The Estimation of Transport Emissions.

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Abstract:

This paper presents a standard methodology for calculating gaseous emissions from Australian transport. The paper defines methods for estimating annual emissions of greenhouse and noxious gases from mobile sources due to fuel combustion and fugitive releases (fuel evaporation and air-conditioner refrigerant leakage). Emission factors are presented for air transport, passenger cars (subdivided by vehicle age), trucks (subdivided by vehicle mass), buses, motorcycles, railways, and marine transport. Emissions from miscellaneous off-road mobile engines (such as tractors, quarry trucks, trail bikes and lawn mowers), military transport, and pipeline distribution are also covered. As an example of the methodology, an emissions inventory for the Australian transport system is compiled for 1993. The inventory is used to derive approximate environmental damage costs due to noxious transport emissions and approximate control costs for carbon dioxide emissions from transport. The derived costs are used to illustrate how the ability to readily calculate transport emission inventories can contribute to the assessment of the trade-offs between the economic, environmental and social aspects of transport reform.

The views expressed in this paper are those of the authors, and do not necessarily represent those of the Bureau of Transport and Communications Economics.

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1. INTRODUCTION

Emissions from the transport sector, and particularly from road vehicles, can have significant detrimental impacts on both human well-being and the natural environment. Transport emissions are major components of urban air pollution, and contribute to regional and global atmospheric contamination. The gaseous pollutants formed by transport activities vary considerably in their chemistry, rates of emission, atmospheric concentrations, and environmental effects. Considerable attention has been devoted in recent years to the *anthropogenic* (that is, human-sourced) greenhouse effect. The potential damage of enhanced global warming is enormous, so attention is warranted. However, many studies on greenhouse gas emissions focus solely on the major contributor, carbon dioxide. This approach does not take sufficient account of the complex chemistry of transport emissions and the intricate relationships between local and global air quality. Many noxious emissions contribute to both local air pollution and the greenhouse effect, and are often easier to reduce than carbon dioxide emissions. Any policy debate concerning transport emissions should be based on analysis of all the major gases emitted and their effects, not on carbon dioxide alone

Generally, assessment of changes to transport systems should take account of the possible effects on transport emission levels and the economic, environmental and social aspects of those changes. Such assessment includes three main components: emissions inventory (the estimation of current emission levels), impact analysis (the economic and environmental effects of transport emissions) and analysis of alternatives (the judgement of how much transport reforms would increase or decrease emissions, and at what net cost). For example, analysis of a transport reform could include the evaluation of the costs and benefits associated with the resulting changes in emission levels.

This paper deals primarily with the inventory process and summarises a standard methodology, based on Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC/OECD 1994), for calculating greenhouse gas emissions from mobile sources. The methodology is detailed in an inventory workbook prepared by the Bureau of Transport and Communications Economics (BTCE 1994), in conjunction with a working group (representing scientific, industrial, commercial, community and government organisations), for the Commonwealth Department of the Environment, Sport and Territories on behalf of the National Greenhouse Gas Inventory Committee

The following section presents methods for estimating gaseous emissions by mobile combustion engines from both fuel combustion and fugitive releases (fuel evaporation and air-conditioner refrigerant leakage). Emission factors are given for carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), oxides of nitrogen other than nitrous oxide (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), sulphur oxides (SO_x), fluorocarbon (FC) species and particulate matter (PM). FCs consist of chlorofluorocarbons (CFCs), which are being phased out, and other less ozone depleting species (such as hydrofluorocarbons) which are being used as CFC replacements. NMVOCs consist primarily of non-methane hydrocarbons (NMHCs), with a small proportion of other organic substances such as aldehydes. A basic schematic summary of transport emissions and their interactions is provided in Figure 1

