APPLYING SYSTEM DYNAMICS TO CLIMATE CHANGE ISSUES

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ABSTRACT

Global climate change has emerged as a major policy issue in industrialized as well as developing countries. The increasing emissions of greenhouse gases such as carbon dioxide, methane, and CFCs are believed to be the primary cause of Man's contribution to climate change. This trend would have to be slowed down and subsequently reversed, if the earth's climate is to remain relatively stable.

System dynamics can be used to calculate future emissions of carbon dioxide (CO_2) from the use of fossil fuels and to examine the effects of introducing new energy technologies on such emissions. In this paper, we illustrate this approach by estimating the future emissions of CO_2 from energy use in the transportation sectors in India, the Republic of Korea, and Thailand. The sensitivity of such emissions to improvements in automobile efficiency, and to the relative use of public and private transportation is examined.

The approach discussed in the paper can be easily extended to other energy use sectors, such as electricity generation, or industrial uses. Studies of this type can provide valuable input to policy-makers for optimizing the allocation of scarce resources to meet the challenge of global climate change.

INTERNATIONAL CONCERN ABOUT CLIMATE CHANGE

During the past five years, global climate change has emerged as one of the major issues requiring the attention of policy-makers throughout the world. A number of scientific conferences, as well as several called by Heads of government, were followed by the setting up of an Intergovernmental Panel on Climate Change (IPCC). The studies undertaken by the IPCC working groups (IPCC 1990) have gone a long way towards convincing many skeptics of the likelihood of climate change induced by human activities.

Greenhouse gases (GHGs) are the principal agent of climate change. The relative contribution of each of the GHGs to the Greenhouse Effect depends on a number of factors, the most important of which are:

- The amount that is emitted into the atmosphere each year
- The estimated life-time of the gas in the atmosphere
- The "Global warming potential" associated with each gas
- The time horizon under consideration

If, for example, we look at the relative contribution of each of the GHGs over a 100- year time horizon, we get the results shown in Table 1. We see from the Table that carbon dioxide is by far the largest contributor to climate change. This is still the case, if we use shorter (e.g. 20 years) or longer (e.g. 200 years) time horizons, even though the percentage contributions of the different gases will be different.

Table 1: Contribution of different greenhouse gases to the total warming effect. The Table shows the integrated effects over a 100-year time horizon of total emissions in 1990, given as a fraction of the total effect.

Trace Gas	Current Man Made Emissions $Tg\ yr^{-1}$	Proportion of total effects %
CO_2	26000	61
CH_4	300	15
N_2O	6	4
CFC-11	0.3	2
CFC-12	0.4	7
HCFC-22	0.1	0.4
CFC-113	0.15	1.5
CFC-114	0.015	0.2
CFC-115	0.005	0.1
CCl_4	0.09	0.3
CH_3CCl_3	0.81	0.2
CO	200	1
NO_x	66	6
NMHCs	20	0.5

Carbon dioxide emissions given on CO_2 basis; equivalent to 7 GtC yr^{-1}. Nitrous oxide emissions given on N_2O basis; equivalent to 4 MtN yr^{-1}. NO_x emissions given on NO_2 basis; equivalent to 20 MtN yr^{-1}

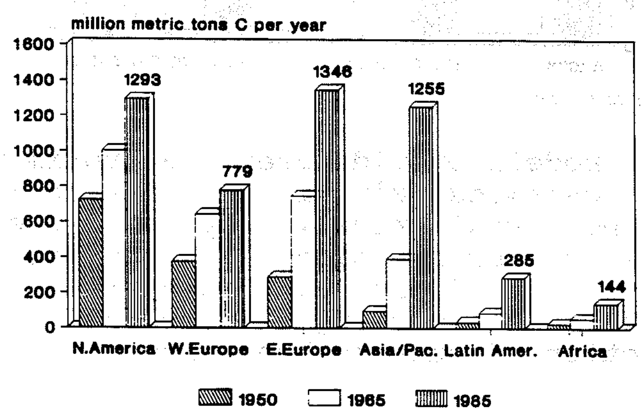
It is estimated that, of the approximately 6.0 billion tons (Gt) of carbon emitted during 1985, about 5.1 Gt came from the use of fossil fuels (coal, oil, and natural gas) for energy. Deforestation in the tropics contributed most of the remainder. Energy use thus contributed more than 80% of the total anthropogenic emissions of CO_2, the principal greenhouse gas.

