Economics of Greenhouse Gas Limitations

HANDBOOK REPORTS

Sectoral Assessments

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Sectoral Assessments

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Introduction

This publication contains five papers that were written as a part of the GEF project, *The Economics of Greenhouse Gas Limitations*. The main goal of the project was to assess the greenhouse gas reductions and incremental costs of mitigation options in Ecuador, Argentina, Senegal, Mauritius, Vietnam, Indonesia, Estonia and Hungary. In addition, regional studies were conducted for the Andean Pact nations and Southern Africa to assess various aspects of regional co-operation in reducing greenhouse gas emissions. The GEF study also involved the development of a methodological framework for climate change assessment, with a special emphasis on developing countries. These guidelines have been published in a separate document, *Economics of Greenhouse Gas Limitations: Methodological Guidelines* (Halsnæs et al. 1999).

The papers in this publication focus on various methodological and policy aspects of greenhouse gas mitigation at the sectoral level, and are outgrowth of work performed on other parts of the GEF project.

The first paper introduces the GACMO (for **G**reenhouse G**a**s **C**osting **Mo**del), developed by Jørgen Fenham at the UNEP Centre for Energy and Environment (UCCEE). In earlier mitigation assessments performed by UCCEE in developing countries, it became clear that there was a need for an analytical tool that could be used to evaluate the benefits and costs of a wide range of mitigation options in developing countries. This tool should be able to calculate both the greenhouse gas (GHG) emissions reduction associated with different options, as well as the average mitigation cost, for all kinds of GHG mitigation options. It should also be able to combine the options in the form of an emissions reduction cost-curve, displaying the average cost of reducing GHG emissions for a number of different alternatives. The tool should also be transparent so that users could easily follow and understand the different calculations and, finally, it should be easy to use. GACMO was developed to fulfil these needs. To date, the model has been used in GHG mitigation assessments in Botswana, Zambia, Peru, Colombia and Denmark.

The paper in this publication describes the structure of the GACMO model. It also provides directions for users to implement the model in assessing various mitigation options. Finally, the paper contains an example that shows how the model can be used to assess the GHG reductions and incremental costs associated with several hypothetical options in a developing country.

The second paper, by John M. Callaway (UCCEE) focuses on greenhouse mitigation in the agricultural sector. It outlines a methodology for introducing market economics into the assessment of options to reduce methane emissions from enteric fermentation in livestock. Calculating the emissions reduction for these options is somewhat challenging because the methane emission reduction is composed of two parts: a) the effect of the mitigation option on methane emissions per animal and per unit of animal product, and b) an indirect effect due to the reduction in livestock numbers, while holding production constant. The direct effect of most options in this category is to increase the productivity of livestock, so that each animal can produce more work, milk, or meat. In the process, methane emissions per animal actually increase. However, methane emissions per unit of product decrease by a larger proportion than the increase in methane emissions per animal. Therefore, it is possible to reduce the total number of production livestock in order to satisfy a given level of product demand. Assuming that product demand remains constant, total methane emissions are reduced, even though emissions per animal increase.

Existing studies of mitigation options in this field generally use estimates of current and projected product demand and livestock numbers that are derived independently. However, as this paper shows, these mitigation options, which generally involve changes in animal diets and feeding practices, directly affect the costs of livestock individual producers. This, in turn, has the potential to influence the market-clearing prices and output levels for these products, which also influences the number of livestock needed to achieve these output levels. This suggests that both base case and mitigation scenario projections of product demand and supply, as well as the projections of livestock numbers should be methodologically linked to the costs of the mitigation options and their impact on animal productivity.

The paper outlines a procedure for this, by linking the costs of the mitigation options and their effects on animal productivity to the estimation of market supply and demand curves for the relevant product markets. This allows the calculation of the market-clearing product levels and livestock numbers in all scenarios to be dependent upon the cost and productivity impacts of the mitigation option. Using a hypothetical example, the paper shows how this methodological approach might be used to assess the methane emissions reduction and incremental costs of feeding supplements to dairy cattle in a hypothetical developing country. In addition, the paper also outlines some of the challenges associated with implementing this type of mitigation option in a developing country.

A vast amount of carbon is stored in terrestrial ecosystems. However, the amount of carbon stored in these systems has been decreasing, largely due to deforestation in developing countries. Thus, increases in greenhouse gas emissions from non-forest and forest sources can be offset to some degree by reducing the current rate of deforestation and by creating new forests, either to be conserved, or to act as the resource base for sustainable wood products or fuels. The third paper in this publication, by Willy Makundi and Jayant Sathaye of Lawrence Berkeley National Laboratory (LBNL) covers the mitigation of GHG emissions in the forest and land use sectors.

The paper highlights the **Co**mprehensive **M**itigation **A**ssessment **P**rocess (COMAP) model, a model that was used extensively in a number of the GEF country studies to assess the impact of various forest and land use mitigation options on carbon sequestration and mitigation costs. The paper presents the rationale for the development of COMAP, as well as a description of the model structure. What is noteworthy about this paper is that it contains instructions about how to use COMAP. It also presents two illustrative examples about how to use the model to evaluate afforestation and a forest protection option.

This publication includes two papers that address greenhouse gas mitigation in the transportation sector by Roger Gorham of the World Bank. The transportation sector is often dealt with as a part of the energy sector. However, these two papers underscore the importance of taking a more focused view of the transportation sector. This is because the mitigation options are qualitatively different from many of those in the energy sector and, more importantly, because the underlying economic motivation of the many different actors in the transportation sector are quite different than in the energy sector.

The first paper examines various methods for estimating the greenhouse gas reductions and costs associated with mitigation options in that sector. It presents a conceptual framework for characterising the behaviour of economic agents in the transportation sector that gives rise to variations in different technology and fuel choices, modal choice, and activity levels of the different transportation modes. It then shows how transportation decisions regarding these factors can be parsed out into a model of transportation emissions.

In many mitigation studies, the options for reducing greenhouse gas emissions are treated as if they were, essentially, projects. Given this approach, it often appears that the only requirement for implementing these options is to find the prerequisite financing. This is in keeping with a traditional view of development financing. The second transportation paper, also by Roger Gorham, takes a different perspective. It explores domestic policy options that will induce different economic agents in the transportation sector to make choices that will result in lower greenhouse gas emissions.

The paper looks at nine different policy groups:

1. The cost of fuel consumption
2. Other costs of motor vehicle use
3. The conditions of road traffic
4. Public transport and other alternatives to road transport
5. Vehicle fleet production
6. Vehicle fleet demand
7. The built environment
8. Household / firm location choices
9. Public attitudes toward transportation

As the paper points out, many of these policies are complementary and reinforce each other so that applied in concert, they would probably be more successful than each would individually. Within in each policy group, the study identifies a number of possible specific policy options. For example: to change the costs of motor vehicle use, for example, one might charge for road use, charge for parking, or change the way insurance is assessed. However, the purpose of the paper is not to identify all of the possible policy options. It is, rather, to show the possible effects of the policy group on various factors that shape transportation energy consumption to allow policy makers and analysts a clear view of both the intended and unintended impacts of their decisions. Finally, the paper draws connections to conventional transportation goals to suggest ways that initiatives to reduce GHG emissions might be part of a broader transportation policy agenda in both developing and developed countries.

Chapter 1: Introduction to the GACMO Mitigation Model

Jørgen Fenham, UNEP Center

1.0 Introduction

In connection to the UNEP Greenhouse Gas Costing Study for Zimbabwe that was finalised in 1993, there emerged a need for an analytical tool that could be used to evaluate the benefits and costs of a wide range of mitigation options. The tool should be able to calculate the greenhouse gas (GHG) emissions reduction associated with different options, as well as the average mitigation cost, e.g. in US$ per ton of CO_2 equivalent emission reduced, for all kinds of GHG mitigation options. It should also be able to combine the options in the form of an emissions reduction cost-curve, displaying the average cost of reducing GHG emissions for a number of different alternatives. The tool should also be transparent so that users could easily follow and understand the different calculations and, finally, it should be easy to use. The model, which finally emerged from this exercise was the GACMO (for Greenhouse Gas Costing Model), developed at the UNEP Centre for Energy and Environment. Stockholm Environment Institute in Boston assisted in developing the macros. To date, the model has been used in GHG mitigation assessments in Botswana, Zambia, Peru, Colombia and Denmark.

2.0 A Description of the GACMO Model Inputs, Calculations, and Outputs

The GACMO model is an EXCEL spreadsheet notebook containing the following spreadsheets: Main, Graph, Assumptions, Prices, Option 1, Option 2, …, Option N.

The basis for a mitigation analysis is a baseline or reference scenario for the development of the GHG emissions from the base year (e.g. 1990) until a “target” year, which is chosen by the user. In the examples in this chapter the target year is chosen to be 2010 or the midyear in the first commitment period 2008-2012 in the Kyoto Protocol to the United Nations Framework Convention on Climate Change. In a perfect baseline there is a total knowledge of the energy services supplied in the different energy consuming sectors i.e. the number of energy consuming units and the annual energy consumption by each unit. Ideally this information is needed to do a good mitigation study for a country.

The mitigation scenario combines the emissions in the reference scenario with the changes (i.e., reductions) in emissions introduced by the various mitigation options being evaluated. For each mitigation option, the technologies that deliver energy services in the reference option are changed. A mitigation unit of emissions from these new technologies offsets a unit of energy consumed in the reference scenario. A very important assumption that is made in this regard is that the level of energy service delivered by the reference option and the mitigation option does not effect the demand for the energy service. In other words, there is no change in the level of energy service demand when the new technology is introduced, e.g. the temperature in the room is kept constant, or the amount of person-km transported is the same. Here it can sometimes be difficult to draw the borderline between what is changed and what is unchanged. There can also be some welfare changes, e.g. usage of time, which are difficult to quantify. When an electricity saving option is analysed it is important not only to include the change of the appliance using the electricity but also the reduction in the demand for investment in new power plant capacity (and maintenance of the new capacity).

The structure of the mitigation options in the different sectors varies a lot. It is impossible to describe them all in the same standard format. Therefore a flexible representation is used in GACMO for the options. Table 1 shows the standard template, which is created when the user wants to start working on a new option. The template is created with formulas in some of the cells. The user has to insert data in other cells. The main elements are the following:

1. On the top left line in Table 1 the name of the mitigation option is written. The model uses this name in the first column in Table 4; therefore the name should not be too long.
2. To the left in Table 1 are two boxes. In the *upper box* the total annual costs for the reference and the mitigation option and the increased cost of the mitigation option is calculated. The costs consist of three components: (1) the investment (to be inserted by the user) levelized over the project life using the discount rate in the spreadsheet "Assumptions". (2) The annual operation & maintenance cost (to be inserted by the user) and (3) the fuel costs calculated by multiplying in the cells "Total fuel use" (in the cells to the right of the boxes) with the appropriate fuel prices from the spreadsheet "Prices". The model does this.
3. In the *lower box* the emissions of greenhouse gases is calculated. The model again uses the cells "Total fuel use" and multiplies them with the appropriate emissions factors from the "Assumptions" spreadsheet (IPCC emission factors in kg/GJ fuel are used as default). In the lines with the names "Fuel CO_2, Fuel N_2O and Fuel CH_4 " the unit is tons of gas emitted, while in the next line "Total CO_2 equivalent" the sum of the emissions of CO_2, N_2O and CH_4 is multiplied with their Global Warming Potential from the "Assumptions" spreadsheet. If there is a GHG emission not originating from the combustion of fossil fuels, the user has to insert an extra line in the bottom box, e.g. leakage of CH_4 in a landfill option, and adding this emission to the formulas in the total line.
4. Finally the increase in annual costs is divided by to reduction in total GHG emissions in order to calculate the cost/ton CO_2 equivalent. This number is transferred to the second column of Table 4, forming the "y-axis" of the cost-curve.

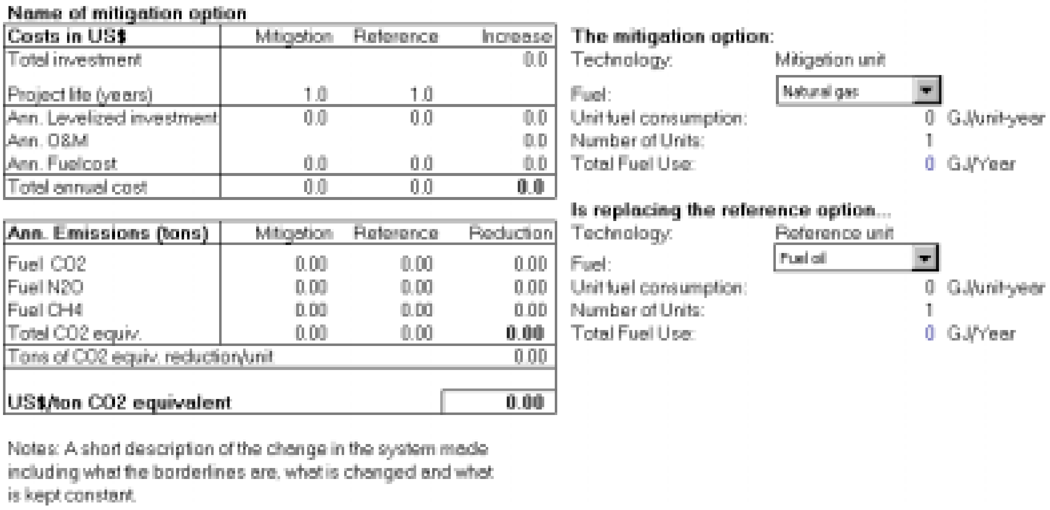
For each mitigation option, a "unit" measure for the new technology has to be defined. The penetration of the mitigation option in the country is measured in the number of these units. As shown in the third column in Table 4, a unit can be: a refridgerator, a bulb, a landfill, a MW, etc. Since the calculation can be done for a project consisting of a certain number of units, an extra line in the emission box calculates the "tons of CO_2 equiv. Reduction/unit". This number is transferred to column four in Table 4, forming one of the basis inputs for the "x-axis" of the cost-curve.

To the right in Table 1 the inputs and assumptions for the option are shown, at the top for the mitigation option and at the bottom for the reference option. It is very important that the user show all background calculations down to a reasonable level of detail, so that it is easy to understand for a reader.

At the top of the inputs for both the mitigation and the reference option, the name of the technology is written. Below that the energy form used by the technology is chosen in the drop-down menu, which ensures that the total annual fuel consumption calculated below is multiplied with the correct GHG emission factors and correct fuel prices. Below the drop-down menus the user should enter the annual fuel consumption for one technology unit. Here it has been necessary to enter flexibility in the model. The user should insert the lines needed here in order to show clearly how the annual fuel consumption is calculated (production information, consumption in weight/volume, densities, calorific values, efficiencies etc.) and enter the result in this cell. The model will then multiply with the number of units, entered below, by the fuel consumption and calculate the total fuel use in the last line, from which the model calculates the annual fuel costs and GHG emissions as mentioned before.

For some types of mitigation options additional lines may be required for a clear description of how the investment cost and operation & maintenance cost is calculated. The annual O&M cost is e.g. often calculated as a percentage of the investment.

Table 1. Standard template



Name of mitigation option

Costs in US$	Mitigation	Reference	Increase
Total investment			0.0
Project life (years)	1.0	1.0	
Ann. Levelized investment	0.0	0.0	0.0
Ann. O&M			0.0
Ann. Fuelcost	0.0	0.0	0.0
Total annual cost	0.0	0.0	**0.0**

Ann. Emissions (tons)	Mitigation	Reference	Reduction
Fuel CO2	0.00	0.00	0.00
Fuel N2O	0.00	0.00	0.00
Fuel CH4	0.00	0.00	0.00
Total CO2 equiv.	0.00	0.00	**0.00**
Tons of CO2 equiv. reduction/unit			0.00
US$/ton CO2 equivalent			**0.00**

Notes: A short description of the change in the system made including what the borderlines are, what is changed and what is kept constant.

The mitigation option:

Technology:	Mitigation unit	
Fuel:	Natural gas	
Unit fuel consumption:	0	GJ/unit-year
Number of Units:	1	
Total Fuel Use:	0	GJ/Year

Is replacing the reference option...

Technology:	Reference unit	
Fuel:	Fuel oil	
Unit fuel consumption:	0	GJ/unit-year
Number of Units:	1	
Total Fuel Use:	0	GJ/Year

It is important to understand that the template shown in Table 1 can not be used for end-use options associated with conservation of electricity. The reason is that the changes in the end-use implies a change in the electricity supply system, with has to be included in the calculation.

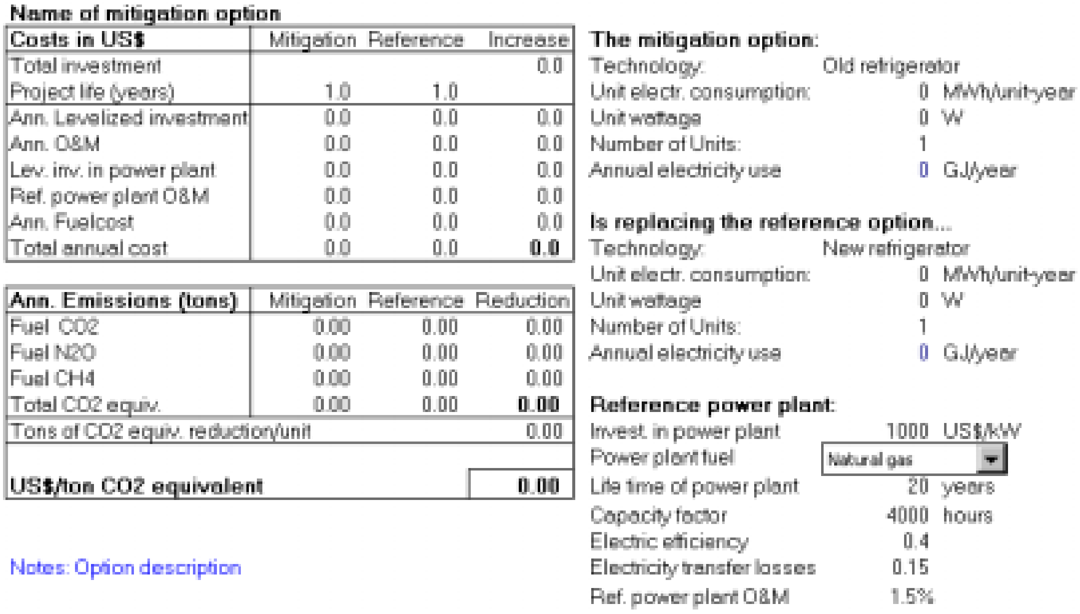
For electricity conservation measures, the electricity saving template in Table 2 is used. The template is equal to template 1 with some changes and a few elements added. In the upper box with the cost calculation, two lines have been inserted representing the levelized investment cost and O&M cost for the reference power plant, where the electricity is assumed to be produced.

In order to calculate the total annual electricity use for the mitigation and the reference option, the user must enter additional lines to the right of the boxes, enough to calculate the annual electricity consumption of the units based on the power consumption of the units.

Below these inputs in Table 2 is an additional block of lines describing the reference power plant. The investment in US$/kW entered here is discounted using the same discount rate, employed throughout the model for all options, and the lifetime of the power plant, entered below. The percentage, entered below, for the reference power plant O&M cost is multiplied with the investment in the cost box. The amount of fuel used at the power plant is then calculated by dividing the annual electricity use by the power plant efficiency and the efficiency in the power transfer seen below. The capacity saved is reduced by the capacity factor. The model calculates the GHG emissions from the power plant and the fuel costs by using the emission factors and fuel prices for the fuel chosen in the drop-down menu.

The information for the reference power plant is copied from the "Assumptions" spreadsheet. The modelling assumption behind using a reference power plant in the calculation is that the electricity saved in the future implies that size of a future power plant can be reduced. If the electricity capacity expansion plan in the country assumes constructions of power plants using a mix of fuel, a fuel with the name “mixfuel” can be used. The user has to define this mixfuel in the “Assumption” spreadsheet as a percentage mix of fuels.

Table 2. Template for electricity saving



Name of mitigation option

Costs in US$	Mitigation	Reference	Increase
Total investment			0.0
Project life (years)	1.0	1.0	
Ann. Levelized investment	0.0	0.0	0.0
Ann. O&M	0.0	0.0	0.0
Lev. inv. in power plant	0.0	0.0	0.0
Ref. power plant O&M	0.0	0.0	0.0
Ann. Fuelcost	0.0	0.0	0.0
Total annual cost	0.0	0.0	**0.0**

Ann. Emissions (tons)	Mitigation	Reference	Reduction
Fuel CO2	0.00	0.00	0.00
Fuel N2O	0.00	0.00	0.00
Fuel CH4	0.00	0.00	0.00
Total CO2 equiv.	0.00	0.00	**0.00**
Tons of CO2 equiv. reduction/unit			0.00
US$/ton CO2 equivalent			**0.00**

Notes: Option description

The mitigation option:

Technology:	Old refrigerator	
Unit electr. consumption:	0	MWh/unit-year
Unit wattage	0	W
Number of Units:	1	
Annual electricity use	0	GJ/year

Is replacing the reference option...

Technology:	New refrigerator	
Unit electr. consumption:	0	MWh/unit-year
Unit wattage	0	W
Number of Units:	1	
Annual electricity use	0	GJ/year

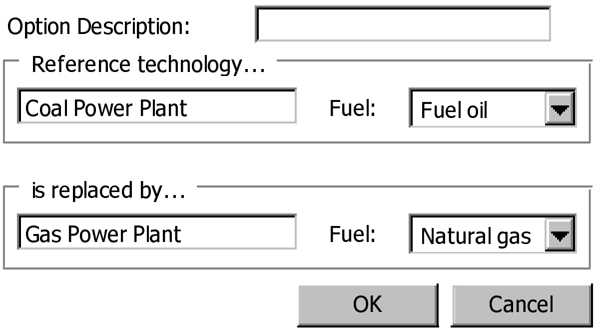
Reference power plant:

Invest. in power plant	1000	US$/kW
Power plant fuel	Natural gas	
Life time of power plant	20	years
Capacity factor	4000	hours
Electric efficiency	0.4	
Electricity transfer losses	0.15	
Ref. power plant O&M	1.5%	

The normal way to introduce a new option in GACMO is to press the button “Add” at the top of the “Main” spreadsheet. The macro connected to this button, first, sorts the reduction options in Table 4 by increasing order of reduction cost (column 2). Then the add-option dialog box in Table 3 is shown on the screen. At the top line in the box the user writes the name of the option. This text is written in the top left of the new option spreadsheet, which the model creates when the OK button in Table 3 is pressed. The names of the reference and the mitigation technology should be entered and the fuels chosen in the two drop-down menus. If one of the fuels in is chosen to be electricity, the model uses template 2, otherwise template 1 will be used.

After creating a new option spreadsheet the macro connected to the OK button also inserts a new line in the “Main” spreadsheet with the results from the new option.

Table 3 Add option dialog box



Option Description:

Reference technology...

Coal Power Plant — Fuel: Fuel oil

is replaced by...

Gas Power Plant — Fuel: Natural gas

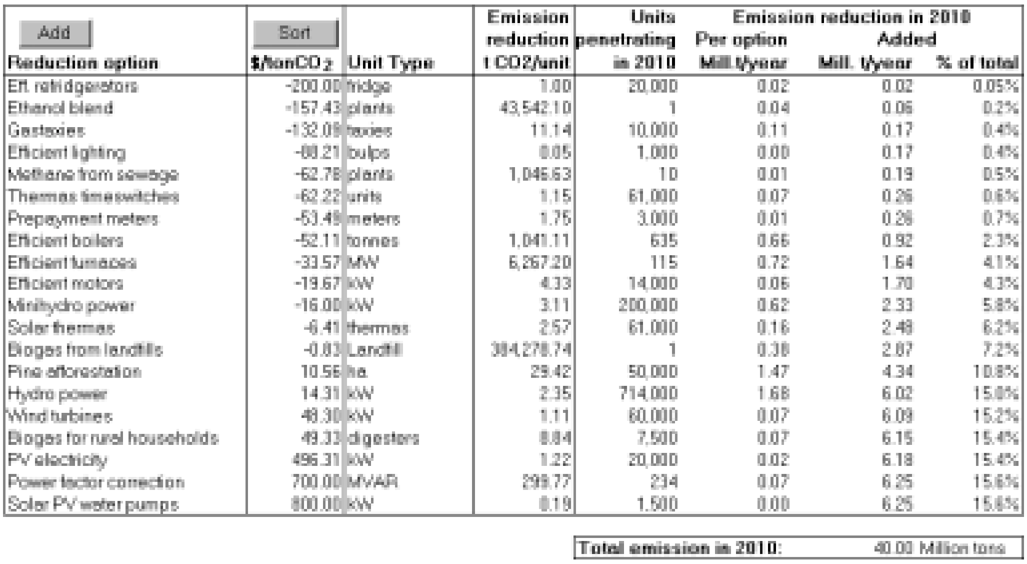
As mentioned above, Table 4 contains the information necessary to construct the cost curve. The values in the second column are the y-values of the points on the cost curve. The x-values can be in ether column 7 or 8 depending on whether the user want to show the cost curve for reductions in million tons of CO_2 equivalents or in percentage reduction of the total emission of the country at the target year. The user has to insert this value at the bottom at Table 4. Like the annual reduction cost in column 2 the model also transfer the emission reduction per unit in column 4 to the "Main" spreadsheet from all the option spreadsheets.

In order to calculate the total emission reduction in the target year, the user must introduce the number of technology units penetrating into the system until the target year (2010 in Table 4) in column 5 and write a short and understandable unit name in column 3. The model will then calculate the total emission reduction for the option in column 6 by multiplying the reduction per unit by the number of mitigation units introduced. Since the x-values on the cost curve represent the cumulative reduction of CO_2 equivalents this is calculated in column 7. Finally, the cumulative percentage reduction is calculated in column 8 by dividing column 7 by the total emission at the bottom of the table.

The same discount rate is used for all options, and the user can do a quick sensitivity analysis by changing the discount rate in the "Assumptions" spreadsheet. In the examples in this chapter a discount rate of 10% was used. However, the examples are from different countries with different assumptions on fuel price projections.

Instead of using the "Add" button in the "Main" spreadsheet, it can sometimes be faster to copy an existing option spreadsheet and make some changes in the copy, if another option with many similarities already has been made. However, in this case, the user must remember to insert a new line in the "Main" spreadsheet, in order to capture the results from the new option.

Table 4. Example of the sheet "Main" in GACMO



Add	Sort		Emission reduction	Units penetrating	Emission reduction in 2010		
					Per option	Added	
Reduction option	**$/tonCO2**	**Unit Type**	**t CO2/unit**	**in 2010**	**Mill.t/year**	**Mill. t/year**	**% of total**
Eff. refridgerators	-200.00	fridge	1.00	20,000	0.02	0.02	0.05%
Ethanol blend	-157.43	plants	43,542.10	1	0.04	0.06	0.2%
Gastaxies	-132.09	taxies	11.14	10,000	0.11	0.17	0.4%
Efficient lighting	-88.21	bulps	0.05	1,000	0.00	0.17	0.4%
Methane from sewage	-62.78	plants	1,046.63	10	0.01	0.19	0.5%
Thermas timeswitches	-62.22	units	1.15	61,000	0.07	0.26	0.6%
Prepayment meters	-53.49	meters	1.75	3,000	0.01	0.26	0.7%
Efficient boilers	-52.11	tonnes	1,041.11	635	0.66	0.92	2.3%
Efficient furnaces	-33.57	MW	6,267.20	115	0.72	1.64	4.1%
Efficient motors	-19.67	kW	4.33	14,000	0.06	1.70	4.3%
Minihydro power	-16.00	kW	3.11	200,000	0.62	2.33	5.8%
Solar thermas	-6.41	thermas	2.57	61,000	0.16	2.49	6.2%
Biogas from landfills	-0.83	Landfill	384,278.74	1	0.38	2.87	7.2%
Pine afforestation	10.56	ha	29.42	50,000	1.47	4.34	10.8%
Hydro power	14.31	kW	2.35	714,000	1.68	6.02	15.0%
Wind turbines	48.30	kW	1.11	60,000	0.07	6.09	15.2%
Biogas for rural households	49.33	digesters	8.84	7,500	0.07	6.15	15.4%
PV electricity	496.31	kW	1.22	20,000	0.02	6.18	15.4%
Power factor correction	700.00	MVAR	299.77	234	0.07	6.25	15.6%
Solar PV water pumps	800.00	kW	0.19	1,500	0.00	6.25	15.6%

Total emission in 2010: 40.00 Million tons

On the "Graph" spreadsheet the cost curve is drawn automatically by the model. By using the drop-down menu the user can choose between a cost curve with an x-axis in the unit of tons of CO_2 equivalents reduced or in percentage reduction. The graph is updated both when the update button and the drop-down menu for choosing the curve type are pressed (see Figure 1)

3.0 Examples using the GACMO model

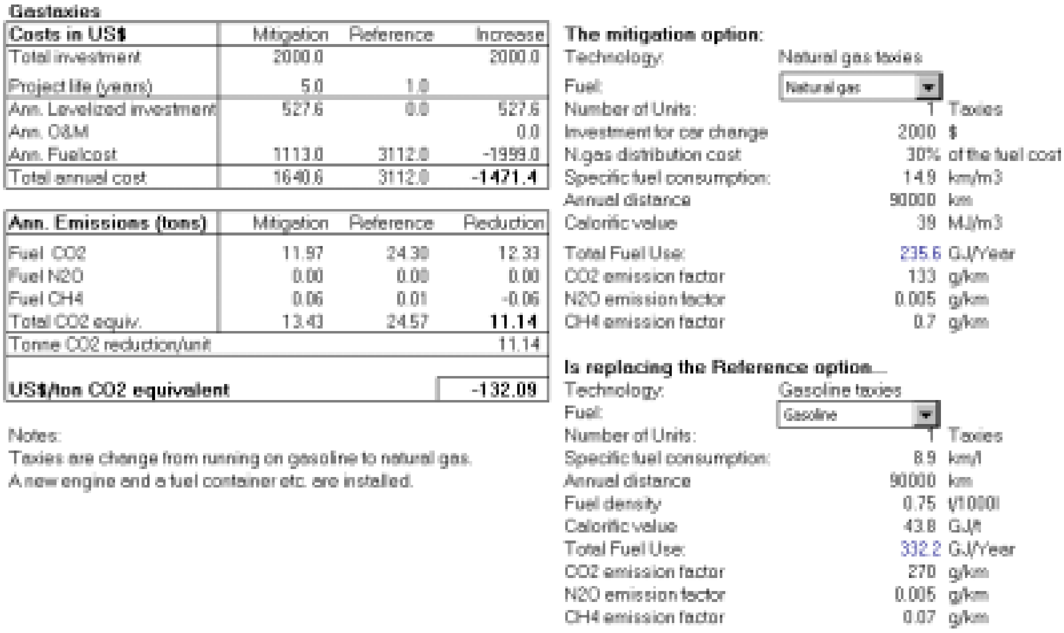
In the following two examples of how to use the GACMO model are shown. Both are mitigation options for the hypothetically country study shown in Table 4. The values used for the options are only indicative and the size of the key parameters will vary from country to country.

In many cases the templates created by GACMO have to be changed quite a lot by the user, before a reasonable picture of the option is created, especially for transport options. Table 5 shows an example of this kind, where template 1 is used. A simple mitigation option in the transport sector, where one taxi is changed to run on natural gas in stead of using gasoline as fuel.

The investment part is rather simple. It consists only of an investment in the mitigation option of 2000$ for a new engine and a natural gas fuel container etc. as mentioned in the notes in the example. The extra investment in the natural gas distribution network is assumed to be proportional to the fuel consumption, and 30% is added to the fuel cost for the mitigation option to cover this cost.

In order to calculate the cell in the template 1 named "Total fuel use" for the reference option the user has inserted new lines with the annual distance cover by the taxi, the specific fuel consumption (km/l), the fuel density and calorific value. For the mitigation option the same information is given for natural gas. The way the model calculates the GHG emissions was changed in this option, because the user wanted to use emission factors for transport in the unit gGHG/km in stead of kgGHG/GJ. Therefore three new lines was inserted for these emission factors.

Table 5 Example: Natural gas taxes



Gastaxies

Costs in US$	Mitigation	Reference	Increase
Total investment	2000.0		2000.0
Project life (years)	5.0	1.0	
Ann. Levelized investment	527.6	0.0	527.6
Ann. O&M			0.0
Ann. Fuelcost	1113.0	3112.0	-1999.0
Total annual cost	1640.6	3112.0	**-1471.4**

Ann. Emissions (tons)	Mitigation	Reference	Reduction
Fuel CO2	11.97	24.30	12.33
Fuel N2O	0.00	0.00	0.00
Fuel CH4	0.06	0.01	-0.06
Total CO2 equiv.	13.43	24.57	**11.14**
Tonne CO2 reduction/unit			11.14
US$/ton CO2 equivalent			-132.09

Notes:
Taxies are change from running on gasoline to natural gas.
A new engine and a fuel container etc. are installed.

The mitigation option:

Technology:	Natural gas taxies	
Fuel:	Natural gas	
Number of Units:	1	Taxies
Investment for car change	2000	$
N.gas distribution cost	30%	of the fuel cost
Specific fuel consumption:	14.9	km/m3
Annual distance	90000	km
Calorific value	39	MJ/m3
Total Fuel Use:	235.6	GJ/Year
CO2 emission factor	133	g/km
N2O emission factor	0.005	g/km
CH4 emission factor	0.7	g/km

Is replacing the Reference option...

Technology:	Gasoline taxies	
Fuel:	Gasoline	
Number of Units:	1	Taxies
Specific fuel consumption:	8.9	km/l
Annual distance	90000	km
Fuel density	0.75	t/1000l
Calorific value	43.8	GJ/t
Total Fuel Use:	332.2	GJ/Year
CO2 emission factor	270	g/km
N2O emission factor	0.005	g/km
CH4 emission factor	0.07	g/km

With these inputs the result (of cause heavily dependent on the fuel price projections and the discount rate used) the result is a reduction of 11.14 tons CO_2 equivalent with a cost of –132.09 US$.