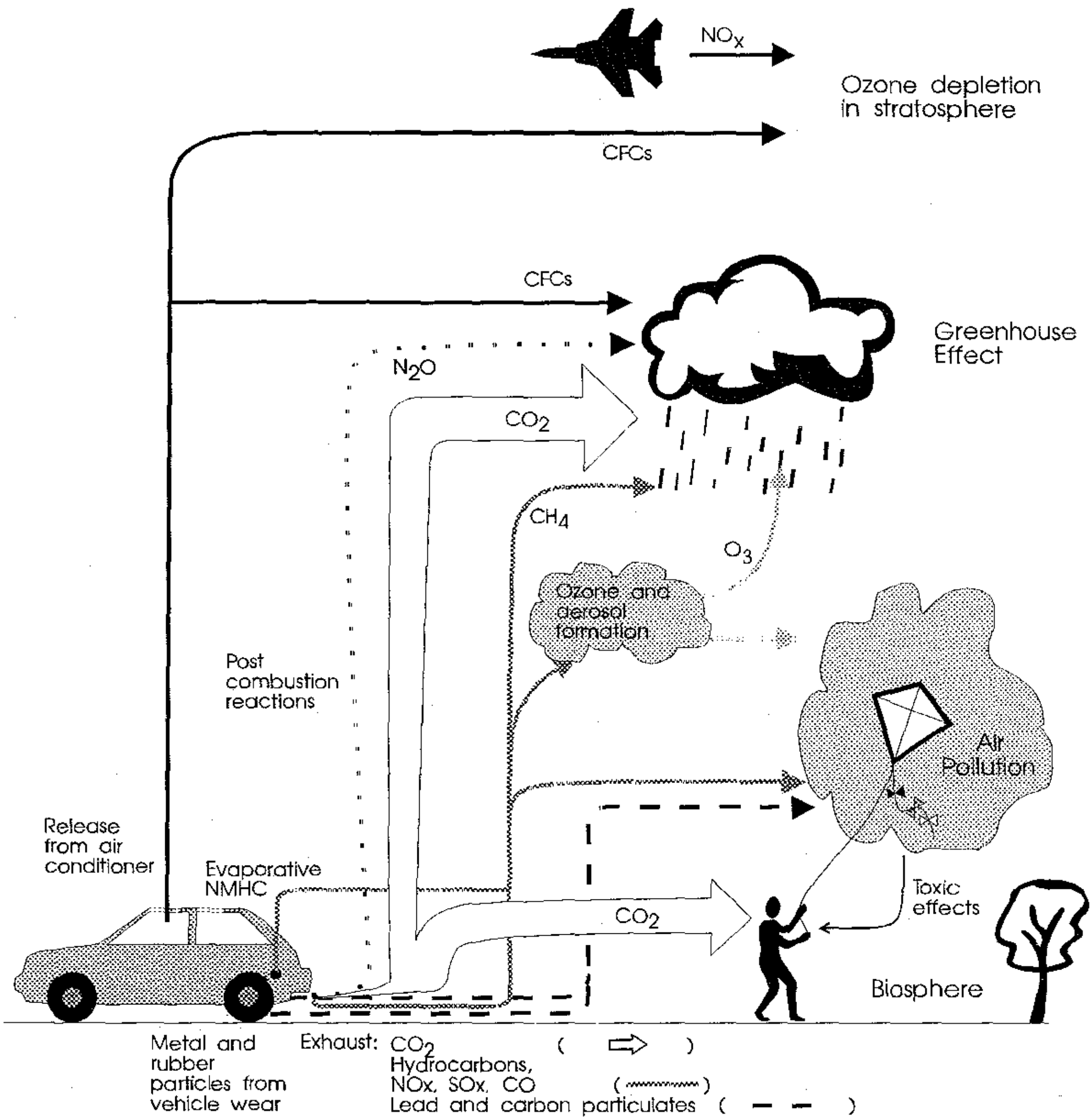

Figure 1 Summary of gaseous emissions from transport

The methodology covers emissions from all mobile combustion engines; including transport vehicles, agricultural and forestry mobile equipment (such as tractors), construction and industrial mobile equipment (such as quarry trucks and fork lifts), unregistered recreation or competition vehicles (such as trail bikes), miscellaneous mobile utility engines (such as lawn-mowers), and military vehicles Emissions from transport energy production (such as refining automotive gasoline or generating electricity for electric railways), services to transport (such as road construction) and pipeline transport are not dealt with in detail, but rough estimates of their magnitude are included in the following analysis

For this paper, light commercial vehicles are vehicles designed to carry goods (or equipment) and not exceeding 3 5 tonnes gross vehicle mass (GVM), medium trucks (including rigid trucks, articulated trucks and special purpose vehicles) have GVM exceeding 3 5 tonnes but not exceeding 12 tonnes, and heavy trucks have greater than 12 tonnes GVM Transport fuels include automotive gasoline (petrol), automotive diesel oil (ADO), liquefied petroleum gas (LPG), aviation gasoline (Avgas), aviation turbine fuel (Avtur), industrial diesel fuel (IDF), fuel oil, natural gas (NG) and coal

