STRATEGIC MODELLING OF TRANSPORT AND ENERGY SCENARIOS

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0 INTRODUCTION

Given the complex interrelation of transport with other systems such as society, economy or environment, modelling of the transport system at a strategic level is a complex task. It is necessary to consider medium and long term horizons, dealing with both primary and secondary effects of transport policies to get a complete picture of the changes induced in mobility and other sectors.

In recent years there have been a growing number of applications of System Dynamics Modelling in the transport sector (see Christidis et. al. 2003; Fiorello et al., 2004; Fiorello and Martino, 2006; Monzón and Nuijten, 2006; Schade, 2005; Shepherd and Pfaffenbichler, 2006). In conventional transport models, analysis is often restricted to the interaction of mobility demand and transport supply. The System Dynamics approach allows the representation of complex linkages among various systems such as transport, environment and the economy, thus extending the focus of the analysis. The approach has a huge potential to explore sustainable paths, accounting for the development of the results through the years and the generated feedback effects.

This paper presents the application of two different strategic System Dynamics models in the STEPs (Scenarios for the Transport System and Energy Supply and their Potential Effects) project, which was part of the 6th Framework Programme of Research of the European Commission DG RTD. The STEPs project had the objective to develop, compare and assess possible scenarios for the transport system and energy supply of the future taking into account the effects on the environment and economic and social viability.
The two strategic models discussed in this paper operate at different levels: the ASTRA model (IWW et al., 2000) is a European one, while the scope of the MARS model (Pfaffenbichler, 2003) covers the metropolitan area of Edinburgh. Both models have been developed in the course of co-funded European research projects during the last few years.

This paper consists of four further sections, the next section discusses the systems dynamics approach in general, section two gives a brief overview of the two models, while section three presents results and section four draws conclusions.

1 THE SYSTEM DYNAMICS APPROACH

1.1 Theoretical background

System Dynamics is an academic discipline created in the 1960s by Jay W. Forrester of the Massachusetts Institute of Technology (Forrester, 1995). System Dynamics was originally rooted in the management and engineering sciences, although has gradually developed into a tool useful in the analysis of social, economic, physical, chemical, biological, and ecological systems. A dynamic system is a system in which the variables interact to stimulate changes over time. System Dynamics can be defined as a methodology used to understand how complex systems change over time.

A central concept in System Dynamics, which makes significant the analysis of the evolution of a system through time, is the concept of feedback. Feedback is the process through which a signal travels through a chain of causal relations to re-affect itself. Feedback is positive if an increase in a variable, after a delay, leads to a further increase in the same variable. On the other hand, feedback is negative if an increase in a variable eventually leads to a decrease in the variable itself.

An example of a positive feedback system is represented in figure 1. The more one smokes, the more addicted one becomes to nicotine, developing a need for more cigarettes. The “need” caused them to smoke even more, which produced an even stronger “need” to smoke. The reinforcing behaviour in the addiction process is characteristic of positive feedback.
Instead, negative feedback negates change and stabilizes systems. For instance a child who learns to ride a bicycle is using a negative feedback process: when the bike sways too much to the left, the child corrects by swaying to the right, and then when the bicycle sways too much to the right, he compensates again by swaying to the left. Negative feedback loops are balancing and stabilizing.

The construction of System Dynamics models assumes that the behaviour of systems is primary determined by its feedback mechanisms. Dynamic processes and feedback effects need mathematical relationships like differential equations and integration over time to be modelled, but actually, the mathematical aspects often remain hidden in the development of a system Dynamics model, as dedicated software allows the structure of the model and the linkages between variables to be defined using intuitive graphical interfaces. The modeller can concentrate on the conceptual aspects while the software solves the difference equation system.

In brief, the System Dynamics is a way of examining problems and not a theory or a model in itself. An interesting feature of this approach is that it is not constrained within any specific theoretical approach. There are considerable degrees of freedom concerning the variables to be used as well as the mathematical relationships among them. This makes System Dynamic modelling a very flexible methodology, which can be applied to a wide range of issues. This paper deals with the application of System Dynamics to the analysis of transport systems and their links with the economy and the environment.