The other important GHGs are Methane (CH4) and Chlorofluorocarbons (CFCs). A global agreement, generally referred to as the Montreal Protocol, has already been reached to phase out the use of CFCs during the next 2 decades. The largest sources of methane are rice paddies, wetlands, and enteric fermentation in animals. All of these are likely to be very difficult to reduce, at least during the immediate future. Thus efforts to address climate change concerns by reducing GHGs are focussing mainly on reductions in CO_2 emissions. With energy use contributing 80% of these, that sector offers the largest scope for reduction strategies, although a reversal of tropical deforestation also has an important role to play.

CARBON DIOXIDE EMISSIONS FROM ENERGY USE IN ASIA

The 1970s and 1980s have been decades of very rapid growth in energy use in Asia. Since most of this increase was in the form of fossil fuels, primarily coal and oil, there have been corresponding increases in the emissions of carbon dioxide. While the CO_2 emissions from the Asia-Pacific region (defined here as Asia plus Oceania) were only about 1/7 those from North America in 1950, the contributions of the two regions were about equal in 1985, as shown in Figure 1. It is quite likely that the Asia-Pacific region was the largest contributor to CO_2 emissions from energy use during 1991.

Figure 1
Industrial Emissions of Carbon Dioxide
by world region, 1950-1985



Source: Toufiq Siddiqi (1990)

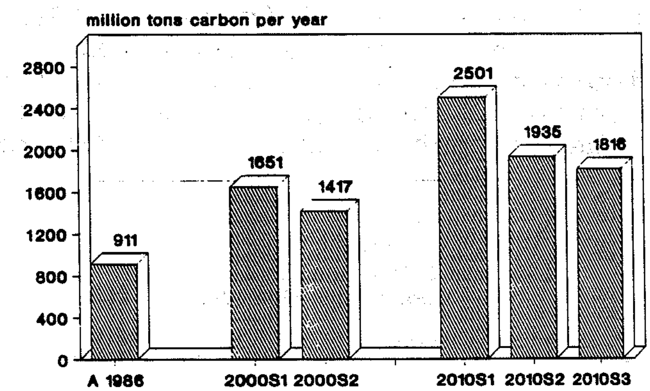
It is thus essential that the countries of Asia also make a commitment to reducing CO_2 emissions, if the anticipated global agreement on limiting GHGs is to be effective. However, these are all, with the exception of Japan, developing countries, and have much smaller per capita consumption of energy than the industrialized countries. It is anticipated that energy use, and carbon dioxide emissions in these countries will keep on rising for a number of years. Thus reductions in CO_2 emissions means reductions from future levels where no efforts at reduction are made, rather than from present emission levels.

APPLICATION OF SYSTEM DYNAMICS

A number of projections of future CO_2 emissions from energy use in a number of countries have been made in recent years (e.g. ESCAP 1990; IPCC 1990). In most cases, the projections were made for specific years, e.g. 2000 or 2020, using linear models. An example of this approach is provided in Figure 2, where the projected emissions of CO_2 from the use of commercial energy in the developing countries of Asia and the Pacific (ESCAP 1990) are shown for the years 2000 and 2010.