For this paper, the notation used in equations and tables of emission factors distinguishes between different mobile source categories, fuel types and gas emission species using subscripts The values of the subscripts appropriate to particular types of mobile engine (h, i, j), fuel (k) or emission (l) are given in Table 1

Examples given in Section 3 illustrate how the ability to readily calculate approximate emission inventories (for transport activities) can contribute to the assessment of the trade-offs between the economic, environmental and social aspects of transport reform

2. EMISSIONS

The adverse impacts on the environment due to transport emissions relate to local air quality (through the formation of smog, the greater incidence of respiratory ailments and increases in urban levels of toxic substances such as benzene), regional air pollution (by the formation of highly reactive compounds capable of damaging crops and buildings, and the generation of suspended particle hazes which reduce visibility), and global atmospheric change (through the depletion of stratospheric ozone due to the release of chlorofluorocarbons from vehicle air-conditioners, influences on cloud formation and climate change due to greenhouse gases)

Emissions from mobile sources consist of the gaseous products of engine fuel combustion (exhaust emissions) and gaseous leakage from vehicles (fugitive emissions), essentially comprising: CO_2 emissions (due to the oxidation of fuel carbon content during fuel combustion); CH_4, N_2O, NO_x, CO, NMVOCs, SO_x and PM emissions (resulting from incomplete fuel combustion, reactions between air and fuel constituents during fuel combustion and post-combustion reactions); and fugitive emissions of FCs (due to vehicle air-conditioner refrigerant release) and further NMVOCs (due to fuel evaporation)

The estimation of mobile source emissions is complex since emission levels depend on a large number of factors, including class of vehicle and type of pollution control equipment fitted, type of fuel consumed and the average rate of fuel consumption, condition of the vehicle (such as vehicle age and level of maintenance), and operating characteristics (such as driver behaviour, weather conditions, road type and traffic levels) Calculation of gaseous emissions from the combustion and evaporation of fuels in mobile engines is generally carried out by converting activity data (either on fuel consumption or distance travelled) to an emission estimate through multiplication by a conversion rate or *emission factor*

Table 1 Summary of mobile source categories, fuel types and emission species

Mobile source					Fuel Type	(k)
Sector	(h)	Category / Class	(i)	(j)		
Air transport[a,d]	1	Domestic aviation	1	1	Automotive gasoline[a]	1
		International aviation	2	1	Automotive diesel oil	2
Road transport[a,b,c]	2	Passenger cars	1			
		Post-1985		1	LPG	3
		1981-1985		2	Aviation gasoline	4
		1976-1980		3		
		Pre-1976		4	Aviation turbine fuel	5
		Light commercial vehicles	2	1		
		Medium trucks	3	1	Industrial diesel fuel	6
		Heavy trucks	4	1		
		Buses	5	1	Fuel oil	7
		Motorcycles	6	1	Natural gas	8
					Coal	9
Rail transport[a,c]	3		1	1		
Marine transport[a,d]	4	Domestic marine	1		**Emission type**	**(l)**
		Small craft		1		
		Ferries[a]		2	CO_2	1
		Fishing[e]		3	CH_4	2
		Shipping		4	N_2O	3
		International marine	2	1	NO_x	4
					CO	5
Military transport[d]	5	Air	1	1	NMVOCs	6
		Land	2	1	SO_x	7
		Water	3	1	FCs	8
					PM	9
Other mobile sources	6	Recreational vehicles	1	1		
		Farm equipment[e]	2	1		
		Industrial equipment[e]	3	1		
		Utility engines	4	1		

a Automotive gasoline refers to both leaded and unleaded petrol

Note: Annual national energy consumption for mobile engines can be obtained from Australian Bureau of Agricultural and Resource Economics (Bush et al 1993); with supplementary activity data available from: a Apelbaum (1993), b Australian Bureau of Statistics (ABS 1993), c Cosgrove and Gargett (1992), d Department of Defence (Martin, N 1994, pers. comm.), and e Australian Customs Service (ACS 1991).