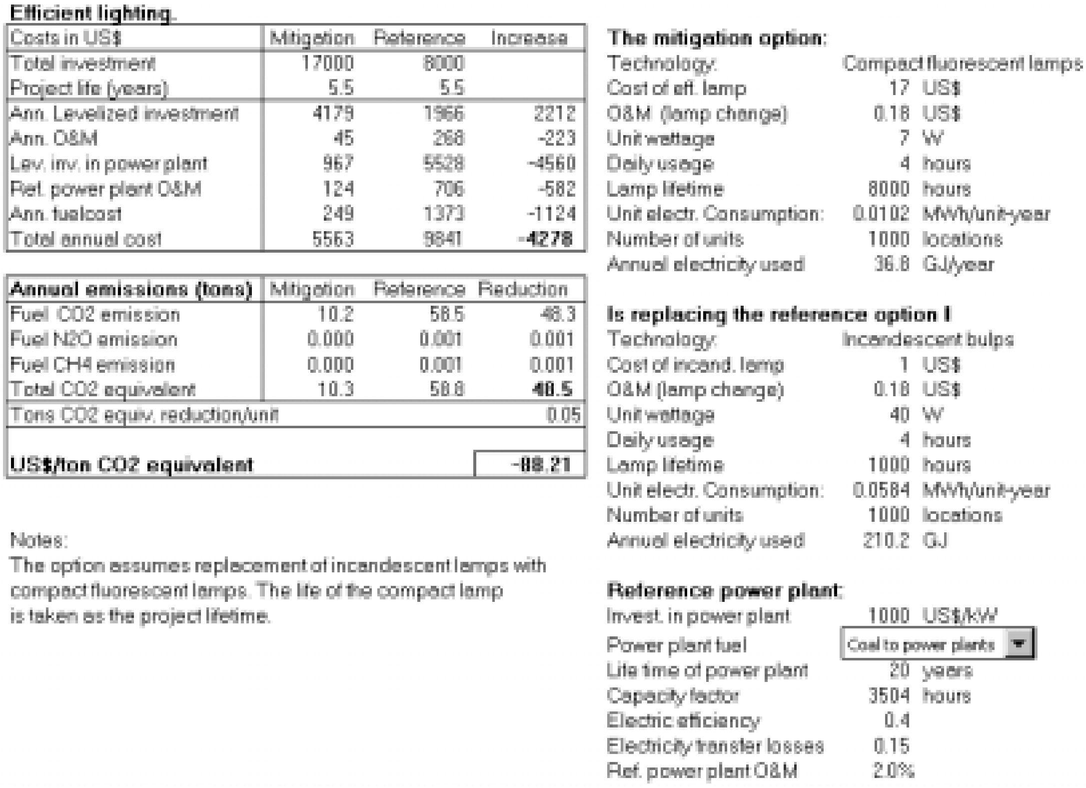
Table 6 shows a second example of the use of template 2. It involves efficient lighting in the service sector.

In office buildings 1000 incandescent lamps are replaced with new energy efficient compact fluorescent lamps. The investment is the cost of the lamp multiplied with 1000 lamp locations, and the O$M cost is not zero, since it is assumed that somebody is paid (0.18 US$/lamp change) to replace the lamp after the 1000 hours and 8000 hours respectively. The project life is equal to the lifetime of a compact lamp (8000 h = 5.5 years), therefore compact lamp is replacing 8 incandescent lamps over its lifetime.

The power consumption of the lamp is multiplied by its assumed daily usage time (4 h) and the number of days in the years in order to get the Unit electricity consumption (in MWh/year). The annual electricity used is calculated by multiplied this number with the number of locations and converting to the unit GJ.

The levelized investment and the O&M cost for the reference power plant is decreased for the mitigation option compared to the reference option due to lower need for capacity due to electricity savings. The reference power plant is assumed to use coal. In the drop-down menu the fuel "coal to power plants" is chosen. The model operates with two different time series for coal prices, one for power plants and one for industry, where some costs are added for the extra transport and handling costs to bring the coal to the industry.

Table 6 Efficient lighting in the service sector



Efficient lighting.

Costs in US$	Mitigation	Reference	Increase
Total investment	17000	8000	
Project life (years)	5.5	5.5	
Ann. Levelized investment	4179	1966	2212
Ann. O&M	45	268	-223
Lev. inv. in power plant	967	5528	-4560
Ref. power plant O&M	124	706	-582
Ann. fuelcost	249	1373	-1124
Total annual cost	5563	9841	**-4278**

Annual emissions (tons)	Mitigation	Reference	Reduction
Fuel CO2 emission	10.2	58.5	48.3
Fuel N2O emission	0.000	0.001	0.001
Fuel CH4 emission	0.000	0.001	0.001
Total CO2 equivalent	10.3	58.8	**48.5**
Tons CO2 equiv. reduction/unit			0.05
US$/ton CO2 equivalent			**-88.21**

Notes:
The option assumes replacement of incandescent lamps with compact fluorescent lamps. The life of the compact lamp is taken as the project lifetime.

The mitigation option:

Technology:	Compact fluorescent lamps	
Cost of eff. lamp	17	US$
O&M (lamp change)	0.18	US$
Unit wattage	7	W
Daily usage	4	hours
Lamp lifetime	8000	hours
Unit electr. Consumption:	0.0102	MWh/unit-year
Number of units	1000	locations
Annual electricity used	36.8	GJ/year

Is replacing the reference option I

Technology:	Incandescent bulps	
Cost of incand. lamp	1	US$
O&M (lamp change)	0.18	US$
Unit wattage	40	W
Daily usage	4	hours
Lamp lifetime	1000	hours
Unit electr. Consumption:	0.0584	MWh/unit-year
Number of units	1000	locations
Annual electricity used	210.2	GJ

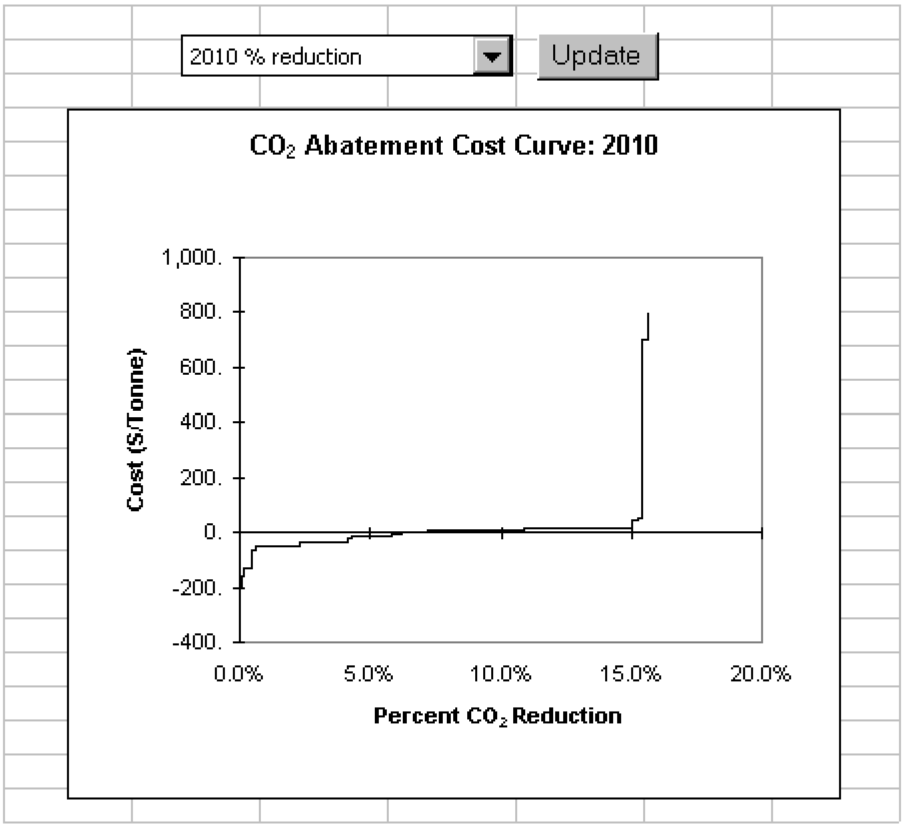
Reference power plant:

Invest. in power plant	1000	US$/kW
Power plant fuel	Coal to power plants ▼	
Life time of power plant	20	years
Capacity factor	3504	hours
Electric efficiency	0.4	
Electricity transfer losses	0.15	
Ref. power plant O&M	2.0%	

The "Prices" spreadsheet contains all the fuel price time series for the main fuels. Since the cost curve covers all mitigation options penetrating into the system until the target year (here 2010) and since there is assumed no information of when the mitigation options are introduced in the period, the model calculates an average fuel price over the period. This is done by calculating the net present value of the fuel cost over the period, and then levelising this net present value over the period.

In Figure 1 the cost curve is show, illustrating the results in the “Main” spreadsheet in Table 4. The user has chosen to show the results as the costs versus the percentage reduction in the CO_2 equivalent emissions.

Figure 1 CO_2 Abatement cost curve



Chapter 2: Integration of Market Economics in the Assessment of Mitigation of Enteric Methane Mitigation Options In Developing Countries

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1.0 Introduction

This paper provides an example of how one might assess the mitigation of methane from enteric fermentation in ruminant livestock in a developing country. The strategy to be assessed involves introducing strategic supplementation to improve the feed conversion efficiency of dairy cattle, and thereby significantly reduce methane emissions per unit product from these livestock. The example integrates the IPCC methodology for calculating methane emission reductions from ruminant livestock within a conventional neo-classical economic framework for estimating product (i.e., milk) supply and demand. The economic framework is used to estimate the effects of exogenous changes in population, income, animal productivity and livestock feed costs on milk production and consumption, milk prices, and the number of dairy cattle required to satisfy the demand for milk. The IPCC methodology is then used to determine the change in methane emissions as a result of the change in animal productivity, the digestibility of feed and animal weight, and livestock numbers. As such, this analysis departs from most existing livestock mitigation studies in that the levels of production and animal numbers are determined endogenously, within the economic framework, rather than treated as exogenous parameters that one must forecast by other methods.

The example in this paper is hypothetical in that the much of the data used to characterise economic development, mitigation costs, the characteristics of the livestock population, and the effects of changes in feeding practices on feed digestibility and animal productivity are made up. Nevertheless, the data were chosen to be indicative of conditions in a developing country and the results are in line with what might be expected in a developing country context, based on a sampling of previous studies.

The paper is divided into six parts. Following the introduction, Section 2.0 presents a brief overview of methods for mitigating methane emissions from enteric fermentation in ruminant livestock. Section 3.0 provides background information about the broad opportunities for, and limitations associated with, reducing methane emissions in developing countries. Section 4.0 describes the integrated methodology for projecting livestock numbers, production, and methane emissions reductions. Section 5.0 provides the data and assumptions used in constructing the base case and the mitigation scenario. Finally, Section 6.0 presents the results of the mitigation analysis. Appendix A contains a listing of the computer code used to generate the economic results for the example.

2.0 Strategies for Reducing Methane Emissions from Enteric Fermentation

Methane is produced in herbivores as a by-product of *enteric fermentation*, a digestion process by which carbohydrates are broken down by microorganisms into simple molecules for absorption in the bloodstream. Both ruminant animals (like cattle and sheep) and some non-ruminants like pigs produce methane. The amount of released methane depends on the type, age and weight of the animal, the quality and quantity of the feed and the energy expenditure of the animal.

Methane emissions per animal can vary widely – from 50 l/day to 500 l/day – depending on the above factors. However, under a wide variety of every day conditions, these emissions are a relatively constant fraction of the diet consumed, about 6% of diet energy or 2% of the diet by weight. Most of the options used to reduce methane emissions from ruminant livestock focus on decreasing the feed intake required per unit of product – milk, meat and work – by means of simultaneous improvements in diet quality and animal productivity.

The effectiveness of this strategy is based on shifting feed intake from maintenance to production. The feed required to maintain livestock is approximately the same for a low producer as for a high producer. However, when productivity is increased, the proportion of feed going to maintenance is reduced, and methane emissions per unit of product decrease. For example, for a 400-kg dairy cow an increase in productivity from 2.2 to 4.4 kg/day can reduce methane emissions by 40% per kg of milk. This means that one can produce the same amounts of milk, meat and work as in the base case from fewer animals. By cutting the herd size, while maintaining production at base case levels, methane emissions are reduced.

The range of options available for reducing methane emissions from enteric fermentation in ruminant animals include:

1. Mechanical and chemical feed processing. These measures generally involve chemical treatment of straw, using alkali/ammonia and chopping of low quality straw. Assuming that feed digestibility is increased by 5%, methane emissions per unit of product may decrease around 10 to 25% depending on management practices.

2. Strategic supplementation. These options include using molasses/urea supplements, rumen bypass product, bioengineering of rumen microbiota, and mineral supplements. Using these methods can reduce methane emissions by 25 to 75% per unit of product.

3. Enhancing Agents. Methane emissions per unit of product can be reduced substantially by using bovine somatotropin, anabolic steroids, and other agents.

4. Genetic Improvement. Crossbreeding and upgrading (especially in developing countries), as well as genetic improvements in the stock and genetic engineering are among the methods that can be used to increase animal productivity.

5**. Reproductive improvement**. Methods that improve animal productivity indirectly reduce the numbers of animals needed to produce offspring, and this leads to reduced methane emissions However, there are direct measures which can achieve the same result, including twining, embryo transplants, artificial insemination, and estrus synchronisation.

3.0 Background: Mitigation Opportunities in Developing Countries

According to IPCC (1992) estimates, domesticated ruminant animals are the second largest source of global methane emissions, accounting for around 15-20 percent of total methane emissions worldwide. In many developing countries, rural and urban populations are highly dependent upon ruminant animals for food and milk, and in many developing countries, ruminant animals are the primary source of draft power. In these countries, methane emissions from ruminant animals may constitute half, or more, of total methane emissions. Thus, the livestock sector in developing countries represents an important potential target for mitigating methane emissions.

3.1 Opportunities for Methane Mitigation

One need only look at the statistics on production and methane emissions per unit product for dairy cattle (Table 1) to understand the potential for reducing methane emissions in developing countries through better feeding practices and improved animal husbandry. For example, mature dairy cattle in North America produce about 14 times as much milk, on average, as dairy cattle in Africa and the Middle East. By contrast, diary cattle in North America produce only 3.28 times more methane per head. Thus, methane emissions per kg of milk are roughly 75% ([.0176-. 0758]/. 0758) lower in North America than in Asia, a significant difference.

Table 1. Comparative Regional Estimates of Milk Production, Enteric Methane Emissions per Head, and Enteric Methane Emissions per Unit of Milk for Dairy Cattle

Region	Ave. Milk Production kg/head/yr	Emissions kg/head/yr	Emissions per kg Milk Kg/yr
North America	6700	118	.0176
Western Europe	4200	100	.0238
Eastern Europe	2550	81	.0318
Oceania	1700	68	.0400
Latin America	800	57	.0713
Asia	1650	56	.0339
Africa and Middle East	475	36	.0758
Indian Subcontinent	900	46	.0511

Source: IPCC, 1997. Computed from Table 4-4, p. 4-11

3.2 Barriers to Implementing Mitigation Options in Developing Countries

However, while the figures in Table 1 are indicative of the potential reductions in methane that can be achieved by better feeding and animal husbandry practices, it would be wrong to assume that the results from developing countries can easily be applied in developing countries. There are a number of reasons for this, many of them related, generally, to the problems of improving productive efficiency in subsistence agriculture.

In many developing countries the majority of livestock are held by owners of small farms, operating at a subsistence or near-subsistence economic level. These individuals may own less than 5 mature animals, used for multiple purposes – as draft animals, for milk production, to produce calves for slaughter, etc. The products from these animals are consumed by family members, although a small portion of production may be sold in local markets. Under these conditions, improving productivity may make sense in some cases, for example to increase milk production for family use. But in other cases, such as with draft animals, improving productivity on small holdings frequently has no economic justification, because the existing demand for work can be met by the existing animals, maintained for most of the year on a low quality diet. But even if there is an economic rationale for improving productivity on these types of farms, in many cases it will be impossible to reduce animal numbers to achieve methane reductions. This is because the herds are so small and cash to buy these products in the market is scarce.

Cash constraints in subsistence farming are also important because improving feeding practices and animal husbandry comes at a cost. While it is clear that the benefits of improving livestock productivity often outweigh the costs, the low levels of household cash income often make it impossible to realise these opportunities. At the same time, the same cash constraints on the demand side in the local economy also make it difficult to increase animal product supply, since the markets for these products are quite thin. These problems are compounded by the fact that the marketing and distribution systems required to sustain a viable trade in animal products, even within the domestic economy, are poorly developed in rural subsistence economies. Without a high level of certainty that perishable products can be marketed and sold at profit, incentives to spend scarce cash to improve animal productivity are extremely limited in subsistence economies.

There are also information problems. While changes in feeding practices and diet that improve animal productivity provide economic and sustainability benefits in their own right, information about these practices is not widely available in developing countries. Also, farm extension systems, if they exist, in many cases are not able to get this information into the hands of small farmers in rural areas. Recent interest in climate change has accelerated research in developing countries about the best practices and diets appropriate to improving animal productivity and reducing methane emissions. However, for mitigation programs to be effective they must include action plans to teach farmers how to apply new practices and use new diets. Lack of information and the systems to deliver this information to many small rural farmers is compounded by the problem that it is often difficult to get small rural farmers to change their traditional practices, even if economic conditions are right for doing so. This type of inertia, to the extent that it is present, is likely to require more emphasis, and spending, on extension programs in order to convincingly demonstrate the benefits of changing feeding practices and animal husbandry in subsistence economies.

Finally, even if: a) the right information is available at the local level, b) farmers have the cash to purchase the inputs required to improve animal productivity, and c) markets and distribution systems exist to ensure that farmers can make a profit from their activities, the incentives to reduce the size of animal herds at the individual farm level, and thereby achieve methane reductions, may be mixed. In developed countries, like the US, reductions in herd sizes have been the result of economic forces in well-developed, fairly competitive markets. Increased productivity in the US, for example, led at first to "over production" and lower livestock product prices. Over time, as productivity has increased, herd size has fallen in response to these narrower profit margins. In the process, the number of livestock operations, especially in the dairy industry, has dropped while the size of these operations, in terms of the number of livestock, has increased. In the context of subsistence farming, long term developments may take the same general trends, and reductions in methane emissions can be expected as a natural outcome of the evolution from subsistence to commercial livestock economies. However, in the short run, increasing productivity may not help subsistence farmers if it leads to reduced prices, and cutting herd size is often infeasible, given the small numbers of animals on each farm.

3.3 Screening Criteria

Given these types of limitations, it is necessary in most cases to develop screening criteria in order to target the best opportunities for enteric methane mitigation options in developing countries. Based on the work of Bowman et al. (1993) in Tanzania, we suggest the following criteria:

The characteristics of target livestock:

1. A large bovine population of which a high percentage of animals are in production;
2. Less than optimal current production from these animals due to poor nutrition.

The characteristics of the farmers who manage these cattle:

1. Reliance upon the sale of animal products as the primary source of farm income;
2. Established linkages to an animal product marketing networks;
3. Access to feed inputs needed to improve production.

These criteria may be somewhat restrictive in that their application will limit the size of the target population of farms and animals to which mitigation measures can be effectively directed. The alternative is to target the larger population of animals where these characteristics are not present. However, in doing so one would have to develop a strategy for market transformation and include the costs of programmes to achieve this transformation in the cost of the mitigation strategy. This is an unrealistic option, as such.

4.0 Methodology

The methodology used in this example is divided into two parts. The first part involves projecting the demand for milk and the number of livestock required to produce that amount of milk for the base case and the mitigation scenario. The second part consists of the methodology to predict the methane emissions associated with the projected levels of milk demand and livestock numbers.

4.1 Economic Methodology

Most existing studies of enteric methane mitigation options focus on the dietary aspects of the problem and on the translation of changes in diet into changes in methane. The economics of changing livestock diets, if it is treated at all, it is treated from the farm, as opposed to the market (Bowman et al. 1993, Bowman et al. 1992). That is: the economic costs and benefits of changing feeding practices are estimated for a typical livestock operation, assuming that changes in input costs and production do not affect market prices for livestock products. As such, economics does not really enter into the projection of future product demand. Instead, the level of future product demands are extrapolated from existing trends in population growth and income, without reference to the possible impacts of changes in diet on future market prices.

The problem with this approach is that it neglects the effects of changes in feeding practices, directly and indirectly, on future product prices and the inter-relationship between market prices, population and income growth, and production levels. This is not a serious problem if the demand for milk is not very price responsive and the changes in production that are anticipated are small. However, these are empirical, not theoretical issues.

Illustrative Example

Figure 1 can be used to illustrate the problems of projecting the market demand for milk. In this figure the market demand curve for milk in the base period is shown as D1 and the corresponding market supply curve for milk is S1. We assume that the market demand for milk

(Q^d) is a function of the market price of milk (P), population (Pop), and income (Inc). We can write this expression as a linear function:

$$Q^d = A_0 + A_1P + A_2Pop + A_3Inc \qquad (1)$$

where the parameters A_1, A_2, and A_3 measure the linear effect of a one unit change in P, Pop, and Inc, respectively, on the quantity demanded, Q^d. The parameter, A_0, or the intercept term, indicates the level of product demand, when the other variables on the right-hand side of the "=" expression are all zero. In this case, we assume that an increase in milk price reduces the demand for milk (i.e., $A_1 < 0$). Thus, the demand curve is downward sloping. We assume that increases in the last two variables, income and population, have the effect of increasing the demand for milk and shifting the demand curve to the right, for example to D2. Thus, A_2 and $A_3 > 0$.

We assume that the amount of milk supplied to the market (Q^s) is a linear function of the market price of milk (P) and the unit (milk) cost of feeding cattle, which we express as F/Yld, where F is the average cost of feeding a single milk cow and Yld is a measure of the average daily yield of milk cattle. This expression can be written as:

$$Q^s = B_0 + B_1P + B_2(F/Yld), \qquad (2)$$

where the parameters B_1 and B_2 measure the linear effect of a one unit change in the price of milk and the unit (milk) cost of feeding cattle, respectively, and B_0 is the intercept term. In this case, we assume that $B_1 > 0$, meaning that an increase in the price of milk increases the amount of milk supplied to the market. An increase in the unit cost of producing milk, on the other hand, has the opposite effect, reducing the amount of milk supplied to the market, and shifting the supply function to the left, for example to S2. So, $B_2 < 0$. Note, however, that the unit (milk) cost of feeding cattle is composed of two terms, the average cost of feeding a cow, F, and the average daily milk yield, Yld. An increase in F, holding Yld constant, results in a decrease in Q^s; however an increase in Yld, holding F constant, reduces the unit (milk) cost of feeding cattle and, thus, increases production through a shift in the supply curve to the right, for example to S3.

The selection of the variables F and Yld and their translation into a single expression in the supply function is not arbitrary. First, there is an underlying theoretical rationale for putting input costs into the supply function for a commodity (Silberberg, 1978). Second, these two variables are likely to be the ones most directly effected by mitigation options that involve improving the nutrition of cattle. In particular, the use of dietary supplements to improve nutrition and animal productivity will result in both higher average costs of feeding cattle and increases in average daily milk yield. Therefore, to effectively model the market supply of milk, both terms should be included in the supply function. Expressing these two variables as the ratio, F/Yld, has the effect of combining these two variables in a theoretically correct manner in a single term that represents the unit (milk) cost of the mitigation option[1].

In the market depicted in Figure 1, both the market production level of milk (Q) and the market price of milk (P) are determined endogenously solving equations 1 and 2 for Q and P. The base period market price-quantity equilibrium is determined by the intersection of the D1 and S1

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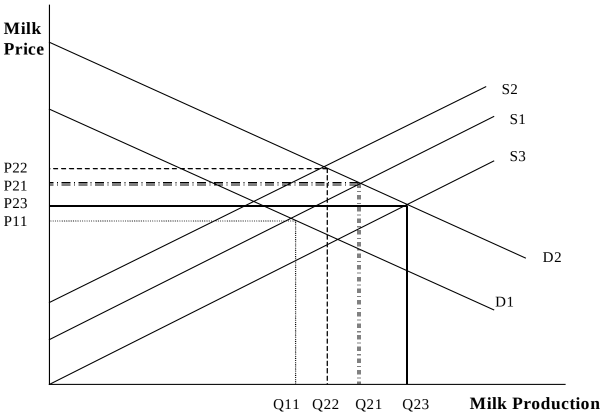
[1] For example if F is expressed in \$/animal and Yld is expressed in kg milk/animal, then combining the two terms in the ratio F/Yld gives a result expressed in \$/kg milk.

curves, where $Q^s = Q^d$ at the market clearing price P. At this equilibrium the market clearing price is P11 and the market clearing level of milk production is Q11.

Figure 1. Supply and Demand for Milk



Now let us assume that an increase in population and income, over time, result in a shift in the demand curve from D1 to D2. For any given market price along this new demand curve, more milk is demanded than along the original demand curve, D1. How will improving the diet of cattle effect the future level of production in the market, given a change in the average cost of feeding cattle and average daily milk yield?

Three different scenarios are depicted in Figure 1, as follows:

1. Supply Curve S1 – F and Yld increase by the same percentage,
2. Supply Curve S2 – F increases by a greater percentage than Yld,
3. Supply Curve S3 – Yld increases by a greater percentage than F

In Scenario 1, the supply curve does not shift at all because the unit (milk) cost of feeding cattle does not change. In this case, both the market clearing level of production, Q21, and market price, P21, increase relative to the base case. In Scenario 2, the supply curve shifts to the left because the unit (milk) cost of feeding cattle increases. As a result, the market clearing level of milk production falls to Q22 relative to the base case, while the market price of milk increases to P22. In Scenario 3, the supply curve shifts to the right because the unit (milk) cost of feeding cattle is lower than in the base case. As a result of this shift, milk production is higher at Q23 than in the base case and all of the other scenarios, while the market price, P23, is lower than in the other scenarios, and only slightly above the base case price. A relatively larger increase in Yld, holding F constant, would result in even higher milk production in the market and a lower market price. Obviously, Scenario 3 is the most beneficial from the standpoint of economic development and consumers.

The preceding illustration and discussion highlights the difficulties of projecting livestock product output for use in a mitigation assessment, and draws attention to the need to try to introduce a bit more economic rigour into the assessment of these options. However, the graphic analysis needs to be expanded to show how the problems illustrated above might be overcome in practice.

Estimation of Milk Supply and Demand Equations

To project the demand for milk in the base case and in various mitigation strategies, it is first necessary to estimate the parameters of demand and supply equations, like those shown in equations 1 and 2. In carrying through our example, we will assume that linear demand and supply equations are appropriate functional forms for the analysis. This simplifies the analysis for the sake of exposition and the steps that one takes to implement the economic methodology for other functional forms is not any different than in the linear case.

To estimate the parameters (the A and B terms) in equations 1 and 2, one needs to have time series, or cross-sectional, data for all of the variables in the two equations, consisting in this example of observations on:

- Milk production
- Milk consumption
- Market prices of milk
- Population levels
- Income levels
- Average cost/animal of feeding milk cattle
- Average daily milk yield.

The most important aspect of the data development involves targeting the correct production system. As stated earlier, the most opportune mitigation strategies and those that are likely to be most effective involve the market sector of livestock production. Therefore the data on milk production, average cost of feeding livestock and milk yields, in particular, must be relevant for the sector that has been targeted for the mitigation strategy. However, this sector may constitute less than half the milk production in the country as a whole, and represent an even smaller share of livestock holdings.

One strategy for getting around this problem, as far as data on total production and consumption are concerned, is take advantage of the relatively slow growth in most developing countries of the subsistence part of the livestock sector and the fact that livestock production in this sector is relatively insensitive to market price fluctuations. If these conditions hold true, then it may be possible to construct a simple model to account for annual milk production/consumption in the subsistence sector from existing data on population, livestock numbers, and product yield from subsistence agriculture, and then subtract these estimates from the annual estimates of total milk production/consumption in the time series. Data series on the average cost of feeding animals and average milk yields can be constructed from the same type of farm level data used in existing studies to estimate the cost and benefits of improved livestock nutrition.

The parameters of equations 1 and 2 can not be estimated directly by ordinary least squares (OLS), because the parameter estimates obtained from doing so are inconsistent (Johnston, 1974). One way to get around this problem is to estimate "reduced form" equations for the equilibrium levels of production and market prices. The reduced form forms for equations 1 and 2 in this example can be found by setting $Q^s = Q^d$ and solving for P and Q in terms of the four exogenous variables Pop, Inc, F and Yld. The resulting coefficients on these variables are the parameters of the reduced form equations, all of which are linear combinations of the parameters in equations 1 and 2. Consistent estimates of the parameters in equations 1 and 2 can be found by solving a system of equations in which these parameters are expressed as linear combinations of the reduced form parameters[2].

For this example, we assume that the resulting estimates of the supply and demand equations are as follows:

$$Q^d = \mathbf{-154.8961 - 9.6993}P + \mathbf{35.2619}Pop + \mathbf{.4403}Inc \qquad (3)$$

$$Q^s = \mathbf{-375.1065} + \mathbf{34.3643}P - \mathbf{2.2031}(F/Yld). \qquad (4)$$

The Economic Model

The market demand and supply equations for milk in equations 3 and 4 can be used to project not only milk production, but also the economic costs and benefits associated with changes in population and income, over time, and the mitigation scenarios (through changes in F and Yld). To do this, one can use equations 3 and 4 to form a benefit function, which expresses the sum of consumers' and producers' surplus for a given level of milk production. Consumers' surplus is measure of the net benefits which consumers receive from purchasing a good, as opposed to doing without it, while producers' surplus is a measure of the net benefits received by farmers, as opposed to not producing the good. It is also a measure of the "quasi rents", or profits, associated with production. The maximisation of consumers' and producers' surplus yields production and consumption outcomes that are consistent with profit maximising behaviour in competitive markets (Just, Hueth and Schmitz, 1982). To form this benefit function, equations 3 and 4 are used to form the inverse demand and supply functions[3]:

$$P = -15.9670 - .1031Q^d + 3.6355Pop + .0454Inc \qquad (5)$$

$$P = 10.9156 + .0291Q^s + .0641(F/Yld) \qquad (6)$$

The sum of consumers' and producers' surplus is equal to the total willingness to pay for milk ($TWTP_M$):

$$TWTP_M = \int(-15.9670 - .1031Q^d + 3.6355Pop + .0454Inc)dQ^d \qquad (7)$$

$$= -15.9670Q^d - .1031\, Q^{d^2} + 3.6355Pop*Q^d + .0454Inc*Q^d$$

minus the cost associated with producing milk (PCost):

$$PCost = \int (10.9156 + .0291Q^s + .0641(F/Yld))dQ^s \qquad (8)$$

$$= 10.9156Q^s + .0291Q^{s^2} + .0641(F/Yld)*Q^s$$

---

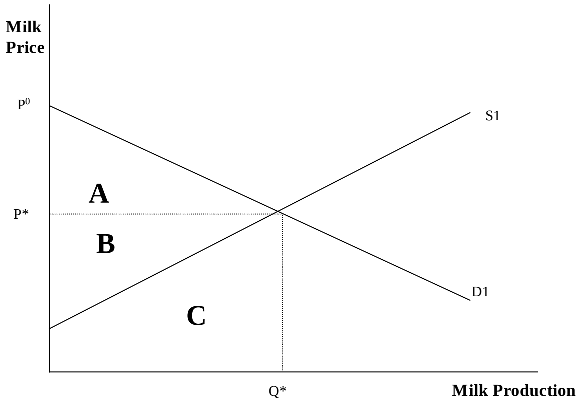
[2] In fact, this particular system is "over-identified" because there are a total of eight structural parameters in the two reduced form equation, but only seven parameters in the two supply and demand equations.

[3] These functions are derived from the parameters of the demand and supply functions, directly. The only difference is that the dependant variable is the market price of the good and the quantity demanded or supplied is an independent variable, along with the other exogenous variables.

minus the investment cost (InvestCost) associated with the mitigation option, not reflected in the additional feeding cost. This would include public investments in infrastructure, marketing, and extension services required to ensure the effectiveness of the mitigation option.

The relationship between TWTP, producers' and consumers' surplus and PCost is illustrated in Figure 2. This figure shows the same demand and supply curves for milk, as in Figure 1. The market equilibrium (P*, Q*) is represented by the intersection of the demand and supply curves, where the marginal cost of producing milk, just equals the price at which milk is demanded. Total willingness to pay for milk is a measure of the gross benefits consumer receive from being able to purchase milk at the price P*, instead of P^0. This measured in money terms by the area A+B+C. To calculate consumers' surplus we subtract the expenditure on milk (P*xQ*), or the area B+C, from TWTP, leaving the area A as a measure of consumers' surplus. Producers' surplus is equal to the revenue which producers receive from milk sales (P*xQ*), less the variable production cost, PCost represented by the area C, leaving the area B as a money measure for producers' surplus. Thus, the sum of producers' and consumers' surplus, A + B, is equivalent to TWTP minus PCost, or A + B + C – C = A + B. The value of the investment cost can not be illustrated in this diagram, because it is not a function of milk production.

Figure 2. Welfare Measures in Milk Markets



Given the above definitions, the market model in the example involves solving for the milk demand and supply levels, Q^d and Q^s, that maximises the sum of consumers' and producers' surplus (CS + PS):

Max CS + PS = Max TWTP – PCost – InvestCost =

$$-15.9670Q^d - .1031\, {Q^d}^2 + 3.6355Pop*Q^d + .0454Inc*Q^d - \tag{9}$$
$$(10.9156Q^s + .0291{Q^s}^2 + .0641(F/Yld)*Q^s) - InvestCost$$

Subject to:

$$Q^d - Q^s = 0. \tag{10}$$

From this model, the market clearing price for each solution can be calculated using equations 5 or 6. In addition to providing the information to calculate the total surplus (CS + PS) and production cost, market profits can be calculated as P*Q – Pcost, and total livestock can be estimated as $Q^s/(Yld*365)$. This model, slightly modified to include imports of milk and processing capacity constraints, was programmed in GAMS and used to estimate milk production, consumption, the number of dairy cattle, and the various welfare measures. A listing of the model is provided in Appendix A.

4.2 Methane Emissions Methodology

The methodology to calculate methane emissions associated with a given type of feeding practice for an "average" milk cow in the target herd is calculated following the Tier 2 methodology for estimating enteric methane emissions in the IPCC guidelines for constructing greenhouse gas inventories (IPCC 1997). This methodology is used in this example to calculate methane emissions both in the base case and in the emissions reduction scenario.

Methane emissions should be estimated for different groups, or sub-populations, of animals in each of the targeted populations. For example, a specialised dairy production herd generally consists of mature milking cows, some of which are pregnant for part of the year, calves, and breeding bulls.