Figure 2

CO2 Emissions from Energy Use in Asia-Pacific Developing Countries under different Scenarios



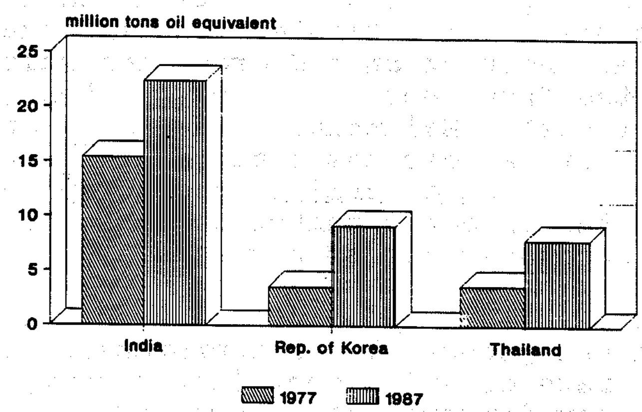
Source: ESCAP (1990)

While linear models provide useful approximations, it is felt that system dynamics, with its ability to incorporate feed-backs might more realistically represent the complexities of the energy system. System dynamics also provides policy-makers with the results of introducing particular technologies at specific times, as well as assessing the implications of different rates of introduction of such technologies.

ENERGY USE IN TRANSPORTATION

Initially, we have attempted to model only the energy use for transportation, rather than all energy uses in a country. The transportation sector is a substantial user of energy in many countries (Figure 3), and shows very rapid growth in energy use in most of the developing countries in Asia. Since it is almost entirely based on oil, CO2 emissions from this sector are also rising rapidly. In addition, the results of introducing one type of technology, i.e. more energy-efficient automobiles, can be readily examined.

Figure 3
Energy Use for Transportation in Selected Countries

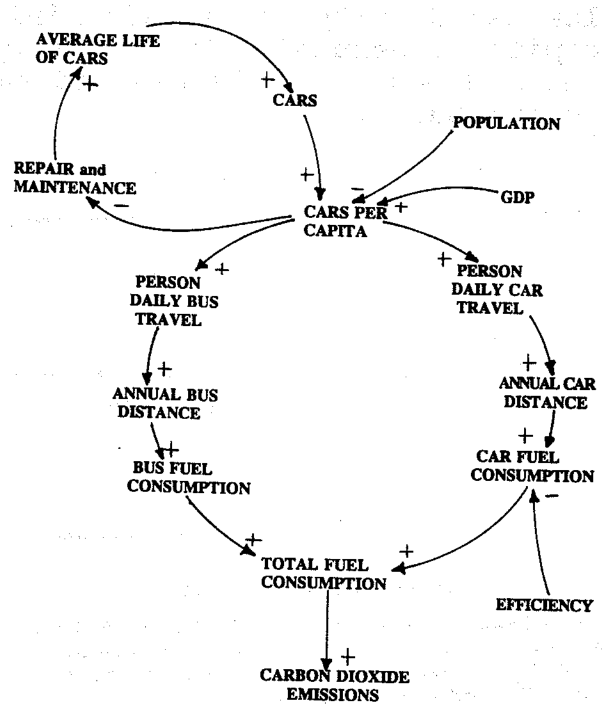


Source: Asian Development Bank (1989)

MODEL STRUCTURE

The important components and relationships in the determination of the transportation fuel consumption and the consequent carbon dioxide emission are shown in figure 4. They include the number of cars, the public transportation modal split as a function of increasing motorization, the distances travelled by a particular mode of transportation and the efficiency of the vehicle stocks. A complete listing of the equations is given in Bossel and Parayno (1991).

Figure 4. Causal relationships in the determination of fuel consumption and CO_2 emissions.