The emission level of a greenhouse or noxious gas from a mobile fuel combustion engine, using a specified fuel type, is thus calculated by:

$$E(l)_{hijk} = A^m{}_{hijk} \times F(l)^m{}_{hijk} \qquad \text{for } m = 1 \text{ or } 2 \text{ and } l = 1 \text{ to } 9 \qquad (1)$$

where, for a mobile source of category i and class j (within sector h), using fuel type k,

$E(l)_{hijk}$ is the emission of gas l in gigagrams (Gg, 10^9 grams);
$A^m{}_{hijk}$ is the activity level, where m=1 refers to energy consumption in petajoules (PJ, 10^{15} joules) and m=2 refers to distance travelled in terametres (Tm, 10^{12} metres); and
$F(l)^m{}_{hijk}$ is the emission factor, in units of grams of gas l emitted per megajoule of energy use (g/MJ) for m=1, and grams of gas l emitted per kilometre travelled (g/km) for m=2

The required form of the equation (whether m equals 1 or 2) for a particular calculation depends on the units of the emission factor generally used for that calculation Emission factors for non-CO_2 gases from road vehicles are usually derived in terms of g/km So the estimation of non-CO_2 greenhouse gases from road vehicles is based on equation (1) with m=2 Alternately, CO_2 emissions and non-CO_2 emissions from off-road engines are generally estimated by using equation (1) with m=1

Fugitive releases of fluorocarbons during motor vehicle operation can be roughly estimated by either: multiplying the number of post-1990 and pre-1990 vehicles fitted with air-conditioners by emission rates of 35 grams and 75 grams of FC per annum respectively (based on data from R King, Federal Chamber of Automotive Industries, 1994, personal communication), or multiplying the annual amount of FC compounds used to fill vehicle air-conditioning systems (given in CEPA 1993) by an average leakage rate of 34 per cent (based on DME 1990)

The emission factors for the other gases (reproduced in tables 2 to 5) represent national average default values, and have been calculated on the basis of Australian vehicle characteristics wherever possible Where data specific to Australian conditions have not been available, emission factors have been derived from international data given in *Estimation of Greenhouse Gas Emissions and Sinks* (OECD 1991) If emissions are to be estimated on a more detailed basis than is covered here (for example, disaggregated by time of day or type of road), then more specific emission factors should be sought Many of the default emission factors are approximate or uncertain, and before attempting an inventory compilation, the most up-to-date factors should be sought If emission factors specific to a particular set of operating conditions are unavailable, the national default values (given in following tables) can be used Though the default emission factors allow the straightforward construction of short-range *business-as-usual* projections for transport emissions, they are not a suitable basis for long-range forecasting of transport emissions The default emission factors relate to current vehicle fleet compositions and operating conditions, while long-range emission projections need to allow for future technological and structural change within the transport sector

Table 2 Non-CO_2 emission factors for off-road sources and natural gas vehicles

Source (*h, i, j*) and fuel type (*k*)	Emission factor $(F(l)^{m=l}{}_{hijk})$ (g/MJ)					
	CH_4 (l=2)	N_2O (l=3)	NO_x (l=4)	CO (l=5)	NMVOCs (l=6)	SO_x (l=7)[a]
Aircraft						
(h=1, i=1) & (h=5, i=1)						
Avgas (k=4)	0.057	0.0009	0.076	22.8	0.513	0.013
Avtur (k=5)[b]	0.0011	0.002	0.27	0.079	0.010	0.013
(h=1, i=2)						
Avtur (k=5)[b]	0.0004	0.002	0.26	0.050	0.004	0.013
Road (h=2)						
NG (i=1,2; k=8)	0.261	0.001	0.19	0.11	0.02	0.0004
NG (i=3,4,5; k=8)[c]	0.101	0.001	1.2	0.2	0.01	0.0004
Rail (h=3)						
ADO (k=2)	0.006	0.002	1.71	0.580	0.124	0.083
IDF (k=6)	0.006	0.002	1.71	0.580	0.124	0.204
Coal (k=9)	0.002	0.001	0.30	0.088	0.0	0.37
Marine						
(h=4; i=1,2) & (h=5, i=3)						
Petrol (k=1)[d]	0.030	0.0009	0.35	19.61	5.83	0.013
ADO (k=2)	0.005	0.002	1.52	0.475	0.105	0.083
IDF (k=6)	0.005	0.002	1.52	0.475	0.105	0.204
Fuel Oil (k=7)[e]	0.003	0.002	2.00	0.044	0.063	1.35
NG (k=8)	0.243	0.001	0.243	0.095	0.029	0.0004
Coal (k=9)	0.002	0.001	0.31	0.088	0.0	0.37
Military (h=5, i=2)						
Petrol (k=1)	0.026	0.0009	0.418	4.24	0.67	0.013
ADO (k=2)	0.01	0.002	0.86	0.60	0.124	0.083
Other mobile (h=6)						
Petrol (i=1, k=1)	0.030	0.0009	0.37	7.0	1.08	0.013
Farm equipment (i=2)						
ADO (k=2)	0.01	0.002	1.43	0.57	0.22	0.083
Industrial engines (i=3)						
ADO (k=2)	0.004	0.002	1.1	0.36	0.086	0.083
LPG (k=3)	0.01	0.001	0.23	0.086	0.066	0.008
Lawn-mowers (i=4)[d]						
Petrol (k=1)	0.030	0.0009	0.07	15.3	5.8	0.013

