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Sustainable transport policies under scarcity of oil supply

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A strategic land-use–transport interaction model is used to investigate the impacts of policies in technology, infrastructure, pricing and regulation under different assumptions about energy supply. Six scenarios have been defined, analysing three policy strategies in two different contexts of energy supply—A, generally accepted energy supply forecast and B, worst-case energy supply forecast (scarcity of energy). Policies include: business as usual; investment in infrastructure and technology; and a demand regulation based approach involving changes in taxation and tolls. The paper assesses the impact and robustness of each policy against assumptions about future oil supply/demand. Our results demonstrate three key issues. First, scarcity of oil will accelerate the development and take-up of alternative fuel technologies; second, investment in alternative technologies alone will alleviate the impact of local emissions and reduce energy consumption per kilometre travelled but will only reduce yearly carbon dioxide (CO_2) emissions after a time lag of about 15 years; so that, third, some form of regulation of demand will be necessary to reduce total emissions and externalities caused by congestion. Research is required to define the necessary level of regulation in combination with technology investments. However, we suggest that a policy involving improvements in infrastructure coupled with investments in fuel technology and differentiated fuel taxes will be required in the future.

1. INTRODUCTION

The future framework of the transport system is intimately linked with the general energy supply of the future. The relatively cheap availability of petroleum oil has allowed the expansion of transport systems over the past hundred years. This relationship between energy supply and vehicle technology and the characteristics of the transport system is typified by the internal combustion system that powers much of the transport system. The wide availability of the fuel, its cheapness, and the relative simplicity of the engine itself and its storage requirements has meant that the transport system has facilitated an era of increased dispersion of activities with high levels of mobility for those with the means to purchase vehicles. The nature of fuel technology has been a major influence on the transport system and mobility patterns of today.

However, circumstances are changing. There is increasing concern over the environmental consequences of the fuel technology used and the future availability of the quantities of fuel required. Driven by these two issues a wide range of new or improved fuel technologies are being proposed and developed.

In response, the European Union has set out its main energy policy targets[1] to ensure the functioning of the energy market and the security of energy supply in the Union, and to promote energy efficiency and energy saving and the promotion of new and renewable forms of energy. In parallel, the Commission of the European Communities (COM) European Transport Policy[2] proposed four main priorities: (i) adjusting the balance between the different modes of transport; (ii) implementing the trans-European transport network; (iii) placing the user at the heart of transport policy; (iv) managing the effects of transport globalisation. The COM Green Paper[3] on energy supply established three major strategic priorities: (i) controlling the increase in demand; (ii) managing dependence on supply; (iii) ensuring that the internal energy market works well.

In order to support the achievement of the European objectives outlined above, the European Commission established several research priorities within the Sixth Framework Programme. The research presented here is based on the project Steps (Scenarios for the Transport system and Energy supply and their Potential effects), which is funded within the research priority ‘Sustainable Surface Transport’. In Steps, different scenarios for the transport system and energy supply of the future are developed. Different models on European and regional scales and a multi-criteria analysis are employed to compare and assess these scenarios. The results are translated into policy recommendations and needs for future research identified. In this paper we report results from one of the regional case studies conducted using a strategic model (Mars–Metropolitan Activity Relocation Simulator) of Edinburgh and its surrounding area. The following sections give an overview of the Mars model, describe the scenarios modelled, discuss the results and draw conclusions.

2. THE LAND-USE AND TRANSPORT INTERACTION MODEL MARS

Metropolitan Activity Relocation Simulator is an integrated strategic and dynamic land-use and transport interaction (LUTI) model. The basic underlying hypothesis of Mars is that settlements and activities within them are self-organising systems. Mars is thus based on the principles of systems dynamics[4] and synergetics.[5] The development of Mars started in the year 2000. An early version was described in 2002 in the *European Journal of Transport and Infrastructure Research*.[6] The model was developed further and Mars became its actual name within a PhD thesis.[7] Recently the model has been transferred to another software basis. The case study presented here is the first application of Mars in Vensim® (www.vensim.com).

Mars is usually implemented such that land-use is part of a dynamic system that is influenced by transport infrastructure rather than being constant. However, for this case study we use land-use scenarios where, under the demand regulation policy, strict controls on developments are imposed resulting in a compact city. Two person groups, one with and one without access to a private car are considered in the transport model. The transport model is broken down by commuting and non-commuting trips, including travel by non-motorised modes. Car speed in the Mars transport sub-model is volume and capacity dependent and hence not constant. The model forecasts the impacts of the transport and land-use policies over a period of 30 years.

For the case study presented here it was necessary to refine the energy consumption and emission sub-models of Mars. Speed-dependent specific emission factors by different vehicle categories are utilised.[8,9] The development of car ownership and vehicle fleet composition are outputs from the transport and energy models ASTRA (www.iww.uni-karlsruhe.de/ASTRA/astra_d3.pdf) and POLES,[10] which represent the impacts of transport policy, technology investments and oil prices on the fuel price and fleet composition at the European level.

