energy system. It can be used to calculate the effects of new energy technologies. Within MATTER, the model is used to optimize an energy and material system. Improvement options to reduce CO₂ emissions are defined for the energy system, material production system and for individual products. The model calculates the most cost-efficient way to produce a fixed demand within a given CO₂ emission level. It thereby compares different technologies in different systems and chooses the optimal solution over the whole system. Within the project, a separate analysis is made on implementation barriers.

2. Methodology

The reduction potential of passenger transport is calculated in relative terms, resulting in a reduction percentage per unit of transport. The unit used to calculate energy use in 1990 and 2050 is the transport of one person over 1 km (passenger-km). This unit most accurately represents the demand for transport, which is usually not a demand for vehicle-km, but a demand to cover a certain distance. The magnitude of the demand is largely influenced by the spatial settings and the activity patterns of each individual.

For a reduction potential analysis, the motorized transport demand is of importance. One can differentiate between individual and public transport systems. In Europe, 14% of motorized transport demand is covered by public transport and 86% by individual passenger cars (Schol and Ybema 1999). We do not include soft modes like walking and cycling in the analysis, as their energy use and emissions are already minimal. Information about the overall share of soft modes in Europe is not available. Of the total mobility demand in The Netherlands in 1994, ~10% is covered by soft modes (CBS 1995). As the proportion of bicycling is relatively large in The Netherlands, this share is most likely higher than the average European value.

The reference energy use in 1990 is the energy use per passenger-km in a passenger car. This energy use is calculated based on both the direct and indirect

energy use of the vehicle as well as the average occupancy rate. Figure 1 gives an overview of the calculation of the reference energy use.

Direct energy use per vehicle-km comprises fuel used for transport and depends on engine technology, car size, etc. Indirect energy use comprises the energy use associated with production, maintenance and discarding of the vehicle. Indirect energy associated with the infrastructure is not included in the analysis. The indirect energy use is influenced by vehicle production energy use, the energy needed to produce car materials (gross energy requirement, or GER, of the materials), the annual use of the vehicle and the vehicle's total lifetime. To convert the direct and indirect energy use per vehicle-km to per passenger-km, the values are divided by the average occupancy rate of the vehicle. The next step in figure 1 is the conversion of direct energy use to primary energy use. To do so, the direct energy use is multiplied by the energy demand for fuel winning (ERE, or energy required for energy).

The goals set in the Introduction for the reduction potential needed for transport are based on overall reductions. The total primary energy use per passenger-km refers to the energy requirements of all processes associated with the use of a passenger car. Calculating this value for the average OECD Europe passenger car and occupancy rate provides an energy use of 0.4 MJ indirect and 1.9 MJ direct per passenger-km. This gives a primary energy use of 2.3 MJ per passenger-km in 1990. This paper assesses the possibility of reducing this by 50% by 2020 to 1.2 MJ per passenger-km, and by 90% by 2050 to ~ 0.2 MJ per passenger-km.

The energy use of 2.3 MJ per passenger-km is the value for the standard 1990 passenger car. Over time, passenger car characteristics also change. For this reason, development of car characteristics is implied in the analysis. The development in vehicle weight is the most important characteristic for our analysis, as this relates directly to the fuel economy of a vehicle. A 10% weight increase generally results in a 5% decrease in fuel economy (Hughes 1993).

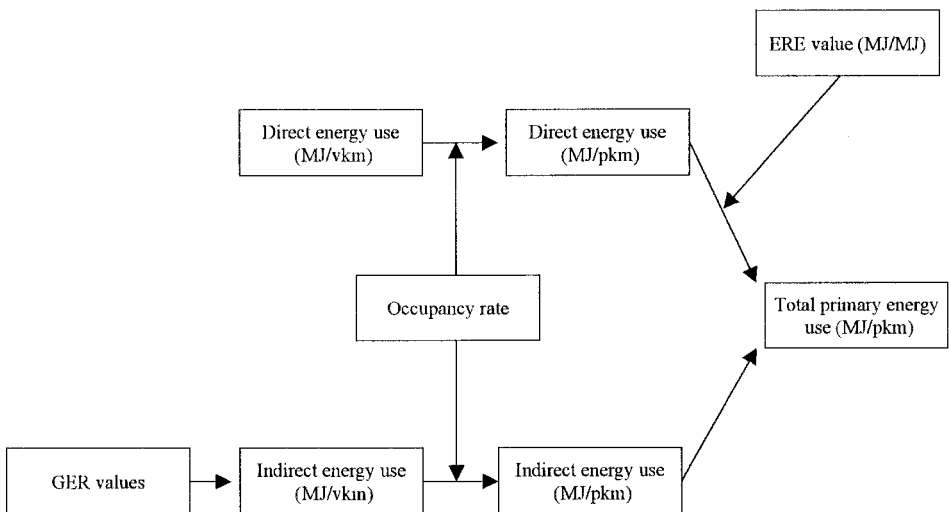


Figure 1. Calculating the total primary energy use per passenger-km.