The methodology follows four steps, as follows:

1. **Step 1: Data Collection**. The following data need to be collected to implement the methodology:

- Annual average number of animals in the target sub-populations– this is an out put of the economic model,
- Methane conversion rate – percentage of feed energy converted to methane, and
- Average daily feed intake.

- If data are not available for average daily feed intake, this can be calculated using the Tier 2 methodology in conjunction with the following data for the target sub-population:
  - Average animal weight,
  - Average weight gain per day,
  - Milk production per day,
  - Average amount of work performed each day, for draft animals,
  - Percent feed digestibility.

2. **Step 2: Estimation of Feed Intake**. Feed intake can be estimated based on the feed energy requirements of the different types of animals, using the data described above. The Tier 2 methodology uses the NRC (1984, 1989) methodology as a starting point. The 17 equations that form this methodology can be found in the IPCC guidelines (1997) in Section 4. This methodology first calculates the net energy requirements associated with maintenance, growth, lactation, draft power, and pregnancy. Then, the net energy requirements are translated into gross energy through a second set of equations. The estimates of gross energy requirements are used in the next step of the methodology to estimate emissions factors for each animal sub-population.

3. **Step 3: Estimation of Emissions Factors**. Emissions factors for an "average animal" in each sub-population are estimated using the following equation:

Emissions$_i$ (kg/yr) = Gross Energy (MJ/day)*Methane Conversion Rate (a fraction)*6.56 (a constant conversion factor)

where i is an index which denotes the sub-population.

4. **Step 4: Estimation of Total Emissions**. To estimate total methane emissions, the emissions factors from the previous step are multiplied by the number of animals in each population group, and then summed over all the sub-populations.

4.3 Methodology Summary

The methodology, presented here, can be summarised as follows:

1. Calculation of Base Case Emissions, Costs and Benefits (1998, 2010, 2030) – to accomplish this we take estimates of population, income, the unit (milk) costs of feed, and average daily milk yield for each of the three periods and enter them into the economic model. The economic model calculates:

- Annual milk consumption/production,
- Herd size,
- Total surplus,
- Economic cost,
- Profit,
- Per capita milk consumption.

Next we use the IPCC methodology to estimate gross energy requirements and methane emissions for the dairy herd, given projected feeding practices, average daily milk yield in each period, and the size of the dairy herd, as projected by the economic model.

2. Construction of Methane Mitigation Scenario (2010 and 2030) – this involves determining the impact of improved feeding over time (i.e. in 2010 and 2030), through the use of strategic supplements, on:

- Average daily milk yield
- Average animal weight,
- Average weight gain per day,
- Milk production per day,
- Average amount of work performed each day, for draft animals,
- Percent feed digestibility,
- Unit cost of feeding cattle, and
- Public investment in infrastructure, marketing and extension programs, etc.

3. Calculation of Emissions, Cost and Benefits for the Mitigation Scenario (2010 and 2030) – first, the economic model is used to forecast milk production, the size of the dairy herd, and the associated costs and benefits (see 1, above), given changes in the unit cost of feeding cattle and average daily milk yield, holding population and income constant at base case levels. The IPCC methodology is then used in conjunction with the herd size estimate obtained from the economic model, and the scenario information (see 2, above) to calculate methane emissions for the two periods.

4. Estimation of Emissions Reductions and the Costs and Benefits of these Reductions (2010 and 2030) - Estimates of emissions reductions for 2010 and 2030 are estimated from 1 and 3 above. Further, we present the normalised costs and benefits for the emissions reduction scenario from two different perspectives, as follows:

- Change in total surplus per ton of reduced methane emissions,
- Change in economic cost per ton of reduced methane emissions.

5.0 Characteristics of the Base Case and Mitigation Option

The livestock sector country in this example is assumed to have three different farm systems.

An agro-pastoral system, in which the farmers and their families move with their livestock in search of pasture. The cattle held by these farmers are native breeds and are used as multi-purpose animals to produce milk and meat. An average family owns from 5 to 10 animals. Most of the animal products from these herds are consumed directly by the farmer, although some milk is sold locally for cash when markets are within reach. Herds are maintained almost entirely on low quality forage from grazing lands. Average milk production per head in this system is about one to two litters per day.

Small, family subsistence farms, which exist within a private land tenure system. The small cattle herds owned by these farmers consist almost entirely of native breeds, and are used to provide draft power for the cultivation of subsistence crops, meat and milk for family consumption. A “typical farmer” in this system own 3 to 4 multi-purpose cattle. Depending on farm size and proximity to local village markets, some milk (approximately twenty-five percent of total production) is sold locally in nearby markets, as conditions permit. Herds are maintained on a combination of low quality forage from unmanaged pastures and low quality supplements in the form of straw and leaves, and this is sometimes fairly low quality hay. Average milk production is around two to three litters per day.

Intensively managed commercial livestock enterprises, consisting largely of improved or crossbred dairy cattle. The average dairy farmer in this system owns about 20 mature dairy cattle, although on some farms the number is over 50. Milk production from this part of the sector meets about thirty percent of the country’s average annual average milk consumption, most of it originating in urban areas where population is heavily concentrated. However, improved dairy cattle in this type of economy will typically make up a much smaller fraction of the national herd. This imbalance is due to the fact that dairy animals in the commercial herd are much more productive than in other segments of the sector. Animals are fed on a combination of improved forage and locally available supplements, and sometimes grain. Average daily milk production from these herds can be as high as about 10 litters per day for cross-bred cattle to about thirty litters a day for pure-bred cattle. Still, because many of the animals receive sub-optimal nutrition, average daily milk production for this group as a whole is quite low by developed country standards, averaging around 1.9 to 2.4 kg/day.

This example focuses on the production by the last group of farmers and their urban outlets. While the agro-pastoral and subsistence farms systems have by far the largest number of cattle, they also have the lowest levels of milk production, and are poor candidates from an economic development perspective for implementing a methane mitigation strategy. This is because farms in these sectors generally lack access to markets both for milk and the inputs needed to increase production, and because they do not operate in a cash economy.

The current milk market supply and demand in this country is depicted by the input-output structure, shown in Table 2. The rows in this table show average annual production from the three milk supply systems, above, while the columns show the demand for milk from three market segments – subsistence families, rural villages, and urban centres.

Table 2. Input-Output Table for Milk

	Kg Milk Sold from Production Sectors (Rows) to demand sectors (Columns) in 10^6 Kg/yr			
Production Sectors	Family units	Rural villages	Urban	Total Supplied
Agro-pastoral	220.5	0.0	20.8	241.3
Subsistence farms	355.2	0.0	135.0	490.2
Commercial farms	0.0	307.4	8.5	315.4
Total Demanded	575.7	307.4	164.3	1046.9

Current and projected urban population and urban per capita income are shown in Table 3. Between 1998 and 2030, the urban population is expected to grow at an average annual rate of about one percent, while per capita income is expected to grow at about half that rate, implying an average annual growth rate for total income of about 1.5 per cent. Assuming current levels of urban per capita milk consumption (43 kg/yr), the government has projected a fifty- percent increase in urban milk consumption by the year 2030.

The projected estimates for population and income are used in the analysis for both the base case and the mitigation scenario. However, the projections for urban milk consumption and livestock, shown in Table 3, are probably not reliable, because they are based on extrapolations of existing milk consumption and productivity estimates, respectively. It is more likely that, as the urban milk market increases in size, two things will happen. First, as per capita incomes rise, milk consumption will increase more rapidly than the population. Second, as urban milk consumption increase milk prices will rise and this will provide incentives for farmers to increase the productivity of their livestock. As a result of these increases in productivity, production will increase, but the number of dairy cattle required to meet this production will fall. It is even possible that the total number of cattle will decrease even though milk production will increase by 50% or more.

Table 3. Current and Projected Urban Population, Per Capita Income, Milk Consumption, and Commercial Dairy Cattle 1998-2030

	1998	2010	2030
Urban population (millions)	7.1	8.0	9.9
Urban Per capita income (USD)	140	150.4	169.5
Urban Milk[1] consumption (10^6 kg/yr.)	307	345	425
Dairy Cattle[2] (10^6)	444	498	612

[1] Projected assuming current per capita consumption (43 kg/yr.).
[2] Projected assuming current productivity (1.9 kg/yr./animal).

There are two chief problems facing the domestic production market, if it is to expand these demands for milk in future years. The first is that the diets on which many dairy cows are fed are protein and mineral deficient. This stems from the fact that the improved breeds on many of the small commercial farms are fed fairly traditional diets. Farmers can make an adequate profit using diets consisting of locally available forage and supplements, and the government extension service is too small to undertake the programs necessary to educate farmers about the benefits of using supplements to increase both milk production and farm profits from existing herds. The second is that milk-processing capacity in the country is under-utilised, and is running at about 30% of total capacity. This situation exists because small commercial farmers often prefer to use non-formal channels, where they can make a higher profit. As fewer and fewer farmer's sell to processing plants, the state-owned facilities are forced to lower the offer price for delivered milk, and to cut back on operation and maintenance costs, thus aggravating the situation.

It has been typical in the literature to assume that the projected future demands for milk, like those shown in Table 3, can be achieved by one of the two following strategies. The first is to increase the size of the existing dairy herd by around 150 thousand, or more, animals. The second is to improve the productivity of existing animals, while making much more modest additions to the total herd size. In the former case, methane emissions could be expected to rise in direct proportion to animal numbers. In the latter case, however, improvements in productivity would likely offset increases in methane, and while methane emissions could be expected to increase in relation to 1998 levels, they would undoubtedly much smaller than in the first scenario.

However, as will be seen, it is possible that as the demand for milk increases, this will stimulate farmers to make productivity improvements on their own, based purely on the additional net revenue that can be generated by these improvements. As such, a more realistic market projection might not show a very large increase in the number of dairy cattle required to meet the higher demand levels. On the other hand, it may be possible to increase productivity still further by modest government investments in extension services and milk marketing. While this may (or may not) lead to some reduction in total welfare, these expenditures could increase the average productivity of the dairy herd so that the herd size could be reduced, without reducing milk production, and at the same time reducing methane emissions from the base case.

5.1 The Base Case

The base case is a "market-driven" scenario. In this case, it is assumed that newer feeding practices, involving the use of supplements to correct protein and mineral deficiencies, will penetrate the market slowly without additional government programs. This is because these practices are more profitable than existing practices, and the number of farmer's who recognise this is expected to increase.

The effects of these supplements on mature dairy cows, the increased costs of feeding animals the better diet, as these practices are projected to penetrate the commercial milk market is shown in Table 4.

Table 4. Base Case Production Parameters

	Current Rations 1998	Improved Rations 2010	Improved Rations 2030
Cow weight (kg)	400	400	400
Kg milk/day	1.90	2.47	3.80
Digestibility %	60.00	60.75	62.50
Lactation days/yr.	125.00	127.50	132.50
Economic Cost ($/yr)	100	106	120

5.2 The Mitigation Scenario

In the mitigation scenario, the government commits itself to making a number of investments designed to speed the adoption of the new rations by the commercial livestock sector. An important objective of this policy is to reduce methane emissions below base case levels while limiting the growth of the domestic herd size. These investments include:

- Expansion of the existing agriculture extension system to provide more trained staff in the field to assist farmers in adopting the new rations.
- Subsidies for expanding the production capacity of supplements by giving producers low interest loans with long term pay back provisions.
- Refurbishing of existing milk processing facilities and increased staff training so that these plants can compete more effectively in the market with the informal channels of milk marketing.

The gross level of these investments, their annualised values and their expected effects on livestock production and costs are shown in Table 5.

Table 5. Mitigation Scenario Production Parameters

	Current Rations 1998	Improved Rations 2010	Improved Rations 2030
Total investment ($/yr.)	0	50.00 million	40.00 million
Annualised investment ($/yr.)	0	3.59 million	2.87 million
Cow weight (kg)	400	400	400
Kg milk/day	1.90	4.18	5.70
Digestibility %	60	63	65
Lactation days/yr.	125	134	140
Economic cost ($/yr)	100	124	140

6.0 Results of the Analysis

This section presents the results separately for the base case, the mitigation scenario, and a comparison of the changes in welfare and methane emissions between the two cases.

6.1 Base Case

The main results for the base case in the example are highlighted in Table 6. Between 1998 and 2010 domestic milk consumption/production increased by around 105%, from 307.4 million kg/yr. in 1998 to about 630 kg/yr. in 2030. This rapid rate of increase in milk consumption/production are due to a combination of two factors: 1) increases in per capita milk consumption, which rose from about 43 kg/year to around 64 kg/yr. between 1998 and 2030 and 2) the 2-fold increase in animal productivity projected for the base case.

During the entire projection period, milk prices increased by about 35%, due to the increased demand for milk as a result of population and income growth. This price increase would have been even greater, but for the increases in animal productivity that lowered marginal production costs.

Domestic welfare associated with the production and consumption of milk also increased substantially over the projection period, from $62.6 million in 1998 to $262.2 million in 2030. Roughly $155.7 million of this almost $199.6 million/yr. gain in total surplus came in the form of increases in consumers' surplus (not shown), due to increased demand. The remaining portion, about $43.9 million/yr. can be attributed to gains in producers' surplus (i.e., farm profits). Farm profits are simply the difference between revenues from the sale of milk and on-farm production costs. During the period 1998 to 2030, annual farm revenues increased from around $72 million to about $197 million, or an increase of about $125 million/yr. Annual on-farm production costs increased from roughly $58 million/yr. in 1998 to $139 million/yr. in 2030, or an increase of around $81 million/yr.

Despite the approximate doubling of milk production during the period 1998-2030, the number of dairy cattle hardly increased at all, from about 444 thousand in 1998, to 454 thousand in 2010, to 454 thousand in 2030. This phenomena was due to the large increase in animal productivity projected in the example, as a result of normal market development.

The average methane emissions per animal were estimated using the NRC methodology. These emissions rose from 49.5 kg/yr. in 1998 to 59.4 kg/yr. 2030, about a 20% increase over the entire period. This can be compared with a doubling in animal productivity, so emissions per kg of milk actually fell substantially during the period. The two factors, combined, led to only a small increase in total methane emissions from 22 million kg/yr. in 1998 to 24 million kg/r in 2010, and to 27 million/kg in 2030.

Table 6. Base Case Results, Summarised

	1998	2010	2030
Domestic milk consumption/production 10^6 kg/yr.	307.37	409.042	629.845
Per capita milk consumption kg/yr.	43.3	51.1	63.6
Domestic milk price $/kg	0.23	0.26	0.31
Total surplus 10^6 $/yr.	62.598	110.596	262.222
Domestic farm revenue 10^6 $/yr.	71.533	104.592	196.944
Domestic production cost 10^6 $/yr.	57.754	80.248	139.233
Domestic farm profit 10^6 $/yr.	13.779	24.344	57.711
Total economic cost 10^6 $/yr.	57.754	80.247	139.223
Dairy Cows	443,744	453,710	454,106
Average methane emissions/Cow Kg/yr.	49.52	52.62	59.43
Total Methane Emissions Tonnes/yr.	21,974	23,874	26,988

6.2 Mitigation Scenario

The main results for the mitigation scenario in the example are highlighted in Table 7. For the period 1998 - 2010 domestic milk consumption/production increased from roughly 307.4 million kg/yr. in 1998 to 415.5 million kg/yr. in 2010, and to 633.2 million kg/yr. in 2030. Over all, this represents about a 105% increase in milk production and consumption, about the same as in the base case. Thus, the higher levels of animal productivity projected for the mitigation scenario did not appreciably affect domestic milk consumption/production and per capita milk consumption. Per capita milk consumption estimates in the mitigation scenario are less than 1 kg/yr. higher than in the base case.

Milk prices in the mitigation scenario were slightly – 1 to 4 cents – below those estimated for the base case. This can be explained by the fact that the price of milk in the example is relatively insensitive to changes in production. Thus, while the increases in production costs and productivity levels in all of the mitigation scenarios, jointly, had the effect of lowering the unit cost of feeding cattle relative to the base case, it did not have a big impact on milk prices. Also, the added investment costs in the mitigation scenario had no impact on market prices or production, because these were treated as fixed annualised costs, independent of milk production.

Domestic welfare associated with the production and consumption of milk in the mitigation scenario increased substantially over the projection period, from $62.6 million in 1998 to about $110.5 million in 2010, and to about $262.2 million in 2030. The estimates of total welfare in

2010 and 2030 are lower than in the base case – about \$ 92,300 in 2010 and \$34,000 in 2030 – because of the inclusion of the annualised investment cost in each of the two periods. Of the total \$199.6 million/yr. change in total surplus between 1999 and 2030, roughly \$155 million is represented by increases in consumers' surplus (not shown), due to increased demand. The remaining portion, about \$44.6 million/yr. can be attributed to gains in producers' surplus (i.e., farm profits). As stated previously, farm profits in the model equal the difference between revenues from the sale of milk and on-farm production costs. During the period 1998 to 2030, annual farm revenues increased from around \$71.5 million to about \$195.8 million, or an increase of about \$124.3 million/yr. Annual on-farm production costs increased from roughly \$57.8 million/yr. in 1998 to \$137.4 million/yr. in 2030, or an increase of around \$79.6 million/yr. Except for the difference in total welfare, the differences in farm revenues, farm production costs, and farm profits are almost the same – differences are around one million dollars, or less – as in the base case.

Table 7. Mitigation Scenario Results, Summarised

	1998	2010	2030
Domestic milk consumption/production 10^6 kg/yr.	307.37	415.468	633.248
Per capita milk consumption kg/yr.	43.3	51.9	63.9
Domestic milk price \$/kg	0.23	0.25	0.30
Total surplus 10^6 \$/yr.	62.598	110.503	262.188
Domestic farm revenue 10^6 \$/yr.	71.533	103.483	195.786
Domestic production cost 10^6 \$/yr.	57.754	78.368	137.440
Domestic farm profit 10^6 \$/yr.	13.779	25.115	58.346
Total economic cost 10^6 \$/yr.	57.754	81.962	140.315
Dairy Cows	443,744	272,313	304,373
Average methane emissions/Cow Kg/yr.	49.52	61.26	68.434
Total Methane Emissions Tonnes/yr.	21,974	16,682	20,829

The most important aspects of the mitigation scenario are on the number of livestock and methane emissions, relative to the base case. Even though the increases in milk production and milk consumption per capita are about the same in the two scenarios, projected livestock numbers in the mitigation scenario are much smaller. In 2010, the estimated number of dairy cattle in the mitigation scenario is about 272 thousand animals, or about 40%, below the base case estimate. The corresponding herd size estimate for the mitigation scenario in 2030 is about 305 thousand animals, or about a 33% reduction in herd size relative to the base case. Thus, the major impact of productivity improvements in the mitigation scenario is to reduce the number of dairy cattle, while maintaining production levels that are consistent with the base case.

The average methane emissions per animal in the mitigation scenario are somewhat higher in the mitigation scenario than in the base case. These emissions increased from 61.3 kg/yr. in 1998 to 68.4 kg/yr. 2030, about a 38% increase over the entire period, as compared with a 20% increase in the base case. However, these results can be compared with a tripling of animal productivity, so emissions per kg of milk actually fell substantially during the period. The two factors, combined, led to actual reductions in methane emissions, both over time and relative to the base case. Total methane emissions fell from 22 million kg/yr. in 1998 to roughly 16.7 million kg/yr. in 2010, and then rose slightly up to 20.8 million kg/yr. in 2030.

Thus, the investments by the government in information, training and improved marketing can be seen to have paid dividends in the example in the form of reduced methane emissions. This was accomplished without major impacts on milk production, milk prices, or the welfare of consumers and producers of milk, although tax payers as a whole would be required to absorb the burden of additional taxation to cover the investment costs by the government.

6.3 Mitigation Costs

Average mitigation costs in this example are measured in two different ways. The first approach is to use the ratio of the difference in total surplus to the difference in methane emissions, where the differences are measured between the base case and the mitigation scenario for 2010 and 2030. The second approach uses the ratio of the difference in total cost to the difference in methane emissions. The surplus measure is the superior of the two from a theoretical standpoint because it captures the net welfare, including both benefits and costs that producers and consumers give up as a result of the mitigation scenario. As such, it is a measure of the net market benefits, exclusive of course of environmental benefits, which society must sacrifice in order to reduce methane emissions. The second measure is the one that is typically used in cost-effectiveness calculations of mitigation measures. It includes only the cost of the real resources which producers and the government must give up as a result of the mitigation scenario. It does not include any change in market benefits. Formally, the two measures can be compared as follows:

1. Surplus $\text{Ratio}_t = \{\text{TWTP}_{mt} - \text{PCost}_{mt} - (\text{TWTP}_{bt} - \text{PCost}_{bt} - \text{InvestCost}_{mt)})\}/\{\text{ME}_{mt} - \text{ME}_{bt}\}$

2. Cost $\text{Ratio}_t^4 = -\{\text{PCost}_{mt} + \text{InvestCost}_{mt} - \text{PCost}_{bt}\}/\{\text{ME}_{mt} - \text{ME}_{bt}\}$

3. $\text{Ratio1} - \text{Ratio2}_t^4 = \{\text{TWTP}_{mt} - \text{TWTP}_{bt}\}/\{\text{ME}_{mt} - \text{ME}_{bt}\}$

where:

TWTP = total willingness to pay of consumers
PCost = sum of on-farm production cost and government investment
InvestCost = annualised cost of government investment
ME = methane emissions
m = a subscript denoting the mitigation scenario
b = a subscript denoting the base case
t = 2010, 2030

---

[4] The cost ratio has a minus sign in front of it, so it is compatible for accounting purposes with the surplus ratio. Conceptually, this is justified by the fact that costs represent a loss of welfare to society.

Thus, the cost ratio approach does not include changes in consumer willingness to pay as a result of the mitigation measure.

Table 8 presents the differences for all of the components used to calculate the two measures of the average cost of methane reductions, as well as the measures themselves. As can be seen, there are considerable differences in the magnitudes of the two measures.
For 2010, the average cost of methane emissions using the loss in net surplus as a measure of cost is around \$13/tonne methane (\$0.62/tonne CO_2), while the corresponding cost-based measure is around \$240/tonne methane (\$11.36/tonne CO_2). For 2030, the corresponding estimates of the average cost of methane emissions reductions are in the neighbourhood of \$5/tonne methane (\$0.26/tonne CO_2) and \$177/tonne methane (\$8.44/tonne CO_2).

The large differences in the "cost"/ton of methane for the two measures are due to the fact that there are offsetting differences in the sum of producers' and consumers' surplus in the mitigation scenarios due to slightly lower market prices. The resulting average cost differences in the two measures are potentially large enough to change the cost-effectiveness ranking of various options that the example country might be using for policy purposes to compare this mitigation option with others.

Table 8. Differences between the Mitigation Scenario and the Base Case for TWTP, Net Surplus, Economic Cost, Methane Emissions, and Two Measures of the Average Cost of Methane Reductions in 2010 and 2030

	2010	2030
TWTP difference 10^6 \$	-1.808	-1.126
Net surplus difference 10^6 \$	-0.093	-0. 034
Economic cost difference 10^6 \$	1.715	1.092
Emissions difference Tonnes methane/yr.	-7,192	-6,158
Surplus Ratio \$/tonnes methane \$/tonne CO_2	 12.93 00.62	 5.52 0.26
|Cost Ratio|[1] \$/tonnes methane \$/tonne CO_2	 238.46 11.36	 177.33 8.44

[1] The cost ratio is expressed in absolute terms to make it compatible with the surplus ratio.

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A.1 Appendix A

This appendix contains a listing of the GAMS program, used to conduct the example analysis. It can be copied into another document and saved as a text file and run from any platform with GAMS installed. The model includes import demands for milk at fixed prices set by the user. It also includes a capacity constraint on milk processing. These features of the model were not used in the analysis.

```
* An example model used to calculate milk supply and demand
* in an hypothetical developing country.

PARAMETERS
           POL   POPULATION IN MILLIONS
           Y     INCOME IN MILLIONS
           D     MILK PER COW IN KG per day
           FC    FEED COST PER COW
           FCC   Feed cost per Kg milk
           INV   Economic investment
           TP    IMPORT PRICE TIMES 100
           Tax    Import tax percent ;

*                         Scenarios
*
*             Pol       7.1           8.0           9.9
*             Y         994        1203.2          1678
*             D         1.9     2.47/4.18       3.8/5.7
*             FC        100       106/124       120/140
*             FCC     52.63   42.91/29.67   31.58/24.56

           POL =  7.1;
           Y =    994;
           D =    1.9 ;
           FC =   100 ;
           FCC =  FC/D;
           TP  =  50;
           INV =  0;

VARIABLES
           QS     MILK PRODUCTION (million kg)
           QD     MILK DEMAND (million kg)
           IMP    IMPORTS OF MILK
           Z      NET SURPLUS;

POSITIVE VARIABLES QS,QD,IMP;

EQUATIONS
         OBJFUN   OBJECTIVE FUNCTION
         SDBAL    SUPDEM BALLANCE
         PCON     DOMESTIC PROCESSING CONSTRAINT ;

*  The objective function is scaled by .01, since prices are expressed
*  in money units times 100.

OBJFUN..    .01*( -15.967*QD-.5*.1031*QD*QD+3.6355*POL*QD+.0454*Y*QD-
            (10.9156*QS+.5*.0291*QS*QS+.06411*(FCC)*QS) -
             (1+tax)*TP*IMP) - INV =E= Z;
SDBAL..      QD-QS-IMP =E= 0;
PCON..       QS =L= 1000000;
```

```
MODEL CATTLE /ALL/;
SOLVE CATTLE USING NLP MAXIMIZING Z;

parameters       scal      scale parm for quantities
                 pct       scale parm for milk prices
                 milksp    domestic milk supply price
                 milkdp    milk demand price
                 totwtp    Willingness to Pay
                 Totsurp   CS plus PS
                 DRevn     Domestic Reveniew
                 DProf     Domestic Profit
                 Prodc     Domestic Production Cost
                 milkc     Per Capita Milk Cons
                 ecost     Total Economic Cost
                 cows      milk cows
                 milk      milk production
                 frevn     foreign revenue
                 grevn     government revenue ;
                 scal=1000000;
                 pct=.01;
                 milksp=pct*(10.9156+.0291*qs.l+.06411*(FCC));
                 milkdp=Pct*(-15.967-.1031*qd.l+3.6355*pol+.0454*y);
                 totwtp=(scal)*pct*(-15.967*Qd.l-
                             .5*.1031*qd.l*qd.l+3.6355*pol*qd.l
                             +.0454*y*qd.l);
                 totsurp=z.l*scal;
                 drevn=milksp*qs.l*scal;
                 frevn=pct*scal*tp*(qd.l-qs.l);
                 grevn=.1*frevn;
                 prodc=scal*pct*(10.9156*qs.l+.5*.0291*qs.l*qs.l+
                                            .06411*(FCC)*qs.l);
                 dprof=drevn-prodc;
                 ecost=prodc+inv;
                 milkc=qd.l/pol;
                 cows=scal*(qs.l/(d*365));
                 milk=qs.l*scal;

display milksp, milkdp, totsurp, totwtp, drevn, frevn, grevn, prodc, dprof,
ecost, milkc, cows, milk, qd.l, qs.l, imp.l;
```

Chapter 3: Comprehensive Mitigation Assessment Process (COMAP) – Description and Instruction Manual

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1.0 Introduction

In order to prepare policies and plans to reduce GHG emissions, national policy-makers need information on the costs and benefits of different mitigation options in addition to their carbon implications. Policy-makers must weigh the costs, benefits, and impacts of climate change mitigation and adaptation options, in the face of competition for limited resources. The policy goal for mitigation options in the land use sector is to identify which mix of options is likely to best achieve the desired forestry service and production objectives at the least cost, while attempting to maximize economic and social benefits, and minimize negative environmental and social impacts.

Improved national-level cost estimates of response options in the land use sector can be generated by estimating the costs and benefits of different forest management practices appropriate for specific country conditions which can be undertaken within the constraint of land availability and its opportunity cost. These cost and land use estimates can be combined to develop cost curves (Andrasko *et. al.* 1991 and Dixon *et. al.* 1991), which would assist policy-makers in constructing policies and programs to implement forest responses.

1.1 Previous Approaches to Mitigation Assessment

The analyses of the costs, benefits, and economics of forest response options have varied in the extent and treatment of components, which should be included in the analysis of mitigation options. Table 1 summarizes the components arranged from those commonly included to those least addressed in the analyses.

Studies of the costs of mitigation options have evolved in complexity and specificity of data over the last few years. The initial studies (Sedjo and Solomon 1989, Grainger 1988, Meyers 1989 assumed a large programmatic goal and estimated land requirements and vegetation growth rates to meet it. These studies have largely been replaced by more detailed bottom-up studies (Andrasko *et. al.* 1991, Trexler *et. al.* 1989, Swisher 1991, Winjum and Lewis 1993, Dixon *et. al.* 1991). The Bottom-up studies use economic and physical data at the project and mitigation option level and report results at the national, regional or global level. However, they do not capture the dynamics of the wood-product and land-use market explicitly. Dynamic studies (Adams *et. al.*, 1993 and Alig *et. al.*, 1997) portray forest product markets, and include timber prices either exogenously or endogenously, and allow land to move between forests and other land uses in response to changes in price or land availability constraints. Such studies are more appropriate to industrialized countries where property rights are well defined and there exists functioning formal markets for wood-products and for land. Since these conditions only obtain at varying degrees in developing countries, the bottom-up approach as described in this paper would be more suited for mitigation analysis in the land use change and forestry sector.

The past approaches in analyzing mitigation options have been most useful in analyzing individual projects and/or programs in the land use sector. In order to achieve the policy goal of reducing GHG emissions while providing the desired goods and services from the sector at a minimum cost, one needs to use a comprehensive approach. The approach described here has been used in many country-level studies, and was specifically used in the UNEP study on Economics of GHG Limitation.

Table 1. Components addressed in mitigation assessments	
1.	Infrastructure and establishment costs
2.	Land and growing stock costs (opportunity)
3.	Monetary benefits (revenue)
4.	Non-monetizable costs and benefits
5.	Net present value of continuous rotations over a fixed (e.g., 50 years) or infinite period (perpetual)
6.	Capital requirements
7.	Project or regional economic impacts
8.	Macroeconomic impacts at national level
9.	Other environmental impacts (biodiversity, water quality)

In Section 2 of this paper, we briefly describe the framework of analysis, with specific attention on key concepts and terms used in mitigation analysis, and also on the description of the cost-effectiveness indicators needed to compare and rank different mitigation options. In Section 3, we present the structure of the model used to undertake mitigation assessment, with a step by step description of two modules, one covering reforestation and the other dealing with forest protection. This section includes a description of a third module for balancing the demand and supply of biomass under different assumptions regarding baseline and mitigation projections. Section 4 presents two examples of the use of COMAP to evaluate a reforestation project and a forest protection mitigation program. Appendix A presents the theory underlying the "continuous rotations" approach employed in COMAP. A brief list of generic mitigation options in land use and forestry is presented in Appendix B, including some mitigation activities in the sector that are not a part of the forest actions allowed under the Kyoto Protocol.

2.0 Brief Description of COMAP

The COMAP approach is mainly dependent on finding the least expensive way of providing forest products and services while reducing the most amount of carbon emitted from the land use sector. The approach consists of the following key steps:

(a) identification and categorization of the mitigation options appropriate for carbon sequestration for each country
(b) assessment of the current and future land area available for these mitigation options
(c) assessment of the current and future wood-product demand
(d) determination of the land area and wood production scenarios by mitigation option
(d) estimation of the carbon sequestration per unit area for major available land classes, by mitigation option

(e) estimation of the unit costs and benefits
(f) evaluation of cost-effectiveness indicators
(g) development of future carbon sequestration and cost scenarios
(h) exploration of the policies, institutional arrangements and incentives necessary for the implementation of options
(i) estimation of the national macro-economic effects of these scenarios (not reported in this paper)

The first step in the approach is to identify and categorize the mitigation options that are suitable for implementation in a country. The next step is to determine the forest and agricultural land area that might be available to meet current and future demand, both domestic and foreign, for wood products, and for land. Demand for wood products includes that for fuel wood, industrial wood products, construction timber, etc. Potentially surplus land in the future may be used solely for carbon sequestration or other environmental purposes. On the other hand, in many countries not enough land may be available, in which case some of the wood demand may have to be met through increased wood imports or through substitute fuel sources. Alternative combinations of future land use and wood product demand patterns will lead to different scenarios of the future. The most-likely-trend scenario is chosen as the baseline scenario, against which the others are compared.

The mitigation options are then matched with the types of future wood-products that will be demanded and with the type of land that will be available. This matching requires iterating between satisfying the demand for wood products and land availability considerations. Based on this information, the potential for carbon sequestration and the costs and benefits per hectare of each mitigation option are determined. The carbon and cost and benefit information is used to establish the cost-effectiveness of each option, which yields its ranking among other options. In addition, the information, in combination with land use scenarios, is used to estimate the total and average cost of carbon sequestration or emission reduction.

Assessment of the macro-economic effects of each scenario, on employment, balance of payments, gross domestic product, capital investment, may be carried out using formal economic models or a simple assessment methodology (Kadekodi and Ravindranath 1994). For completeness of the mitigation assessment, one should identify and explore the policies, incentives and institutions necessary to implement each option, as well as the barriers that must be overcome.

2.1 Main Types of Mitigation Options in Forestry

The main purpose of forestry mitigation options is terrestrial carbon storage, which would reduce atmospheric accumulation and thus delay its impact on global climate. Mitigation options may be classified into three basic types (Brown *et. al.* 1996). One option is to expand vegetation stocks and the pool of carbon in wood products. Expansion of stocks will capture carbon from the atmosphere and maintain it on land over decades. The second option is to maintain the existing stands of trees and the proportion of forest products currently in use. Maintenance of existing stands, whether achieved through reduced deforestation, forest protection, prolonged useful lifetime of products or through improved cook stoves, lengthens the duration the carbon stays trapped in terrestrial ecosystems and provides immediate carbon benefit. A third avenue to reduce carbon emissions is to substitute wood derived from renewable sources, e.g., plantations, for more GHG-intensive products, particularly fossil fuels (Dixon *et. al.* 1992). Fossil fuel substitution with biomass derived from sustainably managed renewable sources delays the release of carbon from substituted fossil fuel indefinitely and may increase the standing stock of carbon on land if the biomass is from newly afforested/reforested areas. An expanded list of generic mitigation options in the sector is presented in Appendix B.

