APPENDIX B: DATA FOR OTHER COUNTRIES

An Appendix to the Report, "A Lifecycle Emissions Model (LEM): Lifecycle Emissions From Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials"

UCD-ITS-RR-03-17B

December 2003

by

Mark A. Delucchi
Institute of Transportation Studies
University of California,
Davis, CA 95616, USA
madelucchi@ucdavis.edu

Institute of Transportation Studies
One Shields Avenue
University of California
Davis, California 95616
Tel: 530-752-0247 Fax: 530-752-6572
http://www.its.ucdavis.edu/
email: itspublications@ucdavis.edu

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or by contacting itspublications@ucdavis.edu.

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University of California
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BACKGROUND

Using the LEM to estimate lifecycle end-use emissions in countries other than the U.S.

The Lifecycle Emissions Model (LEM) estimates emissions of urban air pollutants and greenhouse gases from the complete fuels and materials lifecycle of a variety of transportation modes, fuels, and technologies. The LEM was one of the first such models developed for transportation, and has been used extensively in U. S. and international analyses. Published and in-progress documentation are available.

The LEM originally was constructed and specified for the U. S. only. Starting in the late 1990s it was extensively revised to be able to estimate lifecycle emissions from the use of transportation energy and materials in countries other than the U. S. Data sets for countries other than the U. S. were created for the most important parameters in the model. Now, the LEM can estimate lifecycle emissions from the use of transportation fuels, transport modes, electricity, and heat in any one of up to 30 countries. The user specifies a country (which I will refer to as a "consuming" country), and the LEM looks up the corresponding data sets and uses them in the "active" calculations.

In the LEM, the calculation of end-use emissions from transportation, electricity, and heat involves many hundreds of parameters. There are parameters that describe inputs and outputs of fuel-conversion processes (e.g., crude oil refining to gasoline), the efficiency of fuel use by motor vehicles (e.g., fuel economy in urban driving), emissions from motor vehicles (e.g., g/mi of particulate matter), and so on. If one had unlimited time and resources, one would have country-specific values for every parameter in the model. For example, there would be a unique set of emission factors for each country, because combustion technology and emission controls vary from country to country. However, because I do not have unlimited time and resources, I have developed country specific-values for only the most important parameters. For these relatively important parameters, the LEM has 30 values or sets of value – one for each country. All of the country-specific values or sets of values have a "weight" attached to them; this is the weight the user decides should be given to each country's data. To run the model for any one country C, all data values for C are given a weight of 1.0, and all non-C data are given a weight of zero. These weights are specified in one place in the LEM, and applied to all country-specific data sets everywhere.. The weighted data-values are used in the "active" calculations in the model.

For most parameters, though, the LEM does not have country-specific data sets. For example, as a general rule, I have assumed that fuel qualities (apart from sulfur content), CO2-equivalency factors (e.g., GWPs), land-use impacts (e.g., changes in carbon storage due to cultivation), and the energy intensity and emissions of new technologies (e.g., energy use of FT-diesel production, or emissions from natural-gas vehicles *relative* to emissions from gasoline vehicles) are the same in all countries. For these parameters, I use either generic technology values (e.g., parameters specifying inputs and outputs for converting natural gas to hydrogen are based on a generic technological specification, not on the actual inputs and outputs for any one country), or values specific to the U. S. (e.g., shipping distances for fuels by truck are based on U. S. data). I believe that most of the non-country-specific technologically generic assumptions are reasonable for all countries. Some of the U .S.- based assumptions are likely to be inaccurate for other countries, but because these parameters are relatively unimportant (in the sense that changes in the value of the parameter have a relatively minor impact on total estimated lifecycle emissions), the inaccuracies are relatively unimportant.

The following shows the parameters for which the LEM has country-specific data sets:

DATA CATEGORY	**COUNTRY-SPECIFIC PARAMETERS**
Motor-vehicle fuel use	City fuel economy, highway fuel economy, and city fraction of total VMT, by vehicle type (light-duty vehicles, heavy-duty trucks, and buses).
Motor-vehicle emissions	Emissions by pollutant (relative to emissions from US vehicles) and vehicle type (light-duty vehicles and heavy-duty vehicles).
Motor scooters	Fuel economy and emissions by pollutant, relative to US values.
Mini cars (up to 500 kg)	Fuel economy and emissions by pollutant, relative to US values.
Motor vehicles (all)	Lifetime to scrappage.
Rail transit (heavy rail and light rail)	Capacity factors, BTUs/capacity-mile for traction energy, BTUs/capacity-mile for station energy, and energy for construction relative to energy for traction.
Evaporative emissions	g/gal emissions from refueling and fuel marketing, in a base year; rate of change of g/gal emissions
Electricity generation and distribution efficiency	Generation efficiency in a base year, by type of fuel; percent change in generation efficiency per year, by type of fuel; distribution efficiency in a base year; percentage change in distribution efficiency
Electricity generation fuel mix	Generation mix (coal, oil, gas boiler, gas turbine, nuclear, hydro, other) for EV recharging, crop-ethanol production, biomass-ethanol production, operation of rail transit, water electrolysis (for hydrogen production), and generic power. (For generic power, data are base year generation by type in gWh, and percentage change per year in absolute generation.)
Electricity generation	Efficiency of emission controls, by pollutant, relative to

emissions	US values.
Diesel fuel sulfur	Estimated in ppm for various years between 1970 and 2050, for highway, offroad, and heating fuels.
Other fuel quality	Sulfur content of coal and various petroleum products, relative to that in the U. S..
Material flows	Imports of materials by source (the major material exporting regions of the world) and by material (iron, aluminum, plastics, and "other materials"), transport distances between producing and consuming countries, transport modes by source.
Oil flows	Imports of petroleum by source (the major oil exporting regions of the world) and by kind of petroleum (crude oil, light petroleum products, heavy petroleum products), transport distances between producing and consuming countries, transport modes by source.
Coal flows	Imports of coal by source (the major coal exporting regions of the world), transport distances between producing and consuming countries, transport modes by source.
Natural-gas flows	Imports of natural gas by source (the major gas exporting regions of the world) and product (natural gas by pipeline, liquefied natural gas natural-gas-derived liquids), transport distances between producing and consuming countries, transport modes by source.
Natural gas losses	Leakage from domestic distribution systems (percent of end use consumption).
Motor-vehicle flows	Imports of motor vehicles by source (the major vehicle exporting regions of the world) and type of vehicle (heavy-duty, light-duty), transport distances between producing and consuming countries, transport modes by source.
Uranium production and enrichment	Production of uranium by country; imports of enriched uranium (as "separative work units" [SWUs] by source (the major SWU-producing-countries of the world), SWUs per MWh generated, and tons of enriched uranium per GWh generated.
Crop production and fertilizer use	Harvest yield in base year, change in harvest yield/year, rate of nitrogen use, and distribution of land types displaced, by crop type (corn, soy, grass, and wood).
Corn-ethanol production	Total energy requirement (BTUs-process-fuel/gal-ethanol), electricity use (kWh/gal), type of process fuel

	(coal, oil, gas, biomass).
Nitrogen deposition	Distribution of land types affected by deposition, by country.
Multi-modal emissions	Parameters for the estimation of emissions per passenger/mi and emissions per ton-mi for multi-modal transportation policies: vehicle occupancy by mode (passenger cars, motor-scooters, mini-cars, bicycles, minibuses, and buses), capacity fractions for rail heavy and light rail, passenger-miles of travel by mode (light-duty vehicles, buses, minibuses, minicars, and motor scooters [including a wide range of alternative fuels and electric vehicles], heavy rail, light rail, bicycling, and walking), and tons and miles of travel by freight mode (large and medium diesel, CNG, and ethanol trucks, diesel trains, cargo ships, tankers, barges, and pipelines).

Representation of producing countries

The table above describes data sets specific to the target or consuming countries designated for end-use analysis of lifecycle transportation, heating, or electricity emissions. Note that among the country-specific parameters listed above are several that describe imports of fuels or materials for consuming countries. For each consuming country and fuel or material commodity, the user specifies the fraction imported from each of the major producing regions of the world. For example, for any consuming country (say, Japan), one specifies the amount of crude oil imported from the major crude-oil producing and exporting regions of the world (the Persian Gulf, Indonesia, and so on).

Important energy use and emissions parameters are specified for each producing region. For example, the energy intensity of petroleum refining is specified for each major petroleum-product-exporting region, and venting and flaring of associated gas is specified for each major crude-oil-producing region. The shipping distance between producing regions and designated end-use consuming (target) countries also is specified. The energy, emissions, and distance parameters for each producing region are weighted according to the region's contribution to the total consumption of the target country.

The model represents producing regions and flows between producing regions and consuming countries for two reasons: 1) to properly represent differences in energy intensity and emission factors from one region to the next; 2) to allow users to separate "domestic" emissions, associated with the designated consuming country, from foreign emissions. This second purpose can be useful in national GHG accounting inventories.

In the LEM the commodities exported from producing regions to consuming countries are crude oil, petroleum products, natural gas (including liquefied natural gas), natural-gas liquids, coal, uranium, SWUs, vehicles, steel and iron, aluminum, plastics, and other materials. The producing regions vary by commodity, and are those that actually account for the bulk of the production of the commodity in the world today. The following shows the key producing regions, commodities produced, and energy and emission parameters characterized. First we show the producing regions or countries and the commodities they produce.

Producing region or country	Commodity produced
U. S.	all
Canada	all except SWUs
Japan	SWUs, MVs, all materials
N. Europe	all except MVs, uranium
S. Europe	petroleum products, NG, NGTLs, all materials
Former Soviet Union	all except MVs
China	coal, SWUs
Korea	MVs, materials
Asian Exporters	all except SWUs, uranium, MVs
Venezuela	petroleum products, crude oil
North Africa (Algeria, Libya)	petroleum products, crude oil, NG, NGTLs
Nigeria	petroleum products, crude oil, NG (LNG)
Indonesia	coal, petroleum products, crude oil, NG, NGTLs
Persian Gulf	petroleum products, crude oil, NG, NGTLs
Malaysia	NG (LNG)
Caribbean Basin	petroleum products, crude oil, coal, NG (LNG)
Other	all
Mexico	crude oil, NG, NGTLs, MVs
France	SWUs, MVs
Germany	MVs, materials
Other Europe	MVs
Australia	coal, uranium, NG (LNG)
Colombia	coal
Poland, Czech Republic	coal
South Africa	coal, uranium
Other Middle East	crude oil
Other Africa	crude oil
Target developed (domestic)	all

Target LDC (domestic)	all
International transport	all except SWUs, uranium

"All" = crude oil, petroleum products, natural gas (NG) including liquefied natural gas (LNG), natural-gas liquids (NGTLs), coal, separative work units (SWUs; for enriching uranium), uranium, motor vehicles (MVs), steel and iron, aluminum, plastics, and other materials; "All materials" = steel and iron, aluminum, plastics, and other materials.

The "target developed" and "target LDC" categories are used to account for domestic production in target countries that are not part of any of the major producing regions.

For each commodity produced and traded in the LEM, there are a number of producing-region-specific parameters relevant to the estimation of lifecycle energy use and emissions. The following table shows commodities produced and traded in the LEM, and the corresponding energy use and emissions parameters for the commodity and producing region:

Commodity produced	Energy and emission parameters for producing regions
crude oil	amount of oil recovery onshore, offshore, and from unconventional reserves; energy intensity of oil recovery in each the foregoing categories; venting and flaring of associated gas; CO_2 and SO2 emissions from oil production; emissions associated with using concrete to plug oil wells
petroleum products	energy intensity of petroleum refining; mix of fuels used by petroleum refineries; electricity generation mix for petroleum refineries; sulfur content of fuels
natural gas	energy intensity of gas production; energy intensity of gas transmission; leakage from gas recovery, processing and transmission; CO_2 and SO2 emissions from oil production; emissions associated with using concrete to plug oil wells
NGTLs	energy intensity of NGTL production
coal	energy intensity of coal production; amount of production from underground and surface mines; methane emissions from underground and surface mines; fate of methane emissions from coal mining
materials	energy intensity of materials production
vehicles	energy intensity of vehicle assembly; electricity generation mix for vehicle assembly
uranium	energy intensity of uranium production
SWUs	SWU production by gas diffusion, centrifuge, and laser-based technologies; electricity requirements of each

production technology

The values of these parameters are given and documented in the main report, which documents all parameter values for the U. S. (This documentation is given in the main report rather than here because the U. S. trades all of the tradable commodities and has as a potential trading partner every producing region or country.)

Reporting of results by emissions sector and geographic area

The LEM has a major new enhancement which allows the emission results to be reported by emission “sector” and geographic area rather than by stage of fuelcycle. Formerly, CO_2-equivalent g/mi emissions were presented *only* by “stage” of the fuelcycle: vehicle operation (fuel), fuel dispensing, fuel storage and distribution, fuel production, feedstock transport, feedstock and fertilizer production, CH_4 and CO_2 gas leaks and flares, emissions displaced by coproducts, vehicle assembly and transport, materials in vehicles, lube oil production and use, and refrigerant (HFC-134a) use. Now, these results by stage can be mapped into two different sectoral accounting frameworks.

First, a new set of tables maps the results calculated by “stage” of the fuelcycle (e.g., petroleum refining) into the emissions “sectors” used in the IPCC greenhouse-gas emissions-accounting frameworks. The IPCC sectors, underlined in the table below, comprise my fuelcycle stages as follows:

IPCC energy/road transport: fuels	
Vehicle operation: fuel	Note: This mapping includes credits for plant uptake of CO_2. Changes in soil and plant carbon are in "Land-use/forestry/agriculture".
IPCC energy/industry: fuels	
Fuel dispensing	
Fuel storage and distribution	
Fuel production	
Feedstock transport	
Feedstock, fertilizer production	
CH_4 and CO_2 gas leaks, flares	Note: related to fuel production and use.
IPCC energy/industry: materials, vehicles	
Vehicle assembly and transport	
Materials in vehicles	

Lube oil production and use
Refrigerant (HFC-134a)

IPCC land-use/forestry/agriculture

Land use changes, cultivation	Note: this does not include any energy-related emissions (e.g., from fuel use by tractors).

Not mapped to IPCC sectors:

Emissions displaced by coproducts

Second, a new macro ("Results_by_area") and another set of tables maps the CO_2-equivalent emission results into several geographic sectors:

- the energy/road transport sector of the designated consuming country (the country selected for analysis; e.g., the U. S.);
- the energy/industry sector of the designated consuming country;
- the energy/industry sector of a selected major exporter (e.g., Canada) to the designated consuming country;
- the energy/industry sector of a second major exporter;
- the energy/industry sector of a third major exporter
- the energy/industry sector of a fourth major exporter;
- international transport; and
- the rest of the world.

This mapping reveals how policies in one country affect emissions in other countries. International transport is a separate source because in the IPCC accounting it is not assigned to any country.

In essence, the macro turns on and off "weights" on a particular exporter (producing region) and commodity in such a way that permits the calculation of the emissions attributable to the production or transport of that commodity from the particular exporter (producing region). More specifically:

The trading of each commodity is represented by a matrix, which shows, for each consuming country and commodity, the contribution of each producing region to the total consumption of the commodity by the consuming country. (The tables above show the relevant commodities and major producing regions in the LEM. The values in these trade matrices are discussed in this appendix or the relevant commodity or process sections in the main model documentation.) The contribution of each producing region to the total consumption of the designated consuming country *also* has a zero/one weight on it. The macro first runs the LEM with these weights all set to 1.0, and records the result, which is all emissions from all regions and sectors. Next, the macro assigns a weight of zero to all cells associated with the contribution of the producing region selected as the first major exporter (see above), runs the model again, and takes the difference between this new result and the earlier result with all weights equal to 1.0. This difference is the emissions value attributable to the energy/industry sector of the first selected major exporting country. The macro then does the same for the second major exported selected, the third, the fourth, international transport, and rest-of-world, in turn.

In all cases *except* some alternative fuels, the assignment of a commodity to international transport is consistent with the assumptions regarding foreign production of the commodity. However, in the case of biomass feedstocks and fuels, LNG, and LPG, it is possible to specify international transport without also having foreign production. This potential inconsistency exists because it is simple to model international transport, but more complicated and in the case of biomass not worth the effort to model foreign production. (It is not worth the effort because there is not likely to be much international trade in biofuels.)

PARAMETER VALUES PERTINENT TO CONSUMING ("TARGET") COUNTRIES

General

As discussed above, the LEM has country-specific data sets for a number of parameters in the model. This major section documents the values used for all of the country-specific parameters in the LEM.

The LEM presently has at least some data sets for the following countries, which I have classified as "developed" or less-developed countries ("LDC") for the purpose of estimating emission factors:

U. S.	developed
Canada	developed
Italy	developed
China	LDC
India	LDC
South Africa	LDC
Chile	LDC
Mexico	LDC
Australia	developed

Brazil	LDC
Egypt	LDC
Germany	developed
Japan	developed
Korea	developed
Poland	LDC
Russia	LDC
Thailand	LDC
Turkey	LDC
United Kingdom	developed

The documentation first is organized by model parameter rather than by country. However, following this are sections focusing on Canada, Chile, China, India, Mexico, and South Africa. Canada and Mexico are highlighted because they were the subjects of separately funded, relatively detailed studies. Chile, China, India, and South Africa are highlighted because for these countries alone data sets for rail transit and multi-modal emissions were developed (also as part of a separate project).

Motor vehicle fuel use

General. The LEM requires as an input the fuel economy of gasoline passenger cars, full-size diesel buses, diesel minibuses, and gasoline motor scooters. For alternative-fuel vehicles, it requires inputs that describe thermal efficiency and weight relative to conventional petroleum-fuel counterparts. Given these and other inputs, the LEM calculates the fuel economy of alternative-fuel vehicles, including diesel-fueled passenger cars and gasoline buses. (See the main documentation report for more details.)

In the LEM, fuelcycle emissions from minibuses are calculated with respect to fuelcycle emissions from full-size buses, by scaling emissions according to the fuel economy of minibuses relative to that of full-size buses. Material and vehicle lifecycle emissions from minibuses also are calculated with respect to emissions from full-size buses, by scaling according to the weight of minibuses relative to the weight of full-size buses.