To date, the Mars model has been applied to the following seven European case study cities: Edinburgh, Helsinki, Leeds, Madrid, Oslo, Stockholm and Vienna. Within the ongoing project Sparkle (Sustainability Planning for Asian cities making use of Research, Know-how and Lessons from Europe) Mars has been adapted and applied to the Asian cities of Ubon Ratchasthani in Thailand and Hanoi in Vietnam.[11] To test the validity of the Mars model assumptions, a model of Vienna with the base year 1981 was set up and the model results were compared with statistical data up to the year 2001.[7]

3. SCENARIO DEFINITION AND SIMULATION STRATEGY

The modelling of scenarios is needed to derive conclusions about the likely impacts of policies in the fields of technology, infrastructure, pricing and regulation under different assumptions about the evolution of energy supply. Six different scenarios have been defined by the Steps consortium, analysing three policy strategies in two different contexts of energy supply (Table 1). A0 is the reference scenario to which the results of the other scenarios will be compared.

The energy supply scenarios are basically represented by the oil price assumptions. The generally accepted supply forecast resulted in an increase in oil prices of 2% p.a. over the next 30 years while in the worst case prices are increased at 7% p.a. These increases were put through the energy model POLES which equilibrates demand and supply for various energy sectors in a world market model. The results of the POLES runs meant that the increases in oil prices were translated into increases in resource costs of fuel—that is, prior to any fuel duty or VAT changes of 1% and 4% p.a. over the next 30 years.

	Policy		
Energy supply assumption	Business as usual	Technology investments (infrastructure, alternative fuels, etc.)	Demand regulation (taxes, tolls, etc.)
Generally accepted energy supply forecast	A0	A1	A2
Worst-case energy supply forecast	B0	B1	B2

Table 1. Energy supply and policy scenarios as defined in the STEPs (Scenarios for the Transport system and Energy supply and their Potential effects) project

The policy-variable assumptions were derived from an analysis of current and future policy trends at both European and urban/regional scales. A summary of the scenario assumptions is given in Table 2. The policy variables at the regional level include bus priorities, bus speeds, fare changes, car ownership and operating costs including fuel taxes and cordon charges, telework rates and land-use planning restrictions. In addition there are other assumptions about technology improvements, energy use and emissions that affect how fleet composition develops over time. This has been modelled in more detail at the European level using interactions between the POLES/ASTRA models. The Edinburgh model Mars has taken the resulting fleet composition and emission factors from the POLES/ASTRA runs for each scenario. Fleet composition responds not only to the technology assumptions but also (to a lesser degree) to the other policy and scenario variables such as fuel price and car ownership costs.

The basic scenario variable is the resource cost of fuel—all ‘A’ scenarios have an increase of 1% p.a. while all ‘B’ scenarios have an increase of 4% p.a. (Fig. 1). The other policy variables for taxes, speeds and costs are the same for A1/B1 and A2/B2 scenarios, respectively. We notice that the basic scenario variable controlling the resource costs of fuel does not play such a significant role in the overall cost of fuel at the pump between the A and B scenarios. The pump price in B0/B1 is 38% higher than in A0/A1. On the other hand, the policy assumptions regarding fuel tax in A2/B2 result in 150% and 187% increases in total price compared to A0 respectively, with the difference between B2 and A2 only 15%. Thus the major driver of the cost of fuel at the pump appears to be the assumption on fuel tax increases rather than that on the resource cost of fuel. To reinforce the demand regulation, both A2 and B2 scenarios introduce road-user charging in the form of a cordon charge scheme (i.e. charging vehicles that enter a defined area), which increases to €5 by year 30. These charges are assumed to be applied all day.

Where things begin to differ between the scenarios is in the fleet composition (Fig. 2) and car ownership growth rates. The fleet composition changes over time in response to the fuel price and

Policy/scenario variable	Business as usual (A0/B0)	Technology investments (A1/B1)	Demand regulation (A2/B2)
Fuel resource cost	A0 +1% p.a. B0 +4% p.a.	As A0 As B0	As A0 As B0
Fuel tax	Petrol +0·7% p.a. Diesel +1·5% p.a.	As A0/B0	Petrol +4·7% p.a. Diesel +4·7% p.a.
Public transport speeds	+0·3% p.a.	+1·1% p.a. (peak) As A0/B0 (off-peak)	As A0/B0
Public transport fares	+0·8% p.a.	As A0/B0	–1·7% p.a.
Road pricing—double cordon	—	—	€2 rising to €5 by year 30
Teleworking	No change	As A0/B0	+0·3% p.a. work trips saved
Land-use controls on new developments	As in structure plan	As A0/B0	Compact city: new developments split 30/70/0 (CBD[§]/urban/extra urban)
Fleet shares derived from POLES/ASTRA (year 2030)	A0: 86/8·2/0·6/0·1/4·8[*] B0: 74/13·5/0·3/0·3/11·6	A1: 69/17/0·1/0/13·8 B1: 51/20/0·1/0/28·6	A2: 86/9/0·5/0·1/5·4 B2: 76/13·4/0·4/0·2/10·2
Car ownership growth rate[†]	A0: 1·20% p.a. B0: 1·12% p.a.	A1: 1·21% p.a. B1: 1·15% p.a.	A2: 1·02% p.a. B2: 0·76% p.a.
Energy use[‡]	Petrol –0·5% p.a. per km Diesel –1·0% p.a. per km	Petrol –2·0% p.a. per km Diesel –3·0% p.a. per km	As A0/B0
Emission factors[‡]	−8·1% p.a.	−16% p.a.	As A0/B0

[*] Share of conventional/hybrid/compressed natural gas/electric/hydrogen.