2.2 Land Use and Wood-Product Demand

The technical availability of land for the implementation of response options does not appear to be an important constraint to carbon sequestration in the tropics (Grainger 1988). Dixon *et. al.* (1991) concluded that land technically available in the tropics for expanded management and agroforestry ranged from 620 million to 2 billion hectares. A subsequent survey concluded that 950 million hectares might be available (Dixon *et. al.* 1994). Whether technically available lands are ever used for biomass growth depends on economic, political, demographic, social, cultural, and other factors. Based on interviews with experts, Trexler *et. al.* (1989) reported that it was socio-economically feasible to utilize about 69% of the technically available land.

2.3 Scenarios

An important element of the approach is the development of scenarios of land use and wood products demand. These scenarios depict the amount of wood that would be demanded as well as the land area that could be consequently sequestering carbon over time. The amount of sequestered carbon that can be potentially stored, and the associated cost varies with the types of options that are included in the scenarios. Although different types of scenarios can be envisioned, this approach encourages the use of two main scenarios, that is a baseline and a mitigation scenario. The baseline serves as a benchmark for determining the additionality in carbon stored through the mitigation policies.

A common method used to specify a baseline scenario is extrapolation of current trends of land use, tree planting and forest protection as well as consumption of forest products and services. A recommended method in this approach is to use end-use scenarios, which are mainly driven by the projections of the demand for wood products and for land in a country. The end-use approach has been used extensively to understand the magnitude of future demand for energy (Sathaye *et. al.* 1989, Goldemberg *et. al.* 1988). However, while it has been used routinely to determine the future demand for forest products (FAO 1991), the use of this approach has not been reported in the climate change mitigation context.

End-use scenarios have the advantage that they take into consideration an end-user's needs for forest products and land. In tropical countries, where wood may be scarce and forests are used as sources of many non-timber products, planting trees for carbon storage alone may not be sustainable or politically justifiable. The trees will most likely be cut and used for their varied products. Thus, forestry mitigation options that provide multiple and adequate benefits, including carbon storage, to a diverse set of beneficiaries are more likely to be implemented and managed sustainably (Sharma 1992). In order to satisfy our central assumption that tree stock should be maintained in perpetuity, it is important that all participants in an option be adequately compensated. An end-use based approach, which explicitly recognizes the needs of the participants, is likely to yield more plausible and sustainable future scenarios than other scenario construction approaches.

2.4 Key terms and Concepts used in COMAP

Carbon Flows in Land Use Sector:

The aforementioned mitigation options either maintain or expand the stock of carbon in biomass, soil and/or wood products. Two approaches have been used in the past to evaluate the value of stored carbon. The "plant and store" approach assumes that trees will be planted for the purpose of storing carbon and will not be harvested after they grow to maturity (Moulton and Richards 1990). Hence, it suggests that carbon stock be estimated on the basis of the amount accumulated in forest biomass, soil, and litter over a period of time. The time period may be that of a single rotation or of multiple rotations. The "sustainable rotations" approach assumes that carbon will need to be stored for an indefinite period. In this approach, we estimate the amount of stored carbon on the basis of an average amount of carbon on-site over an indefinite number of rotations (Dixon *et. al.* 1991). Harvested stock can be stored in pools (e.g., wood products) or substituted for fossil fuels at harvest or at the end of the products' useful lifetime.

A modified version of the second approach has been used by Swisher (1991), which adjusts average stock for the biomass remaining at maturity. Swisher also includes the carbon in soil, litter and understory and wood products in estimating the total carbon storage. It should be noted that none of the mentioned methods for carbon flow estimation in the forest sector take into account the amount of carbon which may be removed from the site by natural processes like erosion and sequestered elsewhere like in water bodies or other ecosystems. Some anecdotal evidence from siltation rates indicates that this may be a significant amount in areas where there is substantial removal of topsoil by erosion.

The IPCC's 1996 revised methodology is based on the stock approach, with the emphasis being on estimating the change in carbon stocks over a given period (IPCC 1996). This method was developed for the inventory of GHGs in the whole country, with a chapter dedicated to land use change and forestry sector. The methodology can not easily be adapted to mitigation assessment since it is a wide area approach, and uses long term approximations (up to 20 years for abandoned lands). Furthermore, some important aspects such as trade in forest products, emissions from bio-fuels, C-translocation from project site by natural processes and emissions from below-ground biomass, are not yet covered by the methodology.

Value of Stored Carbon[5]

Mitigation options store carbon and keep it from being released to the atmosphere for varying lengths of time. The economic value of storing carbon will depend on the damage being caused by atmospheric carbon at the time the carbon was stored and at the time it is released to the atmosphere. If the discounted economic damage being caused by atmospheric carbon is higher when the stored carbon is released, then a mitigation option would cause more economic damage and vice versa (Sathaye at al. 1993).

However, there is great uncertainty regarding the rate at which damage, caused by higher greenhouse gas concentrations, might increase in the future. The uncertainty about future damage is compounded by the possibility of catastrophic damages, and that of moving to a radically different new equilibrium state, which will, by definition, invalidate any prior

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[5] For a mathematical formulation of this issue see Sathaye J., Norgaard R. and Makundi W. (1993). A Conceptual Framework for the Evaluation of Cost-Effectiveness of Projects to Reduce GHG Emissions and Sequester Carbon, LBL Report No. 33859.

assumptions on value of economic damage and discount rates. Given our limited knowledge regarding the rate at which the economic damage might increase, our approach assumes (i) that the damage will increase at the rate of discount, and (ii) that, everything else being equal, the expected economic damage will respectively influence the rate of discount. An important implication of this assumption is that the discounted economic value of damage caused by atmospheric carbon does not change over time. Therefore, the implied course of action would be to create a stock of carbon in the biosphere, which would last in perpetuity. This assumption about creating a perpetual stock of carbon has important implications for evaluating the carbon flows and the costs and benefits of options, which are discussed in the following section.

Incremental Carbon Storage

In order to evaluate the incremental carbon benefit of a mitigation option, it is necessary to estimate the carbon that might have been stored without the project. For forest protection, the amount of carbon stored may be estimated on the basis of that which would have been released in the absence of a protection measure, such as a physical barrier or relocation of forest users (Swisher 1991). In the case of plantations or management of forests under rotation, the case is more complicated. We need to compare the incremental carbon, which would be sequestered in vegetation, soil, detritus and in products indefinitely. The carbon stored per unit area of a sustainably managed plantation or forest under rotations can be shown to be equal to the sum of change in soil carbon storage and half of the maximum carbon stored in biomass per rotation (Sathate and Meyers 1995).

Costs and Benefits

In evaluating the costs and benefits of a project, it is important to draw a system boundary within which these would be evaluated, which is dictated by the objectives and the nature of each project. Costs are defined as the value of resources expended to implement a mitigation option, inclusive of the value of foregone benefits (opportunity cost). Benefits are defined as the value of all the outputs (goods and services) arising from a mitigation option. In order to be able to compare the stream of costs and benefits in project which occur in different years, the values are discounted to a common time frame, usually to yield a present value of costs and benefits.

Costs

The present value of project costs should include the initial cost of establishing the project, cost of silvicultural operations, management, extension services, protection, and cost of monitoring and evaluating the project's performance. Also, the present value of the opportunity cost is important since it captures the benefits derived from land use in the absence of a mitigation option. Opportunity cost may be evaluated using various methods, depending on the land in question and the likelihood of producing various goods and/or services if it is not used for the given option. These approaches include land rent, land market price and net benefits obtainable from an alternative land use. In all these cases, land values and benefits from alternative use should be adjusted to account for existing significant price distortions due to subsidies, zoning regulations etc. Deriving opportunity costs for many developing countries or countries with economies in transition is particularly difficult. Opportunity costs within a country may vary significantly with proximity to areas with rapid economic growth (Wangwacharakul and Bowonwiwat 1994).

In land use based mitigation options, some of the elements of costs do not have a market value, and a variety of methods are used to impute a value on them. Of specific importance here is land rental which vary significantly depending on land use policy and tenure as well as potential productivity and scarcity.

Benefits

In addition to carbon storage, the implementation of a mitigation option will result in other monetary and non-monetary benefits. These benefits may be classified into: (i) direct and indirect benefits depending on their role in, and level of, economic activity, and (ii) non-monetary intangible forest values. Direct benefits may include goods such as fuel wood and timber and services such as recreation. Indirect benefits may include such items as employment for local inhabitants, air pollution and microclimate control, watershed protection, and the development of social benefits, schools, roads, hospitals, etc. Various methods can be used to impute a monetary value on these indirect benefits. Forest value is derived from the stock in the forest as a resource, which has a recognized value in addition to the above benefits. This value may be influenced by concern for future generations, social status, etc.

Although carbon benefit may be a direct benefit, there is no consensus at present on the monetary value of reducing a unit of atmospheric carbon. Preliminary US fossil-fuel carbon tax estimates to stabilize climate change range between $20 to $200 per tC (Cline 1992 and Nordhaus 1993). Estimates from some developing countries have shown that the unit cost estimates for forestry mitigation options fall well below this range, and for India they are also below the unit costs of the available energy efficiency options (Sathaye *et. al.* 1995 and Ravindranath and Somashekar 1994). Furthermore, when explicit evaluation of direct benefits such as wood products is incorporated, the benefits are sufficiently large to offset the life-cycle cost of many sink expansion options. In effect, carbon may be sequestered at a net benefit to society.

Cost-Effectiveness Indicators

Ideally, in determining the net benefit of a mitigation option, one would include the monetary benefit of storing carbon. However, as discussed above, it is not possible to assess the current and future economic damage that carbon might cause. Estimates of such damage for the United States have been controversial and cover a broad range (Cline 1992 and Nordhaus 1993). However, to allow for a consistent evaluation and comparison of the various mitigation options across categories and with options in other sectors such as energy and agriculture, COMAP proposes to use a set of cost effectiveness indicators. Also, this will allow for an aggregation of the monetary and carbon implications across options. Different indicators of cost effectiveness of an option to store or avoid carbon emissions are:

Initial cost per ha and per tC

This includes initial costs only, and does not include future discounted investments needed during the rotation period. The indicator would provide useful information on the amount of resources required at the beginning to establish the project.

Most cost studies (Dixon *et. al.*, 1991, Andrasko *et. al.* 1991 and Volz *et. al.* 1991) on GHG reduction projects/programs estimate this indicator. The other cost components and the option's benefits are often ignored. The studies take into consideration the carbon stored in live biomass and most account for soil carbon. Whereas very few studies use mean carbon stock to indicate the amount of carbon that would be stored by a mitigation option (Dixon *et. al.* 1991), most of the other studies report estimates of cost per tC although the method of carbon estimation used is unclear.

Present value of cost per ha and per tC

This is the sum of initial cost and the discounted value of all future investment and recurring costs during the lifetime of the project. For rotation projects, it is assumed that the costs of second and subsequent rotations would be paid for by the revenues derived from the first rotation and thus would not be included in estimating the present value. This indicator is also referred to as endowment cost because it provides an estimate of present value of resources necessary to maintain the project for its duration.

A useful way to present the cost per ton of carbon or per hectare is to plot a *cost of conserved carbon (CCC) curve* (Moulton and Richards 1990). The curve shows the amount of carbon that could be stored at increasingly higher per unit costs. Other indicators could also be used to plot similar curves.

Net present value (NPV) per ha and per tC

This indicator provides the net discounted value of non-carbon benefits to be obtained from the project. For most plantation and managed forests this should be positive at a reasonable discount rate. For options such as forest protection, the NPV indicator is also positive if indirect benefits and forest value are included, both of which are subject to controversial evaluation. The formula for deriving this indicator for managed forests is given in Appendix A.

Benefit of reducing atmospheric aarbon (BRAC)

This proposed indicator is an estimate of the benefit of reducing atmospheric carbon instead of reducing net emissions (Sathaye *et. al.* 1993). It expresses the NPV of a project in terms of the amount of atmospheric carbon reduced, taking into account the timing of emission reduction and the atmospheric residence of the emitted carbon. The formulation of the indicator varies with the rate at which economic damage might increase. Appendix A provides a formulation for deriving BRAC when the economic damage caused by atmospheric carbon increases at the real societal rate of discount.

A key shortcoming of the above indicators is their inability to provide a consistent ranking of mitigation options, which are finite, but of different duration or rotation. For example, establishment cost is usually the largest share of cost over a rotation and is incurred quite early in the project, while carbon sequestration occurs gradually over the biological rotation. Projects of varying rotations can not meaningfully be compared mid-stream since the timing of emission pulse e.g. harvesting, is different. To circumvent this shortcoming, an indicator based on annualization of the proposed indicators has been put forth (Halsnæs *et. al.* 1999). Such an approach calculates the annual equivalence of a stream of costs and benefits and normalize this by the annual carbon-flow equivalence. However, the approach still does not resolve the issue related to the timing of the carbon emission or sequestration.

3.0 Flow chart of the Analytical Framework

COMAP is a framework of analysis which guides one to assess and evaluate a set of mitigation options in the land use sector for a country. The flow of the framework is graphically depicted in Figure 1 below.

3.1 Introduction of Modules

The COMAP framework as described above has been operationalized in a spreadsheet model in EXCEL with four main modules (Table 2). The first three modules correspond to the main types of mitigation options in forestry, and each has a set of sub-modules, which are used to analyze specific or similar options. For example, under the Reforestation module, there are sub-modules for natural regeneration (REFREGN), regeneration through reforestation (REGENDX) and reforestation by short rotation forestry (REFROTN).

The fourth module (BIOMASS) balances the demand and supply of biomass in the sector under baseline and mitigation scenarios, given different assumptions on product extraction rates. The module tracks the movement of land between uses as the sector meets the demand for various products and services. Excess demand and supply are allocated to imports and exports respectively. When analyzing individual projects (as in the examples in Section 4), it may not be necessary to use the biomass balance module, but when evaluating state or national forest sector mitigation strategy, it is necessary to use this module.

Figure 1: COMAP Flow Chart

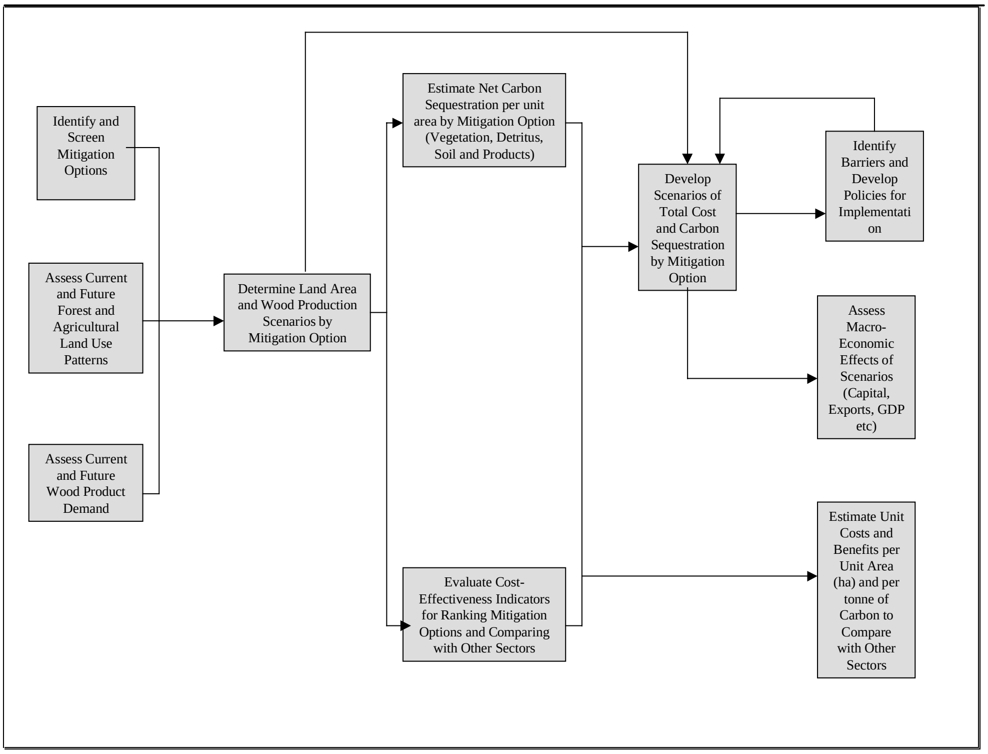

Table 2: Main Module Types in COMAP

COMAP MODULES TYPES	DESCRIPTION
BIOENERGY	Bioenergy mitigation options e.g. biofuel electric generation substituting fossil fuels, efficient stoves and charcoal kilns, etc
PROTECTION	Forest protection and conservation options e.g. forest reserves, parks, sustainable harvesting, deforestation reduction measures, etc.
FORESTATION	Reforestation and regeneration options e.g. natural and enhanced regeneration, afforestation, urban forestry, non-forest tree plantations (rubber, oil palm etc.) and agroforestry.
BIOMASS	Biomass balance module for tracking demand and supply of forest products in the land use sector and the impact on land use distribution.

3.2 Forestation Options Module

This group of options include all projects and policies intended to re-inhabit an area with vegetation, ranging from natural reforestation, enhanced natural reforestation, afforestation, short rotation forestry, agroforestry, community and urban forestry, etc. If non-forest tree plantations such as rubber, oil palm and rattan are not included under agricultural sector mitigation assessment, then they can be analyzed under this module as afforestation/reforestation options. The majority of the potential C-abatement projects in the forestry sector are reforestation/afforestation projects. The REFOREST sub-modules are run under different land use categories with input data for area (ha), carbon density, rates of growth of biomass and cost and benefits. All modules are run for both BASELINE and MITIGATION scenarios. The model then calculates the annual changes in carbon stocks and the cost-effectiveness indicators as described in Section 2 above.

Steps and Data Requirements for REFOREST module

STEP 1: Define land use categories relevant to BASELINE as well as MITIGATION scenarios. Examples of the categories are natural forests (e.g. evergreen, dipterocarp, mangrove, etc), plantation forests, degraded land, rangelands and grasslands.

STEP 2: Specify area (ha) for the BASELINE under different land categories from a base year, for example 1990, to the desired horizon for the mitigation option. Due to long rotations for forestry projects, choose a horizon long enough to allow for at least one rotation so that there is a realistic turnover of the carbon stock into the intended sinks.

Data required for this step should be obtained from any existing projections on land use change for different vegetation types in the country. If no projections are available, it may be necessary to make projections using demographic, social, and economic factors. Normally, the degraded land area is taken to remain stable or increase over the years and forest area declines due to anthropogenic pressures in developing countries.

STEP 3: Specify area (ha) and define activities, which constitute MITIGATION scenario for the different categories of land identified in step 2.
The forestation options to be included in the mitigation assessment of the sector have to be decided in consultation with policy makers and forest planners, in concert with the long-term land resource management plans. The rates of reforestation depend on the availability of land, funding, infrastructure, and the organizational capacity of the Forest Department, industry and the community. Economic and technological factors will also influence the extent and the type of forestation activities.

Area to be reforested has to be entered for each year (or each period of implementation), from the base year to the end of planning horizon. It could be at constant or varying rates depending on the expected implementation of the project. Table 3 shows the outline of the three steps in the spreadsheet.

Table 3: Step 1, 2 and 3

REFORESTATION		1980	1990	1991	1992	1993	1994
>>> FROM STEPS 2 AND 3: LAND AREA (ha)							
>> Baseline Scenario							
> Wasteland							
>> Mitigation Scenario							
> Wasteland							
> Reforested Land							

STEP 4:1 Estimate C-storage in soil and vegetation under BASELINE scenario (t C/ha). The data needed include C-densities of vegetation (above and below ground biomass) and soil carbon in tC/ha, to a specified depth e.g. 100 cm. The vegetation C-density is usually calculated from biomass and carbon content data (Table 4). Some C-density data are available in literature (published as well as unpublished) for vegetation as well as soil, though site specific measurements may be required to supplement the data, especially the soil C-data since it is not as abundantly available. Normally, C-densities are expected to decline under BASELINE scenario due to anthropogenic pressures. Soil C densities are likely to decline from year to year depending on the prevailing land use (agriculture, pasture, or abandoned wasteland), with agricultural conversion losing the most soil carbon, depending on the extent of tillage.

Table 4: Estimates of C-density in Baseline Scenario

>>> STEP 4.1: BASELINE SCENARIO -- WASTELANDS							
			1980	1990	1991	1992	1993
>> Vegetation Carbon							
> Dry Weight (t/ha)							
> Carbon content (%)							
>> Soil Carbon							
> Amount of carbon stored in soil (tC/ha)							

STEP 4.2: Estimate C-sequestration and storage in soil, vegetation and products under MITIGATION scenario (t C/ha). As illustrated in Table 5, the data requirements fall under the following categories:

(i) ***Vegetation:*** C density is projected to increase annually due to natural regeneration and the additional biomass from reforestation and protection of the area. The rate of C accumulation depends on a number of factors such as; tree species, density, rainfall, nutrient supplements and rotation period. The rotation is different for various mitigation options depending on species, provenance and intended fate of the forest.

(ii) ***Soil:*** The soil C density is normally low in degraded forests. Under reforestation options involving tree planting, soil C density increases due to new litter fall and decomposition. The rate of C accumulation is normally low and can be assumed to be constant over the duration of the project, lets say at a rate of 1-2 t C/ha/yr in the short to medium term, and tends towards equilibrium in the longer term.

(iii) ***Detritus:*** The forest and/or plantation litter-fall consists of woody and non-woody plant biomass. The non-woody biomass decomposes in a relatively short period, e.g. 1-2 years depending on weather and biotic conditions. The woody litter stays on the forest floor for several years; at times beyond 10 years, also depending on the species and field conditions affecting microbial activity. The decomposing matter C density could vary from 5-25 t/ha, at different periods. This data is not readily available for specific sites and may have to be obtained from areas of similar conditions available in the literature.

(iv) ***Product Carbon****:* When/if harvested, the biomass has diverse end-uses, which lead to different C-emission streams. Potential biomass uses include wood fuel (where combustion leads to instant C- emissions), industrial wood for pulp and paper production (where emissions normally occur over 2 to 10 years or so), and structural wood for long-term use (timber for construction, housing, mining, etc); with emissions occurring in a few years or in 50 or more years depending on conditions and nature of product utilization.

Table 5: Carbon Pools for the Mitigation Scenario

>>>> STEP 4.2: MITIGATION SCENARIO – REFORESTATION							
				1990	1991	1992	1993
>> 1. Vegetation Carbon							
> Rotation Period (Years)							
> Annual Yield (t/year/ha)							
> Carbon density (%)							
>> 2. Soil Carbon							
> Rotation Period (Years)							
> Amount of carbon stored in soil (tC/ha)							
>> 3. Decomposing Matter Carbon							
> Decomposition Period (Years)							
> Amount of decomposing carbon (tC/ha)							
>> 4. Product Carbon							
> Average Age (Years)							
> Amount of carbon stored in product (tC/ha)							

STEP 4.3: Summarize carbon density (tC/ha) under BASELINE and MITIGATION scenarios. In this step, the average carbon stock under both scenarios are summed up for each year, to be used in Step 6.1 to estimate the aggregate incremental carbon sequestered by implementing the reforestation program. Since the carbon density given is an average standing carbon over a rotation sequence, the actual amount on site may differ, especially in the pre-rotation age initial years. This does not cause a significant distortion of the indicators since the average is strictly correct after the rotation scheme gets in full swing.

STEP 5: Value of inputs, opportunity cost and benefits from the mitigation option.

STEP 5.1: Estimate cost of inputs for reforestation in current year outlays ($/ha) including establishment costs, recurring costs, monitoring costs and harvesting costs, depending on the pre-assumed system boundary. For example, if the concessionaire will be responsible for harvesting, then the only harvesting cost chargeable to the project are those necessary for pre-harvest preparations such as timber cruising, logging access roads, etc.

STEP 5.2: Estimate total direct benefit flows ($/ha) from all products, including timber and non-timber products. The value of indirect benefits such as multiplier effects and other positive externalities should not be bundled together with the direct benefits whose market value can be ascertained. These can be estimated separately and could be used to choose among closely ranked options or to assess the order of implementation depending on the magnitude and likely recipients of indirect benefits.

STEP 5.3: Specify discount rate with which the model computes the NPV ($/ha). For many land use change and forestry projects, we recommend use of the social discount rate rather than the private rate of discount which (the latter) is usually much higher. For the short duration options e.g. biofuel projects one could use the commercial discount rates since the projects can be compared to alternative investments in the economy.

STEP 6.1: For both BASELINE and MITIGATION scenarios the model estimates total C stock for the whole area, the net annual and cumulative carbon storage for the desired length of time (Table 6). This includes the carbon stored in soil, vegetation, and detritus and in products.

Table 6: Total Carbon Pool

>>> STEP 6.1: TOTAL CARBON POOL (Tc)							
				1990	1991	1992	1993
>> Annual Incremental C Protected							
>> Baseline Scenario							
> Wasteland							
>> Mitigation Scenario							
> Wasteland							
> Reforested Land							

STEP 6.2: The model estimates total costs and benefits for the total reforested area. It also provides an estimate of incremental net benefit from mitigation compared to the baseline scenarios. These are compiled for each year for the duration of the project (Table 7).

Table 7: Total Costs and Benefits of Reforestation Project:

>>> STEP 6.2: TOTAL COSTS AND BENEFITS OF CSEQ ($)							
				1990	1991	1992	1993
>> Incremental Net Benefit							
>> Baseline Scenario Benefit							
> Cost							
> Benefit							
>> Mitigation Scenario Benefit							
> Cost							
> Benefit							

STEP 7: REFOREST module generates output on potential mitigation options, the cost-effectiveness of different options and net financial benefits. The cost-effectiveness indicators generated are:

- Establishment cost ($/tC and $/ha)
- Endowment cost ($/tC and $/ha)
- NPV ($/tC and $/ha)
- BRAC ($/tC-yr)

3.3 Forest Protection Options Module

Some of the low cost and most effective mitigation options involve protecting the forests from being deforested and/or degraded, leading to carbon emissions. There are a number of options as mentioned which call for halting deforestation of a given forest in a region or conversion of a threatened forest into a Protected Area. FORPROT module using data on area under relevant categories, biomass density, carbon stocks, C sequestration rates, and costs and benefits, provides estimates of the associated annual and cumulative changes in carbon stocks; and the cost effectiveness indicators for the mitigation policy. This is done for BASELINE and MITIGATION scenarios to obtain net reduction in carbon emissions

Steps and Data Requirements in FORPROT

STEP 1: Define land use categories. These consist of areas under different forest and other land categories relevant to mitigation analysis. Vulnerable forest areas and degraded land, which may need protection to recover, are crucial categories in forest protection module.

STEP 2: Define BASELINE area under land use categories covering annual changes (ha) in forest area (clear-felled or converted to other uses) for the duration of the project. For the land categories selected give the base year area and projections for future years. In the absence of land use pattern projections, one can use factors such as demography, economic activity and technical parameters to estimate forecast future patterns under baseline scenario. At times simple projections can be made based on trends for a period prior to the base year. Forest areas converted to non-forest uses e.g. to degraded land, should be listed here.

STEP 3: Define area protected under MITIGATION scenario (ha). Under mitigation scenario forest area, which would have been deforested or converted to other uses, will be protected and conserved. The area to be conserved will depend on forest policies, capacity and motivation of local and national forestry administration, community awareness, cost of protection, opportunity cost etc. Area that could be potentially conserved every year for the duration of the project has to be estimated. Since the mitigation scenario assumes that such a project would not have taken place under the business-as-usual situation, long term plans for these kind of mitigation policies/projects typically do not exist. To project the activity level under mitigation one may need to apply current and short-term data and extrapolate outwards.

STEP 4.1: Define biomass density (t/ha). Data for this step need to be entered for both BASELINE MITIGATION scenarios. Biomass density data (aboveground woody biomass in t/ha) can be obtained from the Forest Department or from literature. Since this data is often recorded in terms of volume (m3/ha), it may need to be converted by applying a factor for converting volume to dry matter (t/ha), which depends on the species in the project area. Another conversion factor may be necessary to estimate total biomass including non-tree vegetation, litter and roots. Normally under BASELINE scenario, the biomass density is expected to decline annually due to conversion and other forest utilization activities. On the contrary, under MITIGATION scenario the biomass density may stabilize or increase.

STEP 4.2: Define **c**arbon density of wood (t C/ha). Enter the carbon content of wood. The default value is 0.5, but use site specific data if available. This coefficient will not vary significantly between BASELINE and MITIGATION scenarios in the early and middle years, but may change in the out years when pioneering vegetation is replaced by a climax vegetation.

STEP 4.3: Define **s**oil carbon density (tC/ha). Soil C density declines with removal of trees, forest clearing, and forest conversion. With protection soil C density is likely to increase gradually. Soil C data is available from literature for different forest types, but may need to be complemented by local soil C estimates.

STEP 4.4: Define total C-loading (tC/ha). Estimate total C density for each year for the site, which is the sum of the vegetation, litter and soil carbon pools.

STEP 5.1: Define stream of protection costs ($/ha). Annual cost of forest protection should be done for MITIGATION scenario. Data for costs can be obtained from forest protection section in the Forest Department, or can be estimated based on previous experience in other protection programs/projects in the country. The protection costs include the following elements:

***(i) Initial costs*:** Cost involved in initial years to enforce protection often referred to as establishment cost ($/ha) include such items like cadastral activities, gazetting, relocation of forest dwellers, and protection measures such as observation towers and fire lines.

***(ii) Recurring costs*:** These costs occur annually or at periodic intervals and may include labor for protection e.g., field patrols, boundary maintenance activities, fire line clearing, management and administration.

***(iii) Monitoring costs*:** This would involve monitoring of protection arrangements, biomass growth rates, soil C accumulation and possible product extraction.

STEP 5.2: Define benefits from land conversion ($/ha/yr). Estimate the value of goods and services, which are directly obtained from converting the area to other land uses in the BASELINE scenario. These may include wood products, agricultural land, pasture for cattle, etc. The market value of the outputs from the converted area is a good measure for benefits from conversion. In the absence of a market value for such products or services e.g. pasture, a value should be imputed using any one of methods which have been suggested for estimating non-market benefits of natural resources (Freeman 1993).

STEP 5.3: Define benefits or costs of providing alternative products ($/ha/yr). Under MITIGATION scenario when the area is protected, we assume that some of the goods and services which were being obtained from the area before will be procured from other sources, either in true form or as substitutes. In some situations, in order to offset the loss of timber from the protected forests, a country may have to import. In rare cases where the same product can be obtained more cheaply from an alternative source e.g. imports, then the net savings will be considered negative opportunity cost (benefits) of the protection project.

STEP 5.4: Define benefits from Forest Protection ($/ha/yr)**.** Under MITIGATION scenario benefits from forests could include fuelwood from deadwood and lopes, non-timber forest products, eco-tourism, etc.

STEP 6.1: Define total and incremental carbon pool (tC). Total carbon sequestered or conserved in soil and vegetation for the BASELINE as well as MITIGATION scenarios is used to calculate the annual incremental C protected due to implementation of the forest protection project.

STEP 6.2: Define incremental net cost ($). This is calculated from difference between the BASELINE and MITIGATION scenarios, i.e. (protection costs +- opportunity costs) - (benefits from forests). The module computes this for every year and cumulatively for the whole period using a discount for values in different years.

STEP 7: Cost-effectiveness indicators. The model generates a number of cost-effectiveness indicators to enable comparison of mitigation options, some of which are also used to construct carbon reduction emission supply curves for a country.

(i) Net Present Value of Benefits - NPV in $/t C and NPV in $/ha
(ii) Initial Cost of forest protection - Cost in $/t C and cost in $/ha
(iii) Present Value Costs (Endowment cost) - PVC $/t C and $/ha
(iv) Benefits of Reduced Atmospheric Carbon - BRAC $/tC-yr

3.4 Biomass Demand and Supply Module (BIOMASS Module)

One of the main roles of the forestry sector in any country is to meet the current and projected biomass demands (fuelwood, industrial wood, sawnwood, etc.). These demands can be supplemented by imports when necessary. When the demand on biomass exceeds the rate of growth, a decline in the size of the forest estate (deforestation) or degradation of the biomass density becomes evident. In many countries some of the mitigation options cannot be implemented, without arrangements for meeting biomass demands, including imports to cover biomass deficits. The module applies simple projection techniques using variables such as the growth rates of the population, income, industrial sector versus agriculture, etc to estimate demand for land use sector products.

Given the population increase and declining land productivity in many developing countries, more and more forestland is being converted to agricultural land for food production and other farm output. Furthermore, forestland is also converted to infrastructure and human settlements. Thus it is necessary to analyze the current and projected changes in land use patterns and the resulting changes in biomass supply. This is then followed by assessing the impact of the proposed mitigation options on biomass supply, with a goal to match it with the demand on biomass. The BIOMASS module is used to track the dynamics of land use patterns over time, including changes in biomass pools, product supply and demand. The steps involved in the BIOMASS module are listed below.

Steps Involved in Assessing Biomass Supply and Demand

In the example used here, we assume that this mitigation project begins in 1990 and runs through 2030. In this module a periodic estimation of biomass balance is done every 10 years, for both BASELINE and MITIGATION scenarios. The module performs two separate biomass supply projections under the MITIGATION scenario, one covering biomass balance under unconstrained rate of extraction of wood products, and the other under sustainable rate of extraction, which constrains the model by extracting biomass which *does not exceed the gross mean annual increment.* This restriction has a significant impact on land use patterns since most extraction and forest conversion rates for exceed the sustainable rate. The user inputs the specified information in each step, as described below.

Baseline scenario assessment

STEP 1.0: Define the land use categories relevant for the country.

STEP 1.1: Define baseline land use categories (ha) for the whole period.

STEP 1.3: Specify biomass density for different land categories (t/ha)

STEP 2.1.1: Estimate/input product supply for the base year, 1990 (t/yr). Use the area under the specified land categories at
- product rate of extraction
- sustainable rate of extraction

STEP 2.1.2: Estimate/input biomass demand (t/yr) for the base year, 1990

STEP 2.2.1: Estimate/input biomass supply for year 2010 using baseline area under projected product rate of extraction
- sustainable rate of extraction

STEP 2.2.2: Estimate/input projected product demand for year 2010

STEP 2.4.1: Estimate/input projected biomass supply for the year 2030 under
- projected product extraction rate
- sustainable extraction rate

STEP 2.4.2: Estimate/input projected biomass demand for the year 2030

Mitigation scenario assessment

STEP 1.2: Specify land area (ha) under different categories for 1990 and each year there after up to 2030.