Parameter values. The sections on Chile, China, India, Mexico, and South Africa present estimates of the actual fuel economy values for vehicles in these countries. For other countries, I assumed 25 mpg city driving, 36 mpg highway driving, and 55% of VMT in city for LDVs, and 3.0 mpg city, 4.8 mpg highway, and 75% of VMT in city for buses. (Note that the fuel economy is not important, and in fact should be kept the same in all countries, if one wishes to compare “inherent” between fuels and production processes.)

Motor vehicle emissions

General. In the LEM, motor-vehicle emissions in countries other than the U. S. are estimated relative to emissions from vehicles in the U. S. The LEM calculates U. S. emission factors on the basis of model year, target year, deterioration rates, mileage accumulation rates, and other factors. It then looks up the pertinent country-specific relative emission factor for each pollutant, and multiplies this with the calculated U. S. emission factor.

In the LEM, emissions from alternative-fuel vehicles are estimated relative to emissions from gasoline light-duty vehicles or diesel heavy-duty vehicles. I assume that the relative emissions depend on "inherent" technological differences (between alternative and conventional fuels) that do *not* vary from country to country. The relative emission factors are estimated on the basis of a comprehensive literature review (see the main text LEM documentation).

Emissions of course depend greatly on emission -control technology, which in turn are driven in large part by emissions standards. Hence, my estimates of emission factors in other countries relative to those in the U. S. are informed in part by emission standards in other countries relative to those in the U. S. With this in mind, I show below Walsh's (2002) compilation of NOx and PM emission standards for gasoline ("gas") and diesel LDVs and HDVs internationally.

LDVs:

Country	Level	Year	NOx gas (g/mi)	NOx diesel (g/mi)	PM diesel (g/mi)	useful life (mi)
US National	Tier 1	1994	0.60	1.25	0.10	99,441
	NLEV	2001	0.30	0.30	0.08	99,441
	Tier 2	2004	0.07	0.07	0.01	120,000
California	TLEV	1994	0.60	0.60	0.08	99,441
	LEV	1994	0.30	0.30	0.08	99,441
	ULEV	1994	0.30	0.30	0.04	99,441
	LEV2	2004	0.07	0.07	0.01	120,000
	ULEV2	2004	0.07	0.07	0.01	120,000
	SULEV	2004	0.02	0.02	0.01	120,000
Japan	Japan 2000*	2000*	0.13	0.45	0.08	49,720
EU	Euro 3	2000	0.24	0.80	0.08	49,720
	Euro 4	2005	0.13	0.40	0.04	62,150

* Year 2002 for diesel PM.

HDVs (g/kWh):

Model Year	NOx -- US	EU* - NOx	Japan NOx	US --PM	EU* -- PM	Japan -- PM
1990	8.2	15.8				
1991	7.2	15.8				
1992	7.2	15.8				
1993	7.2	9		0.3	0.15	0.4
1994	7.2	9	6	0.15	0.105	0.4
1995	7.2	9	6	0.15	0.105	0.4
1996	7.2	7	6	0.15	0.075	0.15
1997	7.2	7	6	0.15	0.075	0.15
1998	5.8	7	4.5	0.15	0.075	0.15
1999	5.8	7	4.5	0.15	0.075	0.15
2000	5.8	5	4.5	0.15	0.075	0.1
2001	5.8	5	4.5	0.15	0.075	0.1
2002	5.8	5	4.5	0.15	0.075	0.1
2003	2.9	5	3.38	0.15	0.075	0.1
2004	2.9	5	3.38	0.15	0.075	0.1
2005	2.9	3.5	3.38	0.15	0.075	0.02
2006	2.9	3.5	3.38	0.15	0.075	0.02
2007	0.16	3.5	3.38	0.0075	0.0075	0.02
2008	0.16	2	3.38	0.0075	0.0075	0.02
2009	0.16	2	3.38	0.0075	0.0075	0.02
2010	0.16	2	3.38	0.0075	0.0075	0.02

* Euro IV from 2005 and Euro V from 2008.

The IEA/WBCSD data spreadsheet presents other information on emission standards used to estimate relative emissions. Generally, I assume that emissions in developed countries are the same as those in the United States. Also, more detailed analyses were done for Canada, Chile, Mexico, and South Africa (see the country sections below).

Other relevant information:

- Egypt has implemented a vehicle emissions testing program, which has helped bring emissions more in line with regulations (Office of Fossil Energy, 2002; EIA, *Egypt: Environmental Issues*, 2000).

Motor scooters

Some country-specific values were developed for Chile, China, India, and South Africa (see below). I used these data to estimate values for other countries. Generally, I assume that in developed countries emissions and fuel economy are the same as in the U. S., but that in LDCs, emissions are 10-50% higher and fuel economy is 5% lower.

Mini cars (up to 500 kg)

I assume that in developed countries emissions and fuel economy are the same as in the U. S., but that in LDCs, emissions are 10-50% higher and fuel economy is 5% lower.

Motor vehicles (lifetime to scrappage)

The lifetime VMT is a parameter in the calculation of the lifetime average emissions per mile due to the use of materials in motor vehicles: total emission related to making materials for motor vehicles are simply divided by lifetime mileage to produce a gram/mile emission factor which can be added to gram/mile emissions from the use of fuel.

On the basis of some data from China (see the section on China, below), I assume that trucks and buses in LDCs have 80% (trucks) and 60% (buses) of the lifetime VMT of trucks and buses in the U. S.. For all cases, I assume the same lifetime as in the U. S.

Rail transit

Parameters related to rail transit are estimated for Chile, China, India, Mexico, and South Africa only. See the pertinent country sections below.

Upstream liquid-fuel evaporative emissions

In the LEM, upstream liquid-fuel evaporative emissions are estimated as a function of emissions in a base year, the difference between the base year and the target year, and a rate of change exponent. The actual base-year emission rate is the same for all countries, and is the rate in the U. S. in 2000 in the case of refueling and 1988 in the case of fuel marketing. What varies from country to country is the base year in which these emission rates are assumed to be realized, and the annual rate of change parameters. In developed countries, the base years are assumed to be the actual base years of the data in the U. S. In LDCs, the base years are assumed to occur much later than they actually occurred in the U. S.

Electricity generation and distribution efficiency

The LEM estimates the efficiency of electricity generation by type of fuel and country. Actual generation efficiency values are calculated for the year 2000 using data on fuel inputs and electricity outputs reported in the IEA's *Energy Balances of OECD Countries* (2002) and *Energy Balances of Non-OECD Countries* (2002).

I estimate the efficiency of electricity distribution for every country on the basis of data on electricity losses in transmission and distribution and total electricity consumption, reported in the IEA's *Energy Statistics of OECD Countries* (2002) and *Energy Statistics of Non-OECD Countries* (2002). It is important to have an accurate estimate of these losses because in some countries (e.g., Brazil, India, Mexico, Russia, and Turkey) they can be quite high.

The IEA/WBCSD data spreadsheet and the LEM model show the estimated and assumed values.

Generation efficiency is assumed to improve in relative terms at a rate of 0.1% to 0.6% per year, depending on the country and generation fuel. The efficiency of biomass generation is assumed to improve the most (0.6%/year), on the assumption that current inefficient combustors eventually are replaced by integrated gasification-combined-cycle systems.

Distribution efficiency is assumed to improve 0.2% to 0.4% per year (relative terms) in countries where the efficiency currently is less than 90%. In countries where the efficiency is above 90%, the distribution efficiency is assumed to remain the same.

The following information also was relevant to my estimates of parameter values:

- Australia: The Australian government has established very stringent guidelines for the efficiency of electricity generation: 52% for natural gas, 42% for hard coal, and 31% for brown coal (net generation, HHV basis) (IEA, *Energy Policies of IEA Countries Australia 2001 Review*, 2001, p. 47-48).
- Brazil: Electricity distribution losses appear to be quite high in Brazil. The IEA's *Energy Statistics of Non-OECD Countries* (2002) report data that indicate that distribution losses were nearly 17% of generation in 2000. According to Geller et al. (2000), Brazil's national energy conservation program (called "PROCEL") is working with utilities to reduce transmission and distribution losses. I therefore assume that distribution efficiency improves by 0.3%/year (in relative terms).
- China: Shuoyi (1996) reports on the use of coal in China. He states that although coal-fired power plants in China are becoming cleaner and more efficient, they still are dirtier and less efficient than coal plants in developed countries. Daxiong et al. (1996) report that coal plants were about 29% efficient in 1994, and that the electricity distribution system was 91.3% efficient. (The IEA values used here show a similar efficiency for electricity distribution and a higher efficiency for generation in the year 2000.)
- Egypt: According to the Egyptian Environmental Affairs Agency (1999), the average power plant efficiency in Egypt improved from about 20% to 30% from 1980 to 1997. However, the IEA's *Energy Balances of Non-OECD Countries* (2002) shows efficiencies of about 39% in 2000.
- India: Electricity distribution losses appear to be extremely high in India. The IEA's *Energy Statistics of Non-OECD Countries* (2002) report data that indicate that distribution losses were nearly 30% of generation in 2000. This is confirmed qualitatively by the EIA's *India* Country Analysis Brief (2000), which states the electricity transmission and distribution system in India is relatively inefficient. I assume that efficiency improves by 0.4%/year.
- Japan: General information from IEA's *Energy Policies of IEA Countries Japan 1999 Review* (1999): Japan has very few indigenous energy resources, and as a result must import most of its primary energy. The islands of Japan are densely populated, making exposure to air pollution a serious problem which the government has

addressed by adopting strict environmental regulations. The added costs of importing and of environmental controls make energy prices in Japan relatively high. As a result, Japanese energy policy is concerned with finding secure, clean, efficient sources of energy at reasonable costs. I consider this when projecting efficiency and emission factors in Japan.

• Poland: The Office of Fossil Energy's *An Energy Overview of the Republic of Poland* (2002) notes that near-term priorities for the Polish electricity generation sector are to rehabilitate and retrofit aging coal-fired plants to improve efficiency and reduce emissions.

• Turkey: Electricity distribution losses also are high in Turkey – about 18% of generation, according to the IEA's *Energy Statistics of OECD Countries* (2002). The IEA's "Energy Policies of IEA Countries Turkey 2001 Review (2001) confirms the high losses, and says that they are due to outmoded equipment operating at maximum capacity (p. 95). The report also says that the Turkish government recognizes the need for improvement. I assume that the distribution efficiency improves by 0.3%/year (in relative terms).

Electricity generation fuel mix

National average generation mixes. To estimate the national average generation mix for each country, the LEM starts with the actual generation mix by type of fuel, for every country, in the year 2000 (IEA, *Energy Statistics of OECD Countries*, 2002; IEA, *Energy Balances of Non-OECD Countries*, 2002). Given this year 2000 mix, and a projection of the rate of change in generation by fuel type (discussed below), the LEM calculates the generation mix in the target year.

The annual percentage change in generation by fuel type was estimated primarily on the basis of three sets of historical data or projections:

• the actual rate of change in generation by fuel type from 1990 to 2000, as reported in the IEA's *Energy Statistics of OECD Countries* (2002) and *Energy Balances of Non-OECD Countries* (2002);

• the IEA's projections of changes in generating capacity from 2000 to 2020 (IEA, *Electricity Information 2002*, 2002);

• the Asian Pacific Energy Research Centre (2002) projections of changes in generation by fuel type from 2000 to 2020.

Unfortunately, in many cases the two projections differ significantly from one-another and from the 1990 to 2000 history. My assumptions are based on my judgment, informed also by the following, which indicate mainly that the use of natural gas is expected to increase in most countries:

• Brazil: The International Trade Administration (2002) states that "imports of natural gas from Argentina and Bolivia are predicted to continue throughout this decade in order to help fuel 49 power generation plants" (p. 3). The Office of Fossil Energy, *An Energy Overview of Brazil* (2002) shows that most current natural gas generating capacity in Brazil is gas turbine; I assume that this will continue to be the case in the future.

In Brazil biomass supplied nearly 3% of total electricity generation in 2000 (IEA, *Energy Balances of Non-OECD Countries,* 2002). Given Brazil's substantial biomass resources and strong interest in developing domestic sources of energy, it is reasonable to assume that the use of biomass to generate power will continue to grow. In support of this, Carpentieri and Macedo (2000) report on a project to demonstrate and eventually promote integrated gasification/gas-turbine technology for producing power from biomass (wood, in this case), and Azar and Larson (2000) discuss the potential for developing significant biomass-based power in the northeast of Brazil.

- Chile: The EIA projects that in Chile, the share of natural gas generation will increase, and the share of coal will decrease. The EIA's *Chile* Country Analysis Brief (2001) states that "coal use for power generation is slated to fall in coming years as natural gas fuels more of Chile's electricity" (p. 4). The Office of Fossil Energy *An Energy Overview of Chile* (2001) notes that Chile plans to increase its generating capacity by nearly 60% by 2006, of which nearly 80% will be high-efficiency combined-cycle gas-fired power plants. However, elsewhere the EIA (*International Energy Outlook 2001*, 2001) reports that "while there are plans to expand gas-fired capacity in the long run, it has been reported that heavy worldwide demand for combined-cycle plants means that none are available to Chile until at least 2003" (p. 112).

The Office of Fossil Energy (2001) also reports that Chile plans significant additions of hydropower, but other sources indicate that some major new hydro projects are opposed by environmental groups and advocates for indigenous peoples.

- Egypt: The EIA's *Country Analysis Briefs, Egypt* (2002) states that "all oil fired plants have been converted to run on natural gas," and that most additional new thermal capacity will be natural gas (see also Office of Fossil Energy, *An Energy Overview of the Republic of Egypt*, 2002). Egypt also is looking to expand generation from non-hydro renewable energy (Office of Fossil Energy, 2002; EIA, *Egypt: Environmental Issues*, 2000).

- Germany: The EIA's *Country Analysis Briefs, Germany* (2001) states that German imports of hard coal are expected to double over the next 20 years as nuclear power is phased out and domestic production declines

The EIA's *Renewables, Wind Energy Developments: Incentives in Selected Countries* (2002) notes that there has been major growth in wind power in Germany and Denmark, due to a variety of factors.

- Mexico: The EIA projects that in Mexico, the share of natural gas of total generation will increase, and the share of oil, coal, and nuclear power will decrease. Regarding nuclear power, the Office of Fossil Energy's *An Energy Overview of Mexico* (2001) and the EIA's *International Energy Outlook 2001 (*2001) state that Mexico does not plan to add nuclear generating capacity. Accordingly, the EIA's *International Energy Outlook 2001* (2001) projects that total nuclear generation in Mexico in 2020 will be what it was in 2000, and hence a much smaller fraction of total generation in 2020 (2.2%) than in 2000 (5%) because total generation will more than double.

The Office of Fossil Energy (2001) and the EIA's *Mexico* Country Analysis Brief (2001) state that over the next five to six years, Mexico intends to convert many of its oil-fired generators to natural gas, and build new combined-cycle gas-fired plants. Indeed, capacity additions already planned indicate that the share of natural gas will be at least 25% (Office of Fossil Energy, 2001). Consistent with this, The International Trade Administration (2002) reports that most thermal power plants being built in Mexico will use natural gas.

Finally, the EIA's *International Energy Outlook 2001* (2001) projects that absolute generation from hydropower and renewable resources will increase, but at a rate less than the rate of increase in total generation.

• Poland: EIA's *North Central Europe* (2002) states that the Polish government forecasts a 14% share for natural gas by 2020, up from 2% in 2000.

• South Africa: The EIA's *International Energy Outlook 1999* (1999) reports that no new nuclear power plants are planned, and therefore projects no increase in nuclear generating capacity in South Africa. However, the most recent addition of the EIA's *International Energy Outlook 2001* (2001) projects that nuclear generating capacity will increase about 10% by 2010, and by another 10% by 2020.

The *International Energy Outlook 2001* (2001) also reports that South Africa "has plans to build substantial hydroelectric projects during the forecast period" (p. 113).

Turkey: According to the Office of Fossil Energy *An Energy Overview of Turkey* (2002), most of Turkey's natural gas-fired electricity-generation capacity is combined-cycle.

Generation mixes for specific activities. The LEM allows country-specific generation mixes for EV recharging, ethanol production from crops, ethanol production from biomass, the operation of rail transit systems, and water electrolysis. In the absence of information on how the generation mix varies country by country and activity by activity, I assume that for all these activities, the generation mix is the national average mix for the target country and year.

Electricity trade

The LEM has a simple representation of electricity imports, solely for the purpose of allocating emissions between the domestic sector and the rest of the world. For each country there is a parameter for net electricity imports as a fraction of total national electricity consumption. This fraction is assigned to the emissions sector "rest of the world" in the geographical allocation macro. When the geographic allocation macro is run, emissions from the generation of imported electricity are deducted from the national total and assigned to the "rest of the world" sector.

Only Italy (14%), Brazil (11%), and Germany (7%) have significant net electricity imports. Thailand does trade electricity with Malaysia, but according to APERC (*APEC Energy Demand and Supply Outlook 2002*, 2002) the trade is for mutual backup, so that "absolute electricity trade is almost nil" (p. 92).

Electricity generation emissions

In the LEM, emission factors for all fossil-fuel electricity generation in non-U. S. countries are estimated as a multiple or fraction of emission factors for all fossil-fuel generation in the U. S. Data were available to perform somewhat detailed analyses for a few countries, as indicated below. I used these estimates, along with information on emissions standards for new coal-fired power plants (IEA, *Coal Information* 2002, 2002; see the IEA/WBCSD data spreadsheet for details) and my judgment to estimate relative emissions in all countries.

For Mexico, Brazil, and Thailand, I use the values presented below for China. For Poland, Turkey, Chile, and Egypt, I use the values for India. For South Africa I use values for India, except with lower PM levels.