[†] The car ownership growth rate is based on UK TEMPRO (trip end model presentation program) projections for A0 and the relative changes in ownership rates from POLES/ASTRA are applied to the other scenarios.

[‡] The assumptions on costs of car ownership, energy use and emission factors were input to POLES/ASTRA; the fleet composition by class was then used as input to Mars, which affected not only composition but also fuel consumption rates and emission factors.

[§] Central Business District.

Table 2. Overview of scenario variables

other measures including investment in infrastructure for alternative vehicles under scenarios A1 and B1. These impacts are introduced into the Mars model directly by inputting the fleet composition from the POLES/ASTRA model runs for the given scenario. The share of conventional fuel is gradually reduced over time. The major differences occur for A1/B1, which are the scenarios for investment in technology (Fig. 2). A1 reduces the conventional fuel share from 86% to 69% and increases the share of hydrogen-powered vehicles threefold from 4·8% to 13·8%. The increased fuel costs in the B scenarios tend to accelerate the take-up of alternative fuels, with the hydrogen share being approximately double that of the corresponding A scenario. The effect of changes in fleet will be to reduce the cost of car use (albeit slightly) but in the main it will be to reduce emissions per km and energy use per km (Fig. 3).

In terms of public transport (PT) measures the main differences relative to A0/B0 are increased speeds in A1/B1 and fare reductions in A2/B2 (Fig. 4). However, as both improve PT, the relative differences between A1/B1 and A2/B2 will not be so marked.

In A0/B0 and A1/B1 any new land developments are in line with the Edinburgh structure plan, which leads to a rise in population in the urban and extra urban areas (Fig. 5). Under the demand regulation scenarios A2/B2 there is strict control on new developments and a compact city policy is adopted whereby all developments outside the urban area are forbidden and

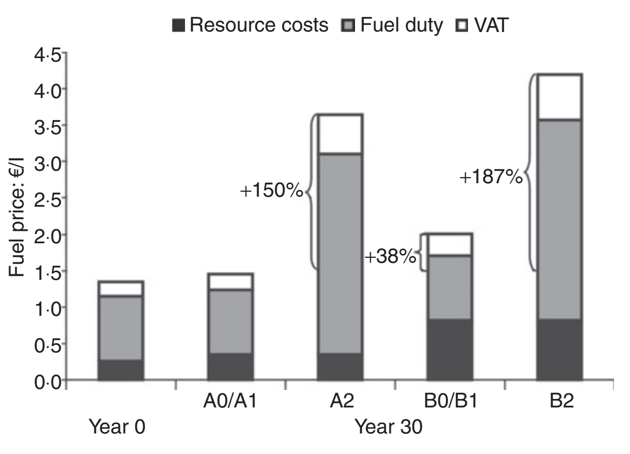

Fig. 1. Fuel price by scenario

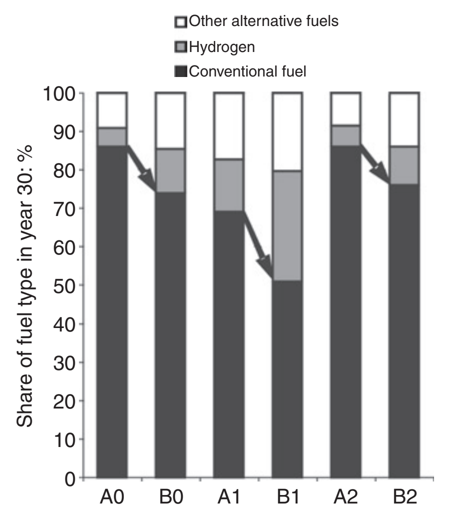

Fig. 2. Share of fuel types used in private cars in year 30

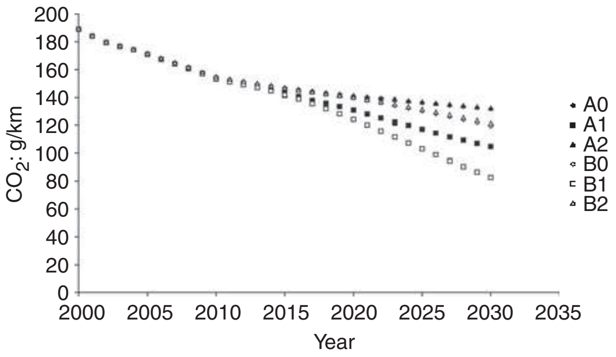

Fig. 3. Specific CO_2 emissions caused by changes in fleet composition

all new developments are assumed to be possible within the urban area—assuming greater use of brownfield developments. Finally, the assumption on telework affects the number of commuting trips in A2/B2—reducing them by 7·8% by year 30.