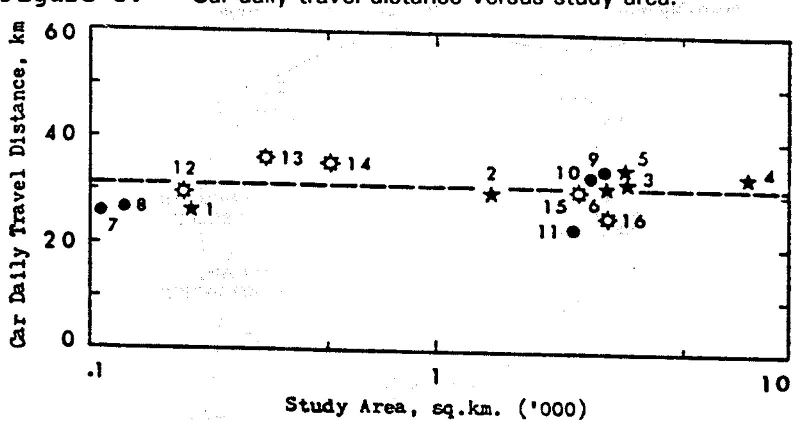


The number of cars in use at any time is estimated from an exponential saturation model for the dependence of cars per capita on GDP per capita; this saturation model is formulated with parameters which are estimated from international statistical data. Population and gross domestic product (GDP) are first computed from specified growth rates (historical and/or scenario assumptions). Maintenance intensity and hence, the average lifetime of car decreases as car ownership increases. The average car lifetime determines the scrapping rate of old cars; this, and the expected number of cars per capita, determines the purchase rate of new cars.

New car fuel efficiency gains are a function of the remaining technical potential for improvement, of the maximum possible annual rate of efficiency improvement, and of the effort put into efficiency improvement. Scrapped cars have a higher specific fuel consumption than new cars. The efficiency of scrapped cars is the average of the current fleet, which is computed from the consumption potential of the fleet. This quantity is constantly updated by the entry of more efficient new cars, and the loss of less efficient old cars.

It has been observed (Zahavi & Cheslow 1979) that the distance travelled by each car approximates 30 kilometers a day, independent of the country or size of the study area. Figure 5 shows the daily car travel distance versus city size in the United Sates, Europe and developing countries. Using an empirical relationship for the modal split (public transportation vs. private car use) as a function of motorization (cars per capita) (Zahavi 1976), and average car and bus occupancy, the daily trip distances of both cars and public transportation can be estimated. At low car density, a certain minimum of powered travel demand per capita is assumed. Fuel consumption and CO_2-emission follow from the trip distances and the fleet efficiencies of cars and buses.

Figure 5. Car daily travel distance versus study area.



Note: 1 = Monroe, 2 = Orlando, 3 = Cincinnati, 4 = Twin Cities, 5 = Washington, 6 = Philadelphia, 7 = Kingston Upon Hull, 8 = Belfast, 9 = Nuremberg, 10 = Copenhagen, 11 = London, 12 = Tel Aviv, 13 = Kuala Lumpur, 14 = Singapore, 15 = Bogota, 16 = Bangkok.

Source: Y. Zahavi and M. Cheslow. 1979. Travel Demand and Estimation of Energy Consumption by a Constrained Model. Transportation Research Record 764, 79-89.

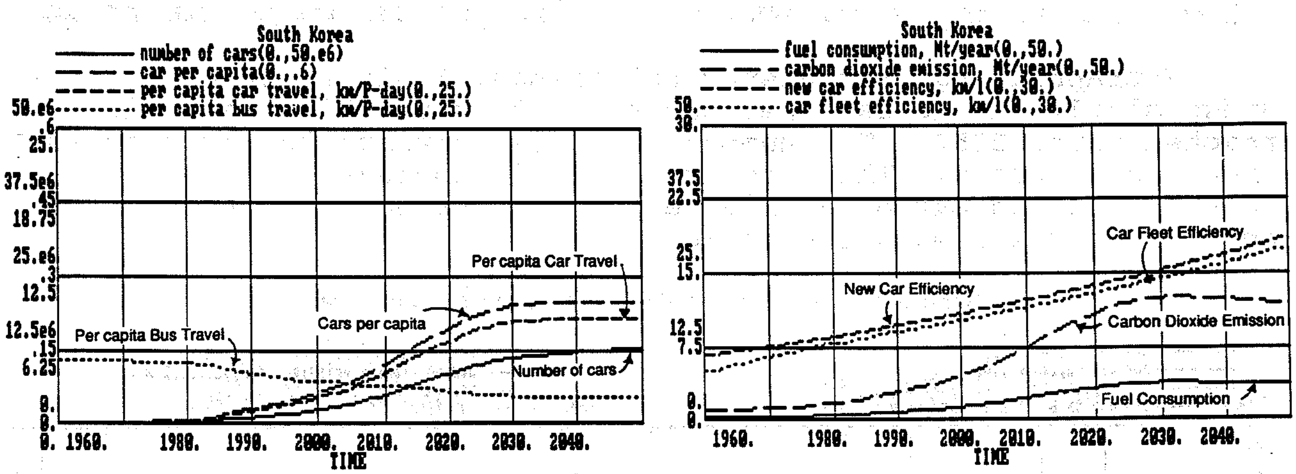
The time-dependent development of total fuel consumption and CO_2 emissions can be studied as a function of a number of parameters determining improvements in fuel efficiency and change in the use of public transportation, as well as population dynamics and economic growth.