Sources: OECD (1991), BTCE estimates based on a Australian Institute of Petroleum (AIP, Corinaldi, R. 1994, pers. comm.), Australian Gas Association (Lyall, K. 1994, pers. comm.), Australian Liquefied Petroleum Gas Association (Borgas, L. 1994, pers. comm.), b Department of Transport (Streeter, J. & Hoss, P. 1994, pers. comm.), Federal Airports Administration (1991) and QANTAS (Bourke, B. 1994, pers. comm.), c De Maria (1992), d Farrington (1988), and e Lloyd's Register of Shipping (1990)

Table 3 Non-CO_2 exhaust emission factors for road vehicles

Vehicle type (*i, j*) for *h*=2 and fuel type (*k*)	Emission factor $(F(l)^{m=2}{}_{2ijk})$ (g/km)					
	CH_4 (*l*=2)[a,b]	N_2O (*l*=3)[a,c]	NO_x (*l*=4)	CO (*l*=5)	NMVOCs (*l*=6)	SO_x (*l*=7)[d]
Cars (*i*=1)						
Petrol (*k*=1)						
Post-85 (*j*=1)	0.10	0.025	1.23	7.81	0.50	0.024
1981-85 (*j*=2)	0.15	0.0037	1.70	28.93	2.38	0.055
1976-80 (*j*=3)	0.18	0.0037	1.87	37.15	2.88	0.056
Pre-76 (*j*=4)	0.21	0.0037	2.15	37.84	3.33	0.056
ADO (*k*=2)	0.01	0.010	1.03	1.08	0.53	0.420
LPG (*k*=3)	0.087	0.0079	1.94	21.60	1.69	0.034
Light trucks (*i*=2)						
Petrol (*k*=1)	0.14	0.012	1.76	23.58	1.97	0.050
ADO (*k*=2)	0.01	0.014	1.18	1.11	0.53	0.394
LPG (*k*=3)	0.089	0.008	1.98	21.99	1.72	0.035
Medium trucks (*i*=3)						
Petrol (*k*=1)	0.174	0.006	4.65	57.80	4.13	0.094
ADO (*k*=2)	0.02	0.017	3.10	1.82	0.99	0.633
LPG (*k*=3)	0.13	0.011	2.82	24.0	2.46	0.050
Heavy trucks (*i*=4)						
Petrol (*k*=1)	0.21	0.009	4.66	121.3	6.09	0.153
ADO (*k*=2)	0.07	0.025	15.29	7.86	2.78	1.412
LPG (*k*=3)	0.22	0.020	4.83	24.0	4.21	0.085
Buses (*i*=5)						
Petrol (*k*=1)	0.15	0.005	3.91	48.61	3.47	0.079
ADO (*k*=2)	0.03	0.025	4.90	2.88	1.56	1.000
LPG (*k*=3)	0.12	0.011	2.76	24.0	2.41	0.049
Motorcycles (*i*=6)						
Petrol (*k*=1)	0.15	0.002	0.21	19.27	4.58	0.026

Sources: BTCE estimates based on Carnovale et al. (1991) and ABS (1993), with supplementary information from a. OECD (1991), b. Hoekman (1992), c. Weeks et al. (1993) and d. AIP (Corinaldi, R. 1994, pers. comm.).