Vehicle weight has increased steadily over the past decades. Two factors influence this weight increase: the demand for ever larger cars and the addition of more safety features and gadgets. Figure 2 illustrates the development in Dutch passenger car weight, a good representative of the development of the average European car.

Figure 2 shows a clear increase in vehicle weight for both the weight of newly sold cars and the average weight of the vehicle fleet. This trend is not likely to change in the coming years. Therefore, it is assumed that the average vehicle weight will increase from 1000 kg in 1990 to 1220 kg in 2020 and 1270 kg in 2050. Figure 3 displays the expected trends in vehicle weight for Europe between 1990 and 2050.

The weight increase will cause a 17% higher fuel use by 2050 compared with 1990 at constant engine performance (Bouwman and Moll 1997).

3. Improvement options

Reducing energy use per passenger-km is possible by changing the magnitude of the direct energy use, the indirect energy use and the occupancy rate (figure 1). Changing ERE values is not fully included in the present analysis since reduction in ERE values requires changes in the energy-producing sector.

Not all possible methods of reducing energy use per passenger-km are equally easily introduced. Therefore, we divide the possibilities into four categories in order of the difficulty of implementation. The technological improvement options are derived from the database gathered by Binsbergen *et al.* (1994). In Ybema *et al.* (1995), a selection of these options is made and efficiency improvement figures for 2000, 2015 and 2030 are calculated. The figures from this database will be used to calculate the reduction potential, supplemented with figures on material substitution (Bouwman and Moll 1997) and some non-technological options. The various

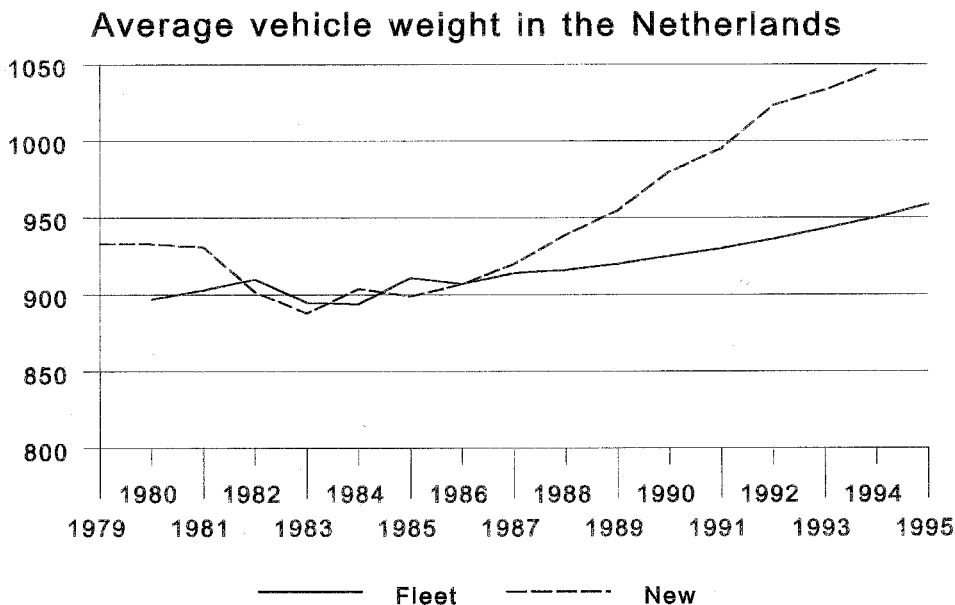


Figure 2. Development of the Dutch vehicle weight between 1980 and 1995.

categories of improvement options are described in more detail below. Table 1 lists a quantitative overview of the expected efficiency improvements.