When describing the results we will be comparing across scenarios A0–A1–A2, B0–B1–B2 and between scenarios A0–B0, A1–B1 and A2–B2. First, the difference between A0–A1 and B0–B1 is expected to be small as the only differences are the peak speed for PT and the change in fleet composition, which includes a more fuel-efficient petrol and diesel fleet as well as a greater share of alternate fuel vehicles. Pairs A0–A2 and B0–B2 differ significantly in the costs of car use and, to some extent, in the cost of PT. Thus we can expect a significant shift between modes. The differences in fleet composition are minimal.

Comparing scenarios A0–B0, the only differences are in the cost of fuel at the pump (increased by 38% (Fig. 1)) and the increased share of hydrogen fuels (tripled (Fig. 2)). The relative differences between A1 and B1 are similar to those between A0 and B0. We can expect similar relative shifts. The differences between B2 and A2 are a 15% increase in fuel costs (Fig. 1) and a doubling of the share of hydrogen fuels in the fleet (Fig. 2). Thus we can expect quite similar results for A2 and B2. At first sight this is surprising but is mainly due to the policy assumption on fuel taxes that dominate the increase in fuel costs.

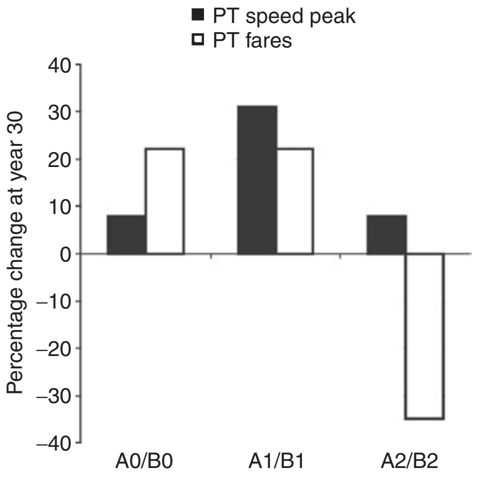

Fig. 4. Changes in public transport at year 30

4. IMPACTS OF THE SCENARIOS

4.1. Process indicators

A list of process indicators was set out in Steps. Here we look only at a small selection of these indicators: the development of the share of private cars; PT and slow mode (bicycle and walking) trips; average car speed; transport costs per trip; and revenues generated by fuel tax.

Figure 6 shows the modal share trajectories for private car by scenario over the 30-year evaluation period. As expected, the impact on modal share can be viewed in pairs of scenarios. Obviously the demand regulation scenarios A2/B2 have the greatest impact on car use due to the significant increases in costs for car use compared with the other scenarios. Similarly, A0/A1 and B0/B1 are paired together and the relative changes are small within these pairings as expected.

In the business as usual (BAU) case A0 there is a trend to more car use in both the peak and off-peak periods. This trend is the same for B0—the greater increase in resource cost of fuel has little impact on modal shares. The technology scenarios A1/B1 have no significant impact on modal share—if anything the more fuel-efficient fleet encourages more car use in the off-peak period. As expected, the demand regulation scenarios A2/B2 have a significant impact on modal shares, reducing car share from 56% to 45% in the peak and from 66% to 52% in the off-peak with increases in both PT and slow modal shares.

Figure 7 shows the development of the average car speed during the peak period. Peak speed decreases continuously in both the BAU scenarios (A0, B0) and the technology investment scenarios (A1, B1). Average speed is around 25% lower in year 30 than in year 0—that is, the level of congestion during the peak period is increased. On the other hand, average car speed stays more or less constant in the demand regulation policy scenarios (A2/B2)—that is, the level of congestion stays more or less the same during the evaluation period.

Figure 8 shows the trajectory of the average car costs per trip. The lower costs for car use in A1/B1 are due to increased fuel efficiency and a move towards alternative fuels. This results in lower costs per km in year 30 than in year 1, cancelling out any tax and oil price increases. The effect is more marked for the peak periods, which suggests the efficiency gains are speed dependent and so the congested peak benefits more than the uncongested off-peak.

The regulation scenarios A2/B2 increase costs for car use by 100% on a per km basis but, because of the land-use and distribution effects, the average increase per trip is around 80–90%. Basically these changes in costs per trip or per km for cars help explain the modal shifts above. The PT costs are also reduced significantly by year 30 with the fare reduction policy in A2/B2.