China: The EIA *International Energy Outlook 1999* (1999) discusses PM and SOx emissions in China. Their data imply that coal-fired power plants emit at least 3 times as much SO_X per kWh as do coal-fired plants in the U. S. Similarly, Shuoyi (1996) states that although coal-fired power plants in China are becoming cleaner and more efficient, they still are dirtier and less efficient than coal plants in developed countries. However, the IEA's *Energy Policies of IEA Countries 2001 Review* (2001) reports that new Chinese energy policy calls for the development of clean-coal technologies (p. 84). Given this, and considering the emissions standards for new power plants reported in the IEA's *Coal Information 2002* (2002), I assume the following ratios of pollutant emissions in China to pollutant emissions in the U. S., from Chinese power generation:

Period	NOx	SOx	PM	Underlying assumption
pre 1980	1.15 times higher in China	1.4 times higher in China	3 times higher in China	Generation in U. S. relatively uncontrolled; generation in China entirely uncontrolled
1980-1998	1.15 in 1980; ratio then increases by 1.5%/year	1.4 in 1980; ratio then increases by 4.0%/year	4.0 in 1980; ratio then increases by 6.0%/year	New generation in U. S. subject to stringent controls; generation in China still uncontrolled
after 1998	ratio decreases by 2.0% per year from 1998 value	ratio decreases by 3.0% per year from 1998 value	ratio decreases by 3.5% per year from 1998 value	New generation in China begins to be subject to controls

India: The EIA (*India*, Country Analysis Brief, 1999) reports that the government of India is trying to reduce incentives to use relatively old, inefficient, and polluting coal-fired plants to generate electricity.

Rajan and D'Sa (2000, p. 78) report emission factors for different types of power plants. I use these, the statement from the EIA, and my judgment as a guide for my assumptions, which are as follows:

Period	NOx	SOx	PM	Underlying assumption

pre 1980	1.15 times higher in India	1.4 times higher in India	3 times higher in India	Generation in U. S. relatively uncontrolled; generation in India entirely uncontrolled
1980-1998	1.15 in 1980; ratio then increases by 1.5%/year	1.4 in 1980; ratio then increases by 4.0%/year	4.0 in 1980; ratio then increases by 3.0%/year	New generation in U. S. subject to stringent controls; generation in India still uncontrolled
after 1998	ratio decreases by 2.0% per year from 1998 value	ratio decreases by 3.0% per year from 1998 value	ratio decreases by 3.5% per year from 1998 value	New generation in India begins to be subject to controls

Poland: The Office of Fossil Energy *An Energy Overview of Poland* (2002) notes that near-term priorities for the Polish electricity generation sector are to rehabilitate and retrofit aging coal-fired plants to improve efficiency and reduce emissions. Towards this end, flue-gas desulphurization systems and low-NOx burners are beginning to be installed on coal-fired plants, and some mines are installing coal-washing plants to reduce the sulfur content of coal. (See also EIA, *Poland: Environmental Issues*, 2000; Prus, 1999).

Russia: The IEA's *Russia Energy Survey* (2002) reports electricity generation by fuel type and total emissions from the electricity sector, from 1993 to 1999. With these data we can calculate emission factors for all fossil-fueled power plants in Russia, in g/kWh-generated. We can compare these calculated emission factors (for all fossil-fuel generation) with emission factors calculated by the LEM for the U. S. for the same years and same fossil-fuel generation mix. The results of this comparison are:

	Russia (g/kWh-generated)		U. S. (g/kWh-generated)		Russia /U. S.	
	1993	*1999*	*1993*	*1999*	*1993*	*1999*
SOx	3.773	2.884	2.527	1.592	1.5	1.8
CO	0.289	0.431	0.212	0.204	1.4	2.1
NOx	2.091	1.713	1.686	1.021	1.2	1.7
methane	0.005	0.005	0.010	0.010	0.4	0.5
VOCs	0.002	0.002	0.033	0.031	0.0	0.1
PM	2.739	1.898	0.128	0.123	21.4	15.4

Given this, and other considerations explained below, I make the following assumptions regarding Russian electricity-generation emission factors relative to U. S. electricity-generation factors:

Period	SO_X (Russia : U. S..)	Underlying assumption
1970-2000	2.0 times higher in Russia	Relative emissions data cited above
after 2000	ratio decreases by 1.6% per year from 2000 value (to a minimum of equal to U. S.)	Stricter environmental controls adopted in Russia

Period	NO_X (Russia : U. S..)	Underlying assumption
1970-2010	1.5 times (50%) higher in Russia	Relative emissions data cited above
after 2010	ratio decreases by 1.0% per year from 2010 value (to a minimum of equal to U. S.)	Stricter environmental controls adopted in Russia

Period	PM (Russia : U. S..)	Underlying assumption
1970-1990	20 times higher in Russia	Relative emissions data cited above
after 1990	ratio decreases by 4.5%/year from 1990 value (to a minimum of equal to U. S.)	Stricter environmental controls adopted in Russia

These assumptions apply to all coal and oil-fired power plants, and to gas-boilers, but not to gas-fired turbines.

• South Africa: Spalding-Fletcher et al. (2000) state that the national power company has "directed most of its pollution control efforts towards the reduction and removal of particulate matter" (p. 11), but has done little or nothing to control emissions of sulfur.

• Turkey: EIA's T*urkey: Environmental Issues* (2002) states that new power plants are required to have flue-gas desulfurization (FGD), and that some older units are being retrofitted with FGD. However, IEA's *Energy Policies of IEA Countries Turkey 2001 Review* (2001) states that power plants routinely exceed limits for SO2 emissions, and that FGD equipment is not very efficient.

• Thailand: According to the Office of Fossil Energy, *An Energy Overview of Thailand* (2002), Thailand has been reducing emissions of SO2 from power plants, and as a result, air quality in Bangkok and other cities has improved.

• All countries: A summary of emission standards for new large coal-fired power plants (IEA, *Coal Information 2002*, 2002; see IEA/WBCSD data spreadsheet) indicates that in most countries PM standards are much higher (less strict) than in the U. S., but that SOx standards actually are lower (more strict), and NOx standards about the same.

I assume that in all countries gas turbines are relatively modern combined-cycle power plants with modern emission controls.

Diesel fuel sulfur content

The sulfur content of diesel fuel is a parameter in the calculation of emissions of SO_2 from motor vehicles *and* from petroleum refineries (see the main documentation report). SO_2 is an urban air pollutant and, as a component of particulate matter, a GHG

The LEM has a table of values of the sulfur content of diesel fuel, by year, for vehicles, off-road use, and heating use, for each country. The information used to estimate these sulfur values is presented in the IEA/WBCSD data spreadsheet. (See also the more detailed presentations for Chile and Mexico, in the country sections below.) Two major general data sources are Walsh's *Car Lines* (December, 2002) and the website www.dieselnet.com. Some other more specific data include:

- China: Dengqing et al. (1996) state that in China diesel fuel has more sulfur than in other countries.
- Mexico: The EIA's *Mexico: Environmental Issues* (2001) reports that PEMEX has started producing a diesel fuel with 500 ppm sulfur.
- Russia: The IEA's *Russia Energy Survey* (2002) reports that production of "low-sulphur" diesel (2000 ppm S or less) was 56% of total diesel in 1990 and 85% in 2000, and that production of "ultra-low" sulphur diesel (500 to 1000 ppm S) began in 1995 and reached 15% of diesel output in 2000. From this we can infer that production of conventional diesel (with, we assume 5000 ppm S) was 44% of the total in 1990 and dropped to zero by 2000. Given this, I estimate sulfur levels for the marker years.

Other petroleum fuel sulfur content

In the LEM, the sulfur content of coal and petroleum products other than diesel fuel is estimated relative to the sulfur content in the U. S. The estimation of the sulfur content in the U. S. is discussed in the main documentation report. I assume that conventional gasoline in the U. S. has a sulfur content of 320 ppm, and that reformulated gasoline has a sulfur content of 236 ppm in 2000, declining to a minimum level of 30 ppm.

The following information was used to estimate relative sulfur contents:

- All OECD countries: The IEA (*Oil Information*, 2002) reports consumption of heavy fuel oil according to sulfur content in OECD countries. It distinguishes low-sulfur (less than 1% S) from high-sulfur (1% or higher S) heavy fuel oil. I use these data to specify the sulfur content of heavy fuel oil in OECD countries relative to that in the U. S. I assume that the relative sulfur content of crude oil is the same as the relative sulfur content of fuel oil.
- European Union: Walsh (*Car Lines*, 2002) reports the following caps on sulfur in gasoline in the EU (ppm):

Current	150
Year 2005	50
Year 2009	10

- China: Walsh (2002) reports the following limits on the sulfur content of gasoline in China:

Year 1993	1500
Year 1999	800

- India: The sulfur content of gasoline in India was reduced to 0.05% (500 ppm) effective May 31 2000 (Kathuria, 2002).
- Korea: The IEA *Energy Policies of EIA Countries The Republic of Korea 2002 Review* (2002) (p. 42-43) reports the following caps on the sulfur content of gasoline (ppm):

Year 2000	200
Year 2002	130
Year 2006	30

- Japan: Japan traditionally had very low levels of sulfur in gasoline, usually below 30-PPM sulfur.
- Mexico: See the detailed discussion of data for Mexico in the country sections below.
- Russia: GM et al. (2002c, Table 3) report that the sulfur content of crude oil from Siberia is 0.6 – 1.8% (cf about 1% for crude oil in the U. S.).
- Turkey: I assume the following ratios of sulfur content in Turkey to sulfur content in the U. S., for petroleum products:

crude oil	1.5	my assumption, based on high sulfur content of products
residual fuel oil	3.0	IEA *Energy Policies of IEA Countries Turkey 2001 Review* says that fuel oil contains 3.5% S (p. 40).
conventional gasoline	5.0	IEA *Energy Policies of IEA Countries Turkey 2001 Review* says that gasoline contains 0.15% S (p. 41).
reformulated gasoline	5.0	see conventional gasoline

- United Kingdom: GM et al. (2002c, Table 3) report that the sulfur content of crude oil from the North Sea is 0.3% (cf about 1% for crude oil in the U. S.).

Coal sulfur content

In the LEM, the sulfur content of coal is estimated relative to the sulfur content in the U. S. The estimation of the sulfur content of coal in the U. S. (generally about 1% by weight) is discussed in the main documentation report. The following information was used to estimate the sulfur content in other countries relative to that in the U. S.:

• Australia: I assume a 35% lower sulfur content of coal than in the U. S. (IEA, *Energy Policies of IEA Countries Australia 2001 Review*, 2001, states that Australian coal is low sulfur [p. 59]; see also EIA *Australia: Environmental Issues,* 2002).

• Brazil: I assume a 40% higher sulfur content of coal than in the U. S., on account of the "high ash and sulfur content" of Brazil's domestic coal (EIA, *Brazil*, Country Analysis Brief, 2002).

• Chile: I assume a 40% higher sulfur content of coal than in the U. S., on account of relatively low quality of Chilean coal (EIA, *Chile*, Country Analysis Brief, 2001).

• China: In its *Country Analysis Brief* for China, the EIA (2000) notes that Chinese coal has a high sulfur content. I assume that the sulfur content is 40% higher than in the U. S.

• Japan: I assume a 25% lower sulfur content of coal, because of strict environmental regulations that force Japanese utilities to use coal with a relatively low sulfur content (IEA, *Energy Policies of IEA Countries, Japan 1999 Review*, 1999).

• Poland: The Office of Fossil Energy (1996) reports that the sulfur content of Polish coal is relatively low – about 0.75% by weight.

• South Africa: Spalding-Fletcher et al. (2000) state that power station coal averages 25% to 30% ash, but is "relatively low in sulfur content" (p. 11). The EIA's "South Africa: Environmental Issues" (2000) reports that South African coal contains about 1.2% sulfur and up to 45% ash. They also note a pilot study of fluidized-bed combustion, which has relatively low emissions. The EIA's (2000) Country Analysis Brief, *South Africa*, states that South African coal has about 1% sulfur. The EIA also reports that the heat content of coal in South Africa is virtually the same as that in the U. S.

• Turkey: I assume a 50% higher sulfur content of coal than in the U. S., on account of relatively low quality of Turkey's coal (EIA, 2001c). (The IEA's *Energy Policies of IEA Countries, Turkey 2001 Review* refers to "high-sulfur domestic lignite [p. 34-35].)

Flows of materials: general

The LEM represents international trade in steel, aluminum, plastics, and other materials. For each consuming country trade is represented as the fraction of the country's total material consumption that comes from each world producing region. For each country/producer pair, the LEM also represents the fraction of transport that occurs by ship, and the shipping distance.

Data on flows of materials are from the United Nations Statistics Division, Comtrade Database (2003), and are shown in the IEA/WBCSD data spreadsheet. Comtrade reports total imports and exports, and imports by country, for every country in the world, for iron and steel (Standard Industrial Trade Classification [SITC] Revision 3 code 67), aluminum (SITC Revision 3 code 684), plastics in primary form (SITC Revision 3 code 57), and more specific materials categories (not used in this analysis). With these data, and estimates of total material consupmtion in each target country, one can estimate the fraction of each country's total material consumption that commes from each world producing region.

Imports and exports. Because energy use and emissions are related directly to the mass of material transported, we would like to know imports, exports, and production by weight. In the case of aluminum (SITC 684), the Comtrade database does report trade in units of weight, but in the case of aggregated steel and iron (SITC 67) and primary plastics (SITC 57), Comtrade reports trade in units of dollars. I assume that the $/kg of imports and exports of steel and iron and primary plastics is similar for all countries, and hence that the fraction of imports from each country on a weight basis (which is what I wish to know) is about the same as the fraction of imports from each country on a dollar basis (which is what the Comtrade data can tell us). (My quick analysis of trade and weight figures for SITCs 6735, 6732, and 6726 indicates that the assumption is reasonable for the bulk of trade in SITC 67.)

On average, the Comtrade data allowed me to allocate about 75% of all steel and iron imports, 75% of all aluminum imports, and 85% of all plastics imports to specific producing countries and regions, with the remaining 15-25% of imports being classified as coming from "other" producing regions. However, materials trade data for Mexico and Egypt for the year 2000 were not available.

Total material consumption in each country. *Steel and iron.* The International Iron and Steel Institute (IISI) (2002a) reports apparent consumption of crude steel and finished steel, imports and exports of finished and semi-finished steel, and production of crude steel, by country. Assuming that semi-finished steel eventually becomes part of the apparent consumption of finished steel, then the total import share can be calculated from these data by dividing imports of finished and semi-finished steel by apparent consumption of finished steel. (The total import share then is distributed to individual countries using the Comtrade data discussed above.) My analysis of the data indicate that apparent consumption of finished steel includes semi-finished steel. (Another IISIA publication [2002b] indicates that apparent consumption is calculated as production + imports less exports.)

Aluminum. The USGS (2001) reports production of aluminum metal by year and country. For some countries, the USGS reports production of primary and secondary aluminum metal; for others (Canada, India, Korea, South Africa, Poland, and Russia), it reports only primary production, and for a few countries (Turkey and Egypt), the type of production is unspecified. In some cases, USGS also reports production of bauxite and alumina.

The Comtrade data base described above reports total imports and exports of aluminum product code 684 in Revision 3 of the Standard Industrial Trade Classification (SITC). The product code 684 is the entire "aluminum" classification under section 68, "nonferrous metals," of major group 6, which is "manufactured goods classified cheifly by material." Hence, it appears the Comtrade data include all aluminum materials whether of primary or secondary production.

With these data, it is possible to first estimate total apparent consumption, equal to production+imports-exports, and then imports as a fraction of total apparent consumption. However, in the calculation apparent consumption, the production data are from USGS, and the import and export data are from Comtrade, and the two sources apparently do not count up "aluminum" the same way. The USGS reports production of bauxite, alumina, primary metal, and secondary metal. Comtrade apparently reports manufactured aluminum goods. One would assume that the "Comtrade" aluminum category corresponds to primary and secondary aluminum metal production in the USGS – i.e., does not include alumina – but if one omits alumina from the USGS production data, the result is that in a few cases exports (as reported by Comtrade) exceed primary+secondary production (as reported by USGS), which is impossible unless some imports are exported (which seems not sensible). Including alumina in the production side eliminates all but one of these cases (in the U. K., total production of alumina and primary and secondary aluminum are a hair less than total exports). And of course, in cases where the USGS has not reported secondary production or alumina production, it is impossible to calculate total consumption. For example, Poland's total exports of aluminum (according to Comtrade) are more than twice its production of primary aluminum (according to the USGS). This suggests that Poland must produce at least as much secondary aluminum as it does primary.

The upshot of this is that in a number of cases, I must use my judgment to estimate total consumption, or imports as a fraction of consumption.

Plastics. Data on total consumption of plastics were not available. I assumed therefore that for every country imports as a fraction of total consumption were similar to imports of refined petroleum products as a fraction of total consumption. For developing countries, I assumed that the plastic imports share was somewhat higher than the refined-products import share.

Other materials. For all other materials, I assume that import shares by producing country are the averages of the estimated or assumed shares for steel, aluminum, and plastics.

Other. All international trade except for between the U. S. and Canada and between some countries in Europe is assumed to go by water. Distances between ports were read off an atlas. Where such an identification was possible, the actual major shipping port(s) of a country were used.

Import fractions by country are assumed to remain constant at year 2001 values over the entire projection period.

Appendix H discusses parameter values associated with energy use for and emissions from the production of materials in the U. S. and other producing regions.

Sources of materials embedded in motor vehicles

The preceding section discusses direct flows of basic materials from producers of materials to consumers of materials. However, in many cases, such as with motor vehicles, there is an an intermediate "assembly" step between production of the basic materials and consumption of a finished product. The assembly step may occur in a country different from the country of material production or the country of final consumption. Thus, steel may be produced in country X, assembled into motor vehicles in country Y, and used in motor vehicles in country Z.

The LEM properly traces the source of materials embedded in vehicles back through assembly to production of basic materials. More formally, the contribution of any material-producing country X to the total final consumption of the material M in motor vehicles in country Z is calculated as the contribution of country X to total use of M for vehicle assembly in country Y multiplied by the contribution of vehicle-assembly country Y to final consumption of vehicles in Z, summed over all assembly countries that contribute to Z[1]. Flows of materials from producing countries to assembling countries are based on the data on material flows discussed above, and flows of materials in vehicles from assemblers to final consumers are based on the data on motor-vehicle flows, discussed below. Because some of the motor-vehicle assembly countries are not explicitly represented as material-using countries, I must make assumptions about sources of materials in these countries:

Vehicle assembler in the LEM:	Assumed to have same material sources as:
France	United Kingdom
Other Europe	Italy
Other	Thailand
General developed country	Germany
General devleloping country	China

It is important to assign embeded materials to their ultimate country of production because the energy intensity of material production varies from country to country, and because the LEM has a macro that apportions total emissions to major producing regions of the world.