Autonomous trend in European vehicle weight

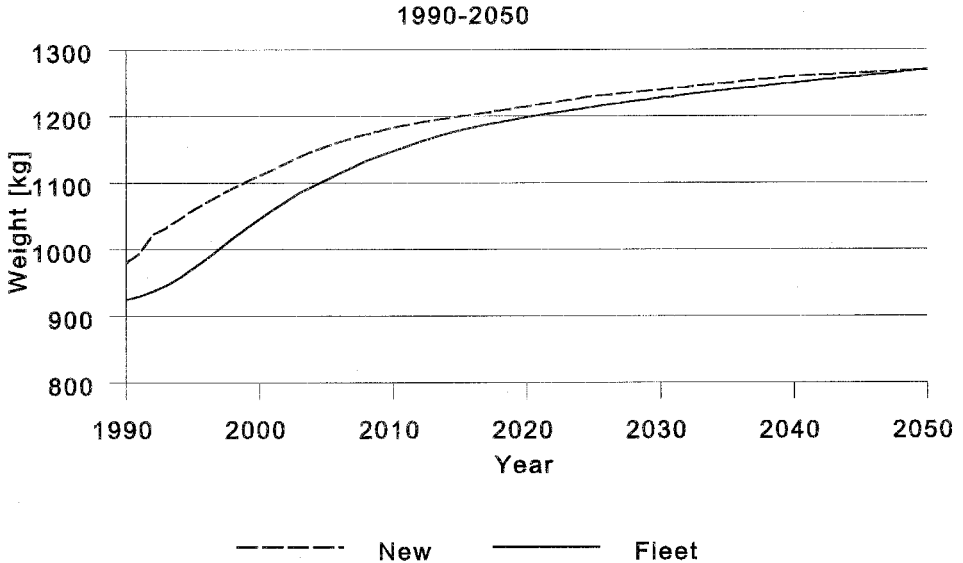


Figure 3. Expected development of the European car weight between 1990 and 2050.

Table 1. Energy reduction of various improvement options.

Improvement option	2000	2015	2030	2050
Improve internal combustion Otto engine ^a	5%	17%	23%	
Improve internal combustion diesel engine ^a	5%	20%	30%	
Improve tyres and aerodynamics ^a	3%	4%	5%	
Introduce continuous variable transmission ^a	3%	5%	7%	
Introduce modified frame ^b	14%	16%	17%	19%
Introduce the electric vehicle ^{1,a}	47%	59%	67%	70%
Introduce regenerative braking ^a	0%	3%	5%	
Introduce the hybrid passenger car ^{2,a}	3%	33%	35%	
Introduce the fuel cell passenger car ^a	na	na	60%	
Change modal split ^c		61% ³		73%
Increase vehicle lifetime ^b	2%	2%	2%	2%
Drive 850 kg vehicles ^{b,c}	15%	20%	21%	22%
Double occupancy rate ^c	50%	50%	50%	50%

^aYbema *et al.* (1995), ^bBouwman and Moll (1997), ^ccalculations described in text.

¹The value for the electric vehicle excludes the influence of the ERE value. If the average 1990 European ERE value for electricity (1.7 MJ/MJ) is included, the score for the electric vehicle worsens and becomes 19, 37, 49 and 54% respectively.

²The energy savings of a hybrid passenger car depend on the share of short-distance trips that can be made with the electric part of the vehicle. It is assumed that this is 33% of the total distance, since in The Netherlands 33% of all kilometres are travelled in trips < 20 km (CBS 1997).

³2020 value.

3.1. *Options emphasizing technological change*

Technological options generally have the fewest implementation problems. Options in this category do not influence the functionality of the vehicle. The options here comprise the improved internal combustion engine (IIC), improved tyres and aerodynamics (ITA), continuous variable transmission (CVT) and modified frame (MF).

The IIC includes many different options, such as lean-burn technology, valve steering management, turbo-charging, direct fuel injection, electronic engine control, etc. The term ICC combines the relevant options for both diesel and petrol vehicles.

Improved tyres and aerodynamics offer small savings, but they are also relatively easy to implement. Continuous variable transmission offers the use of a continuous range of gears. In this way, engine use is optimized, resulting in higher fuel economy.

The modified frame comprises all material substitution options to reduce vehicle weight. Lightweight construction of vehicles is promising because it improves fuel economy. The most common material in the passenger car is steel, which has a high density. Substituting lower density materials for a volume unit of steel results in a weight advantage. Material substitution is not very easy since many demands are made on the construction material, and steel adequately fulfils most of these requirements. For example, construction in aluminium (density about one-third that of steel) requires thicker parts because the strength of aluminium is lower than steel's strength. Material substitution can follow several directions. Generally, new high-strength steel alloys, aluminium and plastics are the most common materials. An extensive review of the possibilities of each of these materials pointed to aluminium as the most promising (Bouwman and Moll 1997).