STEP 1.4: Specify density for different land categories (t/ha)

STEP 2.3: Estimate/input biomass supply under MITIGATION scenario for the year 2010 at

- product rate of extraction
- sustainable rate of extraction

STEP 2.3.2: Estimate/input projected biomass demand for the year 2010

STEP 2.5.1: Estimate/input projected biomass supply for the year 2030 at

- projected product extraction rate and
- sustainable rate of extraction

STEP 2.5.2: Estimate/input projected biomass demand for the year 2030

Data entry in BIOMASS module

Baseline data entry

STEP 1: Define land use categories relevant to the country

- broad categories: forests, cropland, pasture etc.
- specific categories:
    - Forest types (dense/open forests, evergreen/ deciduous/montane)
    - Cropland (annual/perennial)

Data source: land use statistics for the country

STEP 1.1: Area under land categories

- Land categories defined in STEP 1.0 appears.
- Enter area under each category (ha) for the base year 1990.
- Enter potential areas for different categories annually from 1990 to 2030.
- If any projections made are available use those projected area data for the respective years.
- If no projections available, rates of changes during the period 1980 to 1990 could be used for future years

STEP 1.2: Biomass density for land categories

- Enter biomass density (above ground standing biomass in dry t/ha) data for different categories
- Example: undisturbed evergreen forest = 300-600 t/ha
- Eucalyptus plantation (7 to 10 years) = 50-100 t/ha

STEP 2.1.1: Projected rates of extraction - 1990

- Enter current rates of extraction of wood from different categories of land.
- Examples: Protected Area = 0 t/ha/yr.
- Deciduous forest =2 - 25 t/ha/yr.
- Eucalyptus plantation = 5-50 t/ha/yr.
- Degraded forest/pasture = 0.5 t/ha/yr.

STEP 2.1.1, 2.2.1, & 2.4.1: Sustainable extraction rates for 1990, 2010 & 2030

- The current rates of extraction may not be sustainable.
- Need to estimate and input potential sustainable rates of extraction; for example evergreen forest 2 to 4 t/ha/yr. Plantations 4 to 10 t/ha/yr (depending on productivity), degraded lands; 0.1 t/ha/yr.

Table 8: 1990 Biomass Supply for Various Uses

>>>	STEP 2.1.1: 1990 SUPPLY								
>>>	1990 PRODUCT SUSTAINABLE RATE (t/ha)			Ag. Waste*	Fuel Wood*	Industrial	Agric.	Livestock	Other
>>>									
>>	Dense Forest								
>>	Plantation								
>>	Waste land								

STEP 2.2.2: Social, economic and demographic parameters

- To make future demand projections, one need estimates of parameters such as; growth rates of population, GDP growth rate, crop area and income, per capita base-year demand, growth of agricultural output.
- Using such data, the model projects biomass demand for 2010, 2030.

Mitigation scenario data entry

In the MITIGATION scenario data on land use pattern, biomass density and extraction rates will be different from BASELINE scenario, thus needs to be entered at appropriate locations in the module.

STEP 1.2: Land use pattern under MITIGATION scenario

- Enter data on area under different categories as defined in step 1.0.
- There is a need to develop the projected land use pattern for the MITIGATION scenario. This could be done using two approaches:
    - for a given region or location with a project (e.g. reforesting 2,000 ha in a region or converting a forest patch of say 5000 ha into a Protected Area)
    - for the whole forestry sector or as part of land use planning in the country
- Land areas for MITIGATION scenario need to be developed in collaboration with experts in forestry, agriculture, land use planning and policy makers in the country keeping in mind the pressures on land, land use policies, demand for forest land for food production and biomass supply.

STEP 1.4: Biomass density (t/ha)

- Under MITIGATION scenario the biomass density (for above ground woody biomass) could change with protection and management for many land categories such as forests, wastelands, plantations etc.
- Data may be obtained from literature and reports with comparable situations. For example, the biomass density in any undisturbed forest patch in the region could be estimated and used as

input for the area to be brought under protection. Similarly for plantations, use biomass data from existing plantations or estimates from yield studies.

STEP 2.3: Projected and sustainable rates of extraction for 2010 and 2030

- To estimate the projected biomass supply under MITIGATION scenario, it is necessary to estimate projected and sustainable rates of extraction
- Projected rate could be estimated taking area under the category supplying biomass given the demand for products and for forest land, for example, demand on industrial wood and area required for plantation forestry. This assumes that all the biomass will be extracted from that specific land use, and importation is projected when the forest type can not meet the biomass demand.

3.5 Comparison and Ranking of Forestry Options

Using REFOREST and FORPROT modules, output is generated giving the mitigation potential of different forestry options in terms of t C/ha sequestered or emissions avoided. The decision-maker or the funding agencies require information on cost-effectiveness of mitigation options in addition to the total mitigation potential. Not all the mitigation options could be implemented in full. Decision-makers and funding agencies and investors in the mitigation options in this sector are likely going to use different cost-effectiveness parameters in evaluating the options. It may be useful to convert the model outputs for different options into a table or a graph; to enable comparisons. Information to be presented in a summary table should include:

(i) Option name
(ii) Potential area available for the option
(iii) Per hectare and total mitigation potential (tC).
(iv) Investment or life cycle costs per hectare
(v) Investment or life cycle costs per t of C abated
(vi) Total cost for each mitigation option.
(vii) NPV and BRAC indicators for each mitigation option.

4.0 Solved Examples of Mitigation Options

In this Section we present numerical examples of two mitigation options (reforestation and protection) which were analyzed using the COMAP framework.

4.1 Example 1: Reforestation of Wetlands

The first example consists of a mitigation option to reforest a wasteland at a rate of 1000 hectares per year over a 40 year period. In the baseline scenario, this area would have remained as a wasteland with low vegetation biomass density (20 tB/ha), and a stable soil carbon density estimated at 70 tC/ha. This information is entered in steps 2, 3 and 4.1 as described above.

Under a mitigation scenario, the wasteland will be reforested by fast growing species whose rotation age is 10 years, and will be managed in perpetual rotations. As described in Step 4.2, the sequestered carbon will be stored in four pools, i.e.; (i) growing vegetation, (ii) decomposing biomass, (iii) soils and (iv) harvested wood products. In this example, it is assumed that soil carbon will accumulate at a rate of 2 tC/ha through the first rotation, and remain constant after that. It is estimated that the vegetation will store on average, half the maximum amount of carbon that could be sequestered per hectare by the vegetation if the trees would never have been harvested (Sathaye *et. al.* 1995). The amounts of carbon stored in detritus and that in wood products depend on the decomposition period and the product's lifetime respectively. On average, each will store half of the maximum accumulation in the respective pool since the pools are being replenished pursuant to the management of the rotational crop. The difference between the carbon stock under the mitigation and baseline scenarios, provide an estimate of incremental carbon pool arising from the reforestation project (see Step 4.3).

The costs per hectare under baseline scenario are minimal ($5/ha/yr), mainly from wasteland management such as fire protection. In the mitigation scenario, a large initial cost is incurred in the first three years for ground preparation, planting, weeding and beating-up. For the remainder of the rotation, there is a small but increasing maintenance and monitoring cost ($15 – $150/ha/yr) for activities such as pruning, thinning and protection. In this example, the costs are discounted at 10% discount rate to obtain input-based cost effectiveness indicators such as present value of initial costs, present value of all costs, and annualized value of costs.

The value of products obtained from the wastelands such as firewood and non-timber forest products is estimated at $20/ha/yr. Under mitigation these would increase to $75/ha/yr, but the largest benefit comes from the timber products which are valued at $1000/ha at harvest. At 10% discount rate, the reforestation program yields benefits whose present value is estimated at $ 4125/ha, or an annualized value of $ 423/ha/yr. The net present value is estimated at $1198/ha for the mitigation project.

The results for the first example are contained in Table 9. The carbon pool is estimated for both scenarios as well as the total costs and benefits for the program, and these are used as a basis for estimating the four cost effectiveness indicators. The reforestation project would result in a NPV of $4.75/tC or $266/ha of reforested land. This implies that the mitigation project can be economically be implemented, with the monetary benefits outweighing the cost. If benefits were to be ignored, the present value of costs add up to $13.87/tC sequestered or $777/ha. This indicator is useful for ranking projects which have no monetary benefits, or for budgeting purposes, since this is the present value of the resources which are going to be required to implement the project. The present value of initial cost is estimated at $8.5/tC or $476/ha, an amount which is critical for policy purposes, since the availability of such funds is necessary to initiate the project. The net cost of removing a ton of carbon from the atmosphere for a year (BRAC) was estimated at 3.6 cents (negative cost), assuming that the damage caused by its atmospheric residence increases at a rate equal to the societal rate of discount. In this example, we actually gain 3.6 cents (in 1990 value) per ton of carbon withdraw from the atmosphere by the reforestation project. The large NPV and positive BRAC can be attributed to the substantial stream of timber benefits from the project.

4.2 Example 2: Forest Protection

This example involves the protection of a closed dense forest which covered 15,000 ha in 1980 and by 1990 (base year) it had been reduced to 12,000 ha through conversion to agriculture. At this rate, the baseline scenario assumes that all the forest will have been converted to agricultural land by the year 2030. The proposed mitigation option involves protecting the forest through measures such as setting a new policy for the area, boundary demarcation, surveillance, enforcement, and provision of equivalent or better alternatives for the people who were converting the area to farm land.

The results for this example are presented in Table 10. To evaluate this mitigation option requires estimates of carbon densities under baseline and mitigation scenarios. Under baseline scenario, the vegetation carbon per unit area is expected to decline to about 7tC/ha by 2030, though the soil carbon is conservatively projected to remain unchanged. If the area is protected, both the vegetation and soil carbon are projected to increase significantly. The incremental carbon gain is projected to reach 114.5 tC/ha by the end of the program.

Table 9. Results for Example 1: Reforestation for Rotation Management

Year	**1980**	**1990**	**1991**	**1992**	**1993**	**……**	**2029**	**2030**
FROM STEPS 2 AND 3: LAND AREA (ha)								
Baseline Scenario								
Wasteland	40000	40000	40000	40000	40000	……	40000	40000
Mitigation Scenario								
Wasteland		40000	39000	38000	37000		1000	0
Reforested Land			1000	1000	1000		1000	1000
STEP 4: ESTIMATING CARBON POOL AND SEQUESTRATION								
STEP 4.1: BASELINE SCENARIO -- WASTELANDS								
Standing Vegetation Carbon								
Dry Weight (t/ha)			20	20	20	……	20	20
Carbon density		0.45	0.45	0.45		0.45	0.45	
Soil Carbon								
Amount of carbon stored in soil (tC/ha)			70	70	70		70	70
Carbon Pool (tC/ha)			79	79	79		79	79
STEP 4.2: MITIGATION SCENARIO -- REFORESTATION								
1. Vegetation Carbon Pool		30	30	30	……	30	30	
Rotation Period (Years)		10	10	10		10	10	
Mean Annual Increment (tB/year/ha)			12	12	12		12	12
Carbon density			0.5	0.5	0.5		0.5	0.5
2. Soil Carbon Pool			20	20	20		20	20
Accumulation Period (Years)			10	10	10		10	10
Amount of carbon stored in soil (tC/ha/yr)		2	2	2		2	2	
3. Decomposing Matter Carbon Pool			10.5	10.5	10.5		10.5	10.5
Decomposition Period (Years)			6	6	6		6	6
Amount of decomposing carbon (tC/ha/harvest)			21	21	21		21	21
4. Product Carbon Pool			4.5	4.5	4.5		4.5	4.5
Average Age (Years)			3	3	3		3	3
Amount of C stored in product (tC/ha/harvest)			9	9	9		9	9
Carbon Pool due to Mitigation Option (tC/ha)			65	65	65		65	65
Carbon Pool Incl. Baseline Soil Carbon (tC/ha)			135	135	135		135	135
STEP 4.3: TOTAL CARBON DENSITY (tC/ha)								
Baseline Scenario								
Wasteland			79	79	79		79	79
Mitigation Scenario								
Wasteland			79	79	79		79	79
Reforested Land			135	135	135		135	135

Table 9. Continued: Results for Reforestation for Rotation Management Example

Year	**1980**	**1990**	**1991**	**1992**	**1993**	**……**	**2029**	**2030**
STEP 5: ESTIMATING COSTS AND BENEFITS								
STEP 5.1: COSTS ($/ha/yr)								
Baseline Scenario (Wastelands)		5	5	5		5	5	
Mitigation Scenario (Reforestation)			300	300	300		300	300
STEP 5.1.1: STREAM OF COSTS ($/ha) OF REFORESTATION								
Initial Costs ($/ha/yr)			1000	800	500			
Recurrent (Maintenance etc.) Costs ($/ha/yr)			10	20	30		100	100
Monitoring Costs ($/ha/yr)			5	10	15		50	50
Establishment Costs ($/ha/yr)								
Total Costs ($/ha/yr)		1015	830	545		150	150	
Present Value of Costs ($/ha)		**2927**						
Annualized Value of Costs ($/ha/yr)			**300**					
Present Value of Initial Cost			**1946**					
STEP 5.2: BENEFITS ($/ha/yr)								
Baseline Scenario (Wastelands)			20	20	20		20	20
Mitigation Scenario (Reforestation)			423	423	423		423	423
STEP 5.2.1: STREAM OF BENEFITS OF REFORESTATION PROGRAM								
Timber Product ($/ha/yr)			0	0	0		1000	1000
Non-timber benefits (fuel wood) ($/ha/yr)		5	10	15		50	50	
Non-timber benefits ($/ha/yr)			2.5	5	7.5		25	25
Other benefits ($/ha/yr)								
Total Benefits ($/ha/yr)		7.5	15	22.5		1075	1075	
Present Value of Benefits ($/ha)		**4125**						
Annualized Value of Benefits ($/ha/yr)			**423**					
NET PRESENT VALUE OF BENEFITS ($/ha)			**1198**					

Year	**1990**	**1991**	**1992**	**1993**	**….**	**2029**	**2030**	**Total**
STEP 6.1: TOTAL CARBON POOL (1000's tC)								
Annually Created Incremental C Pool		56	56	56		56	56	2240
Baseline Scenario								
Wasteland		3160	3160	3160		3160	3160	
Mitigation Scenario		3216	3272	3328		5344	5400	
Wasteland		3081	3002	2923		79	0	
Reforested Land		135	270	405		5265	5400	
STEP 6.2: TOTAL COSTS AND BENEFITS OF FORESTATION PROGRAM (1000's $/yr)								
Present Value at 10% discount rate								
Incremental Net Benefit	1079	216	323	……	4204	4312	10644	
Baseline Scenario Net Benefit		600	600	600		600	600	5867
Cost	200	200	200		200	200	1956	
Benefit		800	800	800		800	800	7823
Mitigation Scenario Net Benefit	708	816	923		4804	4912	16511	

Table 9. Continued: Results for Reforestation for Rotation Management Example

Year	**1990**	**1991**	**1992**	**1993**	**….**	**2029**	**2030**	**Total**
Annual Cost of Wasteland		195	190	185		5	0	1462
Annualized Cost of Converted Land		300	600	900		11699	11998	29615
Annual Benefit from Wasteland	780	760	740		20	0	5849	
Annualized Benefit from Converted Land		423	846	1268		16488	16910	41740
Present Value of Initial Costs ($/ha)		1946	1946	1946	…..	1946	1946	19029

STEP 7: COST-EFFECTIVENESS INDICATORS FOR THE 40 YEAR PROGRAM

Net Present Value of Benefits	
Dollars/ Tonne C	**4.75**
Dollars/ Ha.	**266.00**
Benefit of Reducing Atmospheric Carbon (BRAC)	
Dollars/ Tonne C	**00.036**
Initial Cost	
Dollars/ Tonne C	**8.50**
Dollars/ Ha	**476.00**
Endowment (Present Value of Costs)	
Dollars/ Tonne C	**13.87**
Dollars/ Ha	**777.00**

The cost of protection is minimal ($2/ha/year) under baseline scenario, mostly for reducing the acceleration of the process by influx of more farmers, and boundary fire protection to avoid burning of the remaining forest or its spread to other forested areas. However, the benefits accruing from the agricultural production are estimated at $50/ha/yr, which will be considered as an opportunity cost of protecting the area under the cost of the program. Furthermore, the annualized value of direct cost of protection under mitigation rises to $ 9.4/ha/yr.

Using the stream of monetary costs and benefits from the program, and dividing this by the carbon benefits which will accrue, the cost effectiveness indicators reveal that it will cost $0.70/tC or a total of $177.50/ha of protected forest. The value of the BRAC indicator implies that in 1990 dollars, it will cost 5 cents per ton of carbon withdrawn from the atmosphere per year, if the damage rate would rise at the same rate as the social rate of discount. The initial cost of protecting the forest is about 2 cents per ton of carbon or $ 5/ha, and it would require an endowment of $64.37/ha in the base year to ensure the protection of the forest, or 25 cents per ton of carbon.

These estimates are consistent with expectations since there are no products with monetary value which is obtained from the area under the mitigation scenario. However, as mentioned earlier, the cost per ton of carbon is still quite low compared to other mitigation options, especially in the fossil fuel sector.

Table 10. Results for Example 2: Forest Protection

Year	**1980**	**1990**	**1991**	**1992**	**1993**	**….**	**2029**	**2030**
FROM STEPS 2 AND 3: LAND AREA (ha)								
Baseline Scenario	15000	12000	11725	11450	11175	….	1275	1000
Land Converted from Forest			275	275	275		275	0
Mitigation Scenario	15000	12000	12000	12000	12000		12000	12000
STEP 4: ESTIMATING CARBON POOL AND SEQUESTRATION								
STEP 4.1: BIOMASS DENSITY (t/ha)								
Baseline Scenario	200	160	158	157	155		108	107
Mitigation Scenario	200	160	162	163	165		236	238
STEP 4.2: BIOMASS CARBON DENSITY (tC/ha)								
Baseline Scenario	100	80	79.2	78.4	77.6		54.1	53.5
Mitigation Scenario		80	80.8	81.6	82.4		117.9	119.1
STEP 4.3: SOIL CARBON DENSITY (tC/ha)								
Baseline Scenario	100	100	100.0	100.0	100.0		100.0	100.0
Mitigation Scenario	100	100	101.0	102.0	103.0		147.4	148.9
STEP 4.4: TOTAL CARBON DENSITY (tC/ha)								
Baseline Scenario	200	180	179.2	178.4	177.6		154.1	153.5
Mitigation Scenario		180	181.8	183.6	185.5		265.3	268.0
STEP 5: ESTIMATING COSTS AND BENEFITS								
STEP 5.1: COST OF FOREST PROTECTION ($/ha/yr)								
Baseline Scenario	2	2	2	2	2		2	2
Mitigation Scenario		9.4	9.4	9.4	9.4		9.4	9.4
STEP 5.1.1: STREAM OF COSTS AND PRESENT VALUE ($/ha.)								
Initial Costs		5						
Recurrent (Maintenance etc.) Costs			0.5	0.5	0.5		0.5	0.5
Monitoring Costs								
Total Costs			5.5	0.5	0.5		0.5	0.5
Present Value of Costs		**9.4**						
STEP 5.2: BENEFIT FROM LAND CONVERSION ($/ha/yr)								
Baseline Scenario	50	50	50	50	50		50	50
STEP 5.3: BENEFIT OR COST OF PROVIDING ALTERNATIVE PRODUCTS (1000's $/yr)								
Mitigation Scenario			-14	-29	-43		-563	-578
STEP 5.4: BENEFIT FROM FOREST PROTECTION ($/ha/yr)								
Baseline Scenario	2	2	2	2	2		2	2
Mitigation Scenario		15	15	15	15		15	15

Year	**1980**	**1990**	**1991**	**1992**	**1993**	**….**	**2029**	**2030**	**Total**
STEP 6.1: TOTAL CARBON POOL (1000’s tC)									
Annual Incremental C Protected		80	80	80		75	75	3062	
Baseline Scenario C Pool		3000	2160	2101	2043	1985		196	154
Mitigation Scenario C Pool			2160	2181	2203	2225		3184	3216
STEP 6.2: TOTAL COSTS AND BENEFITS OF FOREST PROTECTION (1000’s $)									
					<Present Value at 10% discount rate>				
Incremental Net Cost			-39	-10	18		1033	1061	2130
Baseline Scenario Benefit			14	28	41		536	550	136
Cost		23	23	22		3	2	180	
Benefit from Conversion (Opportunity Cost)			14	28	41		536	550	136
Benefit from Forest			23	23	22		3	2	180
Mitigation Scenario Benefit			52	38	23		-496	-511	-772
Cost			113	113	113		113	113	1107
Alternative Supply of Imported Products			14	29	43		563	578	1425
Benefit			180	180	180	….	180	180	1760

STEP 7: COST-EFFECTIVENESS INDICATORS

Net Present Value of Benefits

Dollars/ Tonne C	**-00.70**
Dollars /Ha.	**-177.50**

Benefit of Reducing Atmospheric Carbon

Dollars/ Tonne C	**-00.05**

Initial Cost of Forest Protection

Dollars/ Tonne C	**00.02**
Dollars/ Ha .	**5.00**

Endowment (Net Present Value of Costs)

Dollars / Tonne C	**00.25**
Dollars/ ha.	**64.37**

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Appendix A: Estimating Net Present Value of Forests Managed in Perpetual Rotation

This note explains the computation of the net present value (NPV) for a plantation or forest, which is managed in perpetual rotation. We provide the formulas for computing the NPV for one rotation on a single plot, that for perpetual rotations on a single plot and finally for a mosaic of perpetual rotations on multiple plots. The NPVMP shown in the last equation should be used to calculate the NPV indicators shown in Item 4.

$$NPV = \sum_{0}^{T} (R_t - C_t) e^{-rt}$$

Where:

R_t = Revenue per hectare in time t
C_t = Cost per hectare in time t
r = Rate of Discount
T = Rotation age in years
e = Natural logarithm base

b. NPV per hectare for perpetual rotations on one plot (NPVP):

$$NPVP = NPV(1 - e^{-rT})^{-1}$$

Note that for coppice plantations, a rotation should be taken to mean the length of time until replanting. The coppice harvest and costs should be treated as intermediate output and costs.

c. NPV per hectare of perpetual rotations on multiple plots (NPVMP):

$$NPVP = NPVP(1 - e^{-rT}) / T(1 - e^{-r})$$

d. Estimating the Benefit of Reducing Atmospheric Carbon (BRAC)

For the case where the economic damage caused by carbon increases at the rate of discount, we can estimate BRAC using the following formulation.

$$BRAC = NPV / (a^{-1} \sum_{0}^{Te} C_t)$$

where;

NPV = Net Present Value of Benefits
a = Decay Rate of Carbon
T_e = Time duration of carbon flows
C_t = Net carbon flow in time t

Appendix B: Mitigation Options in Forestry

I. Maintain Existing Stocks:

(1) Forest Protection and Conservation –

Such measures, projects or policies are usually put in place for non-carbon resource management purposes, such as wildlife protection (national parks and game reserves), biological reserves, soil conservation, water catchment reserves, recreational areas, etc.

(2) Increased Efficiency in Forest Harvesting and Product Utilization.

These measures may include selective harvesting, harvesting for multiple end-uses, wood residue utilization for fuel, increased conversion efficiency (esp. in saw-milling and pulping) possibly involving technological intervention; salvage operations during conversion of forests to other landuses like hydropower development, etc.

(3) Bio-energy initiatives

- Efficient charcoal kilns and packaging of charcoal e.g. briquetting, more efficient woodfuel stoves, increased use of charcoal for industry like steel, use of sustainably grown woodfuel in the agricultural processing e.g. tobacco and tea curing, etc.

- Urban tree planting to reduce fossil fuel use for cooling and heating

II. Expanding Carbon Sinks.

Each one of the options under this category has to be separately identified and described depending on the end-use for which the new biomass is intended or the fate of the new land use. These would include: forest products such as woodfuel, timber, pulp and paper; forest services such like recreation, soil protection, emission reduction through fossil fuel substitution, etc. The fate of the biomass influences the carbon flows, cost and benefit streams, as well as the implementation possibilities of the specific mitigation option listed below:

(1) Afforestation - Planting forests in bare land, with biomass density commensurate to the objective of the project.

(2) Reforestation - Replanting and/or natural regeneration of deforested areas.

(3) Enhanced Regeneration - increasing the biomass density of existing degraded and under-stocked forests.

(4) Agroforestry - Some or all of the agroforestry forms listed below may be applicable to different suitable sites in the country. The most commonly practiced forms are:

- inter-cropping for agricultural and forest products

- boundary and contour planting for wind and soil protection, as well agricultural and wood products.
    - taungya system which is applied in tandem with forest management.
    - pastro-silviculture for forest and animal husbandry products
    - non-timber tree farms for rubber, tannins, bamboo, rattan, etc.

(5) Urban and Community Forestry

Include here is non-contiguous tree cover not elsewhere covered. This may include residential shade trees, roadside and demarcation trees.

III Substitution of GHG-intensive products

- The use of sustainably grown biomass for fossil fuels will delay the release of carbon from the fossil fuels for as long as the fossil fuels remain unused (Hall *et. al.* 1991).
- Similarly, wood-derived from renewable sources if used as a substitute for wood obtained from depletable natural forests will also delay carbon release. Biomass products can also be used to replace emission-intensive products such as concrete, steel, plastics, etc.

Chapter 4: Methods for Analyzing the Factors that Shape GHG Emissions in the Transportation Sector

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1.0 Introduction

The transportation sector involves a complex series of interactions relating people with how they and their goods move around. Understanding why people behave as they do is extremely difficult. Unlike the manufacturing sector, a near-universal decision rule, such as minimizing costs, is not capable of explaining even a small part of the observed behavior. There are many complex motivations that factor into a household's or firm are transportation decisions. A given policy or strategy, therefore, will often not produce the intended results. Unforeseen or unpredicted responses by target groups often occur. It is important, therefore, for policy makers and analysts to have a firm grasp of the various factors that shape greenhouse gas emissions in the sector, to be in a better position to understand and evaluate the potential responses of policy target groups.

A number of publications provide guidance and techniques for evaluation of GHG emissions reduction options in the transportation sector. The present paper does not propose a detailed GHG mitigation analysis methodology per se. Rather, it examines in detail the various analytical components of GHG emissions in the sector, and the tools and techniques used by transportation professionals to analyze these elements. In so doing, we hope to shed light and provide insights to analysts of GHG options. One of the motivations behind such an aim is the observation that there exists a wide range of tools and techniques used regularly in the field of transportation which do not get fully taken advantage of in transportation energy or mitigation analysis. This paper hopes to encourage cross-fertilization between the techniques of transportation planning and GHG mitigation analysis at the national level.

2.0 A Conceptual Framework for Understanding GHG Emissions from Transportation

Transportation sector GHG emissions are the product of the amount of transportation activity and the GHG intensity of the sector. Activity is measured as unit-distance over a period of time -- for example, passenger-kilometers per year for the passenger (travel) subsector, and tonne-kilometers per year for the freight subsector. By intensity, we mean the amount of GHGs produced per unit of activity.

Transportation activity can be broken down into component factors, specifically a unit portion (passenger-events or tonne-events of freight) and a distance portion (the average distance per activity unit). The unit portion is assigned to a particular level of event on the transportation hierarchy, most commonly, the trip in the travel sector, and the segment in the freight sector[6]. The unit itself can be broken down into general human activity indicators (population size,

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[6] Nomenclature for discrete transportation events differs in the literature, but generally, events can run the gamut of: boardings (movement on a particular vehicle), stages or segments (movement on a particular mode), trips (one way movement between an origin and destination), chains (movement from a significant origin -- like home or work -- to a significant destination, possibly with interim stops), tours (movement between "home and home", through a number of destinations) and sequences (one or more tours which define an important repetitive lifestyle pattern).

overall economic output) and event rates (number of trips per person, number of tonne-segments per unit of GDP).

The sector's GHG intensity can be thought of as the product of the carbon intensity of each mode and modal structure (share of total activity units made on each mode). The carbon intensity of each mode, in turn, can be decomposed into the energy intensity of the mode (for example, joules per passenger kilometer) and the fuel mix (the ratio of carbon mass to unit of energy). Energy intensity, in turn, is the product of vehicle capacity energy intensity (for example, joules per capacity passenger kilometer or joules per capacity freight tonne kilometer) and the load factor (ratio of actual usage to capacity usage). Finally, vehicle capacity energy intensity is the product of the vehicle-type capacity laboratory energy intensity[7], the vehicle structure (share of modal activity by each vehicle type), and a factor representing on-road deviation from the laboratory intensity (operating conditions factor).

This rather complex structure is represented in Figure 1. Boxes with no sub-units can be called basic components of transportation-related greenhouse gas emissions, and we will use this term to refer to these phenomena. Although there are probably numerous ways of constructing such decomposition (producing different middle level phenomena), any of these should lead to roughly the same set of raw components.

The factors shaping GHG emissions from the transportation sector are expressed in the following equations:

$$G = U * \Delta * D * \sum_{M} (S_m * \sum_{T} [S_t * C * V * 1/O * 1/L]) \qquad (1)$$

and

$$V = E * M \qquad (2)$$

where,

G = Greenhouse gas emissions (CO_2) from the transportation sector
U = # of active units (# persons, # tons of good produced, GDP, etc.)
D = transportation *events* generation rate (segments, trips, chains, etc. per active unit)
Δ = Distance per event
S_m = Share of mode (as proportion of total travel)
S_t= Share of vehicle type and model *t* (as proportion of total modal travel)
C = Carbon factor (content) of fuel used for vehicle type t
V = Vehicle capacity energy intensity of vehicle type *t* (e.g. joules of energy consumed per capacity person or tonne kilometer, under ideal operating conditions)
O = Operational optimum coefficient (0 to 1, 1 meaning that vehicle is operating under conditions that are the most efficient)
L = "Load" or vehicle occupancy factor
E = Engine intensity (joules of energy consumed per unit of power delivered at the flywheel)
M = Motive intensity (power at the flywheel per unit of capacity-movement)

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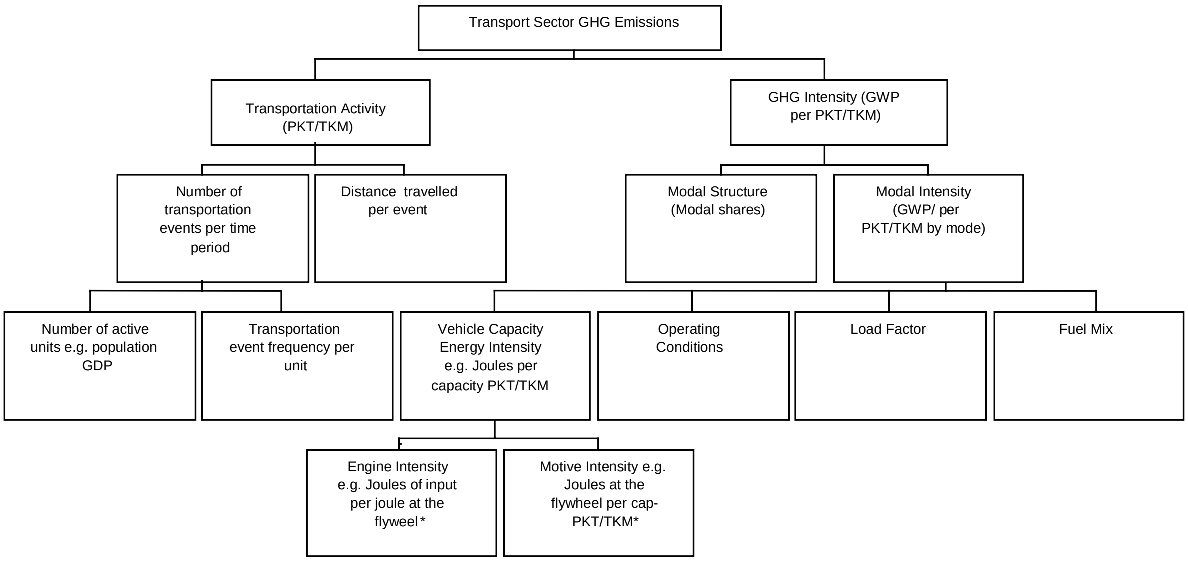
[7] How "vehicle-type" is defined depends on the level of disaggregation of the analysis. It could be very general (i.e. "passenger cars") or quite specific (i.e. "cars of a particular weight class").



*under ideal conditions

Figure 1. Structure of Carbon Emissions in the Transportation Sector

Note that vehicle capacity energy intensity can be thought of as having two components, an *engine intensity* component (amount of energy consumed to produce a certain amount of power at the flywheel), and a *motive intensity* component (amount of power at the flywheel to produce a certain distance moved). The latter is highly dependent on various features of the vehicle itself, including its overall capacity, the type of safety equipment on board, the amount of power demanded by the user, the presence of air-conditioning or refrigeration equipment, etc. Motive intensity, divided by the load factor, produces a "capacity mix intensity" indicator that suggests how well tailored the vehicle fleet is to the loads it hauls.

This paper examines some existing or potential methodologies for assessing the various components of the above equation. In some cases, models or modeling techniques have been well developed to meet the need. In others, there may be no currently existing model that is appropriate to the task, in which case we outline what the parameters of such a model might be.

3.0 The Components of Greenhouse Gas Emissions

The first component of Equation 1 above, the basic unit component U, is taken to be exogenous to the system. Consequently, we begin this discussion with the generation rates of transport events.

3.1 Generation Rates of Transportation Events (Trips)

Travel

We use the term "transportation event" to suggest that different units or levels of analysis are possible, and each is appropriate in its own context. In practice, the trip is the usual unit of analysis for the travel sector, defined as a one-way movement between two addresses for the purpose of accomplishing an activity. Activity, in turn, is usually defined broadly to encompass many possible motives, such as shopping, work, engaging in work-related activities, leisure, etc. The classifications of these motives usually differ from study to study, often making comparison between studies difficult. Other “discrete events” might be a "ride" or boarding, a segment, stage or link, a chain, and a tour, each of which usually has a specific meaning in travel behavior research.

Techniques for modeling trip rates are well developed -- although oft criticized -- at the urban or regional level. These techniques estimate the number of different (and often which type of) activities outside the home the household will participate in during a given time period. The most widely-used of these models are zone-based; specifically, they predict aggregate trip rates generated by or attracted to a traffic analysis zone – that is, number of trips in a given time period[8]. The primary inputs tend to be physical -- for example employment density by industry type, residential density, etc. -- but socio-demographic data, aggregated to the zonal level (median income, for example), often enter as well.