Petroleum production and trade

The LEM represents trade between the major petroleum producing regions and countries of the world and the target consuming countries designated for analysis. Crude oil, light products (gas and diesel), and heavy products (residual fuel) are treated separately. For each consuming country trade is represented as the fraction of the country's total petroleum consumption that comes from each world producing region. For each country/producer pair, the LEM also represents the fraction of transport that occurs by ship, and the shipping distance.

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[1] To avoid programming complexities, the LEM does *not* go through this procedure to determine the mix of fuels used to generate electricity used by aluminum production plants. For this parameter (the mix of fuels...), and this parameter only, the LEM assumes that the aluminum in motor vehicles used in country Z comes from the countries X that supply aluminum to Z in general -- not the countries X that supply assemblers Y who in turn supply vehicles to Z.

My estimates of flows of petroleum are based on IEA's *Oil Information 2002* (2002) and *Energy Statistics of Non-OECD Countries* (2002). This IEA report shows imports by country and total consumption, for the year 2001 (see the IEA/WBCSD data spreadsheet).

All international trade except for between the U. S. and Canada and between some countries in Europe is assumed to go by water. Distances between ports were read off an atlas. Where such an identification was possible, the actual major shipping port(s) of a country were used.

The parameter values for oil recovery (energy intensity, venting and flaring of associated gas, and more) and oil refining in the U. S. and elsewhere are based on data discussed in the main documentation report.

With the following exceptions, import fractions by country are assumed to remain constant over the entire projection period:

- Australia: Australia imports and exports significant quantities of crude oil – both are about 50% of its total consumption (EIA, Country Energy Data Report, 2002). However, the EIA (Country Analysis Briefs, 2002) states that Australia is using oil three times faster than it is finding it, and that as a result, Australian production will be only 40% of consumption by 2010. Consequently, I project increasing import shares for Australia. I assume that 12% of total crude oil consumption comes from the Persian Gulf (the long-run low-cost world supply regionJ) in 1990, and that the share increases by 1% per year (relative terms, not absolute percentage points) up to a maximum of 40%.
- Chile: About 50% of all Chile's crude oil is transported via a 260-mile pipeline from Argentina to Chile (EIA, *Chile* Country Analysis Brief, 2001). The Office of Fossil *Energy Overview of Chile* (2001) states that crude oil imports from Argentina are expected to increase. However, the IEA *Energy Statistics of Non-OECD Countries* (2002) indicates that Chile imports about 80% of its oil from Venezuela, and 20% from Mexico. I assume that oil in the Argentine-Chilean pipeline comes from Venezuela or Mexico and is just in transit through Argentina.
- China: The EIA's *International Energy Outlook 1999* (1999) projects that oil imports to China from the Persian Gulf will grow from almost 20% of total oil consumption in 1990 to over 50% in 2020. I represent this by assuming that 10% of total oil consumption comes from the Persian Gulf in 1990, and that the share increases by 2% per year (relative terms, not absolute percentage points) up to a maximum of 70%. In another document, the EIA (*China*, 2000) notes that oil imports can vary dramatically from year to year, as a result of changes in government policy or the world oil market. I do not account for this here.
- Egypt: Presently, Egypt does not import crude oil or gas. However, declining oil production and increasing oil consumption may result in Egypt having to import oil by about 2010 (EIA, Country Analysis Briefs, Egypt, 2002). I assume that increasing production will delay the date that importation begins to 2012, at which point I assume that 10% of Egypt's oil comes from the Persian Gulf, with this share increasing 2% per year (relative terms) thereafter.

• India: The EIA (*India*, 2000) states that in 1998, India imported more than 60% of its oil, and implies that in 2012 India might import 70% of its oil -- presumably, mainly from the Middle East. I represent this by assuming that 25% of total crude oil consumption comes from the Persian Gulf in 1990, and that the share increases by 0.5% per year (relative terms, not absolute percentage points) up to a maximum of 45%.

The EIA (*India*, 2000) also says that in the 1990s, India imported a large quantity of refined products, but that by the end of 1999, it had "closed the gap". This is consistent with IEA data (*Energy Statistics of Non-OECD Countries*, 2002). For the years prior to 2000, I assume that India imported 13% of its consumption; for year 2000-on, I assume the IEA's 2002 values.

• Mexico: Mexico is a major producer and exporter of crude oil, and does not import any crude oil (EIA, *International Energy Annual 1999*, 2001). However, it does import petroleum products, mainly gasoline produced in refineries on the U. S. Gulf Coast. According to the EIA (*International Energy Annual 1999*, 2001), Mexico imported 28% of its gasoline consumption, 27% of its LPG consumption, 7% of its distillate consumption, and 12% of its residual fuel oil consumption -- overall, about 21% of its light-product consumption -- and 12% of heavy product consumption (The IEA *Oil Information* figures are similar.) The Office of Fossil Energy *An Energy Overview of Mexico* (2001) reports that most of the gasoline imported by Mexico is refined in Texas. However, the EIA's *Mexico* Country Analysis Brief (2001) indicates that Mexico is upgrading its refineries to produce more light products. I assume therefore that the percentage of light products imported from the U. S. decreases from 18% in 2000, by 0.5%/year, in relative terms. I assume that import shares for heavy products remain constant.

Coal production and trade

The LEM represents trade between the major coal producing regions and countries of the world and the target consuming countries designated for analysis. For each consuming country trade is represented as the fraction of the country's total coal consumption that comes from each world producing region. For each country/producer pair, the LEM also represents the fraction of transport that occurs by ship, and the shipping distance.

Data on flows of coal are from IEA's *Coal Information 2002* (2002) and are shown in the IEA/WBCSD data spreadsheet. The IEA reports imports by country and total consumption.

IEA data (*Coal Information*, 2002, Table 4.1) indicate that 92% of the international trade in coal goes by sea. The small amount of overland trade occurs between the countries of continental Europe and between the U. S. and Canada and Mexico. Therefore, in the LEM the fraction of international coal shipment that goes by sea is 1.0 for all import/export country and region pairs except those that represent intra-European or intra-North-American trade.

Import fractions by country are assumed to remain constant at year 2001 values over the entire projection period, except as follows:

• Brazil: The EIA's *International Energy Outlook 2001* (2001) states that coal imports to Brazil are expected to rise substantially as a result of strong growth in domestic steel demand (p. 79). I assume that most of the additional imports come from Columbia/Venezuela and Australia. Specifically, I assume that Columbia supplies 5.3% and Australia 24% of Brazilian coal consumption in 2001, and that the Columbian share increases 0.6%/year and the Australian share 0.3%/year.

The parameter values for coal mining (energy intensity, methane emissions, and more) in the U. S. and elsewhere are based on data discussed in the main documentation report.

Natural gas production and trade

The LEM represents trade between the major natural-gas producing regions and countries of the world and the target consuming countries designated for analysis. For each consuming country trade is represented as the fraction of the country's total natural gas consumption that comes from each world producing region. For each country/producer pair, the LEM also represents the fraction of transport that occurs by ship, and the shipping distance.

Data on flows of natural gas are from IEA's *Natural Gas Information 2002* (2002) and are shown in the IEA/WBCSD data spreadsheet. The IEA reports imports by country and total consumption. In the LEM imports by pipeline are distinguished from imports as LNG.

Import fractions by country are assumed to remain constant at year 2001 values over the entire projection period.

The parameter values for natural gas production and processing (energy intensity, methane emissions from production and processing, and more) in the U. S. and elsewhere are based on data discussed in the main documentation report. Parameters for leaks from distribution systems are discussed in the next section.

Relative shipping distances. For the purpose of assigning emissions from pipeline compressors to in-country or out-of-country sources, the LEM distinguishes domestic from foreign pipeline mileage for every country. Specifically, for each target country C, the LEM estimates the average length of gas transmission pipelines inside of C and the average length of foreign pipelines shipping gas to C (up to the border of C) *relative* to the average length of domestic pipeline transmission in the U. S. I estimate these relative lengths on the basis of my inspections of maps of pipeline systems, and assuming that the average length in the U. S. is 1000 to 1500 miles. The following information was relevant to my estimates:

¨•Australia: The IEA's *Energy Policies of IEA Countries Australia 2001 Review* (2001) shows a map of existing and planned natural gas transmission lines in Turkey; this map indicates that most pipelines are at least 1000 miles.

¨•Germany: The IEA's *Energy Policies of IEA Countries Germany 1998 Review* (1998) shows a map of existing and planned natural gas transmission lines in Germany; this map indicates relatively short transmission distances of about 250 miles.

• Russia: The IEA's *Russia Energy Survey* (2002) also reports that Russian pipeline compressors consumed about 40 Bcm of gas in 1998, or about 7% of throughput. This figure is higher than in the U. S., which is consistent with longer transport distances and perhaps less efficient compressors than in the U. S.

• Thailand: The Office of Fossil Energy (2002) shows a map of existing and planned natural gas pipelines in Thailand, which indicate an average distance of about 350 miles.

¨•Turkey: The IEA's *Energy Policies of IEA Countries Turkey 2001 Review* (2001) shows a map of existing and planned natural gas transmission lines in Turkey; this map indicates that most pipelines are on the order of 500 miles.

• A note on LNG: The EIA's *Energy in the Americas* (2002) notes that Trinidad and Tobago, currently a major supplier of LNG to the U. S., has just increased its estimates of gas reserves, and is planning to build more LNG capacity.

Natural gas losses in distribution

The LEM has leakage rates for natural gas distribution systems in every country. (Note that leakage rates from *distribution* systems are entered for each consuming country, whereas leakage rates from production and processing are entered for producing countries.) As documented in the main report, detailed studies of leakage have been done for the U. S. Generally, where country-specific data were not available, I have assumed that leakage rates from developed countries are similar to those in the U. S., but that leakage rates from developing countries are higher. For countries with high current leakage rates, I assume a gradual reduction over time. Actual assumptions are shown in the LEM.

Note that the methods of Intergovernmental Panel on Climate Change (IPCC, 1997) result in a leakage rate of about 1%.

The following information on leakage rates was found in the literature:

• Australia: The Australian Greenhouse Office (2002) estimates that leaks from the Australian distribution system are 1% of throughput (p. B-13). However, this rate may be based on the IPCC (1997) methods, which probably overestimate leakage rates from modern, well-maintained systems. I assume 0.5% for Australia.

• Canada: See the "Canada" country section, below.

• Egypt: The Egyptian Environmental Affairs Agency (1999), Data Table 1, Energy, 1B2, shows the following "fugitive" methane emission rates for the oil and gas system:

71000 kg/gJ-NG (gas processing)
118000 kg/gJ-NG (gas transmission and distribution)
87000 kg/gJ-NG (Other leakages from NG)
2000 kg/gJ-oil (venting and flaring)
192000 kg/gJ-NG (venting and flaring)
2640 kg/gJ-crude oil (fugitives from production)

Assuming 0.053 gJ/kg natural gas (and assuming that the emission units are mg and not kg!), and that the natural gas is 90% methane, the methane emission rates correspond to NG leakage percentages of 0.4% for natural gas processing, 0.7% for natural gas transmission and distribution, and 0.5% for other leakages. (These figures probably are based on the IPCC [1997] methods.) I use a value of 1.2% for distribution.

• Mexico: The EIA Greenhouse Gas R&D Programme (1997) reports that Mexico uses an emission factor of 194 kg-methane/TJ-natural gas, from the Intergovernmental Panel on Climate Change (1997), to estimate methane losses from natural gas processing, transport, and distribution. Assuming that natural gas contains 19 kg/gJ (19,000 kg/TJ), the estimate by Mexico corresponds to a leakage rate of about 1%. (These figures probably are based on the IPCC [1997] methods.)

• Poland: Poland's National Fund for Environmental Protection and Water Management (2001) has completed a GHG emissions inventory for the United Nation's Convention on Climate Change. This inventory assumes 0.44 kg-CH_4/gJ from the "consumption" of natural gas (p. 78), or about 2.5% of consumption. This is consistent with estimates done for Russia (see below). I assume 2.5%, decreasing at 0.8% per year.

• Russia: Available data suggest that there is considerable leakage from the Russian gas system. The IEA's *Russia Energy Survey* (2002) reports that the Russian gas company, Gazprom estimates that leakage from production and high-pressure pipelines and compressor stations is 1.4% of throughput (p. 126). According to another source cited in the IEA (2002) report, this 1.4% can be apportioned as 0.2% production and processing and 1.2% transmission and storage. The IEA also reports that "estimates of leakage in distribution in 1998 reached at least five Bcm" (p. 252), but suggests that this is an underestimate (p. 126). Consistent with this, in a separate table, the IEA (2002) reports an estimate of 7.2 Bcm of losses from distribution in 1999. Similarly, Reshetnikov et al. (2000; discussed below) estimate that in the 1980s the USSR's distribution system lost 6 – 17 Bcm. Seven Bcm was about 2% of total gas demand in Russia, including demand by the heat and power sector, and 5% of "final consumption" excluding the heat and power sector (pertinent if the heat and power system is not connected to the low-pressure distribution system) (IEA, *Russia Energy Survey*, 2002). (By comparison, about 0.5% of the gas leaks from the U. S. natural-gas distribution system.)

On the other hand, the Russian Federal Service for Hydrometeorology and Environmental Monitoring (1997) estimates that leaks from the Russian gas production and use system are 1-2% of total throughput.

GM et al. (2002b) report measurements and theoretical calculations that indicate that losses from the production, processing, storage, and transmission of gas in Russia are 1% to 1.8%.

Reshetnikov et al. (2000) provide the most comprehensive available analysis of methane losses from the Soviet gas industry. Their detailed estimates of losses for the USSR gas industry in the 1980s are: (loss as a precentage of dry gas production):

- production (wells, cleaning, drying, compression, gathering): 2.4 – 2.8 %

- underground storage: 0.1 – 0.25%
- compressor stations: 0.8 – 1.4%
- linear part of main transmission pipelines: 1.9 – 2.1%
- accidents in transmission: 0.3 – 0.5%
- distribution networks: 0.8 – 2.2% (estimate adopted from an earlier study)

Reshetnikov et al. (2000) cite also cite a 1999 study of that indicates that production and transmission line losses from the newest and most well-maintained parts of the systems are much lower (0.1% for production and 0.2% for the linear part of main transmission lines), although they (Reshetnikov et al.) beleive that the 0.1% figure for production is too low, even for new, high-quality systems. They speculate (p. 3527) that technical improvements and shifts in the destination of gas have reduced the production and transmission loss rate in the 1990s by 15 – 40%.

Given these estimates, and relying heavily on Reshetnikov et al. (2000) but assuming significant improvements since the 1980s, and assuming that the Gazprom slightly underestimates losses, I assume the following for the year 2000 (percentage of throughput at each stage):

recovery	processing	transmission (incl. comp. & storage)	distribution
0.8%	0.4%	twice U. S. rate per mile	2.5%

I assume that the figures for distribution decrease at 0.8%/year from the year 2000.

• Thailand: Thailand's Office of Environmental Policy and Planning (2001) shows 26.2 billion grams methane from natural gas production, and 76.4 billion grams from natural gas processing, transmission, and distribution, in 1994. Thailand produced and consumed about 7100 billion grams of NG in 1994 (EIA, *International Energy Annual 2000*, 2002), so the emission rates are equivalent to 0.4%% leakage from production and 1.1% leakage from processing, transmission, and distribution. (These figures probably are based on the IPCC [1997] methods.)

Flows of motor vehicles

Background. The LEM represents international trade in light-duty and heavy-duty vehicles. For each consuming country trade is represented as the fraction of the country's total vehicle demand that comes from each world producing region. For each country/producer pair, the LEM also represents the fraction of transport that occurs by ship, and the shipping distance.

Data on flows of vehicles are from a variety of sources, and are shown in the IEA/WBCSD data spreadsheet. The general method is as follows. Recall that the objective is to represent, for each consuming country, the fraction of the country's total vehicle demand that comes from each world producing region. To do this, we need two kinds of data, for each consuming country: the quantity of imports that comes from each world producing region, and the total national demand for vehicles.

Quantity of imports from each producing region. The United Nations Comtrade database (2003) shows imports of passenger cars and imports of commercial vehicles, by country of origin, for every country in the world, for the year 2000. Imports are shown as the weight, number, or value of the vehicle imports, from each exporting country. I use these figures to apportion total imports across individual producing countries or regions (exporters). For example, if Egypt imported a total of $132 million in passenger vehicles in 2000, of which $36.5 million worth came from Korea (United Nations Statistics Division, Comtrade database, 2003), then I assume that 28% (36.5/132) of total imports of passenger vehicles to Egypt came from Korea.

Total national demand for vehicles. Given the information presented above, if we also know the ratio total imports : total demand (estimated to be 0.33 in the case of Korea), then we can calculate the figure of interest, which is the fraction of the country's total vehicle demand that comes from each producing region (in the case of Egypt, 0.28 x 0.33 = 9% of total demand is met by imports from Korea). Unfortunately, the calculation of this ratio is not straightforward.

First, I could not find a source that gave an estimate of demand for light-duty and heavy-duty vehicles, by country, as I have defined demand. Thus, domestic demand had to be estimated, as domestic production plus imports less exports. The difficulty with doing this is that no one readily available source provides production, import, and export data, and different sources use different definitions of vehicles and different units of measurement.

The International Organization of Motor Vehicle Manufacturers (2003) provides data on production of passenger cars (used to carry persons, up to 8 seats), light commercial vehicles (used to carry goods, up to 3.5 to 7.0 tons, depending on the country), minibuses, heavy trucks (over 3.5 to 7.0 tons, depending on the country), and buses, by country, in 2000. I combine the "light commercial vehicle" and the "heavy truck" categories into a "commercial vehicle" (or heavy-duty vehicle) domestic production category.

As mentioned above, the United Nations Statistics Division's Comtrade database (2003) provides data on total imports and exports of passenger cars and commercial vehicles, by country, in 2000. Unfortunately, for most countries the Comtrade data base reports imports and exports in units of weight (kg) or value ($). These weight or value units have to be converted to numbers of vehicles, by dividing by an estimate of the average weight or the average value per vehicle. These averages are difficult to estimate.

A final complication is that the Comtrade definitions of passenger cars and commercial vehicles is not identical to the definitions of the International Organization of Motor Vehicle Manufacturers.