Figure 9 shows the changes in fuel tax revenues over time for each scenario. Revenue is obviously affected by the growth in fuel taxes and the VAT element, which depends on resource cost and fuel duty levels. It is also dependent on overall demand and the shift to other modes and to alternate vehicles. The BAU scenario sees revenue increase by 22% over the 30-year period. The regulation scenarios A2/B2 stand out as they increase the tax

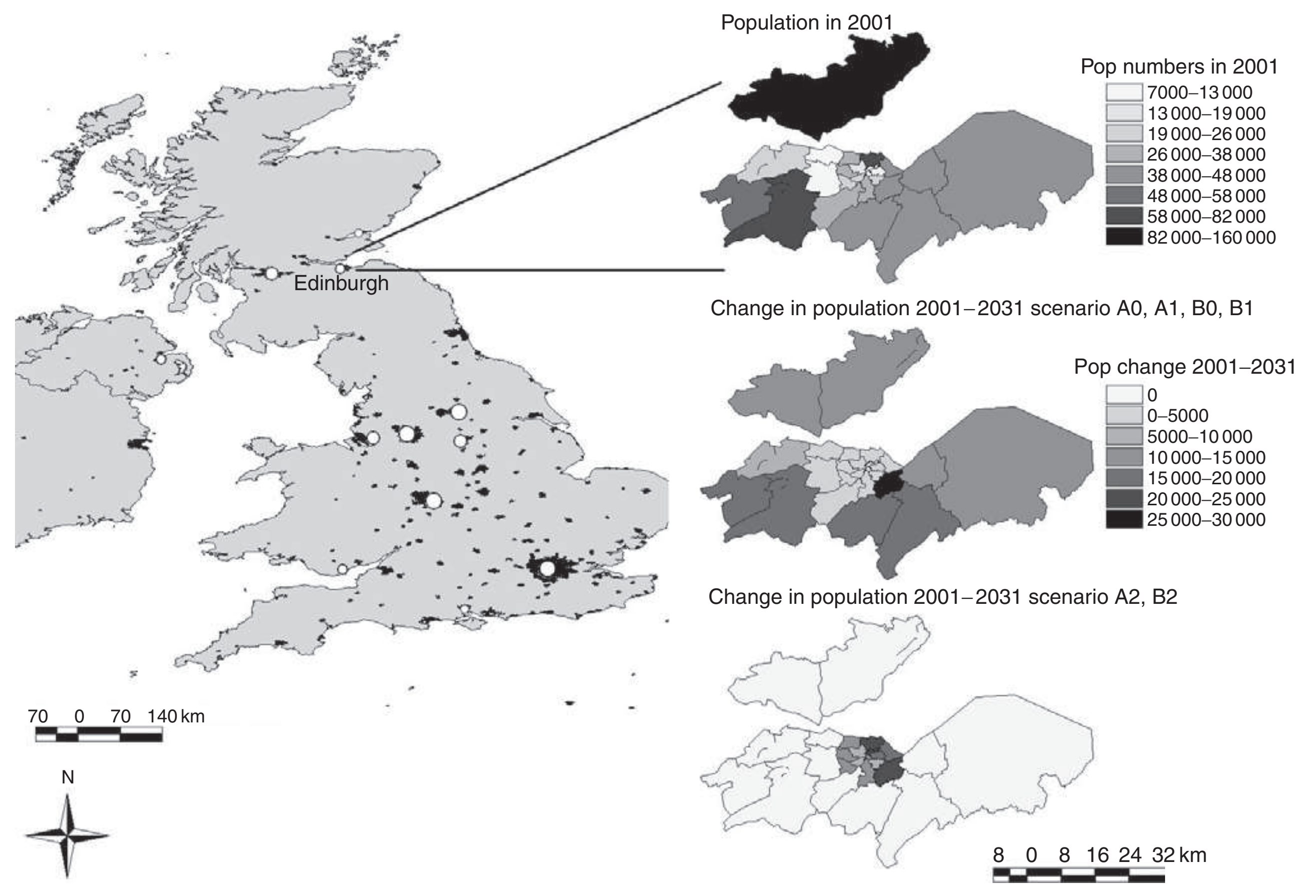

Fig. 5. Land-use population scenarios

revenue significantly—both more than double the tax take compared to the BAU case. It should be noted that scenario A2 increases the revenue take more than in B2 as the proportion of tax to pump price is higher. Conversely, the technology scenarios and B0 result in a reduction in fuel tax revenues compared to A0. For A1 this is due to the more efficient fleet and lower taxes assumed on alternative vehicles. For B0/B1 there is the combined effect of a more fuel-efficient fleet, higher prices for fuel (thus reducing demand) and the shift to alternative vehicles.

4.2. Indicators for a multi-criteria analysis

This section discusses the performance of the scenarios against a set of outcome indicators to be used in a multi-criteria analysis. Here we look at total energy consumption in tons of oil equivalent, carbon dioxide (CO_2) emissions per person km, total CO_2 emissions, local nitrous oxide (NO_X) emissions, local particulate matter (PM) emissions, noise costs and the number of people injured in traffic accidents. The social and economic impacts are not assessed at this regional level but are considered within the European level models which then feed down to our regional models via the assumption in car ownership and changes in fleet composition. NO_X and PM emissions were calculated from pump to wheel as they impact on the local population; emissions from the production of fuel are not considered. For CO_2 we consider well to wheel impacts as it has a global impact—that is, emissions from the production of fuel *are* considered. Table 3 gives an overview of the results.