In addition to zone-based trip generation models, there is a number of household- and individual- based trip generation modeling techniques, which can broadly be classified into aggregate and disaggregate techniques. Aggregate techniques model trip rates attributable to a household (or individual) of a given type by cross-classification techniques. These types might be identified by two or three class variables -- for example, income, car ownership, and stage in family life cycle. Ideally, the categories are designed such that the sum of the standard deviations of the trip rates in each of the cells is minimized. In disaggregate trip generation models, trip rates are modeled as probabilities of choosing a discrete number of trips, meaning that the number of trips chosen is that which maximizes household or individual utility, subject to budget, time, and other constraints. Regardless of the model type, predictive household- or individual-based trip generation models work only as well as the ability to forecast the composition of the population into these groups.

Models of trip generation often segment the trips by purpose, which is usually determined by activity at the destination. Many such modelling systems might distinguish only work from non-work trips, but more elaborate distinctions are possible. A typical set of trip purposes for industrialized countries and/or urban settings might be (Gorham, 1997):

- Home
- School
- Work
- Work-related
- Leisure / Personal Interest
- Food Shopping
- Non-Food Shopping
- Other Personal/Household Business
- Serve Passenger
- Other

For rural trips in developing countries, the set of trip purposes is likely to be different. Dawson and Barwell (1993) report the following identified trip purposes in a survey of rural transport studies in Africa and Asia:

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[8] Traffic analysis zones, or TAZs, are usually designated by local transportation planners based on land groupings of similar physical or socio-economic attributes.

- Water collection
- Firewood collection
- Travel to the grinding mill
- Supply of farm inputs
- Crop production
- Crop harvesting
- Crop marketing
- Travel to market
- Travel to health facilities

These trip purposes fit well into a "Basic Needs" framework of transportation planning (See Dimitriou, 1992). Note that both sets of trip purposes might be modeled as aggregate zonal numbers or individual or household rates for a given time period.

In addition to identifying trips according to purpose, it is also common practice in transportation studies in the industrialized world to identify a trip "base", by examining not only the purpose at the trip destination, but also at the origin. This is particularly true in studies where the "trip" is the only event investigated -- i.e., the researcher is uninterested in trip chaining or tour-making behavior. Trip bases help define the context in which the trip is taken[9].

At the national level, the most practical approach to trip generation studies may be to segment the analysis into region-types. An example of such segmentation might be to try to predict trips separately for the largest metropolises, medium and small-sized cities, rural areas, intercity travel, and agricultural-to-market travel. The kinds of variables that might enter into a model would include socio-economic information about the household and data about the structure and vehicle-owning attributes of the household.

Any trip generation model would need to be calibrated against a set of existing data, and this is perhaps the most problematic or costly aspect of such an effort. However, the type of information necessary for such a calibration could easily be incorporated into the framework of a Basic Needs assessment of one or several regions in a country. This could be collected as part of an overall development planning strategy of which transportation is only one portion (Dimitriou, 1992).

Freight

For various practical and theoretical reasons, the analysis of freight transportation is more difficult than that of passenger transportation (travel). Practically, the main difficulties are associated with the lack of straightforward price or cost data, and the prevalence of many actors in the transport process, whose goals, motives, and behaviors do not always share the same modelable decision rules (Ortuzar and Willumsen, 1994).

Theoretically, some of the problems of modeling behavior are associated with the appropriate choice of the unit of activity to be analyzed. The unit of analysis in the travel sector is the discrete unit person (i.e. we measure person trips or person kilometers traveled). However, a

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[9] The base of a trip is usually either "home" or "other", although occasionally "work" is used as well. A home-based trip is one in which either of the trip ends are the tripmaker's home. A work-based trip is any trip that cannot be categorized as home-based and in which either of the trip ends are the tripmaker's place of employment.

simple, discrete standard does not exist in the freight sector. Instead, it is common practice to use the continuous measure, weight, as the unit standard (i.e. tonnes lifted or tonne-kilometers moved). However, such a measure is not ideal, since it provides no indication of the economic value of the good or goods being moved. A more holistically satisfying unit might be "Value Added Content" (VAC); instead of speaking of the number of tonnes lifted, for example, one might speak of a VAC lifted, and, similarly of the VAC-kilometers instead of tonne-kilometers[10]. (Alternatively, a value-to-weight ratio unit could conceivable be used, as well.) The primary reason that a value-based unit is more desirable is that often an aggregate criterion in freight transportation analysis at the national level -- and particularly so for cost-benefit analysis -- is that value-added is the direct building block of gross domestic product. Regardless of whether this is the appropriate criterion for many countries, it is clear that when tonnage is used as the unit of analysis, hidden relationships between productive output and gross mass of goods produced may go undetected. These undetected relationships may have important implications for transportation policy.

Despite these considerations, however, most of the data available to transportation analysts relate to weight, not value added. The individual event in freight transportation is usually recorded as tonnes lifted, that is, the number of tonnes "loaded" onto various means of transportation[11]. This event is the conceptual equivalent of the "segment" or "stage" in the travel sector. Tonnes lifted are also usually identified by cargo type[12].

From the above discussion, it should be clear that the individual transportation events in the freight sector are even more dependent on other factors than in the travel sector. These include: the total amount of goods produced (by type), the physical structure of production and distribution systems, the extent and character of intermodalism within the transportation network, and the nature of the waste stream and attendant networks. It is unlikely that any formal model will be able to capture the effects of these complex and qualitative elements, but the analyst and policy maker should be aware that policies which impact these elements will have an impact on the number of freight segments generated.

3.2 Distance per Event

Travel

A standardized methodology for predicting the average distance traveled per trip, particularly for aggregating over entire countries, does not exist. However, in urban and regional transportation modeling, where details and characteristics of transportation systems are well documented, techniques for predicting trip distances for particular trips are well established. These techniques involve identifying origin-destination matrices, then iteratively "loading" these trips onto a simulated transportation network along different alternative "paths" until the transportation network reaches an equilibrium point. The "loaded" network at equilibrium then can give trip distances for each O-D pair, and hence it can provide average trip distances as well.

Such techniques, however, do not lend themselves to analysis at the national level. A more promising approach would be to stratify the model into region-types plus inter-regional trips, as

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[10] Even this conceptual advance would not be unproblematic, since the act of transportation itself adds value to goods.

[11] This includes fluids in a pipeline, even though these are not technically "lifted".

[12] Cargo type can be seen as a freight equivalent to trip purpose for the passenger sector.

was recommended for trip generation, and model average distance per trip separately for each trip purpose and region-type. Such a technique would admittedly be quite coarse at finer levels of analysis, especially since trip-chaining behavior is not taken into account, but it might prove quite useful at higher levels of aggregation. Various right-side variables could be experimented with, including variable costs of travel (fare, tolls, fuel costs per kilometer) and average speed of travel. In addition, factors related to the specific type of model could also be included. For the large urban agglomeration or medium sized-cities, for example, (average) size of the agglomeration (both population and geography) might enter into the model. For rural or intercity models, average distance between villages, towns and cities might be a factor where road or rail networks are reasonably extensive, or average number of villages, towns and cities per 1000 square kilometers, where they are not.

It would also be ideal to be able to include variables that reflect the nature of settlement patterns on the landscape, particularly for urban areas. Adequate quantitative indicators of such variables, however, have proved elusive, even in the developed economies of the West. The easiest of these variable types to quantify is density, and many studies in the United States have utilized both residential and employment densities in various travel models (Pushkarev and Zupan 1977, Cervero 1994, Parsons Brinckerhoff 1993). These are usually specified as net persons per unit of land (acre, square mile, square kilometer, etc.)[13]. Density, however, is not the only possible measure, and it is questionable whether it is even the best measure (Gorham 1997). There are a number of difficulties associated with measuring density, not least of which is the question of whether the baseline geographic unit is sufficiently small to capture changes in development intensity from area to area. In California, for example, even the lowest level division of geographic data from the Census Bureau, Census Tract Block Groups, are often still too big to pick up important variations in density and other land-use features (Cervero and Gorham 1995).

Other measures of settlement patterns have been proposed and occasionally used in models. These include accessibility indicators (Cervero 1989, Handy 1993), mixture of use measures (Frank 1994, Frank and Pivo 1995, Messenger and Ewing 1996), characterizations of the road network (Cervero and Gorham 1995, Messenger and Ewing 1996) and pedestrian-friendliness indicators (Parson and Brinckerhoff 1993)[14]. Like density, however, the baseline geographic unit must be fairly small in order to adequately capture differences in land form.

The indicators just discussed can be applied at the local level, when looking at settlement forms of particular neighborhoods. But the settlement form of the agglomeration as a whole -- the regional structure -- is just as important, if not more important, to understanding travel phenomena such as the average distance per trip or modal shares (Handy 1993, Cervero and Gorham 1995). Unfortunately, this aspect of transportation/land-use interactions remains poorly understood at present. Some analysts contend that overall density at the level of the agglomeration impacts automobile use (Newman and Kenworthy 1989), and others have investigated the interrelationship of densities at the origin and destination of trips (Pushkarev

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[13] For policy purposes, it may make more sense to use density measures based on physical attributes (dwelling units per hectare or Floor Area Ratio), since these are the units which planners and architects are most likely to understand and respond to, and zoning and planning codes -- the principal policy regulatory instrument for influencing settlement patterns in most cities and regions -- are usually written in terms of these attributes. It is almost always more difficult to get data on these physical attributes, however.

[14] The indicators listed here were used to model different transportation-related phenomena, not necessarily distance per trip.

and Zupan 1977), but an extensive or more sophisticated understanding of the impact of regional structure on travel behavior has not been operationalized.

Researchers have only begun to understand how to use these indicators, and no doubt, the development of Geographic Information Systems will make their application easier, more objective, and more sophisticated. Nevertheless, the resources required to develop such indicators are demanding. To our knowledge, indicators of this type have not yet been used in transportation studies outside the developed world, and many countries and regions will not have the luxury of being able to use them explicitly in their modeling efforts for some time to come. Nevertheless, policy analysts should bear in mind the important role of settlement patterns in influencing the distance per trip (Gorham 1997).

Freight

Like the distance per trip, the distance per freight segment has generally not been modeled. However, also like distance per trip in the travel sector, it can be derived by modeling O-D matrices within a given (closed) system, and then loading the matrices onto a network to develop actual route assignments. The data collection problem for freight is, however, much more complicated than for the travel sector because of the number of actors who might be involved (Ortuzar and Willumsen 1994). The O-D matrices (that is, the network of shipment points) might be determined by shipping companies, whereas the actual route traveled would be determined by the carrier, which may or may not be the same firm. The problem is complicated by the growing prevalence of own-account transportation (in which firms transport their own goods on their own fleets.)

One way around the difficulty of data collection is to use probabilistic methods of identifying likely O-D matrices, based on easily-observed data (e.g., traffic counts), such as originally proposed by Wilson (1974) and subsequently refined in real-world applications (Tamin and Willumsen 1989, List and Turnquist 1994). These methods formulate linear programming or entropy-maximization equations to "backcalculate" the most likely O-D pairs and route choices according to a set of constraints. These methods have also been applied to the travel sector, where resources do not permit the collection of detailed O-D data.

A more useful and flexible, but also more costly, approach to this analysis might be to model segment lengths according to type -- long-distance (line-haul) rail distances, long-distance truck distances, feeder truck services to rail, feeder truck services to truck, and so on. Depending on resources, the complexity of such a model or system of models might be great or little. To our knowledge, no such work has yet been undertaken.

3.3 Modal Structure

Altering modal structure can be one of the most effective policies toward reducing greenhouse gases and energy consumption in the transportation sector. Policies that try to influence traveler choices away from private automobiles and toward non-motorized and public transportation modes have several attendant benefits. First, a given passenger kilometer that would otherwise have been associated with one vehicle kilometer is now associated with only a fraction of a vehicle kilometer. This, in turn, means that carbon output per passenger kilometer and per trip is lower. Second, non-motorized and public transportation vehicles in the passenger travel sector tend to make much more efficient use of road space than private motorized vehicles, particularly where the load factors of the latter are low.

Some of the most advance and refined tools and techniques in the transportation sector pertain to modeling the structure of transportation activity what share of overall activity occurs on which modes. Numerous forms of modal choice models have been developed, including aggregate and disaggregate approaches, of varying degrees of complexity. The most widely used is the multinomial logit, which predicts the choice of mode as a disaggregate probability that a given individual will choose a particular mode. Its functional form (following Ben Akiva and Lerman 1993) is given as:

$$P_n(i) = \frac{e^{u_{in}}}{\sum_{j \in C_n} e^{u_{jn}}} \qquad (3a)$$

where $P_n(I)$= Probability that individual n will select mode I
C_n = the available choice set for individual n
U_{in} = the *utility* of mode j, which is given by

$$U_{jn} = \mathrm{V}(\mathbf{AX}) + \varepsilon \qquad (3b)$$

where X = a vector of attributes
A = a vector of coefficients to be estimated
ε = an error term, which is assumed to be Weibull distributed

In principle, the functional form of V can be tested empirically, but in practice it is often specified as linear. Several specialized software packages exist to run these models, and, increasingly, there are modules available for more general statistical packages such as SPSS and SAS. (Some, however, only accept linear functional forms for V.)

The kinds of inputs used in modal structure models (such as would enter into X in the model presented above) can be categorized into three types: those that describe the trip maker (such as sex, age, profession, etc.), those that describe the trip itself (such as usual time of departure, trip purpose, characteristics of origin and destination, etc.), and those that describe the modes (such as vehicle availability, service frequency, duration, comfort, etc.). Each of these types of influence is important in the model specification, not only because it helps to understand the potential responses of travelers to policy-driven changes , but also because it allows the analyst to identify interactions among these different types of influence, which may in turn help policy makers better formulate their prescriptions.

One criticism of disaggregate models such as the multinomial logit described above is that they tend to be costly to calibrate, since they require detailed survey-type data. For this and other reasons, aggregate mode-choice models have often been used. However, these models are often integrated into “direct demand” models, which estimate either trip generation, distribution, or both simultaneously with mode choice for a given urban system. Thus, they do not lend themselves well to national-level analysis. Examples of use of these models in particular cities of the developing world abound, however. Two are Matos and Mora-Camino (1986) and Timberlake (1988).

An independent aggregate model of modal choice might model the actual share of total pkm or tkm at a given target date, and include such variables as: variable prices of different modes, supply considerations – measure of infrastructure provision/level of service provision of different modes (e.g. length of intercity road and rail, capacity kilometers provided per capita or unit GDP of different modes) – travel purpose forecasts (i.e. business versus leisure versus commute, etc. as share of total travel), and private vehicle penetration levels. Again, like trip generation and distance per trip models, it might be desirable to segment this model into market types, such as: urban, rural, rural-to-market, and interurban leisure or urban to rural leisure[15].

3.4 Vehicle Capacity Energy Intensity

With this category we begin examining technical as well as behavioral determinants of GHG emissions. Although analysis of energy intensity is important for all modes, we will limit our consideration here to road-based vehicle fleets. In practice, vehicle intensity is a much more widely used indicator than vehicle capacity intensity. The former is measured in units of energy consumed (e.g. joules) per vehicle distance traveled (kilometers). The latter, on the other hand, is measured as energy consumed per potential or capacity passenger-distance or capacity freight-distance (e.g. the number of passenger-kilometers or tonne-kilometers that could be effected if the vehicle were filled to capacity.) The latter definition is more holistically satisfying, since it includes the idea that how well suited a vehicle fleet is to the needs to which it is put is an important component in overall energy consumption. A variation of the vehicle capacity intensity indicator would be to measure capacity by volume of the passenger/freight compartment (i.e. energy consumed per cubic meter-kilometer) (see for example McNutt and Patterson 1986).

A second distinction, also rarely used in actual analysis, but conceptually quite useful, is between engine intensity and motive intensity of the vehicle or vehicle capacity. Engine intensity represents the amount of (potential) energy input needed for a given amount of energy output from the engine – that is, power-time available at the flywheel to actually accomplish work, such as move the vehicle, power the air conditioner, etc. The principal component of engine intensity is the specific power of the engine (that is, the amount of power produced per volume of cylinder displacement), and many of the technologies to reduce engine intensity (boost engine efficiency) focus on specific power. In power units, the engine intensity relationship can be expressed as[16] :

$$P_0 \quad = \quad f\,(Pi, k, V, N, \eta)$$

where P_0 = the amount of power output at the flywheel,
P_I = the amount of power input in the fuel (e.g. gallons of gasoline per minute),
k = an engine friction coefficient,
V = the volumetric size of the engine,
N = the engine speed, and
η = a coefficient of thermal efficiency.

Motive intensity refers to the amount of energy at the engine flywheel needed to produce a capacity person distance – e.g. watt-hours per capacity kilometer. Technologies to reduce motive intensity focus on improvements to power transmission and reduction of load to the vehicle, such as overall size, weight, the nature of the tires, and aerodynamic improvements. Improvements to power transmission also allow the engine to operate at its most optimal speed.

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[15] For rapidly urbanizing countries, this category of trip, which encompasses visiting family and friends, might be quite significant.

[16] Note that the adiabatic mixture can affect Pi, and N is variable, so some combination of Pi and N will minimize the intensity of a particular engine. Engine intensity as a concept, however, refers to improvements that will reduce intensity when these factors, particularly engine speed, are already at their optimum.

The kinds of technical improvements that are applicable to each of these types of intensities are summarized in Table 1, which is adapted from DeCicco and Ross (1993, Table 1).

Table 1. Vehicle Energy Intensity Reduction Technologies

Technology	**Type of intensity reduction**	**Maximum improvement in efficiency***			
		A	***B***	***C***	***D***
Engine Technologies					
Multi-point fuel injection	E	3.0	3.0	3.0	3.0
Four valves per cylinder	E	6.6	6.6	6.6	6.6
Friction reduction	E	2.9	6.0	6.0	6.0
Overhead camshaft	E / PM	3.0	3.0	3.0	3.0
Compression ratio increase	E	0.0	1.0	1.0	1.0
Variable valve control	E	6.0	12.0	12.0	12.0
Boosting intake pressure	E	0.0	5.0	5.0	8.0
Variable displacement	E	0.0	0.0	5.0	5.0
Idle off	E	0.0	0.0	6.0	6.0
Two stroke technologies	E	0.0	0.0	0.0	10.0
Transmission Technologies					
Five speed automatic	PM	5.0	5.0	5.0	5.0
Continuously variable transmission	PM	6.5	6.0	6.0	6.0
Torque converter lockup	PM	3.0	3.0	3.0	3.0
Optimized transmission control	PM	0.5	0.5	9.0	9.0
Optimized manual transmission	PM	0.0	11.0	11.0	11.0
Other Technologies					
Tire improvements	PM	1.0	3.4	4.8	6.1
Aerodynamic improvements	PM	4.6	3.3	3.8	4.3
Weight reduction	PM	6.6	3.9	9.9	15.9
Accessory improvements	PM	0.9	1.7	1.7	1.7
Lubricant improvements	PM	0.5	0.5	0.5	0.5

* in percent on base year of 1992, except category A (see key)

Key	
Type of intensity reduction	
E	Engine Intensity
PM	Power-Motive Intensity
	Improvement Levels
A	Previous Energy and Environmental Analysis, Inc. estimate, on 1987-88 baseline
B	American Council for an Energy Efficient Economy (ACEEE) estimate on demonstrated technologies already in use in mass market production
C	ACEEE estimate on currently available but as yet unused technologies. May require debugging.
D	ACEEE estimate on well developed but as yet unavailable technologies
Adapted from Decicco and Ross (1993) Table 1	

The distinction between engine intensity and motive intensity is useful to highlight several important points about energy intensity. The first is that, where there is an objective standard for fuel efficiency, it is always in the interest of the automobile manufacturer to find ways to reduce engine intensity, even when the fuel efficiency standard is being met. The reason is that consumer and regulatory[17] pressures on vehicle demand tend to push the market toward vehicles that are less motive efficient. To meet this demand and still be in compliance with overall efficiency standards, therefore, manufacturers will seek to compensate by finding ways of reducing engine intensity (Schipper 1995).

A second important reason for separating engine from motive intensity is that policy incentives to enhance vehicle efficiency often exclude non-motorized vehicles from consideration. There is no inherent reason that this need be so. Policies that target motive efficiency specifically, particularly ones which provide rewards or incentives for enhanced efficiency, might include non-motorized vehicles as well. For example, it might be possible to enhance the efficiency of pedal-powered freight vehicles through technology improvements or vehicle design, and these policies should be given an opportunity for evaluation. Of course, there would be no change to overall vehicle intensity (since the amount of fuel energy consumption per kilometer is still zero), but improvements to overall CO_2 emissions reduction may nevertheless be measurable, since intensity reductions may make non-motorized modes more attractive, relative to motorized ones.

These two considerations suggest that the kinds of carrots and sticks that would apply to the two types of intensity are not necessarily the same. Supply-side measures alone may be sufficient to induce manufacturers to improve engine efficiency, while both supply and demand side measures might be necessary in conjunction to address motive efficiency. Nevertheless, in practice this distinction is almost never made, so we will address techniques for evaluating energy efficiency (intensity) as a whole.

We are concerned with understanding how the vehicle fleet can be expected to perform as a whole at a given time, taking into account natural efficiency degradation of older vehicles, but not taking into account sub-optimal conditions which also degrade vehicle performance, such as excessive congestion, poor road surfaces, or inadequate opportunity for vehicle maintenance, since particular policies can be developed to address this aspect of overall fleet performance. (We will discuss these issues in the next section, which talks about operating conditions). However, it should be stressed that these sub-optimal conditions often affect not only the performance of the vehicle fleet per se, but help to define the parameters of the fleet itself, and consequently of vehicle intensity. For example, drivers in countries with particularly poor or otherwise challenging road surfaces are unlikely to respond to policies designed to induce smaller, lighter, and less energy- intensive vehicles unless the quality of the road surfaces are addressed, since larger, heavier cars are generally more capable of negotiating the deteriorating road surfaces (Sathaye and Walsh 1992).

Methodologies for analyzing fleetwide changes in fuel economy generally consist of several steps. First, the envelope of efficiency improvements for various technologies are identified, often for different points along the development cycle of the technology, representing different time periods from a base year. (See Table 1). Next, existing penetration levels of the different technologies are projected into hypothetical penetration levels in the future, each level based on a particular set of assumptions about the market. These hypothetical penetration levels are then

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[17] Especially safety equipment regulations.

assigned costs, based on current production cycles and associated market risks. Elasticity estimates may be used to estimate the extent to which consumers will pay for efficiency improvements. Overall fleet intensities are then estimated at each of the hypothetical penetration/cost levels, allowing for natural fleet degradation, giving a range of feasible fleet intensities and their associated costs. From these, cost-benefit or some other type of evaluation might be used to pick a socially optimum set of policies. This methodology or a variant of it has been used by DeCicco and Ross (1993), OTA (1991) and NRC (1992).

As used in the overall analytical framework presented earlier, projections of vehicle fleet intensities should be divided by the overall capacity of the vehicle fleet (i.e. passenger capacity for travel, and tonnage capacity for freight) to give vehicle capacity intensity. However, it should be observed that this indicator actually presents the estimated average capacity intensity of the vehicle stock, but not an estimate of the average capacity intensity actually produced. Such an indicator would depend not only on what vehicles exist in the vehicle fleet, but also on how these vehicles are actually used (i.e. what proportion of capacity passenger kilometers are made with which types of vehicles.) The latter indicator, if one could be developed, would actually be more appropriate to the framework used in this paper.

It should be remembered as well that reductions in vehicle intensities will reduce the cost of driving a kilometer. This cost differential will produce an income effect in travelers -- that is, they will have that difference in cost available to spend. Since income is almost always positively correlated with travel demand (Schipper 1995) it is likely that, if fuel prices do not change, decreases in fuel intensity will be associated with increase in transportation activity, offsetting somewhat the GHG benefits of the intensity reduction. Exactly how much of an interaction there will be depends on the elasticity of demand for fuel, and for transportation in general.

3.5 Operating Conditions

Calculations of vehicle fleet intensities or efficiencies usually do not take into account the actual conditions under which vehicles are operated[18]. Actual vehicle intensities will be different according to operating conditions on road, track, or tarmac. The function of the "operating conditions" element in the analytical scheme described earlier is to scale the vehicle capacity intensities under ideal conditions to those likely to be achieved under a given set of road conditions. Vehicle "efficiency" is often used as justification for road building and widening projects, as well as traffic management schemes that affect operating conditions.

Four factors will degrade on road vehicle intensity from laboratory intensity. First is the average speed of travel. In a laboratory, a vehicle will have optimized vehicle intensity (i.e. the lowest) when it operates at the engine speed which minimizes engine intensity, and when it is in its highest possible gear (fourth or fifth for most cars.) Actual speeds on the road network may prevent most cars from operating at their most efficient engine speeds and the highest gear. Second, the number and nature of accelerations and decelerations -- the stop-and-go nature of urban traffic -- will also degrade a car's intensity from optimum. These two factors are impacted directly by both the nature and amount of road congestion (primarily, but not exclusively, in urban areas), and by the conditions of the roadways themselves (primarily, but not exclusively, in rural areas).

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[18] In the industrialized countries, manufacturers' published fuel efficiency advertising information often indicate a fuel economy for "highway" and "city" conditions, but the nature of these conditions are usually not specified.

Third, weather conditions, particularly temperature, can adversely impact vehicle intensity, since cold weather causes fuel enrichment, a change in engine stoichiometry to mix more fuel relative to air. Finally, conditions pertaining to the nature of the use of the vehicle might also adversely affect its intensity. For example, vehicles that are overloaded, well above their expected carrying capacity, will exhibit large degradations of fuel efficiency. A rule of thumb is that the lighter the vehicle, the more the efficiency degradation with vehicle overloading. This last factor is particularly important for transit and paratransit vehicles in the developing world. It must be weighed against safety considerations, and the emissions caused by additional vehicles which might relieve the previously overloaded ones.

The concept of an operating conditions factor is somewhat analogous to the Level of Service (LOS) indicator used in urban and regional transportation analysis. LOS usually is a grade (A though F) assigned to a particular facility (for example, a section of roadway, a motorway on-ramp, a subway station turnstile, etc.) to indicate relatively how the facility is performing. It is usually determined on the basis of the ratio of the actual service rate (number of persons or vehicles using the facility per time-unit) and the theoretical capacity service or saturation rate, referred to as the vehicle to capacity or v/c ratio.

An operating conditions ratio would try to wed the idea of the service ratio with the four factors which degrade vehicle efficiency mentioned above. Its components would include: average speeds in uncongested conditions, average speeds in congested conditions, an "acceleration" factor in congested conditions (to quantify the estimated difference in fuel use associated with more accelerations in congested conditions), the amount of vehicle hours of delay per given time period, the number of vehicles involved during that time, and a factor estimating vehicle overloads in a given market area or region. This factor or ratio could be adjusted (seasonally) for specific locations to take into account weather conditions.

An example of the extension of the idea of the v/c ratio to an entire metropolitan regions is the "Roadway Congestion Index (RCI)" developed by the Texas Transportation Institute (TTI 1994) for the state's metropolitan areas. The RCI represents the ratio of all vehicle traffic per lane-distance to the congestion threshold traffic per lane-distance (taken to be 13,000 daily vehicles per motorway lane, and 5,000 daily vehicles per arterial lane.) The RCI might be associated with specific levels of gasoline consumption by estimating the amount of "wasted fuel" per vehicle hour of congestion. The index itself is not appropriate to developing countries, since it is designed for metropolitan regions with extensive, well-developed, and well-maintained motorway facilities. However, the concept is transferable.

There are also several models that examine fuel consumption in relationship to overall speed and driving conditions, rather than in relationship to relative levels of congestion. The two principal models of this type are the Drive-Mode Elemental and Average Speed models. The drive-mode elemental model, as documented in OECD (1985), generally models fuel consumed over a given distance as a function of the fuel consumption rate while cruising (although this will vary according to speed and gear setting), the fuel consumption rate while idling, the average excess fuel during accelerations and decelerations, the total distance traveled, the stopped delay per vehicle and the number of stops. In its simplest form, these elements are considered to be additive, and the model form is given by:

$$G = f_1L + f_2D + f_3S \qquad (4)$$

where G = fuel consumed per vehicle over a given distance L
D = stopped delay per vehicle -- time spent idling
S = number of stops
f_1 = fuel consumption rate per unit distance while cruising
f_2 = fuel consumption rate per unit time while idling
f_3 = excess fuel used in decelerating and accelerating at stops

More sophisticated versions of the model may also include data about fuel consumption at different cruising speeds and acceleration / deceleration rates.

The second type of model, more widely used because of simpler data requirements, is the Average Speed Model, developed by General Motors Research Laboratories. This model predicts the unit consumption of a given vehicle over a given distance as a function of average speed (including stops and starts), and empirically determined constants representing fuel consumption to overcome rolling resistance, fuel consumed while idling, and fuel consumed to overcome air resistance (at higher speeds). The form of this model is:

$$I_u = \frac{\sum_{c=1}^{C} k_1 + \frac{k_2}{\overline{V}} + k_3\overline{V}^2}{C} \tag{5a}$$

and

$$\overline{V} = \frac{d}{t} \tag{5b}$$

where I_u = actual, on road fuel intensity
k_1 = fuel consumed to overcome rolling resistance from the terrain
k_2 = fuel consumed while engine idling
k_3 = fuel consumed to overcome air resistance (at higher speeds)
C = set of vehicles $\{c_1, c_2, \ldots, c_n\}$
$\overline{V}$ = average velocity
d = distance traveled
t = time during which engine is running

Note that this formulation does not allow for accelerations and decelerations to be taken explicitly into account, although these are rolled into the k1 constant. Consequently, this model is less robust than the Drive-Mode Elemental, although its simpler data requirements make it much easier to calibrate. Because of this, a "speed fluctuation" term is sometimes used in the numerator, given as:

$$\frac{k_4}{d}\int_0^t avdt \tag{5c}$$

where a = positive acceleration
v = instantaneous speed

or, more practically useable:

$$\frac{k_4}{d}\sum \Delta\overline{V}^2 \tag{5d}$$

If multiplied by the weighted average of fleetwide vehicle capacity, the ratio of this multiple to the vehicle capacity energy intensity would be an example of the operating conditions factor[19].

3.6 Fuel Mix

The "fuel mix" indicator is actually a carbon factor -- that is, a factor indicating the amount of carbon per unit of energy in the fuel stock used. It is an average of all the carbon factors for all the fuels used, weighted by the relative share of that fuel in the market. We use the term "fuel mix" to reflect that the predictive effort focuses on estimating fuel shares, since the carbon intensity of each fuel is known and does not change.

In principle, the goal of a greenhouse gas policy vis-à-vis fuel mix is to induce fuel switching from more to less CO_2 intensive fuels. It must be stressed that vehicle switching (or penetration) and fuel switching are not necessarily the same thing, the former being a necessary, but not sufficient condition for the latter. Fuel switching occurs when there is a degree of substitution in vehicle use; for example, if a household purchases a compressed natural gas vehicle, fuel switching occurs if the household replaces kilometers it otherwise would have driven using a gasoline ICE engine with kilometers on the new CNG vehicle. On the other hand, if the new vehicle is used to complement existing trips -- that is, take new ones -- then there will be no environmental benefit whatsoever.

Part of the difficulty with this (or any) indicator is that it may not adequately capture switching. If the amount of vehicle kilometers increases overall as a result of purchasing alternative-fueled vehicles, such that the same number of absolute passenger kilometers are being driven with gasoline- and diesel-powered internal combustion engines, there is no benefit to the environment, yet the aggregate numbers will still show a reduction in weighted average carbon factor. (In an ideal world, of course, the increase in overall passenger kilometers would be picked up by one of the activity indicators.)

The above discussion suggests that there are two predictive components necessary to understand fuel share vis-à-vis alternative fuels: vehicle penetration (vehicle-fuel-type shares), and the use of these vehicles. We will consider these two in turn.

Alternative-fueled Vehicle (AFV) Technology Penetration

The market penetration of AFVs -- that is, vehicles powered by methods other than petroleum-based internal combustion -- depends on a number of different factors. The first is that practical technologies have to be available such that functional vehicles are available to consumers at a cost competitive to the petroleum-based ICE vehicle, taking into account such variables as vehicle performance, safety, and range. This does not mean that the AFV must be equivalent to a petroleum based ICE-vehicle in every way; it means simply that it is functional enough that it could replace a conventional ICE vehicle for particular trips, and that these trips are important enough that the consumer purchases the AFV. For example, electric vehicles might be perfectly suited for short trips. These vehicles might not be expected to replace a primary household ICE vehicle (although they may replace a secondary household ICE vehicle), but they might replace the use of the vehicle in specific instances. Second, fuel distribution systems need to be developed enough such that lifetime fuel consumption, on a

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[19] This is not strictly speaking accurate, since the vehicle capacity intensity indicator discussed in the previous section does not take into account actual usage of vehicles, while the intensity of use indicator does.

kilometer-to-kilometer basis, is roughly competitive with that for a petroleum-based ICE engine.

Third, mechanical training and know-how on these alternative vehicles needs to be sufficiently distributed such that consumers feel that they can get their car serviced with roughly the same level of ease as a petroleum-based ICE vehicle. We will not discuss here the logistics of these considerations for each possible technology; interested readers are referred to Sperling (1989). These three factors are so interrelated in the development of the technology, that some government participation in AFV diffusion is necessary -- especially where there are no clear economic incentives for the private sector to act -- even if it consists only of getting members of the various industries to talk with one another.

Technology diffusion, such as that for alternative vehicles, is sometimes characterized in the literature by a logistical distribution over time (Teotia and Raju 1986), which resembles an "S". The time period before the first curve corresponds to the developmental period, during which the technology is developed, production techniques are refined, and early prototypes are produced. The rate at which this period progresses depends strongly on the production concept of the *product cycle*. The product cycle is the amount of time it takes to design a vehicle, design the production mechanism for the vehicle, produce the vehicle, and examine the performance of both the vehicle and production process such that the results of the examination are available to incorporate into a newer, presumably better, version of the vehicle. In the United States, the average product-cycle for a vehicle is 5 years (DeCicco and Ross 1993).

The period in the steeper part of the curve represents the diffusion or absorption rate of the technology. This is the speed with which households and firms opt for the new technology. The experience with many transportation technologies (as with telecommunications) is that this tends to be quite rapid (Santini 1989). The last part of the "S", the upper curve, is where technology penetration slows down. This depends on the *saturation* level that can be anticipated for the technology.