3.2. *Options emphasizing changes in infrastructure*

This category comprises alternative fuel vehicles. The adaptations to be made in this situation are not individual, but they require changes in the infrastructure resulting from the distribution of new fuels. This category includes the introduction of the electric vehicle, the hybrid vehicle and the fuel cell passenger car.

A large battery powers an electric vehicle. The energy use of electric vehicles is very low compared with standard internal combustion vehicles. However, large ERE for the generation of electricity (1.7 MJ/MJ in Europe in 1990) cause a relatively large primary energy demand for electric vehicles. Electric vehicles are equipped with regenerative braking (RB), a system that stores braking energy.

The hybrid passenger car combines the advantages of both an internal combustion engine (unlimited range) and electric propulsion (low emissions and noise). Hybrid passenger cars use the electric part in urban traffic and change to the standard engine when a long range is required. The disadvantage of this system is the relatively high vehicle weight due to the combination of the two systems. This results in higher energy use when driving in the internal combustion configuration compared with the standard vehicle.

A fuel cell passenger car also runs on electricity, but uses fuel that is converted directly into electricity in the car. The technology is not yet very mature; no vehicles with fuel cell technology are on the market yet. Implementation before 2020 is highly uncertain, and at present the costs associated with this technology are very high.

3.3. Options emphasizing behavioural change

These options require important behavioural adaptations. Examples cannot be found in the database used for the technological options. This category comprises a change in modal split (increased use of public transport), increased vehicle life, driving small passenger cars and increasing the average occupancy rate of passenger cars. These category 3 improvement options require societal adaptations. The infrastructural options are assumed to be easier to implement, as the necessary changes can be influenced with policy more directly.

For changing the modal split, it is assumed that the share of public transport in passenger mobility doubles from 14 to 28% by 2020. This implies that this option is only valid for a small share in the total mobility demand. Replacing a car passenger-km by a public transport-km has an average energy advantage of $\sim 60\%$ in 2020 and $\sim 70\%$ in 2050, compared with the 1990 value (reconstructed out of Ybema *et al.* 1994, Schol and Ybema 1999).

Increasing vehicle life from 12.5 to 15 years affects the indirect energy component. Doing so requires major maintenance investments from the various users of a car. The effects of a longer vehicle lifetime are not very large. The gain from dividing the production energy of the vehicle—15% of the lifetime energy (Moll and Kramer 1996)—over a larger number of kilometres is partly lost by the need for increased maintenance, which has an energy requirement of 2 GJ/year (Moll and Kramer 1996).

A decrease in vehicle size may also contribute to energy savings, because lighter cars have higher fuel economy, especially for frequent stop and drive situations. Introducing small passenger cars requires large behavioural adaptations, as this opposes the current trends in the development of vehicle weight (figure 2). Driving an 850 kg passenger car instead of the standard 1000 kg passenger car increases fuel economy by 9% (Bouwman and Moll 1997). For this small vehicle, no weight increases are assumed. As the weight difference in vehicle size between standard and 850 kg passenger cars increases over time, the advantage in fuel economy also increases.

Another method of decreasing energy use per passenger-km is to increase the occupancy rate of a vehicle. By doubling the occupancy rate, the energy use per passenger-km halves. Since this option requires large adaptations from the individual user, this option will be hard to realise. An increased share for public transport, to cover the individual trips that cannot be combined with other individual trips by passenger car, should probably accompany the implementation of this option.

Other behavioural options refer to the use of the car. Changing driving style, adjusting inflation pressure of tyres or changing maintenance patterns can also contribute to overall savings.

3.4. Mobility reducing options

Next to the options mentioned above, which do not influence the total demand for passenger-km, measures can be taken to reduce the individual mobility demand. A higher population density may reduce commuter travel and the construction of new roads may result in shorter routings. An increase in the use of soft modes may also be used as such an improvement option. Since the absolute reduction potential is calculated per passenger-km, a reduction in the number of kilometres is irrelevant. The changes in individual mobility demand are considered as scenario parameters

and will be used for the final calculation of the absolute reduction potential of the passenger transport sector.