Total energy in tons of oil equivalent (toe) is reduced by around 22% over time in the BAU case (scenarios A0/B0) due to

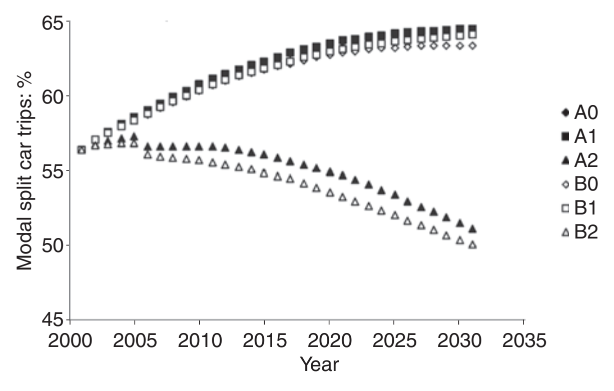

Fig. 6. Car trip modal share trajectory

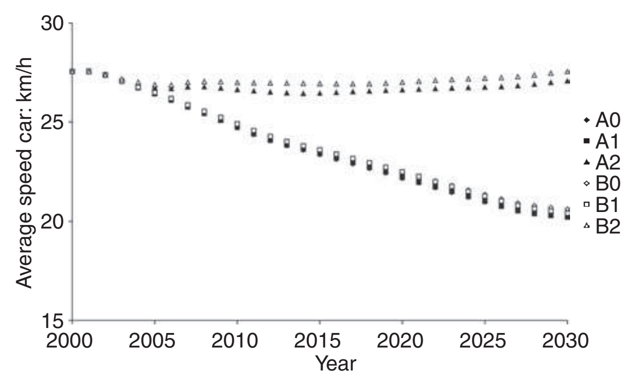

Fig. 7. Trajectory of average car speed during peak periods

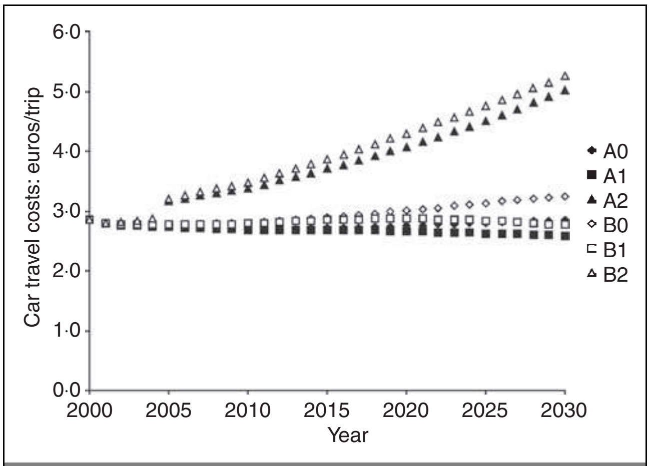

Fig. 8. Trajectory of car travel costs in peak periods

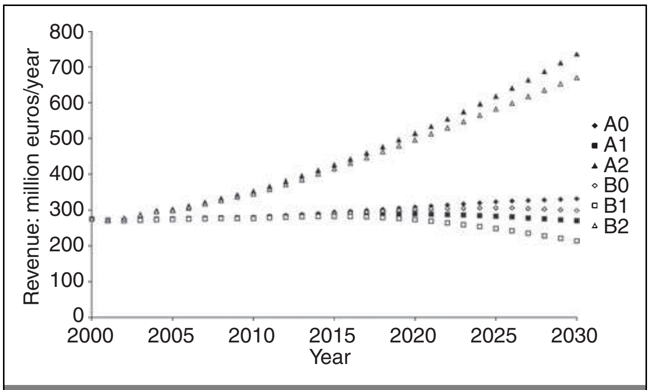

Fig. 9. Trajectory of revenues generated by fuel tax

improvements in vehicle technology for both conventional and alternative vehicles. The technology scenarios (A1/B1) decrease total energy used compared to A0/B0 in year 30 by 16·4% and 22·4%, respectively. The demand regulation scenarios (A2/B2) decrease total energy use by 4·4% and 3·9% for A2/B2, respectively while the induced shift away from car use and shorter trip lengths due to compact land use means a greater reduction in energy used per trip. In terms of energy indicators the technology policies (A1/B1) are more effective than the demand regulation policies (A2/B2).