Predicting AFV penetration at a future year, then, depends on being able to predict the number of product cycles needed in the development of the AFV (as well as the amount of time necessary to develop fuel distribution systems and technological know-how), the absorption rate, and the overall saturation level. In particular, it is important to understand how policies can influence these factors. Various tools, such as historical studies or consumer focus groups can provide insight, but the process is more of an art than a science.

AFV Use

AFVs might be produced and marketed with particular end-uses in mind. For example, small electric vehicles might be sold as "local use" or "station cars", to make short trips between home and a rail transit station. This type of strategy might be crucial where it is perceived that consumers would be reluctant to buy a principal vehicle as an AFV, but might buy a secondary one. In addition, it is also possible that *users* will allocate daily household or business tasks to different types of cars in their vehicle fleet, regardless of the intentions of the vehicle producers. Understanding how consumers use the vehicles in their fleet -- particularly as these fleets diversify – is, therefore, crucial to understanding overall demand for AFVs.

As important as such an understanding may be, experience in the developed countries (let alone developing ones) is limited regarding diversified vehicle fleets. Most research relies on pilot projects, such as CalStart, an experimental project in which commuters rent electric vehicles at rail transit stations (Cervero and Bernick 1996, Pfeiffer 1994) and focus groups (Sperling 1989). Santini (1989) has looked at the historical link between technology penetration and fuel mix for various transportation technologies. He has suggested that 86% of the change in railroad fuel from coal to diesel between 1951 to 1969, 77% of the change in the public transit fuel mix from gasoline to diesel between 1945 and 1985, and 72% of the change from leaded to unleaded gasoline in automobiles from 1965 to 1985 is explained by changes in fleet composition. These figures suggest that it may be unreasonable, on a first order approximation, to use vehicle fleet mix as a proxy for, or at least a primary determinant of, fuel mix.

3.7 Load Factor

Load factor refers to the ratio or percentage of actual vehicle usage to capacity, although it is often colloquially used to describe the average number of persons per vehicle in the case of private motorized transportation. We address here its more formal definition. Even this definition has some ambiguity, since "load factor" has been used to describe vehicle events (e.g. the proportion of used capacity during the average vehicle trip), passenger or freight events (the proportion of used vehicle capacity during which each passenger trip occurs), vehicle distance (the proportion of used capacity per vehicle kilometer) or passenger or freight (tonne)-distance (the proportion of used vehicle capacity during which each passenger kilometer occurs). Each is appropriate in different contexts.

In the travel sector, it often does not make sense from a policy perspective to talk about load factors on collective ground transportation. For example, it makes more sense to discuss policies that try to increase transit mode shares than policies that increase transit load factors (although policies that effectively reduce transit service may in fact reduce transit mode shares while increasing load factors). Rather, load factor per se is a more useful measure when discussing private automobiles or air travel. (And it is always a useful measure and policy goal for the freight sector.)

Load factors are often interpolated between data points, or projected into the future based on past trends. However, we are not aware of any specified models that predict load factors.

4.0 Composite Indicators

4.1 Vehicle Ownership

Ignoring carbon emissions caused by manufacture and delivery of automobiles, vehicle ownership is not, strictly speaking, a direct component of greenhouse gas emissions. Yet it is a significant determinant of many of the other components shown in Figure 1, such as modal shares, load factor, and distance per trip. In addition, the predictive models of vehicle ownership themselves can be altered slightly to address different phenomena, such as the market share of alternative-fueled vehicles.

A number of such models have been developed over several decades for use in various contexts and with varying degrees of sophistication. Many vehicle ownership models are developed as interim steps to studying other phenomena, such as VMT or fuel-use. Consequently, right-side variables in ownership models tend to differ depending on the purposes and policies being investigated.

We highlight two such models -- one developed specifically for application to developing countries, the other a more general automobile ownership model -- to represent a sample of different approaches available. Button and Ngoe (1991) derive separate estimating equations for passenger and goods vehicles. For the former, they apply a quasi-logistic model form specifically to "low income countries" to represent the idea that vehicle ownership will increase at different rates in different countries, depending on how close that country is to its saturation point. The exogenously specified variables, then, are the anticipated saturation level, in cars per capita, the per capita income of the country (PCI), the elapsed time since the base year (1967), and a country-specific dummy variable, estimated by linear regression of car ownership on per capita GDP. The model predicts the probability that a given individual (of income equal to the PCI) will own a car, and was calibrated for five different groupings of countries, based on average car ownership from 1967 to 1986, and per capita GDP.

The commercial vehicle model uses the same inputs, except a saturation point. It is calibrated for three different groupings (Asia, sub-Saharan Africa, Latin America).
This model is effective because it utilizes data that are fairly accessible and inexpensive to obtain, and has a high degree of predictive power. Nevertheless, there are some drawbacks that make it problematic for CO_2 mitigation analysis as well as for other practical applications. First, it has little explanatory power. It relies heavily on country-specific dummies to capture variation, thereby shedding little light on what factors influence vehicle ownership beyond income. Second, it predicts vehicle ownership in quantitative terms only; since it does not predict qualitative factors of vehicle ownership (what kinds or classes of vehicles people choose), it is unable to shed light on these types of responses to policy initiatives. These responses may be quite important, particularly as they might dampen or otherwise impact expected consumer responses. For example, a policy designed to reduce the growth of vehicle ownership might simply push consumers to acquire a different class or type of vehicle, yet the model might not be sensitive to this.

A second example of vehicle ownership model, with vastly different -- and more extensive -- data requirements, is the AUTO modeling system described in Davis et. al. (1995). This is an example of an integrated supply and demand model that predicts not only level of automobile ownership, but the kinds of automobiles consumers are expected to own, as well as various factors of automobile production. The demand side of the system is the CARS model, a disaggregate, nested choice model developed by Train (1986). This nested model predicts first the probability of ownership at a given level (zero, one, or two cars) for a given household, then the types of vehicles owned (a vehicle "class") for each of these levels of ownership[20]. The exogenous variables include supply constraints (the output of the supply side of the modeling system), fuel prices, historical vehicle data (information about the vehicle fleet itself -- fuel type, purchase price, etc.), and household characteristics (household size or structure, annual income, number of workers, city size, access to public transit, urban or rural). Note that more detailed variables related to the neighborhood of residence, such as density, degree of mixture of land-uses, or income mix, might also enter the model. National vehicle fleets are then derived by aggregating the (weighted) household probabilities up.

This model provides a much more detailed and useful predictive framework than that developed by Button and Ngoe, although clearly the data threshold requirements are much higher. The CARS model also requires accurate forecasts of the non-policy contingent

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[20] Except for zero-vehicle-households, obviously. The models also predict VMT -- annual vehicle miles traveled -- for different classes of automobile, but we will concern ourselves with this aspect in a later section.

variables, such as the distribution of income and household structure or consumer taste preferences for different attributes of automobiles, in order to be useful as a predictive tool.

4.2 Vehicular Travel

Vehicle miles (VMT) or vehicle kilometers (VKT) traveled is another common composite indicator in the transportation sector which is frequently tracked and directly predicted. It represents the movement of vehicles as a unit, irrespective of size or capacity. From a technical point of view, the vehicle as a unit makes sense, since it is this unit which emits greenhouse gases. However, for behavioral and policy development reasons, using only vehicular travel as an indicator can mask important behavioral elements underlying transport patterns, that is, how *people* use cars and trucks.

Numerous techniques exist to project VMT or VKT. Following EIA (1998), these can be divided largely into four different approaches: fleet-based, demographic, economic, and four-step metropolitan transportation approaches. In the first approach, fleet-based, vehicular travel for disaggregate cells of vehicle model, age, and fuel types is projected into the future, often as extrapolations of existing trends, with a decay function, but more elaborate specifications are possible. An example in the United States of such an approach is the VMT module of the EPA's MOBILE5 model. The demographic approach looks more specifically at the driver, rather than the vehicle, projecting or predicting driving behavior of individual cells of age, sex, and other demographic variables. Clearly, such an approach is only valid in the travel sector.

The third technique, economic or econometric approaches, can be the most involved. These use vehicle operating costs and personal income as input variables. The difficulty with such an approach at the national level is that *generalized costs* – that is, out-of-pocket plus time-costs – are more significant than out-of-pocket costs alone, and time-costs are difficult to make sense of at the national level. Personal income is assumed to act somewhat as a proxy for time-costs, since value-of-time is linked to income level. However, the value-of-time is highly variable, and supply considerations (such as extent of roadway infrastructure, availability of alternatives, structure of metropolitan areas, or levels of congestion) do not usually enter such models. It is, of course, possible to try to take such supply into account somewhat, for example, by including a variable on public infrastructure investment, but the calibration of such a model – taking into account necessary lag effects – becomes particularly tricky.

Many models combine elements of the above approaches. For example, the CARS model discussed in the previous section also contains a model that predicts VMT, combining elements of the above approaches. In CARS, VMT is modeled as a function of household income and size, operating cost of each vehicle, number of workers in the household, and various variables identifying urban density and geographic region of the household. Finally, in metropolitan areas, VMT can be predicted using the four-step, metropolitan transportation modeling system described above, under “4.2 Distance per Event”.

In this case, the loaded transportation network at equilibrium gives the distance per vehicular trip, based on O-D pairs. These can be aggregated up, giving total VMT. Compared with the other techniques, this is the most comprehensive, since it actively takes into account the generalized costs of travel, including network extent and congestion effects. However, by definition, it is limited in geographic area to metropolitan regions. These types of models are also frequently criticized by economists, who argue that their complex structures are built ultimately on heuristic relationships between infrastructure and built form, rather than on particularly behavioral elements.

5.0 Conclusion

The techniques and methodologies that have been examined in this paper vary from engineering to econometric, and from very local to national in their approaches. Some may be more appropriate than others in attempting to assess greenhouse gas emissions from the transportation sector. Nevertheless, the purpose has been twofold. First, the importance of decomposition in GHG mitigation analysis needs to be stressed. This decomposition is important not only because it permits a better understanding of the likely effects of different types of policies (and identify where policies may be working at cross-purposes), but also because it permits the analyst to borrow from a wide array of tools already in use in other aspects of the transportation sector.

Second, by identifying tools and techniques available for the various elements of the GHG decomposition, we hope to encourage creativity in approaches to their analysis. A familiarity with the various techniques currently in use in the transportation sector can enhance the ability of energy and environmental analysts to develop creative and innovative ways of assessing emissions from the sector. This creativity is necessary not only to produce better predictions of greenhouse gas emissions, but also to be able to do so with limited resources, or limited input data.

Chapter 5: Policies for Reducing Greenhouse Gas Emissions from Transportation

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1.0 Introduction

Transportation policy is usually driven by concerns for economic development or alleviating congestion and air pollution. Greenhouse gas emission reduction is rarely a driving force in transportation policy. The focus of this paper is policy measures that could be used to achieve conventional goals for the transportation sector and also reduce greenhouse gas emissions.

We group policies into nine major categories, based on the intended effect and target population. They are policies to alter or influence:
1. The cost of fuel consumption
2. Other costs of motor vehicle use
3. The conditions of road traffic
4. Public transport and other alternatives to road transport
5. Vehicle fleet production
6. Vehicle fleet demand
7. The built environment
8. Household / firm location choices
9. Public attitudes toward transportation

Many of these policies are complementary; they reinforce each other so that applied in concert, they would probably be more successful than each would individually. Further subdivision of these policies is also possible, including short-term versus long-term, rural- versus urban-based, and fiscal versus regulatory versus infrastructure / physical policies.

Within each policy group, numerous specific policy options are possible. To change the costs of motor vehicle use, for example, one might charge for road use, charge for parking, or change the way insurance is assessed. The purpose here is not to discuss in detail any of the particular policy options. Rather, we hope to show the possible effects of the policy group on various factors that shape transportation energy consumption in order to allow policy makers and analysts a clear view of intended (and unintended) impacts.

For each policy group, we give examples of particular policies, both as theorised and as put into practice. Next, we discuss the effects on various factors that influence transportation energy use. Finally, we draw connections to conventional transportation goals to suggest ways that initiatives to reduce GHG emissions might be part of a broader transportation agenda.

We summarise the policy groups in Table 1. The policy groups are listed in the left-hand column, with policy group 3, policies to alter the conditions of road traffic, separated out into flow enhancement and traffic calming groups. The summary chart includes the types of policies that might be included in each group, examples from real world implementations as discussed in the body of this paper, expected impacts on the factors that shape GHG emissions, and synergies with transportation and transportation-related policy goals, other than greenhouse gas emission mitigation. Among the latter are: balance of payments / economic security goals -- which stems from countries' desires to limit potential imbalance of trade caused by excessive fuel or automobile imports; alleviation of local air pollutant emissions such as carbon monoxide, oxides of nitrogen, and various unburned hydro-carbons (ozone precursors); alleviation of other environmental concerns such as acid rain, ground lead, and noise; relief of traffic congestion; and facilitation of economic development, including the provision of local populations' basic needs through the enhancement of accessibility.

2.0 Transportation Policies to Reduce GHG Emissions

2.1 Policies to Alter the Cost of Fuel Consumption

This category and the next, policies to alter the cost of motor vehicle use, are strongly related, in that they both are examples of fiscal measures to raise the variable cost of automobile use[21]. We separate them in this discussion, however, because manipulating fuel costs specifically will induce not only short responses, but also medium and long-term consumer responses in vehicle markets.

Short-run responses to higher variable costs of motor-vehicle use --whether fuel or other costs-- might include: reductions in trip rates, as motorists seek to chain or group their activities outside of the home more in order to avoid the increased cost of changes to modal structure (i.e. the price of transit and para-transit becomes cheaper relative to the private automobile); reductions in the distance per trip (at least for private, motorised journeys), as costs drive people to reduce the distance they travel; improvement in vehicle operating conditions, as motorists drive less distances and take their cars less in response to the increase in costs, lightening the congestion burden on other motorists; and increases in automobile load factors, as motorists look for ways to offset the increase in variable costs.

These are of course, the ideal responses of motorists. In reality, research shows that short-term price elasticity to fuel is very low (Odum, et. al. 1992). Motorists will probably engage in these behavioural changes only minimally in the short run. In the medium and long runs, however, they may be able to make more of the above kinds of changes, as they alter lifestyle choices, consumption patterns, and possibly even locations. Changing the costs of fuel will probably also induce other behavioural changes in addition to those enumerated above in the medium and long runs. Specifically, motorists might opt for more efficient vehicles or different kinds of vehicles.

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[21] Policy analysts often think separately of policies addressing the cost of automobile acquisition (i.e. tariffs or taxes), ownership (i.e. registration fees), and use (i.e. per distance costs).

Table 2. Policies for Reducing Greenhouse Gas Emissions from Transportation

	Policy Group	*Examples of policies*	*Examples where implemented*	*Expected impacts on carbon components (travel sector example)*	*Expected synergy with /impacts on non-GHG transportation policies*
1	Policies to change price of fuel consumption	Direct fuel taxes; carbon taxes	Currently implemented only as revenue raising measure; under consideration in the Netherlands	Reduce trips per person, reduce distance per trip, induce mode switching, improve load factors, reduce vehicle intensity, and possibly improve operating conditions because of other benefits.	Balance of payments / economic security; local air quality relief; other environmental concerns; congestion relief
2	Policies to change other variable costs	Road pricing (tolls, smart cards); parking charges (taxing parking benefits); variabilizing previously fixed costs (pay-at-the pump insurance)	Road pricing currently in effect for Singapore, Oslo; under consideration for Stockholm; corridor pricing in effect or under consideration in many places	Reduce trips per person, reduce distance per trip, induce mode switching, improve load factors, possibly improve operating conditions because of other benefits.	Local air quality relief; other environmental concerns; congestion relief; basic needs and accessibility
3a	Policies to enhance traffic throughput	Roadway expansion, traffic management programs	Paris, Bangkok, ITS program in USA	Possibly induce more trips per person, possibly induce longer distance per trip, induce mode switching away from transit, possibly reduce load factors, improve operating conditions (decrease on-road vehicle intensity)	Unclear how these policies affect on balance local air quality, congestion, economic development
3b	Policies to restrain traffic	Traffic calming, creation of pedestrian zones	Netherlands (Woonerfs), numerous European cities, Singapore, Portland, Oregon ("Skinny Streets" program)	Possibly reduce trips per person, reduce distance per trip, induce modal switching toward NM or transit modes, possibly improve load factors, degrade operating conditions (increase on-road vehicle intensity)	Unclear how these policies affect on balance local air quality, congestion, economic development
4	Policies to enhance transit	Expansion of service to reduce travel time and/or wait time, expansion of service area, enhancement of comfort, reduction of transit fares by direct (public sector) investment or regulatory reform to encourage private sector investment	Hong Kong Subway (rail), Curitiba (bus)	Possibly induce more trips per person, effect on distance per trip unclear, induce modal switching, improve on-road operating conditions	Local air quality relief, other environmental concerns, congestion relief, basic needs and accessibility

5	Policies to influence vehicle fleet demand	Targeted acquisition, ownership, and registration fees to influence ownership decisions; taxing company car benefits as ordinary income; revenue "neutral" cross-subsidy schemes such as feebates	Singapore Area Licensing Scheme; proposed "Feebate" system in US	Impact on trips per person and mode shares unclear, long run beneficial impact on carbon factor (fuel mix), potential beneficial impacts on load factor (by influencing choice of size of vehicle), reduction of fleetwide vehicle intensity	Balance of payments / economic security; local air quality relief; other environmental concerns; congestion relief; economic development
6	Policies to influence vehicle fleet supply/production	Assistance with manufacturer research and development; sponsorship of independent R & D; regulations and manufacturer performance mandates; tradable permits	Partnership for a New Generation of Vehicles (USA); Low-emission and zero-emission fleet mandates (California)	Potential reduction in carbon factor (by influencing the mix of fleetwide vehicle propulsion systems), reduction in fleetwide vehicle energy intensity (efficiency improvements)	Local air quality relief; other environmental concerns; economic development
7	Policies to influence built environment	Incentives to induce local and regional governments to use land-use control authority to enhance "accessibility"; coordination of transportation and land-use development; formalisation of informal housing developments as transportation policy	Satellite cities program (Stockholm); LUTRAQ project (Portland, Oregon)	(All benefits long run): reduction in distance per trip, enhancement of transit and NMV mode shares, reduction in (private vehicle) load factors, unclear effects on operating conditions	Balance of payments / economic security; other environmental concerns; basic needs and accessibility; unclear effects on local air quality and congestion
8	Policies to influence location choices	Tax benefits to firms and households choosing to locate in "accessible" parts of metropolitan regions; enterprise zones; location-efficient mortgages		Reduction in distance per trip, enhancement of transit and NMV mode shares, reduction in (private vehicle) load factors	Local air quality relief; other environmental concerns; congestion relief
9	Policies to influence public attitudes toward transportation and energy consumption	Media campaigns, youth education campaigns, information "exchange" projects	Leeds (UK) TravelWise program	Can potentially benefit any and all of the components	Balance of payments / economic security; local air quality relief; other environmental concerns; congestion relief; basic needs and accessibility

There are three types of policies that alter costs of fuel consumption from their market value: (petroleum-based) fuel taxes, carbon taxes, and other policies that incorporate previously sunk costs into fuel prices. Fuel taxes are the most widely used form of pricing policy. In many instances they have been intended more as a revenue source than as a policy intervention in the market to reduce fuel consumption. In certain high tax countries such as the Netherlands or Italy, for example, fuel taxes account for as much as 10% of annual revenues. A fuel tax's effectiveness is related to the price elasticity of demand for the fuel in the country. The more inelastic the demand for fuel, the more effective fuel taxes will be as a revenue measure, and the more ineffective they will be as greenhouse gas, energy, or environmental policy, and vice versa. Since elasticity of demand for motor fuel seems to be correlated with income, even within the same country (May and Nash 1996), a fuel tax for countries with a moderate or low per capita income might be an effective public policy mechanism to restrain fuel consumption and GHG emissions.

A second policy to alter the cost of fuel consumption is a carbon tax. Greene (DOE 1996) argues that carbon taxes are more efficient than fuel taxes for GHG emissions reduction, since the "bad" to be avoided is taxed directly. A carbon tax is likely to influence not only the quantity of fuel consumed, but also the fuel mix (i.e. provide incentives for using less carbon-intensive fuels). Nevertheless, a carbon tax is somewhat more difficult to administer than a fuel tax, and the latter might be considered a simpler proxy for a bona fide carbon tax.

Arguments against carbon or fuel taxes, and, indeed, policies which generally raise the variable cost of motor vehicle use, tend to focus on either their regressivity (DOE 1996) or a concern that restraint in transportation activity would restrain overall economic performance. The merits of such arguments undoubtedly depend on local circumstances, and the time frame of analysis involved. For example, uncompensated gasoline or carbon taxes evaluated over a short time period -- say two to three years -- might seem regressive in that they hurt the poor in favour of the rich (the rich pay a lower percentage of their income for these taxes than do the poor, and are therefore less likely to change their behaviour). However, over a longer period of sustained fuel pricing, the regressivity is less clear. If travellers change their behaviour -- by, say, increasing their use of public transportation or demanding services closer to their homes, thereby reducing the catchment areas for retail operations, causing a recentralization -- then the poor may benefit significantly. If fuel or carbon tax funds are used to finance public transportation, assuming the rich continue to drive, the overall system then transitions to one where the rich subsidise the poor within the transport sector. Such an arrangement could not be said to be regressive.

In addition to greenhouse gas emissions reduction, there are a number of other policy goals for which fuel or carbon taxes can be an effective instrument, including improving air quality (Cameron 1995) and, for oil importing countries, improving the balance of payments.

The third policy to alter the cost of fuel consumption is to variabilize previously “lumpy” fixed expenses associated with automobile ownership and use onto the price of fuel. In the United States, the principal manifestation of this variabilization of fixed costs has been discussions of introducing "pay-at-the-pump" automobile insurance. The objective of such a policy can be both GHG and non-GHG related; countries with a high proportion of uninsured motorists, for example, might consider such a policy as a way of reducing costs to the state or society at large these uninsured motorists impose. Pay-at-the-pump insurance, however, removes the choice of insurance policies from consumers, and does not distinguish between good and bad drivers. Nevertheless, it is an attractive policy option, not only because it is a revenue-neutral way of raising the costs of fuel consumption, but also because motorists only purchase as much insurance as they need, thereby reducing an incentive to drive.

With the exception of motor vehicle fuel taxes -- which until now have been more revenue- than policy-driven -- none of the policies reviewed in this section have been tried anywhere. However, the European Union has discussed adoption of a community-wide carbon tax, most recently at 50 ECU per tonne of carbon. Although such a proposal no longer looks realistic, individual members of the community, such as the Netherlands, are going ahead with a carbon tax proposal.

2.2 Policies to Alter Other Costs of Motor Vehicle Use

Changing the variable cost of motor vehicle use can be an effective policy. Even if overall cost burden on households did not change, variabilization of costs -- that is, shifting costs from up-front, fixed or "sunk" costs to pay-as-you-go costs -- is an important way of changing the logic behind transportation decisions. Policies in this group might target either the discrete use of an automobile in a particular area (charging vehicles which cross a barrier), more general use of an automobile (charging per unit distance driven), or vehicle storage at the destination (charging for parking). In addition, these policies can be temporally variable, so that the prices change according to the level of congestion expected at different hours on different parts of the system. Charging per unit distance driven is often referred to as "full cost" or "road" pricing, since the actual tax per unit distance is in principle set at the amount of unpaid "costs" (including externalities) which the user imposes on society per unit distance driven (Button 1986). Ideally, such prices are set at the level where the marginal benefit to the user (the benefit of driving one extra kilometre) equals the marginal costs to society. Full road pricing, however, is effective only insofar as users can understand the pricing system and can, therefore, modify their behaviour in response to price signals. The economic theory underlying road and congestion pricing is laid out in Button (1982). For a lucid explanation of congestion pricing in particular, see Lee (1994).

The short-run impacts of road pricing are similar to those of fuel taxes. Assuming reasonably elastic demand, users respond by restraining their transportation activity in private vehicles to lower their road cost burden. This might mean taking fewer trips or chaining several at once or at one location, taking shorter trips, combining vehicular trips with other people, or going by different modes. For road freight transportation, increasing the variable costs of transportation might strengthen the economic disincentive to "backhauling", whereby truckers carry goods only one way, their trucks being empty during the return trip.

The long run impacts of road pricing are potentially quite profound. Classical urban economic theory suggests that an overall increase in transportation prices will have a strong impact on land markets (Alonso 1964). Changes in land markets, in turn, will impact landform and settlement patterns, particularly in new or fast-growing districts of the metropolitan core, and at the urban fringe. Land markets may also respond to changes in the relative prices among the modes, as demand shifts. The result may be more compact forms of development than may otherwise have occurred, which are more conducive to non-motorised or public transit trips. This, in turn, might have secondary impacts, such as increased efficiency and viability of transit operations, or more willingness by citizens to accept tighter restrictions on automobile use.

In principle, road pricing is also an effective policy to alleviate road-operating conditions, by reducing travel on a given amount of roadway. One advantage of using locator chips in vehicles or smart cards as the toll collection mechanism is that it allows road charges to be scaled according to the particular location and particular time of the day. In other words, a *congested* vehicle kilometre can be charged at a premium over an uncontested one. Unlike other congestion policies, such as roadway widening or traffic management, congestion pricing is a *compensated* policy; that is, users replace one cost (time) with another (money). In principle, if these values are set properly, there should be no latent demand effect, (convergence on the newly created road capacity from other parts of the transport sector). Potentially "new" users who "converge" on the newly uncongested roadway will need to pay in money the equivalent value of what they previously would have had -- and refused -- to "pay" in time. Road pricing, then, is probably an effective policy for alleviating operating conditions without inducing new trips, mode switching, or demand-generating land development.

In practice, there are very few examples of road pricing schemes. Most of these have been driven by the objective of alleviating congestion (particularly peak-hour congestion). One of the better known examples has been in Singapore, whose *Area Licensing Scheme* (ALS) has been in effect for over twenty years. This scheme has required vehicles entering the central business district (CBD) on weekdays and Saturdays to display a central area license, which can be purchased either daily or monthly. Ang (1996) reports that the amount of peak hour automobile traffic entering the CBD in 1989 remained at about 40% of that of 1975, just before the scheme went into place, despite the fact that the CBD grew by a third in the same period, and the private vehicle stock grew by 86%. Undoubtedly, some temporal shifting has taken place, but this evidence suggests strongly that the ALS has induced ride-sharing and/or mode switching.

Despite the beneficial effects of road pricing as a GHG mitigation strategy, a number of arguments against it warrant consideration. First, like fuel and carbon taxes, road charges can be regressive if unmitigated. Second, as a pure GHG strategy, road pricing is less efficient than, say, a carbon tax, since it taxes vehicle kilometres travelled (with which there are, no doubt, some *positive* externalities associated) as opposed to carbon emissions. Nevertheless, a road pricing scheme can be a very efficient element of a transportation policy with broader aims than simply greenhouse gas emissions reductions. Third, for large or rapidly growing regions, particularly those with spatially segmented residential patterns and competition among employment subcenters, road pricing might have important consequences for long-term urban growth and development. For example, a firm in a particular industry which uses a particular type of labour might find its labour pool considerably smaller following the adoption of a road-pricing scheme, if transportation costs are high enough and the segregated housing market inflexible enough that its wages fall below real market wage rates once these costs are factored in. This firm may choose to relocate, further enforcing both wage and residential segregation. These land and labour market changes may or may not be compatible with the region or country's development goals.

In addition to charging for road use or vehicular access to zones, a variable cost pricing strategy might also target the storage of vehicles at the destination. This might involve simply limiting the amount of parking provided at different locations, raising the cost of on- and off-street parking, or taxing "free" employer-provided parking benefits as ordinary income. Free parking not associated with work trips, however, is more problematic, as it is difficult to co-ordinate the various providers of parking (Bradley 1996). In many regions, economic competition renders individual actors, including both public and private entities, impotent to charge for parking, without simply forfeiting market share. (For a good discussion in the context of the United States, see Shoup and Pickrell, 1980.) In many countries, whether and how the problem of free parking caused by economic competition can be addressed becomes a test of how far the state can regulate the uses of private (or privately controlled) property.

Correctly applied, parking charges should result in a reduction of car trip generation rates and a beneficial shift in mode shares (S_m). However, if unevenly applied, parking charges might result in an increase in trip distances as travellers drive farther to find cheaper parking.

A final policy that should be mentioned is the expansion of car-sharing schemes. These schemes involve pools or fleets of cars available to club members on a pay-as-you rent, pay-by-kilometre scheme. The purpose of such schemes is to allow households access to cars without necessarily purchasing or leasing them, which results in significant up-front and fixed costs. Up-front costs can cause a distortion in trip-making decisions, introducing the logic of "I have already paid for the car, I should use it" into choices about when, where, and how to travel. By paying only for the use of the car, members of the car-sharing club have incentive to evaluate among various travel options each time they travel, hopefully inducing more favourable modal usage. Urban form, however, is an important element of car-sharing schemes, because enough people must be within a walking catchment of the pool cars for the operation to be viable.

2.3 Policies to Alter the Conditions of Road Traffic

A wide array of policy options exists to manipulate traffic flow, from expensive road-building and road-widening projects, to relatively inexpensive changes to the traffic management system on existing roads (Transportation Supply Management or TSMs). Although many of these policies are quite effective in their ability to manipulate flow, and such manipulation of flow is often justified, in part, on environmental grounds, it is not at all clear *which* changes to traffic conditions are most likely to bring about a reduction of GHG emissions in the medium and long runs.

Easing traffic means that each car can operate under conditions that allow it to be more operationally efficient. At the same time, though, the better traffic flow conditions *induce* more traffic. More traffic results in potentially more car and truck traffic relative to other modes and an increase in overall travel activity. The net effects of these two tendencies on fuel intensity and GHG emissions (and local air pollutant emissions, as well) are far from clear.

The induced traffic, a phenomenon receiving significant attention from researchers and transportation policy experts, results from the two phenomena *convergence* and *growth*. Downs (1992), who originally suggested the two terms, provides an excellent example of convergence:

Nearly every vehicle driver normally searches for the quickest route, one that is shorter or less encumbered by obstacles (such as traffic signals or cross-streets) than most other routes. These direct routes [in the United States] are usually limited-access roads (freeways, expressways, or beltways) that are faster than local streets if they are not congested. Since most drivers know this, they converge on such "best" routes from many points of origin.

He goes on to observe what occurs when a road or expressway is widened or "improved":

> ....[T]hree types of convergence occur on the improved expressway: (1) many drivers who formerly used alternative routes during peak hours switch to the improved expressway (spatial convergence); (2) many drivers who formerly travelled just before

> or after the peak hours start travelling during those hours (time convergence); and (3) some commuters who used to take public transportation during peak hours no switch to driving, since it has become faster (modal convergence).

Although Downs speaks here explicitly of roadway widening, the phenomenon of triple convergence could be applied to any policy which serves to expand road capacity, including TSMs.

Convergence is a short-term, almost instantaneous, phenomenon. *Growth* on the other hand, is an outcome of the reaction of land markets to changes in relative *accessibility* caused by an increase in capacity. In the medium and long runs, new capacity on the improved roadway is taken up by vehicles going to and from newly developed activities along the road, built on land whose development value was enhanced by the increase of accessibility. A big question, of course, is how much of the growth is caused by, and how much occurs in spite of, the capacity enhancement. This question is particularly vexing since many capacity expansion projects are justified as necessary because of expected growth, raising the spectre in many environmentalists' minds of a self-fulfilling cycle of traffic projection and inducement.

With the preceding discussion in mind, we can divide traffic-oriented policy options into those that seek to enhance capacity and throughput, and those that seek to restrain them. Each reflects a fundamental belief about whether traffic growth is basically impervious to or driven by transportation policy. Policies that enhance traffic flow and operations allow vehicles to operate at more optimal conditions, thereby more closely associating their on-road fuel intensity with their optimum, test-conditions fuel intensity. This has the effect of reducing per-kilometre fuel costs. In addition, policies to enhance vehicle flow generally reduce travel times, which further reduces variable costs per-kilometre. One would expect an attendant price effect for non-automobile drivers -- since the relative cost of driving compared with other modes decreases -- and an income effect among previous drivers, because of the reduction in variable costs. These effects might cause the number of home-based trips to increase, the distance per trip to go up, or the modal structure to shift toward automobile use.

Similarly, policies which seek to reduce flow and throughput of vehicles might reduce trip making, induce people to make shorter trips, or make these trips on alternate modes particularly where the alternate modes avoid the rights-of-way the policy is designed to address. Operating conditions, however, would worsen, thereby driving up the GHG emissions of the vehicles that do remain on the road.

Policy options which enhance capacity and throughput include construction of new roadways or the widening of existing ones, construction or conversion of High Occupancy Vehicle lanes, street and parking management for efficient goods delivery in urban areas, computer-controlled traffic management, including Intelligent Transportation Systems, and traffic signal timing to enhance throughput or otherwise alter flow into bottlenecks. In addition, some transit enhancements might also be considered to be traffic enhancements as well, since grade separation of transit corridors will remove those vehicles from the traffic stream.

Traffic restraint policies include: barriers or prohibitions of vehicular traffic in certain locations or at certain times of day; circulation “rationing” or licensing; and traffic “calming” measures such as speed undulations, traffic diverters, and traffic signal timing and control to slow traffic. In addition, in newly developed areas, road patterns themselves can be designed to discourage high volume traffic. Some countries are also experimenting with entirely new types of roads, streets and public space. These new street and road types alter the traditional “movement versus access” dichotomy in roadway use. The Woonerf in the Netherlands, for example -- literally, "living space" -- is a street designed specifically to put pedestrians, cyclists, and even parked cars, into the street space normally reserved for through-going motorised vehicles. The logic behind the Woonerf is that automobile drivers experience themselves as not the sole users of a street, and thus take extra precautions when driving on it. Such a facility represents the boundary area between a transportation facility per se and an urban enhancement.

The Woonerf is an example of the growing interest in the "urban amenity" aspect of transportation facilities. Jacobs (1993), for example, argues that the loss of urban amenity in highly engineered roads such as the urban or suburban "arterial" creates an inhospitable environment for the pedestrian and cyclist while providing little substantial benefit for the goal of movement of motorised vehicles. In his survey of arterials and boulevards from around the world, he finds that properly designed, the latter are capable of moving nearly as much traffic as the former, while enhancing the experience and enjoyment of both pedestrians and automobile drivers. He also finds no statistical evidence to suggest that well-designed boulevards are inherently less safe than arterials, which is one of the engineer's principal objections to boulevards.