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2 THE TWO MODELS AND THEIR CHARACTERISTICS

2.1 The ASTRA model

The ASTRA model is a System Dynamics model at the European scale focused on describing the linkages between transport, economy and environment. The model has been developed in the last years from the original version built in the ASTRA project (IWW et al., 2000) and updated within the TIPMAC project (Cambridge Econometrics et al., 2003) and, recently in the LOTSE study (IWW, TRT, 2004). ASTRA is implemented in Vensim®, a System Dynamics programming environment.

2.1.1 Overview of the model

The ASTRA model consists of eight main modules: Population Module (POP), Macro-economic Module (MAC), Regional Economic Module (REM), Foreign Trade Module (FOT), Transport Module (TRA), Environment Module (ENV), Vehicle Fleet Module (VFT) and Welfare Measurement Module (WEM). A number of feedback effects can be identified in the model: the following figure 2 shows the interrelationships between the eight ASTRA modules, highlighting the major output variables coming from, and input variables going into, the modules. Herewith an essential description of the modules is provided:

- The Population Module (POP) provides the population development for each modelled country with one-year age cohorts. The model depends on exogenous factors like fertility rates, death rates, infant mortality rates and migration.

- Five major elements constitute the Macro-economic Module (MAC). First, the sectoral interchange model reflects the economic interactions between 25 economic sectors of the national economies by an Input-Output table structure. Second, the demand side model depicts the four major components of final demand: consumption, investments, exports-imports (which is modelled in detail in the foreign trade module) and the government consumption. Third, the supply side model has as basic element a production function of Cobb-Douglas type calculating potential output incorporating three major production factors: labour supply, capital stock and natural resources; technical progress is considered under the form of Total Factor Productivity (TFP), endogenised as depending on sectoral investments, freight transport time-savings and labour productivity changes. The fourth element of MAC consists in the employment model that is based on value-added as output from input-output table calculations and labour productivity. The fifth element describes government behaviour.
- The Regional Economic Module (REM) mainly provides the generation of freight transport volume and passenger trips (see paragraph 2.1.2). The number of passenger trips is driven by the employment situation, the car-ownership situation and the number of people belonging to different age classes. Domestic freight transport depends on output by sector that is translated into flows for the fifteen sectors, which produce goods by means of value-to-volume ratios.

- In the foreign trade module (FOT) trades are mainly driven by relative productivity between modelled countries (or between the modelled countries and the rest-of-the-world), GDP growth of importing country and world GDP growth, as external factors to trade. Additionally, the INTRA-EU trade flows depend on the development of averaged generalized cost of transport between each O/D country pair.

- The major input of the Transport Module (TRA) is the link based transport demand for passenger and freight transport. Using transport costs and transport time matrices, the transport module calculates the modal split based on a classical Logit functions depending on generalised costs.

- The Environment module (ENV) uses the vehicle-kilometres-travelled generated by the TRA module and the information from the vehicle fleet model on the vehicle categories and emission standards to calculate the
most important transport emissions - CO$_2$, NO$_x$ and soot particles as well as fuel consumption and fuel tax revenues. Furthermore, accident rates for each mode form the input to calculate the number of accidents in the European countries.

- The Vehicle Fleet Module (VFT) calculates the vehicle fleet composition for all road modes. Vehicle fleets are differentiated into different age classes based on one-year-age cohorts and into different emission standard categories. Additionally, the car vehicle fleet is differentiated into gasoline and diesel powered cars with different cubic capacity categories.

- Finally, in the Welfare Measurement Module (WEM) major macroeconomic, environmental and social indicators can be compared and analysed.

*Figure 3 Links between the transport sector and the economy in the ASTRA model*
One of the main features of the ASTRA model is that all main variables describing the state and the development of various systems are endogenous. In general, main input concerns basic parameters, like trip rates, transport costs, transport times, emission factors, vehicle occupancy factors, volume-to-value ratios, labour productivity, etc. Figure 3 shows as one example, how main economic variables like GDP and main transport variables like vehicle-kms travelled are linked together via a complex chain including several feedbacks.