CO_2 emissions per person km are reduced by around 18% over the 30-year period despite the increase in car use in the BAU case (A0/B0). This is due to improved technologies and the shift from conventional vehicles. The developments in the fleet will also reduce well-to-wheel total CO_2 emissions but the decrease is only 2·7% over the next 30 years, which is well below the national target to reduce emissions by 20% based on 1990 levels by 2010.[12] Regulation (A2/B2) and technology (A1/B1) scenarios both reduce CO_2 per person-km even further, the technology policies being more effective on a per km basis. In terms of *total CO_2 emissions* the regulation scenario (A2/B2) outperforms the technology scenario (A1/B1) for both A and B scenarios (Fig. 10).

NO_X emissions are reduced by two-thirds by year 10 for all scenarios. This is due to technological improvements that are already in the pipeline. It then becomes a question of how much further NO_X can be reduced by year 30. Accelerating the investment in technology under scenario B1 reduces NO_X emissions by 27·7% compared to B0 in year 30; this is due to the high proportion of hydrogen-powered vehicles expected in use by 2030.

	Total energy: toe/year	Energy: toe/million trips	CO_2 emissions: g per person-km	CO_2 emissions well to wheel: mio. t/year	PM emissions pump to wheel: t/year	NO_X emissions pump to wheel: t/year	Noise cost: mio. €/year	Number of injured persons
Year 0								
All	461·5	0·43	101·1	1·12	126·0	4482	0·93	1694
Year 30								
A0	358·2	0·30	82·3	1·09	53·4	916	1·09	2015
A1	299·4	0·25	69·1	0·93	43·7	743	1·11	2046
A2	342·4	0·26	70·6	0·84	40·2	703	0·92	1681
B0	345·8	0·29	78·6	1·04	46·5	797	1·09	2002
B1	268·3	0·23	61·6	0·83	33·7	577	1·11	2042
B2	332·3	0·25	67·6	0·80	35·5	622	0·91	1660
Percentage change from year 0								
A0	−22·4	−30·2	−18·6	−2·7	−57·6	−79·6	17·2	18·9
A1	−35·1	−41·9	−31·7	−17·0	−65·3	−83·4	19·4	20·8
A2	−25·8	−39·5	−30·2	−25·0	−68·1	−84·3	−1·1	−0·8
B0	−25·1	−32·6	−22·3	−7·1	−63·1	−82·2	17·2	18·2
B1	−41·9	−47·5	−39·1	−25·9	−73·3	−87·1	19·1	20·5
B2	−28·0	−41·9	−33·1	−28·6	−71·8	−86·1	−2·2	−2·0
Percentage change from BAU A0/B0								
A1	−16·4	−16·7	−16·0	−14·7	−18·2	−18·9	1·8	1·5
A2	−4·4	−13·3	−14·2	−22·9	−24·7	−23·3	−15·6	−16·6
B1	−22·4	−22·1	−21·6	−20·2	−27·5	−27·7	1·7	2·0
B2	−3·9	−13·8	−14·0	−23·1	−23·7	−22·0	−16·5	−17·1
Percentage change from BAU A0								
B0	−3·5	−3·3	−4·5	−4·6	−12·9	−13·0	0·0	−0·6

Table 3. Multi-criteria analysis outcome indicators year 0 and year 30 with relative changes as percentages

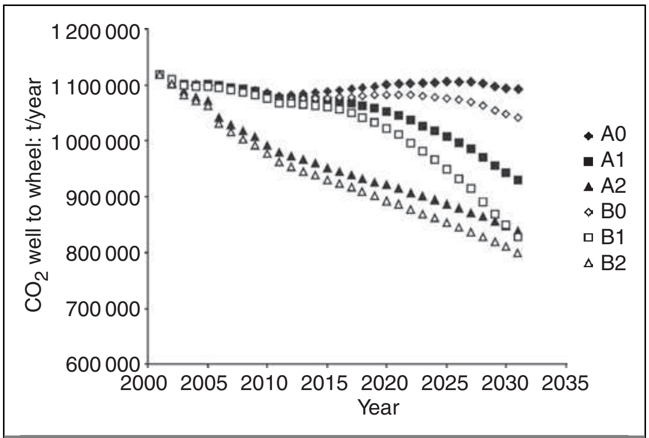

Fig. 10. Total CO_2 emitted (well to wheel) per year

The trajectories for *PM emissions* all show a marked decline around year 10 due to the introduction of EURO V standards. (Note: to date no definition for the EURO V standard exists. It was assumed here that the change from EURO IV to EURO V results in the same percentage of emission reduction as the change from EURO III to EURO IV[8].) PM emissions are reduced by 58% in the BAU case despite increased car kilometres. Further reductions are possible with investment in technology and/or by demand regulation. These reductions are really the icing on the cake as there is significant progress being made in the BAU case.

The case study uses speed-dependent specific noise costs per kilometre.[13] In the current version of the model, potential improvements in vehicle, tyre and road technology are not considered. *Noise costs* increase by 17% in the BAU case but can be reduced to current levels under the demand regulation scenarios (A2/B2). Similarly the *number of persons injured in traffic accidents* increases by 19% under the BAU (A0/B0) and technology scenarios (A1/B1) but is limited to current levels by the demand regulation policies (A2/B2).