Because of these problems of units and definitions, the calculation of total imports, total exports, and total national demand yielded is in some cases very uncertain.

Other. All international trade except for between the U. S. and Canada and between some countries in Europe is assumed to go by water. Distances between ports were read off an atlas. Where such an identification was possible, the actual major shipping port(s) of a country were used.

Import fractions by country are assumed to remain constant at year 2001 values over the entire projection period.

Appendix H and the main documentation report discusses parameter values associated with energy use for and emissions from the production of motor vehicles in the U. S. and other producing regions.

The nuclear fuelcycle

The LEM represents the production and enrichment of uranium in some detail. The main report presents the methods and data used to represent the nuclear fuelcycle in the U. S. For other countries, the LEM represents the nuclear fuelcycle as follows:

Stage	Representation in LEM, for non-U. S. countries
Uranium production	Source of uranium by producing country or method; energy requirements of production relative to that in U. S.
Conversion to UF_6	combined conversion, fabrication, disposal stage: use U. S. (global) values for all
Enrichment	detailed representation of energy requirements, by enriching technology and enriching country (see below)
Fabrication	see “conversion”
Disposal	see “conversion”
Transportation	use U. S. values (transportation-related emissions are negligible)

Uranium production. In the LEM the international parameters for the uranium-production phase of the nuclear fuelcycle are uranium requirements (tons U_3O_8/gWh), sources of uranium, and the energy intensity of uranium production.

Uranium requirements. The EIA (internet projections, 2003) and the World Nuclear Association (December 2002) project the uranium requirements (tons U_3O_8/gWh) of nuclear reactors worldwide. The two sources agree roughly on the requirements for the United States and Western Europe, but do not agree on the requirements for Korea and Japan. However, data analysis and discussion presented in the main documentation report suggest that the value is likely to be similar for all countries – about 0.033 to 0.035 tons/gWh in the year 2000.

The World Nuclear Association (October 2002) states that from 1970 to 1990 the ton/gWh uranium requirement of nuclear reactors in Europe declined by 25% due to the use of more highly enriched fuel and longer burn up of the fuel (to lower levels of U-235 in the depleted fuel). It also shows a graph that projects that this trend will continue worldwide through 2010. The EIA projections of ton/gWh uranium requirements for nuclear reactors worldwide through the year 2025 do show a decrease in uranium requirements in Western Europe (EIA, internet projections, 2003). More detailed projections for the U. S. also indicate a slight decrease (EIA, internet projections, 2003).

Given these data and projections, I assume that uranium requirements decrease by 0.25%/year for countries in Europe, and 0.2%/year for other countries.

Sources of uranium. The EIA's *Uranium Industry Annual 2001* (2002) reports sources of uranium required by U. S. nuclear utilities. The World Nuclear Association (October 2002) projects sources of uranium supply for the world through 2010, and other World Nuclear Association papers (July 2002 and August 2002) show uranium production from world mines. The World Nuclear Association (October 2002) projects that in 2010 mine production will satisfy 75% of world uranium demand, military uranium will satisfy 20%, and reprocessed fuel and re-enriched tails about 5%. It also shows that in 2001 Canada produced 35% of total world mine production of uranium, Australia produced 22%, the FSU produced19%, Niger 9%, the USA and South Africa 3% each, and the rest of the world 10% (World Nuclear Association, July 2002 and August 2002). Finally, the World Nuclear Association (December 2002) shows uranium requirements for nuclear power plants by country in 2002.

With these data, and by comparing each country's uranium requirements with its annual production, I estimate the sources of uranium for nuclear-power countries worldwide.

Energy intensity of uranium production. The LEM requires as an input the energy intensity of uranium production (BTUs/ton-uranium) for each production source *relative* to the energy intensity of production from uranium mines in the U. S. I assume that this relative intensity is 1.0 for all mine production worldwide, 0.50 for reprocessed tails and spent fuel, and 0.30 for military high-enriched uranium.

<u>Uranium enrichment.</u> Because there is international trade in uranium enrichment services (measured in separative work units, or SWUs), the LEM now represents, for each country that provides enrichment services: i) the contribution to the SWU requirement of any one of the consuming countries that can be targeted for analysis; ii) the fraction of SWUs provided by different enrichment technologies (gaseous diffusion, centrifuge, laser isotope separation [AVLIS]); and iii) the MWh of electrical energy required per SWU. The U. S. A., France, Germany, the Netherlands, the U. K., and Russia provide the bulk of the world's uranium enrichment services. With these data, and an estimate of the SWUs required per ton of natural uranium to be enriched, the model calculates the figure of interest: the energy efficiency of uranium enrichment, in MWh-enrichment-energy/MW-power-generated.

Note that the mix of fuels used to generate electricity in the uranium-enriching countries is discussed in the main report.

Sources of SWUs provided to nuclear utilities. The main report documents the methods of analysis and the parameter values pertinent to items ii) and iii) in the paragraph immediately above. It also documents the sources of SWUs provided to U. S. nuclear utilities. To estimate the sources of SWUs provided to nuclear utilities in other countries, I first compare the SWU production capacity of each country in 1999 (IEA, *World Energy Outlook*, 2001) with the SWUs required for the amount of nuclear power that the LEM estimates the country will generate in 2010. On the basis of the discussion in DeLuchi (1993) and the main documentation report there, I estimate approximately 0.0145 SWUs/MWh-nuclear power. I multiply this by the LEM projections of nuclear generation in 2010, and compare the result with the annual SWU production capacity:

Country	China	India	S. Africa	Mexico	Brazil	Germany	Japan	Korea	Russia	U. K.
SWUs needed	358	326	208	120	157	2,109	5,458	2,118	2,194	1,182
SWU capacity	300	0	200	0	0	1,100	950	0	19,000	1,800

I use these estimates to make assumptions regarding the total fraction of SWUs imported. I use my judgment to apportion total SWUs to individual producing countries.

SWUs required per ton of uranium enriched. The LEM also requires an estimate of SWUs required per ton of uranium enriched for the nuclear utilities of each consuming country. The EIA (internet projections, 2003) projects SWU and uranium requirements for nuclear utilities worldwide. These projections indicate that SWU/ton requirements in other countries are similar to those in the U. S. This seems plausible, because the degree of enrichment is the main factor determining SWU/ton requirements, and the degree of enrichment appears to be similar in most countries. Therefore, I assume a base value of 480 SWUs/ton-U_3O_8 in the year 2000, increasing at 0.25%/year as uranium is more highly enriched.

Note that the heavy-water moderated "CANDU" reactors in Canada use natural uranium, and hence do not require enrichment services.

Crop production and fertilizer use

The LEM has parameters for harvest yield and nitrogen use for corn, soy, grass, and wood production, by country. Generally, I assumed that nitrogen inputs per ton or bushel of crop are constant everywhere, but that the resultant harvest yields, in bushels or tons/acre, are lower in developing countries, in the base year. However, I also assume that harvest yields improve at a slightly faster rate in developing countries, the difference in the improvement (developing countries vs. developed) being inversely related to the difference in base-year yields.

A few data relevant to these estimations are presented below.

• <u>Australia</u>: The Australian Greenhouse Office (2002) reports that in Australia one million tonnes grams of fertilizer N (from synthetic fertilizer and manure) were applied to 23.5 million hectares of cropland (this excludes pasture land), resulting in 0.04 tonnes-N/ha.

- Canada: See the "Canada" country section, below.
- Egypt: The Egyptian Environmental Affairs Agency (1999), Data Table 4, 4D, Agriculture, shows 0.18 tonnes-N/ha-cultivated in Egypt, from fertilizer and manure, for all crops.
- United States: In the U. S. in the year 2000, about 14 million metric tons of N fertilizer (synthetic and manure) were applied to agriculture soils (excluding pasture land) (EPA, Inventory of Greenhouse-Gas Emissions and Sinks: 1990-2000, 2002). According to the Bureau of the Census 1997 Census of Agriculture (1999), 125 million hectares of cropland were harvested in 1997. This results in 0.11 tonnes-N/ha-harvested.

The LEM also specifies the types of land uses displaced by crop production. These parameters are pertinent to the calculation of changes in the amount of carbon (and hence effectively CO_2) sequestered in soils and plant material. For example, if a forest is cleared to plant a biofuel crop, the amount of carbon stored in the soil and the biomass will decrease. The main report documents the methods used to calculate the CO_2-equivalent of the changes in stored carbon.

There are nine land uses in the LEM, ranging from tropical forests to tundra. The main report presents assumptions on the extent to which each of these land uses is displaced, by crop, in the U. S. Presently, my assumptions for other countries are based on my judgement, without reference to any underlying studies. However, because these assumptions can significantly affect lifecycle CO_2-equivalent emissions in some cases, it is important that country-specific parameters based on actual data or models be developed.

Corn-ethanol production

The LEM has energy requirements (fuel use and electricity use) for corn ethanol production. Generally, I assume slightly higher energy requirements in developing countries, partly on account of less efficient technology, which in turn is due in part to the lower cost of fuels and electricity.

Nitrogen deposition

The LEM also has parameters that describe the fate of nitrogen deposited from the atmosphere onto different ecosystems, as part of the calculation of a CO_2-equivalency factor for NO_X emissions (Appendix D). Nitrogen deposition has a variety of environmental effects that affect climate, including fertilization and stimulation of plant growth and carbon sequestration, stimulation of emissions of N_2O, and more. Some of these effects depend on the type of ecosystem receiving the nitrogen deposition: tropical forest, temperate forest, grassland, agricultural land, and so on (Appendix D). The distribution of ecosystem types, and hence the fate of nitrogen by type of ecosystems, will vary from country to country.

General data pertinent to the fate of nitrogen are discussed in Appendices C and D. With those data I calculate a global average fate for nirogen deposition (shown below). Given that global average and then using my judgment, I then estimate the fate of nitrogen deposition country by country:

	trop. forest	**temp. forest**	**grass**	**agric.**	**arid**	**urban**	**lakes**	**rivers/ coasts**	**marine**
global ave:	*0.06*	*0.12*	*0.12*	*0.18*	*0.06*	*0.06*	*0.03*	*0.15*	*0.22*
U. S.	0.02	0.12	0.14	0.18	0.07	0.08	0.04	0.15	0.20
Canada	0.01	0.20	0.20	0.05	0.12	0.04	0.05	0.12	0.21
Italy	0.01	0.08	0.08	0.20	0.08	0.08	0.03	0.17	0.27
China	0.06	0.12	0.13	0.21	0.06	0.05	0.03	0.15	0.19
India	0.10	0.10	0.11	0.22	0.02	0.05	0.03	0.15	0.22
South Africa	0.05	0.12	0.14	0.18	0.10	0.05	0.03	0.12	0.21
Chile	0.01	0.11	0.17	0.15	0.12	0.05	0.02	0.12	0.25
Mexico	0.08	0.12	0.12	0.15	0.10	0.06	0.03	0.10	0.24
Australia	0.04	0.07	0.13	0.10	0.18	0.05	0.02	0.13	0.28
Brazil	0.18	0.07	0.12	0.15	0.01	0.06	0.03	0.18	0.20
Egypt	0.00	0.03	0.10	0.18	0.25	0.04	0.03	0.15	0.22
Germany	0.01	0.16	0.13	0.20	0.01	0.08	0.06	0.18	0.18
Japan	0.04	0.10	0.10	0.20	0.01	0.08	0.03	0.17	0.27
Korea	0.08	0.11	0.12	0.15	0.01	0.06	0.03	0.17	0.27
Poland	0.01	0.20	0.15	0.20	0.01	0.06	0.04	0.15	0.18
Russia	0.01	0.15	0.15	0.15	0.12	0.06	0.03	0.15	0.18
Thailand	0.11	0.12	0.12	0.18	0.01	0.06	0.03	0.15	0.22
Turkey	0.01	0.12	0.15	0.12	0.11	0.05	0.04	0.16	0.24
U. K.	0.01	0.12	0.12	0.20	0.01	0.08	0.04	0.15	0.27

Note that each country is the source of nitrogen *emissions*, not necessarily the location of nitrogen deposition. Generally, emissions from country Y will be deposited partly in country Y and partly elsewhere. For our purposes we need identify only the ecosystem types that receive the deposition; we do not need to identify the countries that receive the deposition.

Multi-modal emissions

Parameters related to multi-modal emissions (occupancy, passenger-km by mode, etc.) are estimated for Chile, China, India, Mexico, and South Africa only. See the pertinent country sections below.

CANADA

Motor vehicle emissions

As explained in the main text, motor vehicle emissions, in g/mi, are calculated using a simplified MOBILE5 algorithm. Although the calculation is relatively simple, there still are too many parameters to allow for a manageable specification of country-specific values for each parameter. Consequently, the model calculates final g/mi emissions in the U. S. on the basis of the input parameters for the U. S., and then calculates g/mi emissions in other countries by multiplying the final calculated U. S. values by overall relative emission factors for the other countries. Hence, the user inputs, for each country, and each pollutant, the ratio of on-road g/mi emissions in that country to calculated on-road g/mi emissions in the U. S.

Of course, in reality, the ratio of motor-vehicle emissions in one country to emissions in the U. S. varies with the model year of the vehicle, the age of the vehicle, and the type of fuel. Nonetheless, for simplicity, the model does not account for these relationships; instead, the user enters one set of relative emission factors, which therefore apply to all model years, all vehicle ages, and all vehicle types, including alternative-fuel vehicles.

I assume the following relative emission factors for Canadian vehicles:

	LDVs	HDVs	*explanation*
Fuel evaporation	0.90	n.a.	lower ambient temperatures
NMOC exhaust	1.50	1.20	lower temperatures, less stringent fuel and emissions standards
CH_4 exhaust	1.50	1.20	see NMOC
CO exhaust	1.50	1.20	see NMOC
N_2O exhaust	1.00	1.00	no basis for differentiation
NO_2 exhaust	1.10	1.10	less stringent fuel and emissions standards
PM exhaust	1.10	1.20	see NMOC

Petroleum refining

In the model, the user enters the refinery energy intensity of producing each major kind of petroleum product (conventional gasoline, reformulated gasoline, low-sulfur diesel fuel, etc.), and the breakdown of that refinery energy by type of fuel (refinery gas, natural gas, petroleum coke, electricity, etc.), for each major refining region of the world.

Generally, I assume that refining process technology is the same everywhere, so that it takes the same amount of refinery energy to make a particular product in, say Europe, as it does in the United States. However, I do adjust for significant differences in the quality of input crude oil: if a country tends to process especially heavy crude oil, then the energy intensity of refining likely will be higher. In these cases, I multiply the U. S. refinery energy intensity, for each product, by the ratio of the overall refinery energy intensity (BTU-total/BTU-all-products) in country C to the overall refinery energy intensity in the U. S., where the overall refinery energy intensity is given in eq. 12. In Canada in 1996, conventional refineries and heavy-oil upgraders consumed 450,000 tJ of fuel (HHV, counting electricity at 3412 BTU/kWh, and ignoring the presumably minor feed to the hydrogen plants), and conventional refineries produced $99.4 \cdot 10^6$ m^3 of petroleum products (Nyboer and Olive, 1997). Assuming that all of the output of the upgraders continued on to conventional refineries, and that output averaged $5.38 \cdot 10^6$ BTU/bbl, the energy intensity of the upgrading-plus-refining industry[2] in Canada was 12.7%. In the U. S., the overall refinery energy intensity is around 10%. Thus, for Canada in 1996, I multiply the U. S. energy-intensity values, for individual products, by 1.27. This is consistent with the estimates by McCann and Magee (1999) that the refining of Venezuelan heavy crude results in 33% greater emissions (in Mg-CO_2-equiv/m^3-fuel) than does the refining of light oil.

I assume that this 1.27 scalar increases by 0.3% per year, as Canada produces more and more heavy oil.

In Canada, the breakdown of refinery energy by type of fuel is assumed to be the actual breakdown in 1996, which we estimate to be 53% refinery gas, 16% natural gas, 13% residual fuel, 10% petroleum coke, 6% electricity, and the remainder diesel fuel, LPG, crude oil, steam, and hydrogen (Statistics Canada, 1997?).

Electricity generation efficiency and fuel mix

The LEM has individual country mixes for petroleum refining, uranium enrichment, ethanol production, generic activities, oil and gas refining, auto manufacture, and EV recharging. For Canada, regional detail is provided: you enter the average mix for each of six regions, the marginal mix for recharging EVs in each of six regions, and the distribution of recharging, refining, auto manufacture, and ethanol production activity over the six regions. The default parameter values are based on actual Canadian data and my judgment.

Emissions from power plants

The LEM has adjustment factors by country for power plant emissions relative to those for the U. S. Emissions data indicate that Canadian power plants emit less NO_2 but more SO_2 than do U. S. plants.

Uranium enrichment

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[2] Note that in the Statistics Canada (1997?) data, the two largest upgraders are classified as "mining" industries rather than refining industries (Stanciulescu, 1999).

Because CANDU reactors use natural uranium, no energy is expended on enrichment. (See also the discussion of the nuclear fuelcycle, in the main text.)

Production of alternative fuels

For any generic alternative-fuel production process (e.g., natural gas to methanol), the ratio of particular kinds of inputs (natural gas, diesel fuel, electricity, chemicals, etc.) to output fuel (e.g., methanol) depends on the fuel conversion process (e.g., steam reforming versus partial oxidation), the source of electricity (internally generated, or bought from the grid), the types of fuel used for process heat, and other factors. Ideally, one would specify these variables -- conversion technology, source of electricity, and fuels for heat -- for each alternative-fuel production process in each country. However, for simplicity, I have assumed that for each generic production process, the specific conversion technologies are the same in every country. I do allow, though, for inter-country differences in the use of process fuels for those fuel-conversion processes that require a significant amount of energy for process heat. In this analysis, there is only one such general process: corn-to-ethanol. Thus, in the model, the user specifies, for the corn-ethanol process in each country, the total energy requirement for process heat, and the distribution of the total between coal and natural gas.

My assumptions of energy use per gallon in 1996 are:

	U. S.	Canada
Net electricity purchased (kWh)	1.15	1.15
Total coal+NG (BTUs)	44,540	44,540
Natural gas share	59%	95%
Coal share	41%	5%

In Canada, most corn and ethanol is produced in Ontario (Agriculture and Agri-Food Canada, 1997?). The industrial and manufacturing sectors in Ontario use natural gas almost exclusively (Statistics Canada, 1997?).