Table 1 gives an overview of the expected energy efficiencies. Only the effect of individual options is shown. Various options may be combined to improve the total reduction. The figures are taken from the lower values of the existing estimates on efficiency improvements in passenger cars. Several other authors may have more optimistic expectations. However, the expected increase in mobility is also rather conservative. This makes the total figures on reduction potential quite moderate.

Table 1 also gives an overview of improvement options that might be relevant for the reduction of total energy use and emissions from passenger transport. The division into four categories gives some indication of the difficulties that may occur in implementing these options. As this paper focuses on the reduction potential, it does not concentrate on implementation barriers, though it is clear that such barriers exist. A first analysis of the implementation barriers of various reduction options in the transport sector was recently made by Groenewegen *et al.* (1998).

4. Calculation of the reduction potential

The information presented in table 1 can be used to calculate the energy reduction potential of passenger transport. The goal is to calculate values for 2020 and 2050. To calculate the 2020 reduction potential, the 2015 values are used. For the calculation of the 2050 reduction potential, only limited information is available. The values presented in Ybema *et al.* (1995) have 2030 as a horizon. For these options, no assumptions are made about extra saving potentials, which means that the 2030 value is used if no 2050 reduction potential is given. The total reduction potential can be calculated by multiplying the efficiencies of the various techniques. For example, in the case of an 850 kg passenger car with a modified frame, the efficiency calculation for 2000 is $(1 - 0.14) * (1 - 0.15) = 0.73$. This means that the combination of these two options results in a 27% reduction in energy use.

This section presents the reduction potential per category of improvement options. Reduction percentages are based on a comparison with the 2.3 MJ per passenger-km of the standard 1990 petrol passenger car.

4.1. Implementing category 1 improvement options.

Table 2 shows the results of the implementation of the category 1 improvement option. As costs are not a consideration, all options in the category are implemented. It shows that technological options result in a considerable energy reduction potential, without requiring major behavioural adaptations. The results are corrected for the assumed weight increase. Without the weight increase, a reduction of 37% would be possible by 2050 in a petrol passenger car with MF, ITA, IIC and CVT. The effects of the implementation of the technological options might be compared with the introduction of the 5-litre vehicle. This refers to a vehicle using 5 litres of fuel to drive 100 km and will, according to new legislation in the EU, be implemented by 2010. Compared with the standard 1990 vehicle (8 litre), this implies a saving of $\sim 30\%$ in 2025, when this new vehicle should be fully penetrated in the fleet. The often-mentioned 3-litre car seems to be much further away from implementation.

4.2. Implementing category 1 and 2 improvement options

Category 2 contains the more complicated improvement options. Three new vehicles are introduced. Fuel cell technology is immature and will not yet be available in 2020, but is considered a very promising option for 2050. The electric vehicle is somewhat more difficult to implement than the hybrid or fuel cell passenger car because of its limited driving range. It is, therefore, assumed that the electric vehicle can contribute 70% of the total vehicle fleet.

For both the hybrid and the electric vehicle, the ERE value for electricity is of great importance for calculating the reduction potential of the vehicle. Therefore, these vehicles are shown twice in table 3, once with a high ERE value (2.0 MJ/MJ) and once with a low ERE value (1.2 MJ/MJ). Table 3 gives an overview of the reduction percentages possible with both category 1 and 2 improvement options.

With the new passenger cars, new possibilities for reducing energy consumption are introduced. The ERE value for electricity dominates the outcome of the calculation. In a situation with a low ERE value (1.2 MJ/MJ), the electric vehicle is the most promising option. A reduction of > 50% can be achieved with this vehicle by 2020.

With a high ERE value the fuel cell passenger car is the most promising option by 2050. By 2020, when this technology is not yet available, the electric vehicle performs slightly better than the hybrid and diesel passenger car. Considering both cases, an energy reduction of ~55% is possible by 2050 (the electric vehicle having a maximum share of 70%).

4.3. Implementing category 3 improvement options

The above subsections showed that with only technological options, cutting energy use in half is possible by 2050: still far from the goal of a 90% reduction. To achieve such an energy reduction, more stringent options should be included. Next to the options in categories 1 and 2, there are category 3 improvement options.

Table 2. Reduction percentages compared with 1990 in 2020 and 2050 with category 1 improvement options.