5. COMPARISON BETWEEN SCENARIOS

In order to assess the impact of the scenarios/policies first of all we compare changes relative to A0/B0 by year 30. In terms of total energy consumption the investment in technology scenarios (A1/B1) outperforms the demand regulation scenarios (A2/B2). On the other hand, the demand regulation policy (A2/B2) brings a greater reduction in total CO_2 emissions than the technology policy (A1/B1) under both A and B scenarios. Local pollutants are reduced further with the demand regulation policy under the A scenario but the converse is true under the B scenario. This is due to the high proportion of hydrogen fuel cell technology used under B1, due to increased resource costs. This type of result is difficult to deal with as the effect of the policies is not uniform for all indicators. The technology policy scenario (A1/B1) has an adverse impact on noise and accidents, whereas the demand regulation policy (A2/B2) reduces these to below start-year values.

The increase in resource costs of fuel between scenarios A and B obviously has an impact on the demand for car use but also on the development of the fleet over time. Nevertheless, the changes in energy and CO_2 indicators are relatively small, being around 3–4% lower than in the optimistic A scenarios. There are greater reductions in local pollutants, which are a result of reduced demand and an improved fleet—that is, moving more quickly to hydrogen fuel.

6. CONCLUSIONS

It seems that the scenario variable used to reflect the scarcity of oil supplies in the future, namely the resource cost of fuel, has little impact on the outcome indicators and hence on our policy conclusions. This is not so surprising when we analyse the impact on pump price of fuel between, say, scenarios A2 and B2. The pump price of fuel under scenario B2 is only 15% higher in 2030 than under A2 (€4·19/litre compared with €3·64/litre). The dominating factor seems to be fuel tax (and VAT) in both demand regulation scenarios A2/B2. As fuel cost is only one component of the generalised cost of car use, then this relatively small difference arising from assumptions in oil price means that we may expect similar behavioural responses for A2 and B2. One area where the oil price assumption does affect the scenarios is in the fleet composition over time—it appears that higher resource costs of fuel accelerate the move towards the use of hydrogen fuel cell technologies.

In terms of policy recommendations, it appears from the analysis of the Steps process and outcome indicators that, in general, demand regulation is a more effective policy than the technology policy in terms of reducing total CO_2 emissions, car use and hence congestion. However, the technology policies are more effective in reducing total energy used and under the worst-case scenario B the technology policy also decreases local emissions further than the demand regulation policy.

Although the demand regulation policy appears to be better from an outcome point of view there is a price to pay both politically and by the users of the system. Basically, the charges imposed on car use via fuel tax increases and road-user charges impose significant costs on car use, which brings (in time) benefits and significant revenue streams for governments. The fuel tax element tends to dominate the results here and we have not tested whether such levels are economically efficient via a more traditional cost–benefit analysis. Finally, we can conclude the following.

- Both technological investment and demand regulation play an effective role in reducing environmental externalities, although we expect a certain level of reduction from technology developments that are already in the pipeline. This is based on the fact that in the BAU case there are significant reductions in energy used and local emissions (in terms of pump to wheel at least).
- Demand regulation reduces the externalities associated with congestion whereas technology investments do not. However, we have not shown whether this level of regulation is efficient; other EU projects are working on the issue of optimal levels of demand regulation.
- Both technology and demand regulation can reduce total CO_2 emitted significantly but it will require some combined policy to reduce the levels to meet the national target of a 20% reduction by 2010 based on 1990 levels.[12]
- Increased resource costs have two effects: first, they act to suppress demand for car use; second, they lead towards a more efficient vehicle fleet and the use of alternative fuel technologies. Thus it would seem logical that as resource costs rise, the demand regulation policy could be weakened while

still reducing congestion to the same levels as under A2. It should be noted that the UK Government recently deferred a proposed increase in fuel duty due to recent rises in the cost of fuel. This appears to be a short-term response but demonstrates the fact that it is the overall pump price that is relevant to users and hence to the political will to implement the demand regulation policy required to meet the objective of reducing car use.

- In terms of whether to accelerate the development in fleet technologies through a direct investment policy, we cannot say whether this is cost-effective from our tests. We can, however, see that they can be effective in terms of reducing energy use and local emissions.
- Finally, both types of policy have implications for civil engineering projects. At the European level there should be investments in Trans-European Networks[14] for both road and rail sectors, while at the urban level there should be more light rapid transit or bus-based improvements (see Table 2). Under the demand regulation policy there should also be road pricing related infrastructure but this would depend on the type of system envisaged at local/national levels.

Within the work presented here it was not possible to estimate and compare the costs of technology and demand policies. Thus it was not possible to assess the economic efficiency of the different policies. Instead we analysed the policies in terms of their impacts on sustainability, concentrating on the changes in outcomes related to energy use, emissions, congestion and safety. While this brings us to the rather simplistic conclusion that both investment in new technologies and demand regulation are required to increase sustainability overall, we have not been able to demonstrate what would constitute the optimal combination of technology and demand policies. We recommend these issues are investigated in future research.

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