Oil production

As discussed in the main text, I assume that oil production in Canada is more energy intensive than in the U. S., on account of the significant fraction of oil produced from tar sands.

The EIA's *International Energy Annual 1996* (1998) shows that Canada imports about 5% of its oil supply. (See discussion of oil-flow parameters, above.)

Ocean shipment of crude oil

The model requires estimates of port-to-port shipping distances for crude oil. As discussed in the text, the estimates of distances to U. S. ports are based in part on data from the U. S. Defense Mapping Agency (1985). My estimates of distances to Canadian ports are based on the estimated distances to U. S. ports. For example, I assume that distances to eastern Canadian ports are similar to distances to New York, and that distances to western Canadian ports are similar to distances to Los Angeles.

Coal mining

The energy intensity of coal mining, emissions of coalbed methane, and sources of Canadian coal are discussed in the pertinent sections of the main text.

Natural gas production and transmission

The energy intensity of gas and NGL production, and pipeline transmission, are discussed in the pertinent sections of the main text.

Leaks of natural gas (Canadian systems)

Leaks of natural gas from Canadian systems are estimated in the same way as are leaks from U. S. systems (see the main report) except that the parameter $NGC_{GP,C}$ is specified for Canada (all Canadian gas supply is domestic). The values of $CH4L_{i,GP,92}$ (gas lost) and $TP_{i,GP,92}$ = (gas supply) for Canada are estimated on the basis of the Canadian counterpart to the EPA/GRI (1996) study for the U. S. (Radian International LLC, 1997).

Radian (1997) estimates that in Canada in 1995, $607 \cdot 10^3$ metric tons (kt) of CH_4 were emitted from natural-gas production systems, 115 kt were emitted from processing plants, 271 kt from transmission systems, 6.9 kt from storage, and 141 kt from distribution. 5,227 BCF of gas were marketed. From these data, we will need to estimate BCF of natural gas (not just methane) leaked (excluding emissions from combustion), and dry gas (not marketed gas) output per stage.

First, we subtract from the total estimated emissions the amount that was from incomplete combustion of fuel for compressors and engines, because those emissions we account for separately elsewhere in the model. Table 3.9 of Radian (1997) shows that 11.1 kt of emissions from transmission, storage, and distribution systems were from incomplete combustion, so we subtract 11.1 from the transmission total. Radian (1997) does not separately estimate combustion-related emissions from gas production and processing in Canada, so we turn to the EPA/GRI (1996) study for the U. S. for guidance. Table 4-4 in Volume 2 of that study shows that in the U. S. in 1992, 7.8% of total gas-production emissions, and 19% of total gas-processing emissions, were from incomplete combustion. We subtract those percentages from the Canadian totals reported by Radian (1997).

Next, we convert from tons to SCF, using 19.23 g/SCF for methane (Radian, 1997). Then, we expand the Radian emission estimate, which includes CH_4 only, to include all of the components of natural gas, because we assign separate CO_2-equivalency factors to all of the components. Table B-1 of Radian (1997) shows that natural gas in Canada is 94.4% methane, and in general has a composition similar to that of gas in the U. S. Because of this similarity, we apply the U. S. composition to

Canadian gas, and divide the Radian (1997) CH_4 emission estimates by the volume fraction of CH_4 in U. S. gas (93.8)% (But note that we then multiply the total emission by the volume share of each component and its CEF, so that the original CH_4 estimate for Canada is recovered.)

Now for the denominator of our leakage rage expression, dry gas output per stage. First, we must estimate dry gas production, which is what we want, from marketed production, which is what Radian (1997) reports. (Dry gas is marketed gas less extraction of liquids; it is the gas that actually is marketed and used as a gas.) Here we run into a problem. Radian (1995) reports 5,227 BCF of "marketed" gas in 1995; the EIA's *International Energy Annual 1996* (1998) reports 6,228 BCF of marketed production and 5,638 BCF of dry gas production in 1995. We have four choices: i) assume that Radian made a typo, and meant to print 6,227 (essentially identical to the EIA's 6,228) and not 5,227; ii) assume that the 5,227 figure is right, but refers to dry gas production as defined by EIA; iii) assume that the EIA dry gas production figure is right (practically the same as choice #i); or iv) apply the EIA dry-gas/marketed-gas ratio of 0.905 to the Radian estimate of 5,227. We have chosen the last, because it takes the Radian estimate at face value, and uses a production estimate and leakage estimate from the same source.

Three other adjustments must be made to the denominator. In the case of the gas processing, we want the leakage rate per unit of gas produced from the processing plants, not the rate per unit of any gas produced. We assume that the output of gas plants is 70% of the total dry gas production (the percentage in the U. S.). In the case of gas transmission, we must exclude from the estimate of output the gas consumed by pipelines, which on the basis of data in *Statistics Canada (1997)* we take to be 3.8% of supply. Finally, in the case of distribution, we must exclude the gas lost during distribution as well as the gas used by pipelines.

With these data, leakage rates are calculated as follows:

recovery: 607*0.922/19.23/(5227*0.905)/0.94 = 0.66%
processing: 115*0.81/19.23/(5227*0.7*0.905)/0.94 = 0.16%
transmission and storage: (271+6.9-11.1)/19.23/(5227*0.905*0.962)/0.94 = 0.33%

Harvest yields and fertilizer use for field crops and biomass

The model calls for country-specific values for crop yield in a base year, the rate of change in the yield, and the use of nitrogen fertilizer, for corn, soybeans, wood, and grass. In 1996, Canadian corn farms produced 115 bushel [bu]/acre (calculated from data in (Agriculture and Agri-Food Canada [1997?], which was similar to the U. S. rate of about 120 bu/acre from 1990-1996 (Table 18). Agriculture and Agri-Food Canada (1997?) cite a recommendation of about 1.09 lbs-N/bu, which is the same as the actual U. S. application from 1990-1996 (Table 18). Data for soybean production are not readily available.

It is reasonable to assume that the production of grass and woody biomass feedstocks in Canada will be similar to the production in the U. S.

Given these data and considerations, I assume that yields and fertilizer use for all crops in Canada are the same as yields and fertilizer use in the U. S.

CHILE

Transportation

Light-duty vehicle emission factors. Air pollution is a serious problem in the capital of Chile, and motor vehicles there are a major source of air pollution (O'Ryan et al., 2001; EIA, 2000). Santiago (the capital) is one of the most polluted cities in the world, and frequently has polluton emergencies (EIA, 2000). Chile is attacking this problem by restricting vehicle use (e.g., in Santiago there are restrictions on the use of non-catalyst cars [Export Council for Energy Efficiency (ECEE), 2001a]), encouraging the use of vehicles that use clean-burning fuels such as compressed natural gas (CNG) (O'Ryan et al, 2001;EIA, 2000), tightening emissions regulations for conventional vehicles[3], and encouraging the retirement of old, dirty vehicles (ECEE, 2001a; O'Ryan e al., 2001).

In the lifecycle emissions model (LEM), motor-vehicle emissions in countries other than the U. S. are estimated relative to emissions from vehicles in the U. S. Thus, in the following sections I review emissions estimates and standards for Chile with an eye towards comparing them with emissions estimates and standards for the U. S.

Emissions of course depend greatly on emission -control technology, which in turn are driven in large part by emissions standards. According to O'Ryan et al. (2001), Chiles master plan for air pollution control requires that vehicles from 1992 onwards meet tight exhaust emissions standards achievable only with catalytic converters. Therefore, I assume that Chile began using cars with emission controls in 1992. By contrast, in the U. S. oxidation catalysts were introduced with the 1975 model year, and 3-way catalysts with the 1981 model year.

O'Ryan and Turrentine report emission factors for Chile by transport mode and fuel type (Appendix Table A.2.2) (2000). However, these are generic emission factors recommended by the IPCC. Because the documentation for the LEM considers the IPCC estimates along with other data, I do not adopt the IPCC estimates here, but rather rely on my own estimates. Specifically, I assume the following emission factors for LDGVs in Chile, relative to emissions in the U. S., by pollutant and model year:

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[3] The ECEE (2001a) states that as of early 1994, policy makers in Chile "already have required all new vehicles to be equipped with catalytic converters".

MY:	1960	1975	1981	1992	2010
Fuel evaporation	1.2	2.0	3.0	2.0	1.2
NMOC exhaust	1.2	2.0	3.0	1.5	1.2
CH_4 exhaust	1.1	1.6	2.0	1.2	1.1
CO exhaust	1.5	2.0	3.0	1.5	1.2
N_2O exhaust	1.0	0.2	0.2	0.8	1.0
NO_2 exhaust	1.0	1.2	2.0	2.0	1.2
PM exhaust	1.2	2.0	2.5	2.0	1.2

The LEM calculates the model year given a target year and a mileage accumulation rate, then looks up the pertinent relative emission factor for each pollutant, and multiplies this factor by the estimated U. S. emission factor.

Alternative-fuel LDV emissions. In the LEM, emissions from alternative-fuel vehicles are estimated relative to emissions from gasoline light-duty vehicles or diesel heavy-duty vehicles. I assume that the relative emissions depend on "inherent" technological differences (between alternative and conventional fuels) that do *not* vary from country to country. The relative emission factors are estimated on the basis of a comprehensive literature review (see the main text LEM documentation).

HDV and other emissions. According to O'Ryan et al. (2001), the 1990 "master plan" for air pollution in Santiago required bus fleets to eliminate the oldest vehicles and imposed increasingly stringent emission standards on new buses. Given this, I assume that heavy-duty diesel vehicles (HDDVs) in Chile are only somewhat less well maintained and subject to only somewhat less stringent standards than are HDDVs in the U. S. (O'Ryan et al., 2001). Specifically, I assume that for any given model year, CO and NMHC are 20% higher, NO_X emissions 50% higher, and PM emissions 100% higher than in the U. S.

For scooters and minicars, I assume the following relative emissions (Chile vs. U. S.):

CH_4	NMHC	Evap.	CO	NO_X	PM	N_2O
1.25	1.50	1.50	1.50	1.10	1.50	1.00

Occupancy. The LEM requires as an input the occupancy (persons per vehicle) of cars, buses, minibuses, motor scooters, and bicycles, and the average capacity fraction of light rail and heavy rail transit. O'Ryan and Turrentine (2000) report the following estimates of occupancy[4]: urban cars, 1.9; interurban cars, 2.2; urban buses, 34; interurban buses, 40 (Table 4.10 and footnote 80). I use their estimates for urban cars

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[4] It is not clear if the occupancy estimates for cars include taxis, which typically carry 4 or 5 people and account for a significant fraction of car travel in Santiago. In the LEM the "car" category is meant to include taxis; I assume that the occupancy estimates in O'Ryan and Turrentine (2000) include taxis.

and buses, and my judgement for the other modes (which in any event are of minor importance in Chile).

According to O'Ryan and Turrentine (2000), the Santiago heavy-rail Metro system is capable of carrying 40,000 passengers per hour, but currently carries only 14,000 passengers/hour, and hence is underutilitized. However, they state also that ridership is continuing to grow. I assume a capacity fraction of 40%.

Fuel economy of motor vehicles, and energy use of rail systems. The LEM requires as an input the fuel economy of gasoline passenger cars, full-size diesel buses, diesel minibuses, and gasoline motor scooters. Given these inputs, it calculates the fuel economy of alternative-fuel vehicles, including diesel-fueled passenger cars and gasoline buses.

O'Ryan and Turrentine (2000) report the fuel economy of private cars, commercial vehicles, and taxis, by type of fuel (leaded gasoline, unleaded gasoline, and diesel fuel). Given that in Chile leaded gasoline is being phased out, and that the LEM calculates the fuel economy of diesel vehicles relative to that of gasoline vehicles, I start with their estimates for vehicles using unleaded gasoline, which are: 24.9 mpg for private cars and commercial vehicles, and 23.5 mpg for taxis. Considering these estimates, I assume 25 mpg for all passenger cars (private cars, commercial vehicles, and taxis combined) the entire forecast period.

O'Ryan and Turrentine (2000) report the fuel economy of full-size urban diesel buses to be 4.7 mpg. I assume 5 mpg for the entire forecast period.

In the LEM, fuelcycle emissions from minibuses are calculated with respect to fuelcycle emissions from full-size buses, by scaling emissions according to the fuel economy of minibuses relative to that of full-size buses. Material and vehicle lifecycle emissions from minibuses also are calculated with respect to emissions from full-size buses, by scaling according to the weight of minibuses relative to the weight of full-size buses. My assumptions regarding minibuses and full-size buses are shown below.

Data on scooters are not available. I assume that they have 5% lower mpg and 8% higher weight than is specified for the U. S.

Data on the Santiago rail systems also are unavailable. I assume that energy use per capacity mile, for line-haul and stations, is the same as estimated in the U. S. (see Delucchi, 1996). However, I do assume higher capacity factors than in the U. S..

My assumptions regarding occupancy and fuel economy are as folows:

	Occupancy (per/veh)	City fuel economy (mpg)
Cars (gasoline)	1.9	25
Buses (diesel)	34	5
Minibuses (diesel)	16	10
2-st. scooter	1.0	90
Mini car	1.5	51
Heavy rail	40%*	n.a.
Light rail	60%*	n.a.
Bicycling	1.0	n.a.
Walking	n.a.	n.a.

*Average capacity fraction, not persons per vehicle

Shares of passenger-km by mode. O'Ryan et al. (2001) estimate shares of passenger km by mode for urban Santiago for the years 2000, 2020-low, and 2020-high (their Table6.3). I have used their estimates for 2000 and 2020 "high", except that I have corrected what appears to be a mis-estimate of the modal share for the metro. For the 2000 "low" scenario I have revised their estimates as follows: I assume that all of the full-size buses are hydrogen fuel-cell powered (where the hydrogen is made from natural gas); that electric passenger vehicles have 5% of passenger km, and that mini-cars (half of which are electric) have 5% of passenger km.

Freight shipment. O'Ryan et al. (2001) report that truck is the "most important" freight mode, followed by ship and then rail. They state that coastal shipment has been relatively constant at around 16-20 million tons per year, with international shipment of around 45 million tons per year. About 20 million tons per year are shipped by rail They estimate the following shares of ton-miles by mode:

	2000	2020
Truck	0.752	0.768
Train	0.026	0.026
Ship	0.222	0.206

I use these as the basis of my estimates of input tonnage and mileage of freight shipment, by mode.

Electricity

See the discussion of electricity parameter values, above.

The EIA (2001a) reports that Chile imported 95% of its coal in 1999. The EIA's *International Energy Outlook 2001* (2001b) projects that coal imports to the Americas will come from the United States, Australia, and Columbia and Venezuela -- primarily Australia, according to another EIA (2001c) report.

Oil and gas production and use

Oil. In the LEM, Chile is not a major oil-producing region or a major oil-refining region. Hence, in the LEM the only oil parameters specific to Chile are those pertaining to the source of crude oil.

In 1998, Chile imported 95% of its crude oil consumption, 12% of its gasoline consumption, 58% of its LPG consumption, 17% of its distillate consumption, and 8% of its residual fuel oil consumption (EIA, 2001a). Chile's main sources of crude oil imports are Argentina, Nigeria, Gabon, and Venezuela (EIA, 2001c; Office of Fossil Energy, 2001).

Gas. Chile imports a modest amount (about 30%) of its natural gas, from Argentina (EIA, 2001a). I assume that for all end uses except production of methanol or FT-diesel, 70% of the gas used in Chile is produced domestically, and that 30% comes from Mexico (as a proxy for Argentina, the actual source.) Because Chile has supported large gas-to-liquids projects (e.g., the largest methanol production facility in the world is in Chile [Office of Fossil Energy, 2001]), I assume that 100% of the gas used to produce methanol and FT-diesel is domestic. (In the LEM one specifies methanol and FT-diesel end use separately from all other end uses of natural gas.)

Other industry

Vehicles and materials. In the LEM, Chile is not a major producer of vehicles or materials[5]. Hence, in the LEM the only vehicle or materials-manufacturing parameters specific to Chile are those pertaining to the sources of vehicles or materials.

Chile has no motor vehicle industry, although it does assemble a few vehicles, presumably from imported main parts (O'Ryan, 2001). The CIA's *World Fact Book* (2001) lists motor vehicles as a major Chilean import, and O'Ryan et al. (2001) state that import restrictions on cars were eliminated in the late 1970s and early 1980s. Given this, I assume that in effect 5% of the vehicles used in Chile are manufactured domestically, 35% are from the U. S., 15% from Mexico, 5% from Canada, 5% from Germany, 15% from Japan, 10% from other Asian exporters, and 10% from other sources.

The LEM allows the user to specify the source of iron and steel, aluminum, plastic, and other materials used in the target country (Chile in this case). My assumptions regarding material production and imports are discussed above and shown in the IEA/WBCSD data spreadsheet.

Production of alternative fuels. I assume that alternative-fuel production technologies (e.g., coal to methanol, natural gas to hydrogen) are similar everywhere in

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[5] Chile is the world's largest copper producer, but in the LEM copper is not treated as a separate commodity. And although Chile produces a significant amount of its own iron and steel, it is not a major world producer, and hence in the LEM is not treated as a producing region.

the world, and hence that the inputs and outputs (e.g., ft^3 of natural gas per ft^3 of hydrogen) are similar in all countries. In fact, with but a few exceptions, the LEM has only one set of inputs and outputs for each alternative-fuel production process; i.e., the inputs and outputs are not specified by country. The exceptions are the use of natural gas as a feedstock to produce FT-diesel, hydrogen, or methanol. In these cases, I assume that the amount of natural gas required to produce a unit of output does vary from country to country, mainly on account of differences in the cost of the feedstock. (Where natural gas is expensive, there is incentive to invest in efficiency-improving technologies that increase the output per unit of gas input.) I assume that natural gas in developing counries (a generic category into which I place category) is less costly than in the U. S., and hence that the FT-diesel, hydrogen, and methanol production processes in developing countries use a bit more gas (4% more) per unit of output than do processes in the U. S.