Passenger car type	2020	2050
Petrol passenger car with MF, ITA, IIC, CVT [†]	22%	29%
Diesel passenger car with MF, ITA, IIC, CVT	30%	39%

MF, modified frame; ITA, improved tyres and aerodynamics; IIC, improved internal combustion; CVT, continuous variable transmission; RB, regenerative braking.

Table 3. Reduction percentages compared with 1990 in 2020 and 2050 with category 1 and 2 improvement options.

Passenger car type	2020	2050
Fuel cell passenger car with MF, ITA, RB	not yet available	54%
Hybrid passenger car with MF, ITA, RB (high ERE)	31%	32%
Hybrid passenger car with MF, ITA, RB (low ERE)	36%	37%
Electric vehicle with MF, ITA, RB (high ERE)	35%	44%
Electric vehicle with MF, ITA, RB (low ERE)	54%	59%

Implementing these options not only decreases energy use, but also in most cases diminishes the costs associated with transport. Table 4 lists the results of the implementation of the non-technological improvement options. It shows that, in particular, doubling the average occupancy rate in passenger cars substantially influences the average energy demand. When this high average occupancy rate is combined with small vehicles and an increased vehicle life, the energy use per passenger-km in a passenger car is even lower than in public transport. Therefore, adding a doubled share for public transport results in a lower reduction. However, such a high occupancy rate may be very hard to realise when not all single-person trips are made by public transport. In addition, the combination of small vehicles with high occupancy rates is not very likely.

Adding the non-technological options results in an 80% energy reduction by 2050.

4.4. Implementing category 4 improvement options

Once all possible options to reduce the energy consumption of a given mobility demand are implemented, a reduction of $\sim 70\%$ by 2020 and $\sim 80\%$ by 2050 can be achieved. This means that halving the energy use by 2020 seems possible, but reducing the energy use by 90% by 2050 cannot be achieved with the options presented. To achieve a 90% energy reduction of passenger transport, the mobility demand per person should be halved. Several options could contribute to such a decrease; for example, changing spatial settings, reducing commuter travel or introducing telecommuting at home. Changes in activity patterns may also contribute to a reduction of the individual mobility demand. In addition, a shift to an increased use of soft modes is a possibility for reducing the energy consumption of transport.

5. Implementing growth of mobility demand

Next to the relative energy reduction potential, the absolute potential can be calculated. For doing so, scenarios should be used that describe developments in passenger mobility. Two scenarios are used, which are described in more detail in Ybema *et al.* (1997). The first scenario, called Rational Perspective (RP), is ecologically driven. New technologies can penetrate quickly due to a policy shift that facilitates implementation. Transportation growth is limited, and a shift to an increased use of public transport is assumed.

In the Market Drive (MD) scenario, the market mechanism allows new technologies to compete only in terms of price. Consumption grows more rapidly than in the RP scenario, as does the mobility demand. No modal shift changes are

Table 4. Effect of non-technological improvement options.

Set of options	2020	2050
Without non-technological options	37%	54%
With increased vehicle life (+ 2.5 year)	39%	56%
With 850 kg passenger car	46%	60%
With average occupancy of three passengers	68%	77%
Doubled public transport share	40%	57%
With all non-technological options combined	72%	80%
With all non-technological options except doubled public transport share	74%	81%

assumed. Table 5 gives an overview of the growth in mobility demand for the two scenarios.

With these mobility demand figures, the reduction percentage in 2020 and 2050 can be recalculated. Table 6 shows the results of these calculations for category 1 and 2 options. It shows calculations in which it is assumed that the fuel cell passenger car is totally penetrated by 2050. In 2020 this technology is not yet available. With an assumed average ERE= 1.7 MJ/MJ, the electric vehicle has a share of 70% of the total individual mobility supply. The increase in fuel economy is counteracted by the growth in mobility demand. With technological options, only a reduction of ~20% by 2050 is possible. The situation in 2020 about equals the situation in 1990, because all efficiency improvements are neutralized by the increased mobility demand.

In table 7, the non-technological options are also implemented. The most important non-technological options are the doubled occupancy rate and the 850 kg passenger car. A change in modal split is included in the scenarios. Table 7 shows the same effects as table 4. Because of the high occupancy of individual transport systems, the public systems score worse than the individual systems. Therefore, a

Table 5. Growth in mobility demand for two scenarios (1990= 100).

Mobility demand	Rational perspective		Market drive	
	2020	2050	2020	2050
Passenger car-km	142	190	175	240
Bus-km	181	328	135	182
Train-km	243	589	135	182
Total mobility demand	151	226	170	232

Schol and Ybema (1999).