MODEL BEHAVIOR

We take the cases of three Asian countries namely, the Republic of Korea, Thailand, and India, to check the consistency of the model with the actual behavior. Before the model is run for each case, the historical gross domestic product growth rates and population growth rates of each country are substituted.

Figure 6 shows the results for Korea. A 4 percent GDP growth rate is assumed beyond the available historical GDP growth rates. It is also assumed that the saturation value cars per capita is 0.25. This is less than those assumed for Thailand and India because of the fact that South Korea has maintained a lower car per capita than other countries which have approximately equal GDP per capita (Noll 1982).

Figure 6. Fuel consumption and CO_2 emissions of the Republic of Korea.

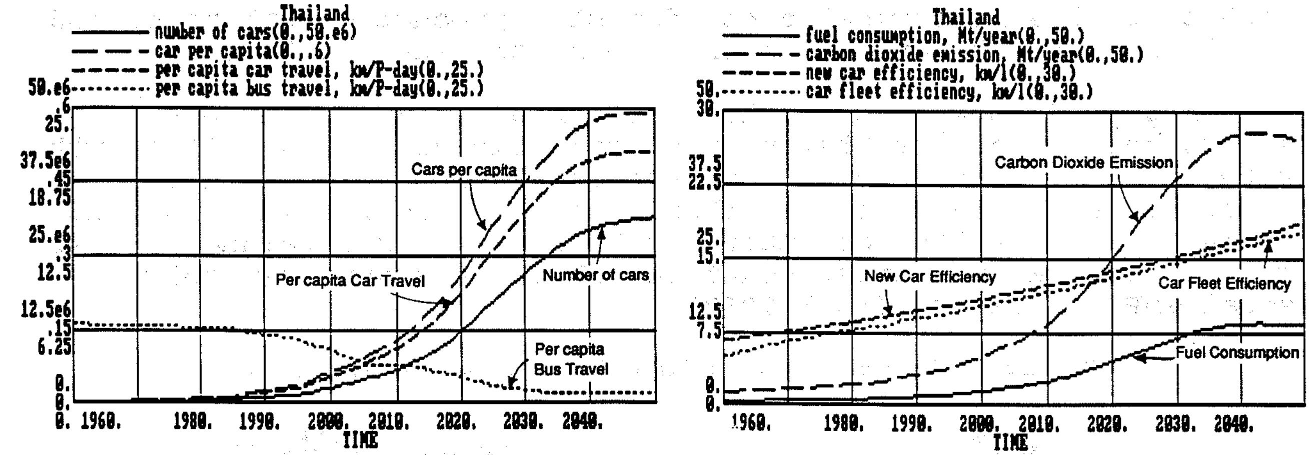


As per capita GDP increases, motorization (cars per capita) increases until saturation is reached. The modal split shifts from public transportation as the preferred mode to transportation by private cars. As the distance travelled per person per day by private cars increases sharply, daily per capita public transportation decreases.

The fuel efficiency of cars improves constantly, with the fleet efficiency lagging the efficiency of new cars by several years. This causes the overall fuel consumption and CO_2 emissions to decrease after their initial strong increase, once the saturation level has been reached for cars.