In the developing world, the controversy between capacity expansion and traffic restraint is clearly visible in the various attitudes found from country to country vis-à-vis non-motorised vehicles (NMVs). Even within Asia, where two- and three- wheeled non-motorised vehicles have been part of the transportation fabric for over a century, attitudes differ sharply. Formally, Indonesian policy in cities such as Jakarta is to discourage them, under the justification that they hinder motorised traffic, contributing to congestion, pollution, and inefficient vehicle operation. In China, on the other hand, alongside an aggressive policy to expand motor vehicle capacity, bicycle facilities are still given serious formal treatment among transportation engineers. Replogle (1991) reports the following categories of NMV facility provision in China:

- Special Bicycle Roads -- bicycle-only thoroughfares -- in development for the CBD of Shen Zhen City.
- Semi-independent Bicycle Roads -- next to automobile facility but physically separated
- Non-independent Bicycle Roads -- next to automobile facility, not physically separated
- Mixed Traffic Roads
- Pedestrian-Bicycle Roads -- roads dedicated to pedestrians and bicycles, which share space.

The GHG benefits of encouraging versus discouraging NMV transportation in an urban network are an open question, as the benefits of encouraging NMVs must be balanced with the loss of efficiency of the motorised vehicles that remain on the roads.

2.4 Enhancements to Public Transport and Other Alternatives to Road Transport

Formally, public transit consists of vehicles operating on fixed routes, with published fares and schedules, and allowing anybody on board who presents themselves for boarding and is prepared to pay (or has paid) the fare. Paratransit consists of all the permutations in between (i.e. some but not all of the conditions apply). Examples of paratransit services include taxis, jitneys, dial-a-ride services, airport transfer services, company van shuttles, and even tour buses, as well as non-motorised modes, such as bicycle-rickshaws. Paratransit is quite important in many developing countries, both in the formal and informal sectors.

The principal advantage of public transit is that it can move more people more efficiently than private transportation. Since the vehicle tends to be larger than private transportation vehicles, a passenger-kilometre can occur using significantly less road space and energy than on private motorised transportation. The throughput capacity of various modes is compared in Table 2, which is adapted from Replogle (1991).

Table 2. Comparison of Throughput Capacity for Various Modes

Mode	**Capacity** *(persons per hr per meter of lane-width)*	**Operating Speed** *(kms per hour)*
Pedestrian	3600	4
Bicycle--mixed	1330	10-14
Bicycle--bikeway	1800	10-18
Cycle-rickshaw	650	6-10
Automobile--mixed	120-220	15-25
Automobile--motorway	750	60-70
Bus--mixed	2700	10-15
Bus--busway	5200	35-45
Trolley bus	1300	10-15
Tram	3000	12-15
Light rail	3600	25
Rapid rail	9000	35
Suburban rail	4000	45
Taxi	400-720	15-25
Paratransit & minibus	1100	12-20

Although public transportation *can* move passengers more efficiently than cars, it does not necessarily do so; a car with a single occupant is much more energy efficient than a bus with a single occupant. Public transit is effective (both for congestion and CO_2 emissions reduction) only when passenger occupancies are above a certain threshold (for example, about 10 to 12 persons seems to be the CO_2 emissions reduction threshold for the San Francisco Bay Area according to Gorham (1996), depending on particular factors) and even then, only when transit enhancements induce mode *switching*, as opposed to simply inducing growth[22].

Circuitry in transit routing can also be a factor in the effectiveness of transit as a CO_2 reduction strategy, since transit trips tend to be less direct than automobile trips. A rule of thumb is that public transit trips are between 5 and 50% longer than the crow-flies distance, depending on the traffic network and the length of the trip. For paratransit trips (such as dial-a-ride or shared-ride taxis), though, this may be significantly higher. Nevertheless, where load factors are high enough, circuitry may be a relatively insignificant factor in transit CO_2 emissions.

A final consideration is whether the transit enhancements occur on mixed or dedicated rights-of-way. This consideration is particularly important for urban areas. On dedicated rights-of-

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[22] Mode switching does not necessarily need to be for existing trips. It can be that a given growth in trips can be diverted from one mode to another. For example, some countries claim CO2 reduction for development of high-speed rail networks. This is justified if it can be shown that the trips that occur on the rail network would have occurred anyway, on a different mode. But if the high-speed rail induces travel, then claiming credit for CO2 reduction is misplaced.

way, transit enhancements might substantially decrease travel times (both on transit, and on the roadways the transit vehicles no longer use as heavily.) The convergence and growth principles discussed in the preceding section may occur, therefore, on both modes. If the transit enhancements occur in mixed rights of way (adding buses, for example), operating conditions for all vehicles may be negatively impacted if the roadways are already at or near congested levels. There may be offsetting benefits, however, in changes in modal structure.

Policies which enhance transit service generally target four areas of service: expanding service to existing areas by increasing frequencies and reducing travel and wait times or extending hours of service, expanding the geographic extent of service (for example, expanding metro or light rail systems), enhancing passenger comfort or safety (for example, building a new intermodal facility), and reducing fares (i.e. subsidising service). On the freight side, enhancing alternatives to road transport involves investment in rail and port facilities, expanding the share of internal waterway and coastal shipping activity, and encouraging "piggy-back" activities for longer distance travel so that containerised freight might take advantage of non-road modes for significant segments. In many countries, regulatory reform might also be an important focus of efforts to make rail and water more viable alternatives to road transport.

Schimek (1996) has shown that, in highly motorised, high-income regions, investing transit money in reducing travel and waiting times (increasing frequencies) and increasing geographic extent of service is both a more effective (maximising ridership) and efficient (minimising costs) use of scarce transit money than reducing fares. Whether such a result is applicable to developing countries or regions with a relatively small number of choice riders is an open question.

In addition to direct spending on these enhancements, national and metropolitan governments might also undertake regulatory and other reforms to introduce more competition into transit and paratransit service provision. For example, governments might change regulations in order to formalise previously informal paratransit or jitney services, or introduce competitive bidding for public transit provision contracts. Such regulatory reforms might positively impact any or all of the four areas of service described above with minimal cost to the public sector.

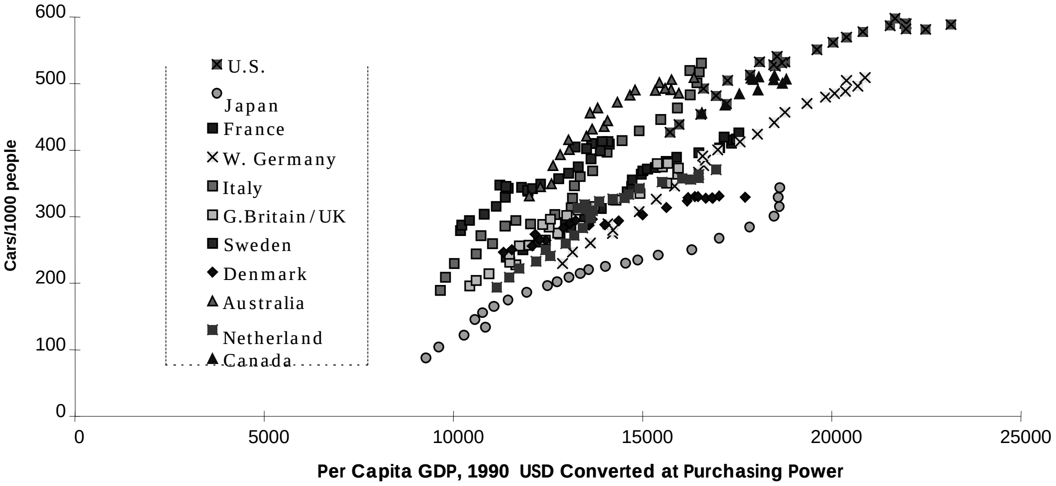
The city of Curitiba, Brazil, has had perhaps the greatest success with transit enhancements, all the more so because these enhancements have been relatively low-cost ones. They were undertaken throughout the 1970’s in concert with long-range, well-conceived, and, particularly important, well-executed land-use planning. Five existing arterial roads radiating out from the city centre were identified as foci for development, while automobile access to the city centre was restricted for private motorists. Bus service was expanded and concentrated on these arterials at the same time that road traffic was diverted or otherwise encouraged onto other roads. Dedicated bus lanes in the centre of the arterials accommodate express bus service using articulated buses to the city centre. This bus system is well known throughout the world for having innovated boarding tubes -- elevated platforms on the sidewalk that patrons pass through a turnstile to enter, and which allow rapid boarding and alighting of multi-doored buses, like a metro. This vastly increases the capacity of the system at peak, at a fraction of the cost of a metro. As a result of these enhancements, Curitiba’s bus-based transit system is the most effective in Brazil (that is, it has the most riders per operating kilometre). Rabinovitch (1993) indicates that 20% of bus riders formerly commuted by automobile, and the same source estimates that this strong ridership results in a saving of 27 million liters of fuel per year.

2.5 Policies to Influence Vehicle Fleet Demand

Vehicle ownership choices not only directly affect the energy intensity (and fuel mix) of the vehicle fleet as a whole, but also indirectly affects the amount of transportation activity. The strength of this multi-faceted influence of vehicle fleet ownership is indicated by the high degree of correlation between per capita energy consumption in the entire transportation sector and automobile ownership in industrialised countries.

An important research and policy question is why vehicle ownership seems to have such a strong influence on many different factors. Much of the reason probably has to do with the nature of household transportation investments: the costs associated with automobile ownership tend to be "sunk" costs. Once the vehicle is acquired and registered, the marginal cost of vehicle use is minimal. Policies that alter the costs of vehicle use, as discussed above, might be part of a strategy to break this strong link between vehicle ownership and energy consumption.

If governments are serious about CO_2 emissions reduction, they may need to look at both policies to influence the types of vehicles that consumers demand, and policies that restrain the growth in vehicle ownership. Several very real political constraints need to be taken into account in addressing the strategy of ownership restraint. First, automobile ownership is often associated with general well being and economic development. The figure below shows the strong correlation between vehicle ownership and per capita GDP.



Source: International Energy Agency and Lawrence Berkeley National Laboratory

If the rise in GDP per capita is driving the growth in vehicle demand, vehicle restraint policies may be reasonable. On the other hand, if the growth in vehicle demand is influencing the increase in GDP, then restraining vehicle demand may have negative economic consequences. The limited evidence from industrialised countries such as Denmark and the Netherlands, as well as the newly industrialised city-state of Singapore -- all of which have either pursued aggressive vehicle restraint policies or had high vehicle acquisition and registration fees (which effectively restrains vehicle ownership) -- suggests that vehicle ownership can be restrained without inhibiting economic growth. Whether the strong coupling of GDP and car penetration holds for developing countries is a matter of contention.

Second, in countries with no domestic automobile industry, a policy to restrain car ownership might be tied to a larger development goal of maintaining an acceptable level of balance of trade. In countries with an existent or a nascent automobile industry, on the other hand, it may be difficult to balance a development strategy which entails the growth of that industry with a strategy that calls for restraint of ownership.

Third, a strategy which seeks to restrain *growth* in automobile ownership risks hindering the natural *turnover* cycle of the fleet, that is, the replacement of older vehicles with newer ones. Vehicle turnover, however, should be encouraged, both because newer automobiles tend to be more engine efficient, and less emissive of local pollutants such as carbon monoxide and volatile organic compounds, and also because less polluting alternative propulsion technologies may become available. The latter reason is particularly applicable to countries in the process of trying to shift from a leaded to an unleaded gasoline vehicle fleet.

Finding ways of restraining the growth of the vehicle fleet while not hindering the turnover of vehicles is particularly tricky. A system of variable registration fees, depending on whether one is registering a replacement or non-replacement vehicle, is one possible way of addressing this issue, but it raises equity questions as those households and firms already possessing a vehicle are advantaged over those which do not. A potentially more promising approach is to price both acquisition and registration, such that acquisition costs are relatively high to begin with, and registration costs are at least linearized -- and more ideally, increase progressively -- over the lifetime of the vehicle as it ages. The fee structure would be set up such that after a certain amount of time, it becomes more economical for a household or firm to purchase a new vehicle than keep the old one. Such a strategy, however, may require enormous increases in the lifecycle costs of the automobile.

Singapore has addressed this issue since 1990 by auctioning off license plates, through a formula based on vehicle scrappage rates and progress in road construction. Plates are auctioned monthly, and prospective buyers of vehicles are not allowed to purchase them until they show that they have acquired the necessary plate. Revenues from the auction are used to finance transportation construction and management projects. The scheme is justified on a number of grounds, not least of which is the matching of supply with demand.

Other policies that might help restrain the growth of household and company vehicle fleets include taxing the value associated with company-provided vehicles as ordinary income, and using various policy mechanisms to minimise space for residential storage of vehicles, especially in urban areas. This latter can include, for the formal sector, land-use regulation (zoning and/or covenants) and incentives to developers to minimise parking.

In addition to an objective of restraining overall levels of vehicle ownership, policies might try to influence types of vehicles owned. For example, policy instruments can be used to provide incentives for households and firms to acquire vehicles that are less CO_2 emitting. One option is to peg acquisition and registration fees to the motive efficiency of the vehicle, or some variant of that measure. Similar policies are quite appropriate to and often used in the road freight sector.

The objective in the above case is to reduce vehicle overconsumption -- that is, a household's or firm's acquisition of a vehicle that is larger or heavier than its ordinary needs. Analytically, this might be understood as the vehicle stock's capacity mix intensity, that is, the intensity of the mix of vehicles and vehicle sizes relative to the needs and uses to which they are put.

(Mathematically, capacity mix intensity is expressed as the number of joules or watt-hours per passenger kilometre travelled or tonne-kilometre moved, and is simply the motive intensity divided by the load factor). The capacity mix intensity provides an indicator of the amount of total energy necessary to move a given number of people or a given amount of freight over a certain distance, for a given stock of vehicle sizes and characteristics. The policy goal here is to reduce the power needed to move a tonne or person kilometre by better matching vehicles to loads.

Policy measures might also target more directly the overall efficiency of the car bought, rather than the size per se. For example, registration fees might be set so that, within each weight class, more efficient cars would be less expensive to register. With such a policy, however, care needs to be taken that the fee structure does not inadvertently induce vehicle owners into buying a heavier class of vehicle than they might otherwise have purchased. Analysts need to be aware that increasing fuel efficiency of automobiles without an attendant increase in fuel prices will produce an income effect -- that is, the cost of automobile use is lowered for a given distance driven. How large or what the actual response of such an income effect might be are subjects of debate, but it is likely that some of this income effect might feed back and induce growth in vehicular travel.

A related policy measure that might address overall vehicle intensity, or power-motive intensity or engine intensity separately, (and, eventually, fuel mix -- to encourage alternative fuelled vehicles, for example) is the use of "feebates". Although the mechanisms can be somewhat involved, at the simplest levels "feebates" are a system of cross-subsidies within the vehicle fleet sector, whereby purchasers of "wrong" vehicles pay purchasers of "right" vehicles. Wrong and right can be defined by weight, propulsion system, power-motive intensity, engine intensity, overall fuel intensity or fuel used. One advantage to feebates over, say, straightforward registration and licensing schemes is that they can be revenue neutral. Although there is no empirical experience with feebates, their effects have been simulated in the United States using vehicle choice models, and have been shown to reduce fuel consumption by six to eight percent while enhancing net social benefit in all scenarios simulated (Davis, et. al. 1995).

2.6 Policies to Influence Vehicle Fleet Production

The range and effectiveness of policies to influence motor vehicle supply is very much determined by whether a country has a domestic automobile industry. Countries with no domestic automobile production can have little direct impact on vehicle production, although they may be able to influence the type of vehicles imported into the country. This is particularly true for countries with a very strong second-hand car market (in relation to the new car market.) Most of the discussion in this section pertains to countries with domestic automobile manufacturing.

Vehicle supply-side policy can target fuel mix (conventional, alternative-fuelled and non-motorised vehicles) engine intensity, motive intensity, or both. In addition, supply-side policy options might also help target the appropriate "capacity mix", as discussed in the previous section. Separating engine intensity and motive intensity in policy formulation has two advantages. First, it ensures that technological improvements will be channelled first into efficiency advances, rather than into other aspects of vehicle performance, such as vehicle power, comfort, or accessories. The experience in the United States, for example, suggests that there has been constant improvement in engine efficiency over the past twenty years, but, following the fleetwide attainment of basic Corporate Average Fuel Economy (CAFE) standards in the mid-1980's, the gains in engine efficiency have been eaten up by declines in motive efficiency, caused mostly by the increasing weight and/or power of vehicles in most classes (Schipper 1995). Second, by focusing policy and incentives on reducing motive intensity, innovation in the non-motorised sector is put on more equal footing with that in the motorised, and technological advances in the latter might be applied to the former.

There are essentially three types of policies that can affect vehicle supply and production: regulations and mandates, transfers and subsidies, and tradable permits. Regulations and mandates refer to obligations that vehicle manufacturers must fulfil, or face penalties from the state. While often used interchangeably, regulations usually pertain to specific actions a producer must take, while mandates generally refer to a performance standard to which they will be held. For example, a regulation may require vehicle manufacturers to build only catalysed engines, while a mandate may require a manufacturer to sell a given percentage of its production as alternative-fuelled cars.

Transfers and subsidies usually are in the form of research and development moneys that are made available to vehicle manufacturers for technological advances in engine intensity, motive intensity, or alternative-fuels. Quantifying the benefits of such R & D programs can be difficult, though.

Tradable permits are a market-based alternative to mandates. Generally, these establish performance criteria for all competitors in the industry. Firms that exceed the performance criteria can sell credits to firms that do not, producing a net (industry-wide) effect at the level of the original performance criteria. A system of tradable permits can work only where there are enough players in the industry that an adequate market for credits can develop.
Whichever of these methods is used in a supply-side strategy, the overall goal is to induce manufacturers to produce more efficient vehicles in the face of its two overriding concerns: keeping production costs down and maintaining consumers' interest in the vehicle. The manufacturers' interest is not simply in not losing market-share; were that the case, it should be fairly straightforward to convince them that any of the above strategies would still keep the automobile market competitive. Rather, manufacturers are concerned about inducing a slump or some other radical change in the vehicle market as a whole (see, for example, Santini 1989), which might depress the entire industry. Analysis and the solutions proposed must address these issues.

2.7 Policies to Influence the Built Environment

This section and the next discuss aspects of the built environment. We discuss first land "suppliers"; public and private entities that improve land for settlement; the next section will discuss policies oriented toward the household or firm facing location choices. In the informal sector of many urban economies, as well as in the rural sector, however, the two may be indistinguishable. The discussion that follows pertains for the most part to the urban sector.

In rapidly growing regions, the ability to control and direct physical settlement patterns is probably the single most important aspect to controlling and restraining the growth of energy consumption in the transportation sector in the long run. Much of the opportunity for influencing the built environment lies explicitly in the domains of economic development or housing policy, often at the regional or subregional level. The agencies and ministries responsible for these areas of government policy may have little interest in transportation-related GHG reduction, and might see little connection with their portfolios, even if they did. Similarly, many transportation or environment officials might conclude that economic development and / or housing policy is beyond their control, and conclude that they should not spend their time on such "tangential" policies. Urban settlement patterns determine, in the long run, not only the nature of the transportation system and the energy consumption associated with it, but also the extent to which system users will respond to targeted transportation and energy policy initiatives.

There exists, then, in many countries an institutional and spatial mismatch in the mechanisms for planning urban settlements and transportation (Dimitriou 1990). In many lower-income countries, these mismatches are exacerbated by a third: formal planning and policy institutions that attempt to exert control over largely informal settlements, such as squatter settlement or "shanty" towns. There is growing recognition of the real linkages between the formal and informal sectors in urban land systems (Durand-Lasserve 1990); consequently, the physical and organisational structure of the informal housing sector is different for different regions and countries. Nevertheless, in order for there to be even modest coordination between transportation planning (particularly infrastructure development) and land development, the housing and land development sector must be formalised as much as possible, although this by no means implies rejecting the institutions and mechanisms of the informal sector (Siddiqui and Khan 1990)[23].

Urban and rural development strategies can provide significant opportunities for governments to influence the built environment to reduce transportation demands in the medium and long runs. There is growing recognition of the impact of development strategies on transportation and demand growth (Dawson and Barwell 1993, Simon 1996, Dimitriou 1992). An integral part of this is the transition from the standard objective of *mobility* to the more meaningful but difficult concept of *accessibility*. A "Basic Needs" approach to "transportation" development (see Dimitriou 1992) might put emphasis on ensuring that goods and services necessary for the basic, day-to-day needs of a community are accessible rather than building transportation infrastructure to enhance mobility. For example, the day-to-day transportation needs of a rural village are probably much better served by construction of a well in the centre of the village than by constructing a road to or from the village, even if the road went strait to the river. The former enhances villagers' accessibility to water, the latter their mobility.

Programs such as "Sites and Services" might be instrumental to enhancing accessibility while minimising the need for mobility. Sites and Services is a strategy pursued variously by the international development community since the mid-1970's, with mixed degrees of success, as an alternative to costly and slow public housing development, in growing regions with rapidly expanding informal sector housing. In these projects, the public sector provides building lots, basic infrastructure (usually water and electricity), and, usually, technical assistance, while the occupants themselves build their own houses. Sites and Services strategies have been used in as different urban environments as San Salvador, El Salvador, and Lusaka, Zambia.

A second, and related approach, is to strategically retrofit existing settlements to provide services, including road, transportation, and even telecommunications infrastructure, to previously ill-served areas. A well-known example is the Orangi Pilot Project in Karachi. An important aspect of this strategy is to identify the residents' accessibility needs, and figure out

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[23] Interested readers are referred to Farvacque and McAuslan (1992) for a detailed discussion of both the practical and theoretical issues behind formalisation of the informal land sector.

ways to minimise or eliminate their need to travel where possible in order to fulfil these needs (Dawson and Barwell 1993). In rural communities, this might be reasonably straightforward by better locating facilities such as agricultural supply stores, grinding mills, water and firewood sources, etc. and by providing incentives for food storage (Dawson and Barwell 1993). In urban communities, the prospect of enhancing accessibility while minimising the need for mobility is trickier, since access to wage employment is probably one of the most important functions of the urban transportation system. Decentralisation of employment is not necessarily a solution, since there is no way of ensuring that each employer decentralises to a location where its employees reside.

In the formal sector, where large-scale production of housing is increasingly the norm in many cultures -- both from the public and private sectors -- settlement patterns which reduce transportation energy requirements can be influenced by both the housing mix and the design of what is actually built. Housing mix affects the overall density of a new area, and density, along with other physical attributes of a neighbourhood, is associated with lower energy-intensive modes such as transit or walking (Pushkarev and Zupan 1977). In addition, housing of any level of intensity can be designed so as to facilitate pedestrian, cycling, and transit trips (Van der Ryn and Calthorpe 1986).

The spatial (and temporal, for that matter) aspects of retail opportunities also present challenges to urban form in developing countries. The norm in industrialised countries increasingly is to segregate retail physically from the rest of the urban fabric with vast expanses of parking facilities that are not conducive to walking or transit. The justification has traditionally been that offstreet parking provision is necessary for a commercial centre to compete with other centres and attract customers. Critics point out that this justification is both a self-fulfilling prophecy and a vicious circle (Calthorpe 1994, Cervero 1989). The less hospitable the walking environment is, the more people will drive if they can, and the more the settlement pattern will change to reflect the growth of the motorised population. Regions with fairly strong separation of the spheres of production and consumption (i.e. one or both occurring predominantly outside the home), such as in Southeast Asia and Latin America, are particularly at risk of embarking on this vicious cycle.

In industrialised countries, retail activity not only takes place increasingly at physically separated commercial centres, but also through increasingly centralised facilities. The corner store has given way to the neighbourhood grocery store, which may in turn be giving way to the subregional supermarket. This centralisation has been associated with more vehicular household travel to accomplish household chores (Giuliano 1986). One open question, however, is whether there has been a decrease in freight activity (tonne-kilometres of freight), as goods no longer need to be distributed to the very local levels. In industrialised countries, this benefit may have offset somewhat the rise in motorised household chore making. This possible offset notwithstanding, it is unlikely that a similar benefit would accrue to many developing countries embarking on a similar development pattern, since a significant amount of non-motorised freight traffic would be displaced by increased household mobility, as well as truck traffic.

In the formal sector, the principal methods of influencing what gets built where are land-use control powers, which can broadly be defined in three categories, depending on the level of intervention by the state. The first is state control of land and/or housing production (the public sector controls land). The second is land-regulation, zoning, and planning (the private sector controls land, subject to constraints placed by the public sector). Third, land-use may be controlled by covenant or contract. (The private sector controls land, subject to constraints placed by previous owners, who may be public or private actors.) Which of these should be used depends on local and national priorities, as well as the nature of land-markets and common law related to land in a given country. In practice, a combination of all of these methods will probably need to be used for effective policy implementation. In many countries, the state power over land is vested in or otherwise delegated to local or regional authorities. The ability of national governments to influence land policy, therefore, may be more indirect than direct.

Changing the nature of the built environment hopes to impact primarily the distance per trip, and reduce the relative importance of car-based modes to the benefit of walking, cycling and public transport use (a shift toward less energy-intensive modes). It might also help to bring up vehicle occupancies (for example, by making car-pooling more viable) and also make car-sharing clubs a more realistic choice for many people. It is difficult to assess, however, whether land-use changes would have any impact on the number of trips generated from each household, because it is not clear how changes in urban form influence decisions about whether to make a given trip, and how such trips are chained with other trips.

On the technical side, changes in urban settlement structure should have no affect on engine intensity, motive intensity, or fuel mix. It is not clear the effect such policies would have on overall operating conditions. On the one hand, presumably higher densities and more concentrated zones of activity would result in more transportation and access activity on streets and roads with the same amount of capacity. On the other, since low density, car-dependent growth is being constrained, roadways on the fringes of the urbanised area would have lower amounts of activity than otherwise, and consequently would be less congested than they would have been. Furthermore, as Levine (1996) has argued, the effects of compact land development on roadway traffic are likely to be similar to that of any other traffic restraint measure: Downs' triple convergence principle is likely to hold. (See discussion of Downs in the section of "Traffic Enhancement.") Nevertheless, as argued earlier, pricing policies that might be able to effectively restrain this triple convergence are more likely to succeed where urban settlement patterns encourage alternate forms of transportation.

There are a handful of metropolitan regions in the world which have had progressive and foresighted planning and urban development policy vis-à-vis transportation and land-use, and most of these are located in industrialised countries. It is difficult to prove that this progressive planning has had a beneficial effect on transportation energy consumption in these regions because: 1) it is hard to know how much transportation energy would have been consumed in the absence of these policies; 2) it is difficult to determine whether the resulting land form directly influences transportation energy consumption, or simply focuses and channels other factors, such as socio-demographics, which are in turn the more powerful explanatory variables behind observed differences in energy consumption; and 3) planning and control over land use and urban form are often carried out in concert with other policies (such as enhancement of transit), so it is not easy to isolate its effects.

Perhaps because of the fact that where land-use strategies are pursued aggressively, they have been used in concert with other policies, evidence from around the world suggests that rapidly growing regions which have sought to direct land use and growth as part of a larger transportation strategy have succeeded in reducing transportation energy consumption. Gorham (1996) shows that transportation-related carbon output per capita in the Stockholm, Sweden Metropolitan Region is about one fifth of that in the San Francisco Bay Area, and that most of this difference is attributable to differences in urban form (neighbourhood form and regional structure.)

Outside the developed world, land-use controls seem to have been quite effective in Curitiba, Brazil, Singapore, and Hong Kong, the latter two of which have successfully implemented joint development strategies as part of the development of their metro systems. Singapore has undertaken the development of high-density, satellite suburbs as part of its heavy rail implementation strategy. These two cities have focused development around rail stations. Curitiba, on the other hand, has focused its development along bus-transit corridors, which finger out from the city centre. High-density residential and commercial uses are encouraged along the corridor (just as these uses are placed in closest proximity to the rail station in the Singapore satellite suburbs.) Densities fall off with increasing distance from the transit corridor. This has the effect of concentrating over 60% of the residential population within walking distance (usually taken to be about 1/4 mile or 400 meters) of the transit line (Rabinovitch 1993).

2.8 Policies to Influence Household / Firm Location Choices

Since land and housing markets can be fundamentally different in different countries, we can only suggest the broadest outlines of what a demand-side strategy might entail. The extent of government involvement in residential housing provision can vary widely. The state might actually construct housing, provide direct financing (subsidised or otherwise) to both suppliers and consumers of housing, or indirectly support the market by providing credits or guarantees to both suppliers and consumers. In addition, the state might provide tax incentives to both suppliers and consumers in all or particular subsectors of the housing market. Tax relief for mortgage interest or rent is an example. Similarly, regional or local governments might also take on any of the above functions. The nature of the policies pursued in this policy group, therefore, would depend on the state's relationship to the housing market as a whole. In the formal sector with an active private market which provides housing for a reasonably broad cross-section of the market, for example, the state might subsidise "energy-efficient" mortgages to households purchasing a residence in a low transportation-intensive area, such as near an activity centre or transit line (Holtzclaw 1994). At the present time, the "energy-efficient mortgage" is merely conceptual; it has not been tried anywhere. In markets where the state itself supplies much of the housing, it might price that housing so as to favour high-density, high accessibility units over lower-density ones. For the informal sector, such a strategy might entail formalising title or other occupational rights (or prioritising the formalisation process) according to whether a settlement meets certain transportation-intensity criteria, such as density, orientation to street and pedestrian ways, etc.

To influence firm location choice, governments might use the equivalent of an "enterprise zone", identified not only as part of an economic development strategy, but also according to transportation criteria. An enterprise zone would be a physically delineated part of a city where businesses that set up operations receive favourable tax status and possibly some other bonuses, relative to businesses that do not. The expected impacts of such policies are similar as those of the previous policy group.

For freight, a demand-side policy would need to be even more comprehensive, and probably more controversial. Influencing simply the location of a production facility, for example, might be relatively ineffective, if the entire production process is highly scattered and, by definition, freight intensive. Whether and how governments might influence these processes in their totality is questionable, and both, plus the extent to which governments would be inclined to do so, depend strongly on local conditions. The growth of just-in-time delivery production systems, for example, comes from the growth of "zero-stocks" production techniques. By understanding better what is driving the demand for "zero-stocks" production -- for example, real estate costs of warehousing, excessive depreciation costs of stocks for certain industries, etc. -- governments may be in a better position to design holistic policies to induce less freight-intensive production processes.

2.9 Policies to Influence Public Attitudes toward Transportation

The final policy group pertains to those policies that seek to alter the public's perceptions of transportation (and related lifestyle choices) -- and, hopefully, their behaviour. This group could include media campaigns (television/radio/billboard advertisements), youth education programs in schools, and adult driver education programs. Such efforts to influence public attitudes, including acceptance of other governmental policies, could in principle target any of the basic elements discussed at length in the previous chapter. For example, they might try to encourage travellers to carpool, tout the benefits of public transportation (induce mode shifting), try to induce people to chain their trips more (reduce trip generation rates), or simply tout the benefits of more efficient vehicles. Similarly, driver-education campaigns, which could be linked to license or insurance requirements, might offer programs or curricula which stress less wasteful methods of driving -- for example, altering acceleration/deceleration habits or instructing on more efficient use of gears for manual transmissions.

Campaigns may be interactive as well as uni-directional. Instead of conceiving of a campaign as simply a way of getting information out to travellers, it might be a tool to exchange information, whereby valuable information about how households make transportation decisions is collected at the same time that "public awareness" information is disseminated.

Innovative methodologies involving such two-way information exchange are being experimented with in the United Kingdom, under the HeadStart and TravelWise programs. Under these programs, households are surveyed to ascertain their current travel behaviour. Next, household interactions are explored by a transportation specialist using stated preference and gaming techniques such as Household Activity Transportation Simulation (Jones and Dix 1978). The specialist then makes specific recommendations to the household about how its members can maintain their current level of outside-the-home activity participation while reducing reliance on and use of the automobile. The household is then re-surveyed at a later date to determine if there is any noticeable change in travel patterns. Such a technique is, of course, very expensive, since it works household-by-household. Nevertheless, for regions where air quality deterioration or congestion are (or may become) an acute problem, it may be an important if small part of a broader strategy. The city of Sydney is establishing a similar program in preparation for the 2000 Olympic Games.

A similar -- but smaller scale and higher profile -- program was attempted in Charlotte, North Carolina in 1989. As part of a TV-based "traffic mitigation" campaign developed by the University of North Carolina, a TV crew followed a family around in their daily trip-making for one whole day, and the results were submitted to a "traffic analyst", who commented and made suggestions to the news reporter of how this family might have avoided contributing to congestion. Unfortunately, the effectiveness of the effort was not measured. However, the report was aired in conjunction with the establishment of carpool/ridepool phone bank, and the resulting volume of calls was considered to be low (Harigen and Casey 1990).

Predicting the effects of education or public awareness campaigns can be difficult. The most widespread method of determining the effectiveness of a public awareness or similar campaign is to look at past success rates, or success rates with pilot projects. Unfortunately, it is often difficult to know what changes in traveller behaviour to attribute to the initiative in question, as opposed to changes in the underlying conditions giving rise to particular choices.

It is likely that the effects of a campaign to alter public attitudes toward transportation will be barely perceptible, especially in the short run. But it may prove to be quite useful as part of a broader CO_2 mitigation strategy in the long run. Furthermore, while such a campaign may have little short-term effects in terms of actual behaviour, it may nevertheless prove an invaluable tool to sell other transportation-related GHG policies to the public. These considerations need to be borne in mind when devising an analytical strategy for evaluating the benefits and costs of public awareness campaigns. Too narrow an objective or too short a time frame may lead to the erroneous conclusion that public awareness campaigns are less effective, and less efficient, than they are.

3.0 Conclusion

The range of policy options available for greenhouse gas reduction strategies from the transportation sector clearly extends beyond the realm of what has been considered "traditional" transportation policy options, potentially encompassing housing, land-use, and even economic development policy as well. Nevertheless, while many governments have talked about these related areas, few have actually been successful at implementing transportation-related policies that address them. It is important to note that those that have -- for example, Curitiba, Hong Kong, Stockholm, Singapore -- seem to have successfully reduced energy consumption and greenhouse gas emissions in the transportation sector.

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