Yields of biomass and fertilizer use

As part of the calculation of emissions from the biomass cultivation stage in the lifecycle of biofuels, the LEM calculates yields of corn (bushels/acre) soybeans (bushels/acre), grass (tons/acre) and wood (tons/acre), in every target country. The input data are the yield in a base year (presently 1996) and the annual percentage change in the yield after the base year. I assume that in Chile the base-year yields and the annual percentage change in the yields are 90% of the values in the U. S.

The LEM also has as inputs the use of nitrogen fertilizer (lbs/bushel or lbs/ton) in every country. I assume that nitrogen is applied in Chile at the same rate that it is applied in the U. S.

CHINA

Transportation

Dengqing et al. (1996) report that gasoline-powered passenger vehicles in China achieve 26.7 mpg. I assume figures that result in 25.4 mpg. Dengqing et al. (1996) also estimate that in China, diesel vehicles are 18-33% more efficient than there gasoline counterparts. I assume that in all countries (including China) diesel vehicles are 25% more efficient.

Jinxia et al. (1996) report a national average fuel consumption of 26-29 l/100km for standard buses, 32-36 for l/100km articulated buses, and 65-85 kWh/100km for trolley bus. I assume 8 mpg for buses (29 l/100 km). Their figure for trolley buses appears to be imply about 100 BTUs/passenger-capacity mile, which I assume here, and which is consistent with data for U. S. light-rail systems (Delucchi, 1996).

Sperling (2000) reports a communication from Prof. Zhou indicating that 2-wheel scooters in China get 81 mpg. I therefore assume that scooters in China are bigger and less efficient than those in India, which apparently achieve well over 100 mpg (Bose and Nesamani, 2000). However, an informal reviewer claims that a manufacturer in China produces a direct-injection 2-stroke scooters that consume only 1.3 l/100 km (180 mpg) and are cleaner than most 4-strokes. I was not abl to verify the claim.

Daxiong et al. (1996) report that freight trucks consume up to 2400 BTU/ton-mile. They do not say what the average is, or to what size truck the figure applies. I assume 2000 BTU/ton-mile for large trucks, and 4000 BTU/ton-mile for medium trucks.

Dengqing et al. (1996) give the following breakdown of gasoline and diesel use in highway vehicles:

	Goods Vehicles			Passenger cars	
	Heavy	Medium	Light	Big, medium	Small
Diesel	100%	10.4%	23.4%	8.3%	0%
Gasoline	0%	89.6%	76.6%	91.7%	100%

Given this, I assume that 10% of LDVs use diesel fuel, and 90% use gasoline.

Jinxia et al. (1996) report that the full-day load factor for buses in China is 50-70%, and that the peak-load factor 80-115%. Assuming a capacity of 45 people, and 60% daily (full-day) capacity, the average load is then 27. They also report that a large percentage of buses run on gasoline; I assume 50%. Finally, they state that buses break down often, and have a lifespan only 40% of that of same type of buses in other countries. I adopt the 40% factor here. (The vehicle lifetime is pertinent in the analysis of emissions from the materials lifecycle.)

My assumptions for the passenger-mile modal share are derived from Zhou and Salon (2000), and are as follows:

Share of trips(%)

	Walking	Bicycle	Scooter	Bus	Train	Car
Year 2000	30	30	10	25	0	5
Base 2020	20	5	10	25	10	30
Scenario 2020	20	15	15	20	10	20

Trip length (miles)

	Walking	Bicycle	Scooter	Bus	Train	Car
Year 2000	1.5	6	8	10	15	20
Base 2020	1.5	6	8	10	15	20
Scenario 2020	1.5	6	8	10	15	18

Calculated passenger-mile shares:

	Walking	Bicycle	Scooter	Bus	Train	Car
Year 2000	7%	27%	12%	38%	0%	15%
Base 2020	3%	3%	7%	22%	13%	53%
Scenario 2020	3%	9%	13%	21%	16%	38%

As a basis for estimating freight flows by mode in China, I use the *1993 Commodity Flow Survey* (Bureau of the Census, 1996), which reports tonnage, ton-mile, and average miles, by mode for the U. S.

Electricity generation

See the discussions of electricity parameter values, above.

Oil refining

The EIA (*China*, 1996) states that Chinese refineries typically generate their own electricity -- mainly, I presume, from coal. Given this, I assume that refineries in Asian oil-producing countries buy less electricity but more coal than do refineries in other major oil-producing regions. And because it takes roughly 3 BTUs of bought coal to produce the equivalent of 1 BTU of bought electricity, Asian refineries in this accounting will have slightly higher total "internal" energy requirements than do refineries that buy electricity rather than purchase it internally. (Of course, in the LEM, the complete lifecycle of bought electricity ultimately does get assigned to the refining stage.)

Materials

Zhiping et al. (1996) report 44 gJ of energy used per tonne of iron and steel produced in 1994, down from about 60 in 1980. They imply that the energy intensity of production in China is higher than in Japan, and indicate that China imports a substantial amount of iron and steel. The EIA (*China,* 1996) confirms that China imports a large amount of steel. I assume, therefore, that the energy intensity of steel and iron production in Asia (excluding Japan) is 10% higher than in the U. S., and that China imports about 50% of its iron and steel.

Note about the results

Contrary to what one might expect, in India and China fuelcycle emissions from rail transit, in g-CO_2-equivalent per passenger-capacity mile, are *higher* in the year 2020 than in the year 2000. They are higher because fuelcycle emissions from coal and oil power plants, which supply most of the electricity, are higher in 2020. Coal and oil power plants have higher CO_2-equivalent GHG emissions in 2020 than in 2000 because they emit significantly *less* SO_X, NO_X, and PM, and these pollutants actually have *negative* CEFs. That is, emissions of SO_X, NO_X, and PM tend to cause global cooling rather than global warming. Thus, as emissions of these pollutants are reduced by emission controls, the global cooling effect is reduced, and the global warming effect enhanced.

Kreucher et al. (1998) have estimated emissons of CO_2, SO_2, NO_x, CO, THC, and PM from the lifecycle of fuels and vehicles for several coal-based feedstock/fuel/vehicle combinations in China: coal to gasoline or methanol, coal to electricity, coal or coke-oven gas to methanol, byproducts to methanol, and (for comparison) crude oil to gasoline or diesel fuel. For these combinations, they show upstream fuelcycle emissions of each pollutant assuming state-of-the art emission factors, and also assuming EPA's AP-42 emission factors. We can compare our estimates of upstream fuelcycle emissions (in g/million BTU) with theirs for oil-to-gasoline, oil-to-diesel, coal-to-methanol, and gas-to-methanol. All of our upstream emission factors (all pollutants, all fuelcycles) are higher (in some cases, severalfold higher) than the "state-of-the-art" emission factors of Kreucher et al. (1998). Moreover, our estimates for CO_2, CO, NO_x, and (we infer) CH_4 in all cases are higher than the "EPA AP-42" emission factors of Kreucher et al. (1998). Our estimates of PM emissions lie between the Kreucher et al. (1998) "state-of-the-art" and "EPA AP-42) cases. We cannot readily explain the differences between the sets of estimates.

INDIA

Transportation

For transportation data for India, I rely mainly on Bose and Nesamani (2000), who estimate the following for Delhi:

- emission factors and energy use of 2-stroke scooters, 4-stroke scooters, cars, and buses, by model year
- vehicle occupancy
- modal split, by year
- billion passenger km and billion tonne km in 1990, 2000, 2010, 2020, and 2030. I use these to estimate total travel in 2000 relative to 2020.

Reddy et al. (2000) also report useful information for India: the energy intensity of different modes (p. 74), modal shares of total veh-km (p. 70).; the electricity use of Indian rail (p. 38); vehicle emission factors (p. 39); fuel economy (p. 37); and data on cycling (p. 32). I use their estimates of the electricity use of Indian rail as a guide for my own estimates.

Kathuria (2002) discusses the effects on air quality in Delhi of various pollution control strategies for vehicles. He states that studies have shown that emissions from 2-strok engines contain as much as 15-25% unburned fuel, which implies extremely high

HC and PM emissions. He also provides a useful tabulation of emission control regulations in India and Delhi. Pertinent to our study, he notes the following:

- filling stations to use low-smoke oil premixed with gasoline, for 2-stroke engines (1998-1999)
- buses to be converted to CNG
- commerciaal and 2-wheeled vehicles older than 15 years were banned by the end of 2000
- all new passenger cars must conform to Euro II standards effective March 31, 2000

The International Energy Initiative and Centre for Monitoring Indian Economy Pvt. Ltd. (2000) reports national energy use in India (p. 7).

The *1993 Commodity Flow Survey* (Bureau of the Census, 1996) reports tonnage, ton-mile, and average miles, by mode for the U. S. I use this as a basis for estimating flows in India.

Note that I assume that the characteristics of rail transit do not change over time.

Electricity generation

See the discussions of electricity parameters, above.

Oil and gas

The EIA (*India*, 2000) reports that India is increasing the amount of associated gas captured rather than flared. This is consistent with my assumption that in the oil-exporting countries of Asia, the fraction of gas flared rather than vented increases 0.2% per year.

MEXICO

Transportation

Light-duty vehicle emission factors. Air pollution is a serious problem in major cities of Mexico, and motor vehicles there are a major source of air pollution. Mexico is attacking this problem by restricting vehicle use (e.g., in Mexico City cars can be driven only ever other weekday), encouraging the use of vehicles that use clean-burning liquefied petroleum gas (LPG) or compressed natural gas (CNG) (Mexico City hopes to have 50,000 CNG vehicles and 70,000 LPG vehicles within the next few years), improving fuel quality (e.g., by reducing the sulfur content of diesel fuel), tightening emissions regulations for conventional vehicles, and encouraging the retirement of old, dirty vehicles (EIA, *International Energy Outlook 2001*, 2001; *Mexico: Environmental Issues*, 2001).

In the lifecycle emissions model (LEM), motor-vehicle emissions in countries other than the U. S. are estimated relative to emissions from vehicles in the U. S. Thus, in the following sections I review emissions estimates and standards for Mexico with an eye towards comparing them with emissions estimates and standards for the U. S.

Emissions of course depend greatly on emission -control technology, which in turn are driven in large part by emissions standards. In this respect, Mexico began producing cars with emission controls in 1991 (EIA, *Mexico: Environmental Issues*, 2001; Schifter et al., 2001a). Model years 1991 and 1992 have oxidation catalysts only, and model years 1993-on have three-way catalysts. Model years 1990 and earlier do not have a catalytic converter (Schifter et al., 2001a). By contrast, in the U. S. oxidation catalysts were introduced with the 1975 model year, and 3-way catalysts with the 1981 model year. According to Diaz et al. (2001), 24% of the vehicles in Mexico city have no catalytic converter, 12% have open-loop engine control systems with oxidation catalysts, and 46% have closed-loop engine control systems with 3-way catalysts (the remainder presumably are diesel vehicles).

Current HC (hydrocarbon) and CO (carbon monoxide) emission standards in Mexico are the same as U.S. Tier 1 standards, but the NO_X (nitrogen oxides) standard in Mexico is higher (g/km) (Schifter et al., 2000d):

	HC	CO	NO_X
Mexico	0.25	2.11	0.62
U. S. Tier 1	0.25	2.11	0.25

The available emissions data are consistent with the emission standards shown above. For example, Schifter et al. (2000d) compared FTP (Federal Test Procedure) hot-transient emissions from 1997 and 1999 model-year Mexican vehicles with FTP hot-transient emissions from model year 1990-1996 U. S. vehicles. Although the results are difficult to interpret, in part because of differences in testing protocols, it appears that Mexican vehicles emit about as much HC and CO as, but more NO_X than, do U. S. vehicles.

Similarly, Gamas et al. (1999) estimate FTP emissions of 0.26 g/km HC, 0.42 g/km NO_X, and 4.71 g/km CO from 1995-1996 model-year vehicles equipped with "modern technology for pollution control" (p. 1185). U. S. vehicles of the same model year would have similar emissions.

Finally, Schifter et al. (2000b) measured emissions of toxics from vehicles in Mexico, and found that emission rates were similar to those of U.S. vehicles of the same model year.

Several sets of data indicate that vehicles in Mexico are not as well inspected and maintained as are vehicles in the U. S., and hence may have higher deterioration factors. Diaz et al. (2001) tested the long-term efficiency of the catalytic converters on vehicles in Mexico City, and found significant deterioration in catalyst performance after 60,000 km.[6] Similarly, Schifter et al. (2001b) note that HC emissions from motor vehicle in Mexico deteriorate rapidly[7]. Diaz et al. (2001) also found that vehicles found to be high-emitters on the FTP satisfied the I&M (inspection and maintenance) emissions test without much difficulty. They suggest that the I&M protocol needs to be improved.

Schifter et al. (2001a) estimate diurnal and hot-soak evaporative emission of about 0.60 g/mi from vehicles with no catalyst, and 0.20 g/mi from vehicles with 3-way catalysts. These are comparable to levels from U. S. vehicles.

As a point of departure for estimating emissions in Mexico relative to emissions in the U. S., I show current LEM estimates of light-duty gasoline vehicle (LDGV) emissions at the midpoint in the life of select model years (MY) of U. S. vehicles (g/mi; note that other emission factors or standards in this section are given in g/km):

MY-->	1966	1975	1985	1995	2005	2020	2045
Fuel evaporation	3.09	1.98	1.16	0.67	0.40	0.22	0.16
NMOC exhaust	3.77	2.59	1.62	0.97	0.57	0.30	0.20
CH_4 exhaust	0.21	0.15	0.10	0.07	0.05	0.03	0.02
CO exhaust	36.02	26.74	18.60	12.10	7.35	3.49	1.57
N_2O exhaust	0.003	0.060	0.124	0.133	0.138	0.064	0.040
NO_2 exhaust	3.14	2.36	1.70	1.20	0.82	0.45	0.20
PM exhaust	0.115	0.082	0.057	0.040	0.028	0.019	0.015

Note that these are estimates of actual emissions in real-word driving, and are not necessarily the same as emissions over the emissions-test cycle.

So, considering all of the data presented here, I assume the following relative emission factors for LDGVs in Mexico, by pollutant and model year:

MY -->	1960	1975	1981	1991	1993	2010
Fuel evaporation	1.2	2.0	3.0	2.0	1.5	1.2
NMOC exhaust	1.2	2.0	3.0	1.5	1.4	1.2
CH_4 exhaust	1.1	1.6	2.0	1.2	1.2	1.1
CO exhaust	1.5	2.0	3.0	1.5	1.4	1.2
N_2O exhaust	1.0	0.2	0.2	0.8	1.0	1.0
NO_2 exhaust	1.0	1.2	2.0	2.0	1.6	1.2

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[6] Diaz et al. (2001) also measured regulated FTP emissions from a fleet of 84 vehicles "as received", and found total HC emissions on the order of 0.3 g/km, CO on the order of 4 g/km, and NO_x on the order of 1 g/km. They estimated that 38% of the vehicles had problems with their catalysts, and that many had air/fuel ratios that were too rich or too lean.

[7] Schifter et al. (2001b) also report that emissions from gasoline distribution are relatively large because of malpractice and poor maintenance.

PM exhaust	1.2	2.0	2.5	2.0	1.4	1.2

The LEM calculates the model year given a target year and a mileage accumulation rate, then looks up the pertinent relative emission factor for each pollutant, and multiplies this factor by the estimated U. S. emission factor.

Alternative-fuel LDV emissions. In the LEM, emissions from alternative-fuel vehicles are estimated relative to emissions from gasoline light-duty vehicles or diesel heavy-duty vehicles. I assume that the relative emissions depend on "inherent" technological differences (between alternative and conventional fuels) that do *not* vary from country to country. The relative emission factors are estimated on the basis of a comprehensive literature review (see the main text LEM documentation). In the following I review estimates of alternative-fuel vehicle emissions in Mexico and compare them with the generic assumptions in the LEM.

As mentioned above Mexico City is encouraging the use of CNG and LPG to reduce emissions from motor vehicles. Because of this, researchers in Mexico have done several studies of emissions from CNG and LPG vehicles. Generally, they have found that emissions from LPG vehicles depend greatly on the quality of the conversion and of the inspection and maintenance program.

Schifter et al. (2000c) measured FTP emissions from 134 in-use (and mostly or entirely catalyst-equipped) LPG vehicles in Mexico City, and found relatively high emissions: 1.99 g/km HC, 3.23 g/km NO_X, and 20.05 g/km CO. These in fact generally are *higher* than emissions from comparable catalyst-equipped vehicles in Mexico. Schifter et al. (2000c) attributed this to poor maintenance and inadequate carburation.

Gamas et al. (2000) also find that vehicles fueled with LPG pollute more than do vehicles fueled with gasoline. Although in another paper Gamas et al. (1999) estimated that catalyst-equipped LPG vehicles have lower emissions than do catalyst-equipped gasoline vehicles, they state that this is due to a proper LPG conversion done by a qualified technician, and a strict maintenance program.

Diaz et al. (2000) measured emissions over the U. S. FTP from catalyst-equipped vehicles optimized for LPG (70% propane) (g/km):

		HC	NO_X	CO
1997 LDT	16,958 mi	0.22	0.40	2.72
1989 LDA	173,412 mi	0.21	0.76	3.60

Gamas et al. (2000), Schifter et al. (2000c), and Schifter et al. (2000f) find relatively high emissions from refueling LPG vehicles, attributable in part to bad practices.

Turning now to CNG, Schifter et al. (2000e) estimated considerably lower emission factors for CNG vehicles than for gasoline vehicles in Mexico City (g/km):

		CO		NO_X		NMHC	
		gasoline	CNG	gasoline	CNG	gasoline	CNG
LDAs	NC	33.7	1.3	1.8	1.2	3.7	0.1
	EC	11.7	1.4	1.0	0.6	0.4	0.0
HDTs	NC	152.2	2.7	4.7	2.6	6.8	0.1
	EC	33.5	1.6	2.3	1.9	0.9	0.0
Microbuses	NC	61.5	1.0	4.8	3.6	4.4	0.3
	EC	31.6	2.6	1.7	1.1	0.9	0.1

NC = nonexhaust control, EC = emissions control

It is not clear, however, if these emission factors are meant to be "in-use", because in the emission tests that generated the basic data used to calculate the fleet-average emission factors, the vehicles were not tested as-received, but rather were inspected and given a new catalytic converter.