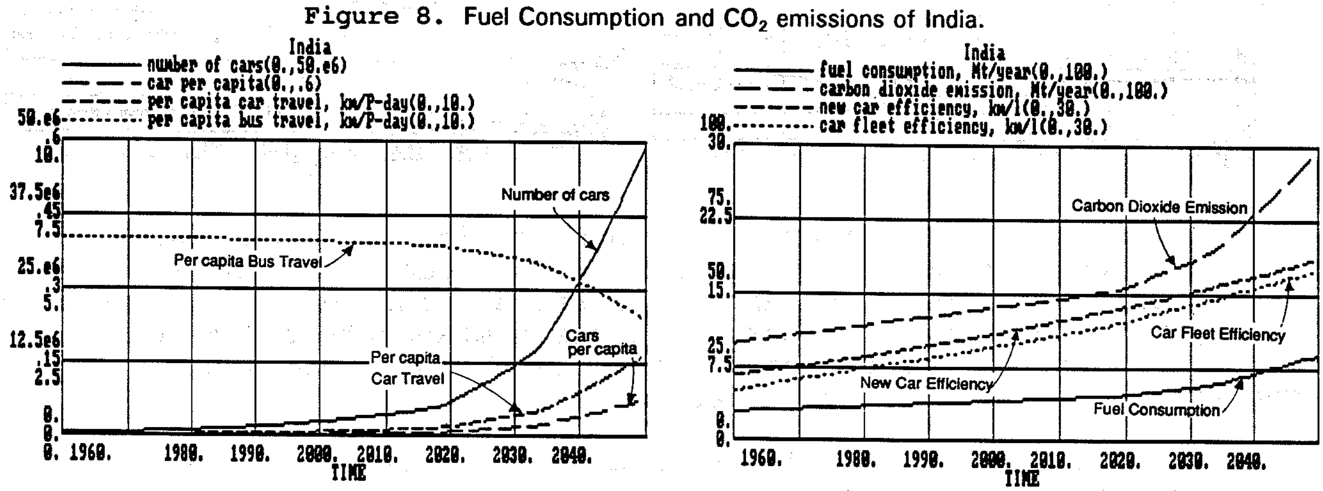
The results for Thailand are shown in figure 7. A 4 percent GDP growth rate is assumed beyond the available historical GDP growth rates. Cars per capita is assumed to reach a saturation value of 0.6. Thailand's GDP per capita increases later than the increase of South Korea's GDP per capita, leading to the later attainment of the saturation value of cars per capita. The modal split behavior follows a pattern similar to that of South Korea, i.e. as private car transportation increases public transportation decreases. The constant improvement in the car fleet efficiency causes the overall fuel consumption and carbon dioxide emissions to start decreasing.

Figure 7. Fuel consumption and CO_2 emissions of Thailand.



Extrapolating from historical trends, India's GDP per capita grows slowly, as do cars per capita. Its saturation value is reached after 2050. The numbers of cars continue to increase as shown in figure 8. This results in rapid increase in fuel consumption and carbon dioxide emissions during the latter portion of the simulation period.

Figure 8. Fuel Consumption and CO_2 emissions of India.



The parameters having the greatest effect on total fuel consumption and carbon dioxide emissions are: the average efficiency improvement effort, the car saturation level, the reference public transportation increase, and the year in which this increase is initiated. The following results are obtained for the case of the Republic of Korea. Similar results can be obtained also for Thailand and India.

The efficiency improvement effort essentially determines the speed with which the technical fuel efficiency potential is introduced into new cars. This has a very strong effect on total fuel consumption and CO_2 emissions. If efficiency improvements are introduced early, the fuel consumption rise due to increasing motorization will only be moderate, and peak consumption will be much lower than for the cases of no or small efficiency improvements as shown in figure 9.

Figure 9. The effect of energy efficiency improvement effort on fuel consumption.