2.1.2 The ASTRA zoning system

The zoning system used in ASTRA is a non-ordinary one, as two different spatial categorisations co-exist. The reason for this double segmentation is that it allows to simulate relevant features of different region types and, at the same time, keeping the spatial description within a level of complexity consistent to the macro level of analysis used in the model.

The first categorisation is based on the countries. The ASTRA model covers the EU25 member states plus Bulgaria, Norway, Romania and Switzerland. The second categorisation is founded on the system of European NUTS II zones that are grouped into four functional zones according to their settlement patterns and population densities: Metropolitan Areas (MPA); High Density Areas (HDA); Medium Density Areas (MDA); Low Density Areas (LDA). Functional zones are “nested” into each European country. This means that up to 4 functional zones exist in every country (see figure 4).

As functional zones do not have a real geographical meaning, distance bands for trips are defined in order to correctly take into account the distance factor in the modal split. Therefore, a specific origin/destination trip within ASTRA is defined from one functional zone of country A to another functional zone of country B for a given distance band.
Figure 4 The zoning system of the ASTRA model

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2.2 The MARS model

MARS is a dynamic Land Use and Transport Integrated (LUTI) model. The basic underlying hypothesis of MARS is that settlements and activities within them are self organizing systems. Therefore MARS is based on the principles of Systems Dynamics (Forrester, 1995, Sterman, 2000) and synergetics (Haken, 1983). The development of MARS started some 10 years ago partly funded by a series of EU-research projects (OPTIMA, FATIMA, PROSPECTS, SPARKLE). To date MARS has been applied to seven European cities (Edinburgh - UK, Helsinki - FIN, Leeds - UK, Madrid -ESP, Oslo - NOR, Stockholm – S, and Vienna – A) and 3 Asian cities (Chiang Mai and Ubon Ratchathani in Thailand and Hanoi in Vietnam).

Figure 5. Basic structure of the MARS sub-models

The present version of MARS is implemented in Vensim®, a System Dynamics programming environment. The MARS model includes a transport model which simulates the travel behaviour of the population related to their housing and workplace location, a housing development model, a household location choice model, a workplace development model, a workplace location choice model, as well as a fuel consumption and emission model. All these models are interconnected with each other and the major interrelations are shown in figure 5. The sub-models are run iteratively over a period of time of 30 years. They are on the one hand linked by accessibility as output of the transport model and input into the land use model and on the other hand by the population and workplace distribution as output of the land use model and
input into the transport model. The next section describes the main cause effect relations in a qualitative way.

2.2.1 Main cause effect relations

This section uses the Causal Loop Diagram (CLD) technique to explain two of the core sub-models of MARS namely the transport model and the land use development model. Figure 6 shows the CLD for the factors which affect the number of commute trips taken by car from one zone to another. From figure 6 we start with loop B1 which is a balancing feedback loop, commute trips by car increase as the attractiveness by car increases which in turn increases the search time for a parking space which then decreases the attractiveness of car use – hence the balancing nature of the loop. Loop B2 represents the effect of congestion – as trips by car increase speeds decrease, times increase and so attractiveness is decreased. Loop B3 shows the impact on fuel costs, in our urban case as speeds increase fuel consumption is decreased – again we have a balancing feedback.

Loop B4 represents the effect of congestion on other modes and is actually a reinforcing loop – as trips by car increase, speeds by car and public transport decrease which increases costs by other modes and all other things equal would lead to a further increase in attractiveness by car. The other elements on figure 6 show the key drivers of attractiveness by car for commuting. These include car availability, attractiveness of the zone relative to others which is driven by the number of workplaces and population. The employed population drives the total number of commute trips and within MARS the total time spent commuting influences the time left for other non-commute trips. Similar CLDs could be drawn for other modes and for non-commute trips as MARS works on a self-replicating principle applying the same gravity approach to all sub-models.