Table 6. Reduction percentages compared with 1990 in 2020 and 2050 with category 1 and 2 improvement options and increased mobility demand.

Year	Rational Perspective		Market Drive	
	Energy use (EJ)	Change (1990= 100)	Energy use (EJ)	Change (1990= 100)
1990	6.8	100	6.8	100
2020	6.5	95	7.6	111
2050	5.3	77	5.5	81

Table 7. Reduction percentages compared with 1990 in 2020 and 2050 with category 1, 2 and 3 improvement options and increased mobility demand.

Year	Rational Perspective		Market Drive	
	Energy use (EJ)	Change (1990= 100)	Energy use (EJ)	Change (1990= 100)
1990	6.8	100	6.8	100
2020	3.2	46	3.4	50
2050	2.9	42	2.5	37

higher reduction potential is achieved in the MD scenario, in which a larger share of the transport demand is filled by individual transport systems, than in the RP scenario with the high public transport share. Once again, it should be noted that this high occupancy of individual systems is more realistic in a system with a large public transport share.

6. Discussion and conclusions

The calculations in this paper show considerable energy saving potentials within the transport system. With only technological options, a 50% reduction is possible by 2020 and a 60% reduction by 2050. When non-technical options are added, requiring major behavioural adaptations, an 80% reduction can be achieved by 2050.

The achieved high-energy consumption reduction in 2050 requires two changes of vehicle types. In the short-term, the shift will be made to the electric vehicle, while in the medium- and long-terms fuel cell vehicles will become the new standard. It is not very likely that in a 60-year span two major changes of vehicle type will occur.

The analysis is limited to motorized land transport. Passenger transport over water is scarce in Europe and does not contribute substantially to energy use for transport. Transportation by air is, however, more common, and it is expected to increase considerably. This may reduce the described reduction potential for the transport sector in general.

The analysis made in this paper may contribute to the current discussion of reduction factors. In current discussions about sustainability the reduction factor approach is often mentioned. The 50% reduction by 2020 calculated in this paper equals a factor 2 reduction, whereas the 90% reduction by 2050 equals a factor 10 reduction.

In the general discussion about sustainability other reduction factors are also proposed: factor 4, e.g. by the Wuppertal Institute (Weiszcker *et al.* 1997), to be realised by ~2025, and factor 20, proposed in the Dutch DTO program (DTO 1997), to be realised by the year 2040. The factor 4 is based on halving the energy consumption at a doubled welfare level; this requires a reduction of 75% in energy use per service. The calculations in this paper show that such a reduction is possible when introducing a number of non-technological options. Without these options, the maximum reduction is a factor 2.

The Dutch DTO investigates the possibility of a reduction by a factor 20 for 2040 with regard to environmental pollution. They also focus on the transport sector. Three strategies are presented to realise this far-reaching reduction: the introduction of renewable fuels, a new transport system and the introduction of an external drive system for vehicles. The introduction of renewable fuels comprises, for example, methanol derived from agricultural crops and wastes or hydrogen produced with photovoltaic electricity. The new transport system integrates individual and collective passenger transport means, while the development of an external drive system for vehicles reduces substantially the vehicle weight to be transported. The DTO study does not present a detailed implementation scenario and does not assess the relative contribution of each of these strategies, so a quantitative comparison of the DTO results with our findings is not possible. We suppose that the DTO strategies of a new transport system and external drive systems have about an equal effect (about factor 5) as the combination of options considered in this paper (such as a change of the modal split, a doubling of the occupancy rate and the introduction of

the small car and the fuel cell or electric car). As DTO focuses on environmental pollution, they probably assume an additional factor 4 reduction by means of renewable fuels to attain a total reduction of factor 20. Such a reduction implies a 75% transition to carbon-free energy sources and will have far reaching effects for the energy and agricultural systems.

This analysis of the transport sector reveals clearly that both energy and material options contribute to the total saving potential. Modifications in the car construction (originating from/affecting the material production sectors) such as the modified frame or the small passenger car offer a saving potential of $\sim 40\%$ by 2050. Modifications in the automotive system (originating from/affecting the energy production system) have a saving potential of the same magnitude. Options that make more efficient use of the transport system (such as doubling the occupancy rate) have the largest saving potential: $\sim 50\%$. To achieve the maximal saving potential in the transport sector, both material and energy options should be included in the analysis.

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