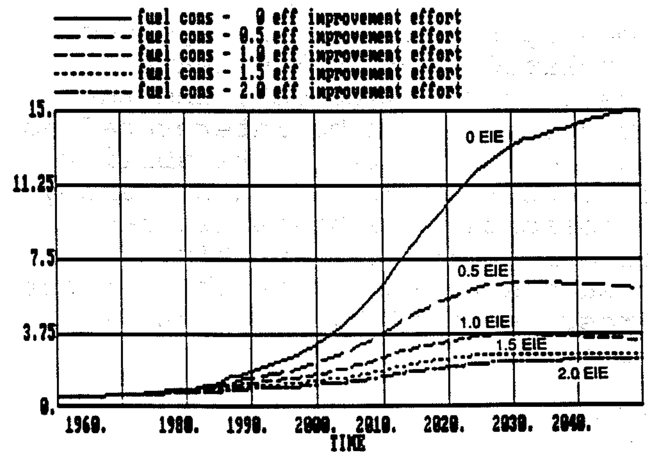
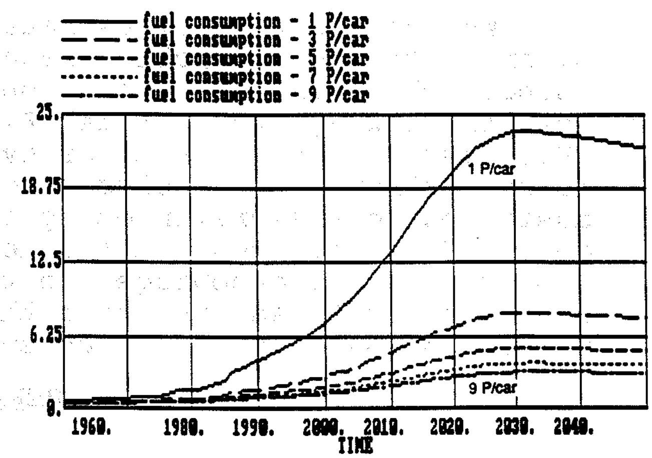


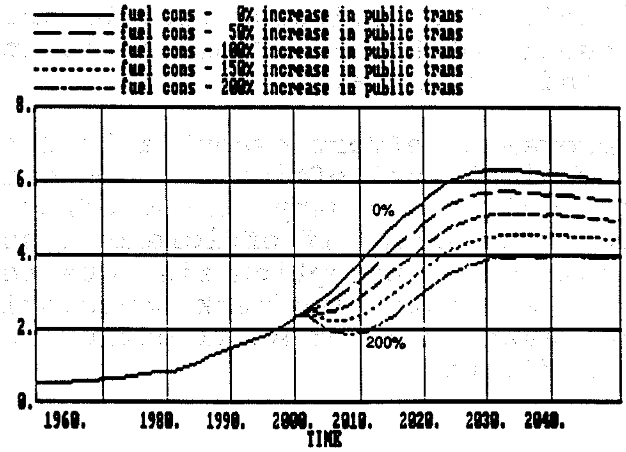
Figure 10. The effect of car saturation level on fuel consumption.



The car saturation level also has a very strong effect on total fuel consumption and CO_2 emissions. This effect is highly nonlinear: if the motorization level is already high, a small increase has much more pronounced effect than at a lower motorization level as illustrated in figure 10.

Figure 11 shows that the effect of increase in public transportation use is relatively small. A very large increase in public transportation usage would have to be achieved in order to have a significant influence on total fuel consumption and CO_2 emissions. This is due to that fact that, at relatively high levels of motorization, the modal split favors car transportation by a wide margin, and even a dramatic increase of public transportation usage would then replace only a relatively small part of the overall travel on roads.

Figure 11. The effect of increase in public transportation on fuel consumption.



CONCLUSION

We hope to have illustrated one approach to using Systems Dynamics to address policy issues related to global climate change. The emphasis here is on the word "illustrate", and the results shown in the earlier Figures should not be interpreted as "Forecasts". The strength of systems dynamics is in its ability to demonstrate the results of different assumptions, and thereby assist policy-makers in designing policies to achieve desired goals. It is our hope that some of our colleagues at this Conference feel encouraged to try such simulations in the context of their countries, and make the results available to those involved in energy and environmental policy-making.

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