Figure 7 shows the CLD for the development of housing in MARS. Loop H1 is a balancing feedback loop which shows that the attractiveness to the developer to develop in a given zone is determined by the rent which can be achieved. The level of the rent is driven by the excess demand for housing which in turn is related to the housing stock and new housing developments. As new houses are developed the stock is increased which reduces the excess demand which then reduces the rent achievable which reduces the attractiveness to develop – hence we have a balancing loop. Loop H2 is a reinforcing loop as new housing reduces the excess demand which reduces rent and hence land price which in turn makes development more attractive all other things being equal. Loop H3 represents the restriction of land available for development as land available is reduced then the attractiveness to develop is reduced. Loop H4 extends H3 to represent the effect of land availability on land price. Finally the drivers of demand for housing are shown
to be population, amount of green space and accessibility to activities from that zone.

*Figure 6. CLD for the transport model – commute trips by car in MARS*

*Figure 7. CLD for development of housing in MARS*
3 THE APPLICATION OF THE MODELS IN THE STEPS PROJECT

3.1 Objectives

The STEPs project had the objective of developing, comparing and assessing possible scenarios for the transport system and energy supply of the future taking into account the state of the art of relevant research within and outside the 6th RTD Framework (Monzón and Nuijten, 2006). STEPs has chosen a two-way approach, combining research, assessment, modelling and forecasting activities with co-ordination and dissemination activities.

3.2 The STEPs scenarios

The development of alternative scenarios was based on a literature review and analysis of current trends across Europe and beyond for energy supply, (STEPS, 2005). The objective was to explore a number of plausible scenarios for the transport system and energy supply of the future, taking into account both exogenous elements (e.g. economic growth, oil resources, technology developments) and policy measures.

Using this framework, eight different modelling scenarios were defined by crossing two policy strategies in two contexts of future energy supply until the year 2030. From the point of view of energy availability, two groups of scenarios were identified:

- “A” Scenarios: based on a generally accepted energy supply forecast, where it is assumed that oil price is to increase 2% per year on average.
- “B” Scenarios: based on the assumption of energy scarcity i.e. oil price is assumed to increase 7% per year on average.

At the same time, two contrasting policy strategies were considered:

- Policy strategy 1 (Technology investment), concentrating on investments in infrastructure, technologies (i.e. improving energy efficiency, supporting innovative vehicles) and in skills and knowledge and production capacity of alternative fuels and rolling stock.
- Policy strategy 2 (Demand regulation), focussed on passenger and freight demand management measures aimed at reducing the need to travel, reducing trip lengths, shifting demand to public modes, etc.

As a reference, the Business as Usual cases (labelled as ‘Scenarios 0’), where only a limited number of policy measures (consistent with current transport and energy policy) were explored. In addition a case where no action is taken at all, No-Policy alternatives (‘Scenarios -1’) was added. The final result is a matrix of eight alternative scenarios, as illustrated by Table 1.
Table 1 STEPS modelled scenarios

<table>
<thead>
<tr>
<th>Energy supply</th>
<th>Energy demand</th>
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<tbody>
<tr>
<td></td>
<td>No policies (-1)</td>
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<tr>
<td></td>
<td>Business as usual (0)</td>
</tr>
<tr>
<td></td>
<td>Technology investments (1)</td>
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<tr>
<td></td>
<td>Demand regulation (2)</td>
</tr>
<tr>
<td>Low oil price growth (A)</td>
<td>A-1</td>
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<tr>
<td></td>
<td>A0</td>
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<td></td>
<td>A1</td>
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<td>High oil price growth (B)</td>
<td>B-1</td>
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<td></td>
<td>B1</td>
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<td>B2</td>
</tr>
</tbody>
</table>

Source: STEPs Deliverable D4.2

The quantification of the different scenarios (i.e. the values assumed for each key input variable) was defined as yearly variations in relation to the base year values for the following sectors: fuel cost, other transport costs, non-road transport, traffic calming, spatial and transport energy.

3.3 The modelling system

The ASTRA and the MARS model were just two of several modelling tools used in the STEPs project in order to simulate the scenarios and to provide quantitative responses on the effects of such scenarios on various respects. Two other European models – the SASI socio-economic model and the POLES energy model – helped to provide a wide range of responses about how changes on the transport side affect the economy. At the regional scale, the Edinburgh MARS model was run in parallel with models of Dortmund, South Tyrol, Helsinki and Brussels.