In the LEM, I assume that CNG and LPG vehicles have about 1/2 the CO and NMOG emissions of gasoline vehicles. Thus, the emissions in Mexico from relative to gasoline vehicles, and from *well-maintained* LPG vehicles relative to gasoline vehicles, are consistent with the generic (all-country) assumptions in the LEM.

HDV and other emissions. It appears that heavy-duty diesel vehicles (HDDVs) in Mexico are less well maintained and subject to less stringent standards than are HDDVs in the U. S. I assume that for any given model year, CO and NMHC are 20% higher, NO_X emissions 50% higher, and PM emissions 200% higher than in the U. S.

For scooters and minicars, I assume the following relative emissions (Mexico vs. U. S.):

CH_4	NMHC	Evap.	CO	NO_X	PM	N_2O
1.25	1.50	1.50	1.50	1.10	1.50	1.00

Fuel characteristics. Schifter et al. (2000b) report that regular Mexican gas has 324 ppm sulfur. However, in other work, Schifter et al. (2001a) test gasolines with 580 to 690 ppm sulfur, and Schifter et al. (2000a) report that regular gasoline has 670 ppm sulfur. Gamas et al. (1999) report 421 ppm S and 814 ppm S for two brands of regular gasoline.

With these data, and much additional judgment, I assume the following ratios of sulfur content in Mexico to sulfur content in the U. S., for petroleum products:

crude oil	1.0
residual fuel oil	1.5
conventional gasoline	2.0
reformulated gasoline	2.0

Fuel economy, occupancy, and mode share. Schifter et al. (2000e) report the following fuel economy by vehicle class in an emissions testing program: LDTs, 13-24 mpg; HDTs, 6-11; LDAs, 18-33; microbuses, 7-10. The vehicles in the program were manufactured by major international companies (e.g., Ford, Nissan, and GM). Diaz et al. (2001) report a value of 23 mpg for 1991-1992 model year vehicles, and 26 mpg for 1993-1995 model-year vehicles, in another emissions testing program. I use these data as the basis for my estimates of the fuel economy of LDVs in Mexico (shown below).

According to Schifter et al. (2001b), "in the last 10 years the number of collective taxis increased the traditional pattern of large cars carrying a maximum of six passengers along a few set routes was overtaken by widespread use of vans carrying 10 to 11 people. More recently, larger microbuses, with 40% less capacity than the typical urban buses) have appeared on many important routes" (p. 6). In this analysis, I lump microbuses and vans into the category "minibus".

In the LEM, fuelcycle emissions from minibuses are calculated with respect to fuelcycle emissions from full-size buses, by scaling emissions according to the fuel economy of minibuses relative to that of full-size buses. Material and vehicle lifecycle emissions from minibuses also are calculated with respect to emissions from full-size buses, by scaling according to the weight of minibuses relative to the weight of full-size buses. My assumptions regarding minibuses and full-size buses are shown below.

Data on scooters are not available. I assume that they have 5% lower mpg and 8% higher weight than is specified for the U. S.

Data on rail systems also are unavailable. I assume that energy use per capacity mile, for line-haul and stations, is the same as estimated in the U. S. (see Delucchi, 1996). However, I do assume higher capacity factors than in the U. S..

With these data, I assume the following for Mexico·

	Occupancy (per/veh)	Fuel economy (mpg)			Modal split (% of PMT)
		city	hwy	city%	
private cars	1.4	24	30	70	58
Buses	28	5.5	8.0	75	13
Minibuses	16	9	n.a.	100	12
2-st. scooter	1.0	90	n.a.	100	2
Heavy rail	70%*	n.a.	n.a.	n.a.	6
Light rail	70%*	n.a.	n.a.	n.a.	2
Bicycling	1.0	n.a.	n.a.	n.a.	2
Walking	n.a.	n.a.	n.a.	n.a.	5

*Average capacity fraction, not persons per vehicle

Alternative fuel shares: The categories shown above must be further broken out by type of fuel used. I estimate alternative-fuel shares on the basis of the following data and assumptions:

- Schifter et al. (2000c) report that there are 10,000 LD LPG vehicles (including taxis) and 8,800 HD LPG vehicles in the Mexico City Metropolitan Area (MCMA).
- Schifter et al. (2000e) report that there were 2,7000 CNG vehicles in the MCMA (with 16.6 million people), and that authorities are considering encouraging the use of CNG to combat air pollution.
- Gamas et al. (2000) state that there are 2. 8 million vehicles in the MCMA, and that 1.1% of the vehicles are powered by LPG.
- I assume that the use of LPG and CNG will continue to grow.
- I assume that electric scooters will begin to be used to reduce air pollution.

With these considerations, my estimates of the fuel shares are:

	Gasoline	RFG	Diesel	CNG	LPG	Electric
LDVs	0.60	0.365	0.01	0.005	0.02	0.00
Buses	0.05	0.00	0.92	0.01	0.02	0.00
Minibuses	0.05	0.00	0.90	0.01	0.04	0.00
2-str. scooters	0.90	0.00	0.00	0.00	0.05	0.05

Electricity

See the discussions of electricity generation efficiency, electricity generation fuel mix, emissions, and fuel quality, above.

Oil and gas production and use

Oil. In the LEM, Mexico is not a major oil-refining region. However, the Caribbean basin is a major oil-refining region in the LEM, and I assume that energy-use data for refineries in Mexico apply to refineries in the Caribbean basin. In this respect, I note that the International Energy Agency's (IEA's) *Energy Balance* data (2001) indicate that Mexican refineries get most of their process energy from oil and natural gas, which seems reasonable (see "other industry" section). I assume this mix for refineries in the Caribbean basin. I assume that the energy intensity of petroleum refining in the Caribbean basin is 15% higher than in the U. S., on account of the large amount of heavy crude processed by refineries there.

For each oil-producing region, the LEM has as inputs the amount of conventional oil produced from onshore wells, the amount of conventional oil produced from offshore wells, and the amount of heavy oil produced. The Office of Fossil Energy (2001) and the EIA's *Mexico* Country Analysis Brief (2001) state that 3/4 of Mexico's oil comes from offshore sites in Campeche Bay in the Gulf of Mexico, and that 52% of the oil Mexico produces is heavy "Maya-22". I infer from the EIA and Office of Fossil energy reports that there is offshore production outside of Campeche Bay, and that virtually all of the heavy "Maya-22" comes from offshore sites. Thus, I assume for Mexico:

conventional oil onshore	conventional oil offshore	heavy oil offshore
10%	40%	50%

The LEM has as inputs the energy intensity of oil production in each category relative to the intensity of producing conventional oil from onshore wells in the U. S. For the U. S., I assume that it takes three times more energy to produce a ton of conventional offshore oil than a ton of conventional onshore oil, and twice as much energy to produce heavy oil onshore oil as conventional onshore oil. In the case of Mexico, it is clear that the "heavy Maya-22" does require additional energy to produce: The Office of Fossil Energy (2001) reports that nitrogen-injection operations in Campeche Bay, intended to increase production of heavy crude, are the largest in the world. With these considerations, I assume the following energy intensities (BTU/ton) for Mexico *relative* to the BTU/ton intensity of producing conventional onshore oil in the U. S.:

conventional oil onshore	conventional oil offshore	heavy oil offshore
1.0	2.5	4.0

Gas. Mexico imports a small amount (about 5%) of its natural gas, from the United States (EIA, *International Energy Annual 1999*, 2001). I assume that for all end uses except production of methanol or FT-diesel, 95% of the gas used in Mexico is produced domestically. I assume that 100% of the gas used to produce methanol and FT-diesel is domestic. (In the LEM one specifies methanol and FT-diesel end use separately from all other end uses of natural gas.)

Other industry

In the LEM, Mexico is a major (listed) producer of vehicles, but not a major producer of materials. I assume that the BTU/lb energy intensity of vehicle manufacture in Mexico is 10% higher in Mexico than in the U. S.

Vehicle manufacturing. The vehicle manufacturing energy is distributed as follows: 41% natural gas, 35% electricity, 17% oil, and 7% coal. (The same distribution is used for all vehicle producing regions.) This mix can be compared with International Energy Agency's (IEA's) *Energy Balance* (2002) breakdown of process energy used in the "Transportation Equipment" sector of Mexico in 1998:

	Coal	Petroleum	Natural Gas	Electricity
Transport Equipment	0.0%	0.0%	42.0%	58.0%

The generic distribution used in the LEM is similar to the IEA estimates shown above specifically for Mexico.

The lifecycle of materials. In the LEM, the energy for materials manufacture in all countries is distributed as follows:

Material	Coal	Oil	NG	Power
Plain carbon steel	59%	5%	23%	13%
High strength steel	59%	5%	23%	13%
Stainless steel	63%	6%	20%	11%
Other steels	59%	5%	23%	13%
Iron	65%	6%	25%	4%
Plastics/composites	0%	28%	70%	2%
Rubber	20%	30%	41%	9%
Wrought aluminum	4%	5%	60%	31%
Cast aluminum	4%	5%	60%	31%
Glass	2%	18%	75%	5%

This breakdown can be compared with IEA's *Energy Balance* (2002) data for Mexico specifically:

	Coal	Petroleum	Natural Gas	Electricity
Iron and Steel	21%	7%	57%	15%
Non-Ferrous Metals	0.0%	0.0%	75%	25%

The generic distribution used in the LEM is not dramatically different from the IEA estimates shown above specifically for Mexico.

Production of alternative fuels. I assume that alternative-fuel production technologies (e.g., coal to methanol, natural gas to hydrogen) are similar everywhere in the world, and hence that the inputs and outputs (e.g., ft^3 of natural gas per ft^3 of hydrogen) are similar in all countries. In fact, with but a few exceptions, the LEM has only one set of inputs and outputs for each alternative-fuel production process; i.e., the inputs and outputs are not specified by country. The exceptions are the use of natural gas as a feedstock to produce FT-diesel, hydrogen, or methanol. In these cases, I assume that the amount of natural gas required to produce a unit of output does vary from country to country, mainly on account of differences in the cost of the feedstock. (Where natural gas is expensive, there is incentive to invest in efficiency-improving technologies that increase the output per unit of gas input.) I assume that natural gas in Mexico is less costly than in the U. S., and hence that the FT-diesel, hydrogen, and methanol production processes in Mexico use a bit more gas (4% more) per unit of output than do processes in the U. S.

Yields of biomass and use of fertilizer

As part of the calculation of emissions from the biomass cultivation stage in the lifecycle of biofuels, the LEM calculates yields of corn (bushels/acre) soybeans (bushels/acre), grass (tons/acre) and wood (tons/acre), in every target country. The input data are the yield in a base year (presently 1996) and the annual percentage change in the yield after the base year. I assume that in Mexico the base-year yields and the annual percentage change in the yields are 90% of the values in the U. S.

The LEM also has as inputs the use of nitrogen fertilizer (lbs/bushel or lbs/ton) in every country. I assume that nitrogen is applied in Mexico at the same rate that it is applied in the U. S.

SOUTH AFRICA

Transportation

The EIA's *International Energy Outlook 2001* (2001) reports that "there is a substantial railway network in South Africa, serving the mining and heavy industries of the country" (p.150).

The EIA's "South Africa: Environmental Issues" (2000) states that "regulations apply to diesel-powered vehicles and are geared towards ensuring proper maintenance," but that "enforcement...is weak and sporadic" (p. 2). This implies that diesel vehicles can have relatively high emissions.

Emission factors. The Department of Environmental Affairs and Tourism (1999) has estimated g/mi emission factors for road vehicles in South Africa, in 1988:

	NO_X	CH_4	NMVOC	CO	N_2O
Petrol Cars	3.4	0.28	10.2	65.3	0.008
Petrol light trucks	4.2	0.28	13.7	71.7	0.010
Diesel Cars	1.6	0.02	0.8	1.7	0.023
Light diesel trucks	2.4	0.03	1.3	2.6	0.027
Heavy diesel trucks	27.0	0.16	4.8	13.7	0.050
Motorcycles	0.3	0.53	10.5	38.3	0.003

I compare these with U. S. emission factors for 1990 (as estimated by the LEM), and then estimate the following relative emission factors for all years (emissions in South Africa divided by emissions in the U. S.; PM based on my judgment):

	NO_X	CH_4	NMVOC	CO	N_2O	PM
petrol LDVs	1.5	3.0	4.0	3.0	0.05 - 1.0	3.0
diesel HDVs	1.0	1.5	1.5	1.0	1.0	4.0

The South African N_2O emission factor for gasoline (petrol) cars increases from 5% to 100% of the U. S. emission factor from 2000 to 2038 as cars with three-way catalytic converters are phased in. (Cars without catalytic converters have very low emissions of N_2O.)

Fuel economy, occupancy, and mode share. Prozzi et al. (2001) provide the following estimates:

	Fuel use (mpg)	Occupancy (persons/vehicle)			Mode split (% of passenger miles)		
	all years	2000 base	2020 low	2020 high	2000 base	2020 low	2020 high
Petrol Cars	21.6	1.2	1.3	1.2	48	46	57
Diesel Cars	26.4	1.2	1.3	1.2	0	0	0
Petrol Minibus	16.8	4.5	5.0	4.5	3	2	2
Petrol Minibus Taxi	16.8 ?	15.5	18.6	15.5	32	7	25
Diesel Minibus Taxi	18.8 ?	15.5	18.6	15.5	0	21	0
Diesel Bus	5.6	44.9	54.0	44.9	12	10	8
Rail Transit	n.a.	n.e.	n.e.	n.e.	5	12	8

In the LEM, fuelcycle emissions from minibuses are calculated with respect to fuelcycle emissions from full-size buses, by scaling emissions according to the fuel economy of minibuses relative to that of full-size buses. Material and vehicle lifecycle emissions from minibuses also are calculated with respect to emissions from full-size buses, by scaling according to the weight of minibuses relative to the weight of full-size buses.

Electricity

See the discussions of electricity generation efficiency and electricity generation fuel mix, above.

Oil production and use

The EIA's *International Energy Annual 1999* (2001) reports that in 1998, South Africa produced 18,000 b/d of crude oil, 11,000 b/d of natural gas plant liquids, 0 b/d of refinery processing gain, and 170,000 b/d of synthetic oil made from coal (classified as "other liquids" by the EIA).

The EIA also reports that in 1998 South Africa imported 321,000 bpd of crude oil, and exported (net) 48,000 bpd of all petroleum products, but imported 6% of its total apparent consumption of motor gasoline. According to the EIA's (2000) *South Africa*

Country Analysis Brief, the country imports crude oil primarily from Saudi Arabia and Iran, but is trying to reduce its dependence on oil from Iran.

The South African Petroleum Association (2000) provides data on sources of crude oil by country of origin (excluding South African production of synthetic oil):

	Iran	Saudi Arabia	other Middle East	Nigeria	South Africa (domestic)	other
year 2000	37.7%	43.5%	9.3%	4.3%	3.5%	1.7%
year 1995	67.0%	6.8%	9.6%	0%	0%	16.6%

The IEA year 2001 data discussed above and used in the LEM are quite different from the year 2000 or year 1995 data shown here.

The DME (2001) reports that South African oil refineries consume 0.05 kJ of electricity and a tiny amount of natural gas for every kJ of petroleum product produced. The rest of the process energy presumably is provided by refinery gas produced from the crude oil feedstock. Surprisingly, according to the DME energy balance South African refineries do not use coal.

The use of process energy derived from crude oil can produce significant amounts of sulfur pollution. In recognition of this, at least one refiner (Engen) has begun to use more gas a process fuel.

The LEM specifies refinery energy use by major refining country or region of the world. South Africa is not a separate category, but rather is included in the category "target country (LDC)" refining region. For this category, I assume that the fuel mix used by petroleum refineries is 10% residual fuel oil, 5% natural gas, 60% refinery gas, 5% electricity, 10% petroleum coke, and 10% coal. These assumptions are reasonably consistent with the DME energy balance data for South African refineries.

I assume that 0.8% of the gas leaks from the South-African natural-gas distribution system. (By comparison, about 0.5% of the gas leaks from the U. S. natural-gas distribution system.)

Synthetic fuels

Diesel-like fuels made from natural gas by the Fischer-Tropsch process. The EIA's *International Energy Outlook 1999* [1999] reports that Chevron and Sasol [the South African oil company] are working to develop a gas-to-liquids facility that would convert natural gas to middle distillates such as diesel fuel and jet fuel. According to the EIA, Chevron and Sasol estimate that it will take 238 SCF to produce a gallon of middle distillates. A detailed analysis by Argonne National Laboratory (Stork, 1997) results in an estimate of 224 SCF per gallon of diesel fuel. I use the ANL estimates.

Synthetic oil made from coal. South Africa is the world's largest producer of coal-based synthetic liquid fuels. South Africa's coal-to-liquid plants consume almost 20% of the country's coal output, and produce more than 25% of the total liquid fuel output (EIA, *International Energy Outlook 1999*, 1999).

The DME (2001) reports energy balances for the “liquefaction” energy sector: 624.7 eJ of coal and 71.8 eJ of natural gas produced 309.3 EJ of synthetic crude oil. This gives an output/input energy ratio of 44.4%. I assume a slightly higher value of 46%.

This low production efficiency results in very high CO_2-equivalent emissions from the fuel-production stage; in fact, the production of a synthetic fuel from coal produces roughly as much CO_2 equivalent as does the end use of the synthetic fuel itself. This can be compared with the production of the same sort of fuel from crude oil via conventional oil refining, which is approximately 85-95% efficient and results in production-stage emissions on the order of 5-20% of those from end use.

According to the EIA’s (2000) *South Africa* Country Analysis Brief, in early 2000 Sasol launched a feasibility study of replacing coal with natural gas, because of high costs of compliance with environmental regulations associated with coal, and high impending capital investments in coal mining. Sasol estimates that the switch to natural gas could be completed within three years. Construction on the pipeline that will supply the natural gas is expected to begin in June 2001 (EIA, *South Africa*, 2000).

Other industry

According to the DME (2001) energy balances, the energy mix in the South African iron and steel sector is 70% coal, 5% natural gas, and 25% electricity. In the LEM the mix used for all countries is about 60% coal, 5% oil, 20% natural gas, and 10% electricity.

According to The National Association of Automobile Manufacturers of South Africa(2001), South Africa imports about 20% of its cars and trucks. I specify the LEM for 80% domestic production, and 15% imports from Europe, 3% from Japan, and 2% from the United States.

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