The definition of the scenarios was based on oil price as this is the primary variable, which drives the cost of all fossil fuels. It was the energy market model POLES – coupled interactively in a feedback process with the ASTRA model - which took care of the simulation of the fuel price development as a consequence of the oil price increments.

Figure 8 summarises which variables are exchanged and how the models are linked to each other. In addition to fuel resource price and vehicle fleet, obtained thanks to the feedback process between POLES and ASTRA, also car ownership trends from ASTRA and average emission factors are transferred to the regional model MARS.
3.4 Model results

The application of models for the simulation of the STEPs scenarios produced a number of results concerning several variables in different domains (passenger mobility, freight mobility, energy use, environment, economy, land use, etc.). In this section we introduce a sample of the most relevant results obtained from ASTRA and MARS.

3.4.1 Transport demand

Figure 9 shows the ASTRA model forecasts on how passenger demand will develop until the year 2030 at the EU25 level. Total passenger demand is increasing in all scenarios. Higher increments result in the A1 scenario (technology investment), mainly due to a slightly higher motorisation rate (car ownership). In all other cases the growth in demand is lowered with respect to both the Business as Usual (A0) and reference (A-1) scenarios, as expected.
Turning to the local level with the Edinburgh model, total demand for passenger-kms increases by around 15-16% over 25 years for all scenarios except A2/B2 – the demand regulation scenarios – where growth is limited to around 5% (figure 10). It can be noticed that these growth rates are slightly lower than those predicted for the European context even if population in Edinburgh is growing while in the whole EU population is stable. This could suggest that interurban trips, with higher average distances grow more than local trips.

The demand for car use in Edinburgh increases faster than total demand except under demand regulation scenarios where car use is reduced by around 2-3% below 2005 levels (figure 11). The minor differences existing between the A and B scenarios indicate a small impact of oil price on overall car transport demand according the simulations.

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Figure 10  Total passenger-kms demand development in Edinburgh

Figure 11  Car passenger-kms development in Edinburgh

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3.4.2 Greenhouse and polluting emissions

The following figures 12 and 13 show that at the EU25 level, emissions are generally declining in all policy scenarios, although in the policy scenarios 1 and 2 the reduction is sharper. The only relevant exception are CO₂ emissions, for which an increase is foreseen in the No-Policy scenarios. The growth is larger for the scenario with lower oil price (A-1 scenario) and this suggests that pure contribution of oil price to the greenhouse emissions dynamics, although not strong enough to reverse the growing trend, is able to almost halve the growth rate.

Figure 12 CO₂ emissions in EU25

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In EU25, transport emissions are reduced significantly due to the renewal of the car fleet. If fuel price increases faster, as in the B0 scenario, the increase of total transport demand is lower and, in turn, also emissions are reduced. Policies implemented in scenarios 1 and 2 contribute to a more intensive reduction of emissions. On this respect, demand regulation scenarios (A2 and B2) are more effective than technology investments scenarios (A1 and B1) which reduce the unitary emission rates rather than demand.

In Edinburgh, (well to wheel) CO$_2$ produced per person km is reduced despite the increase in car use in the reference case A-1 (figure 14). This is due to improved technologies and the shift from conventional vehicles. Demand regulation and technology investments 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$_2$ produced, the demand regulation scenario 2 outperforms the technology investments scenario 1 for both A and B cases (figure 15).

NO$_X$ emissions are reduced by around two-thirds in A-1 and B-1 (figure 16). This is due to technological improvements which are already in the pipeline. Accelerating the investment in technology under scenario B1 reduces NO$_X$ by 27.7% compared to B0 in year 2030.
Figure 14  CO$_2$ Well-to-Wheel emissions per person-km in Edinburgh

Figure 15  Total CO$_2$ Well-to-Wheel emissions in Edinburgh
It can be seen that at the European level (figure 12), the impact on CO₂ is more limited than at the local level (figure 15) and the hierarchy of scenarios is not the same in the two models looking at NOₓ reduction (compare figures 13 and 16). The latter difference can be explained in terms of a lower elasticity of car demand in Edinburgh when demand regulation measures. At the same time, the renewal of the fleet is faster in UK than in the EU as a whole and so technology measures are more effective in Edinburgh.

3.4.3 Economy

According to the ASTRA model forecasts for all STEPs scenarios, the development of Gross Domestic Product (GDP) and Employment is positive in the EU25 until the year 2030 (see figures 17 and 18). In A0 scenario, the average yearly growth rate is 2.5%, slightly lower than the growth rate in no-policy scenarios, where GDP increases by 2.6 to 2.7% per year (respectively in B-1 and A-1 scenarios). In the technology investments scenarios the growth rate is higher (2.8%) and this is true either if a low increase of oil price is assumed (A1) and or a higher increase is applied (B1). The effect of oil price on GDP seems therefore to be almost negligible. In the demand regulation scenarios, the GDP growth is lowered to a 1.9% per year (A2) or 2.0% (B2). Here the effect of a higher oil price is slightly positive, as B2 performs better than A2. This effect depends again on the improved efficiency, which, in this scenario, allows the economy to react better to the diminished demand.
3.4.4 Energy use

Figures 19 and 20 below show the energy use in tonnes of oil equivalent for the Edinburgh results and the energy use per million trips and trajectories over time for total energy used. Without any policies there is a reduction in energy used of 16% in the A-1 scenario and 19% in the B-1 scenario due to the improved fleet which reduces energy used per trip by 21% and 24.5% respectively.

The technology investments scenarios decrease total energy used compared to A0/B0 in year 30 by 16% and 22% respectively. The demand regulation scenarios decrease total energy use by 4.5% and 3.9% for A2/B2 respectively whilst 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 investment policies are more effective than the demand regulation policies.

*Figure 19  Total energy use in Edinburgh*
4 CONCLUSIONS

In this paper we presented the application of System Dynamics models for simulating the energy and transport policy STEPs scenarios. The use of the System Dynamics approach allowed us to simulate the transport system taking into account its linkages with the economy, the environment and the land use. Feedback effects between the various systems are simulated, so enhancing the realism of the simulations. Using one European-wide model and one regional model, a wide range of results at different scale could be obtained.

Modelling results have demonstrated that the business as usual or current policies will have little overall impact on the transport demand and hence fuel consumption and emissions of CO$_2$. In contrast the effect of pure increases in oil price alone resulted in changes an order of magnitude greater than those obtained from the business as usual scenario. This leads us to the conclusion that policies must be changed if we are to tackle the problem of sustainability. In terms of policy recommendations, main conclusions are the followings:

Both technological investments and demand regulation can play an effective role in reducing environmental externalities - though we can expect a certain level of reduction from technology developments which are already in the
"pipeline" - this is based on the fact that in the BAU there are significant reductions in energy used and local emissions (pump to wheel at least).

a) Both technology and demand regulation can reduce total CO₂ emitted significantly but it will require some combined policy to reduce the levels by more than 20%.

b) Increased resource costs have two effects - firstly they act to suppress demand for car use, second they drive the move towards a more efficient fleet and to 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 the demand regulation policy.

c) Demand regulation reduces the externalities associated with congestion whereas technology investments do not. However we have not shown whether this "level" of regulation is economically efficient.

d) In terms of whether to accelerate the development in fleet technologies through a direct investment policy we cannot say whether these are cost effective from our tests. We can however see that they can be effective in terms of reducing energy use and local emissions. Further tests should look at combined technology and demand regulation policies and the impact of harmonisation of fuel duties across Europe.

5 ACKNOWLEDGEMENTS

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7 NOTES

1 A useful introduction to System Dynamics can be found on the Road Maps website: http://sysdyn.clexchange.org/road-maps/home.html.

2 It should be noted that in the UK the Government recently deferred the proposed increase in fuel duty in 2005 due to the rise in the cost of fuel. This appears to be a short-term response but demonstrates the fact that it is the overall pump price which is relevant to the users and hence to the political will to implement the demand regulation policy required to meet the objective of reducing car use.

3 There are many other EU projects working on the issue of optimal levels of demand regulation.