NMVOC emissions from road vehicles using automotive gasoline consist of both exhaust and evaporative emissions. Evaporative NMVOC emissions from petrol-fuelled road vehicles include running losses (that is, evaporative emissions released during engine operation), hot soak losses (from evaporation of fuel at the end of each trip) and diurnal losses (resulting from vapour being expelled from fuel tanks due to ambient temperature changes). Total NMVOC emissions are calculated by adding the exhaust component (estimated using Table 3) and the evaporative component (estimated using Table 5).

Table 4 CO_2 emission factors and liquid fuel energy densities by fuel type

Fuel type (for all vehicle types *h, i, j*)	(*k*)	CO_2 emission factor[a] (*g/MJ*)	Energy density[b] (*MJ/L*)
Automotive gasoline	1	66 0	34 2
Automotive diesel oil	2	69 7	38 6
Liquefied petroleum gas	3	59 4	25 7
Aviation gasoline	4	68 0	33 1
Aviation turbine fuel	5	67 8	36 8
Industrial diesel fuel	6	70 2	39 6
Fuel oil	7	73 3	40 8
Natural gas	8	52 7	..
Black coal	9	90 0	..

.. not applicable

Sources: a Australian Draft Inventory Preparation Group (1991), Wilkenfeld (1991)
b Bush et al (1993)

Table 5 Evaporative NMVOC and particulate emission factors for road vehicles

Vehicle type		Emission factor (g/km)	
		Evaporative NMVOCs	Particulates
Cars	Petrol	1 25	0 05
	Post-1985	0 47	na
	1981-1985	1 29	na
	1976-1980	1 38	na
	Pre-1976	2 77	na
	ADO	-	0 15
Light trucks	Petrol	1 32	0 05
	ADO	-	0 22
Medium trucks	Petrol	2 50	0 05
	ADO	-	0 50
Heavy trucks	Petrol	3 04	0 23
	ADO	-	2 09
Buses	Petrol	2 44	0 05
	ADO	-	0 50
Motorcycles	Petrol	0.76	0.06

na not available
\- assumed negligible

Note: Particulate emissions for off-road sources can be roughly estimated using an emission factor of 0 1 g/MJ, based on data from the Royal Commission on National Passenger Transportation (RCNPT 1992).

Sources: Carnovale et al (1991), OECD (1991), BTCE estimates

Life-cycle effects

Emissions directly from transport vehicle use can be estimated using the emission factors in Tables 2 to 5 However, the environmental impacts of a transport activity are often better assessed by considering the entire *life-cycle* associated with the activity, that is both direct and indirect effects. For transport, life-cycle emissions comprise those arising from fuel extraction, processing and distribution; vehicle manufacture and disposal; vehicle use; services to transport (such as petrol stations); and provision of infrastructure (such as road maintenance)

For example, the major emissions associated with electric trains relate to the generation and distribution of electricity Such emissions depend on the fuel types consumed by the power stations supplying the electricity and the distribution efficiency of the electricity transmission grid. Wilkenfeld (1991) derives emission rates of the order of 260 grams of CO_2 per megajoule of delivered electricity for black coal fired power stations and 400 grams per megajoule for brown coal (lignite)

Gases and liquids, particularly petroleum fuels, are often transported by pipelines Pipeline leakages and fuel consumption by pipeline distribution equipment (pumps and compressors) both generate emissions Wilkenfeld (1991) implies an emission rate of the order of 2 grams of CH_4 per megajoule of delivered natural gas is indicative of leakage from NG pipelines

The authors estimate (from sectoral energy use data in Bush et al 1993, DME 1990 and Apelbaum 1993) that for vehicles using petroleum fuels, emissions from supply of the fuel (due to fuel extraction, refining and distribution) are of the order of 10 per cent of those generated by the fuel end-use in the vehicle engines Similarly, the authors estimate that other indirect effects (for example: emissions from vehicle manufacture, servicing, and disposal, vehicle refuelling, road construction and maintenance) also add around 10 per cent to direct annual vehicle emissions, with the exception of FCs. DME (1990) results imply that FC leakage during vehicle operation comprises only around 25 per cent of total FC emissions associated with the vehicle life-cycle. FC losses also occur during air-conditioner servicing, vehicle disposal, road accidents, and the production of foams for use in vehicle manufacture.

The authors have estimated life-cycle emissions for the Australian transport sector (presented in Table 6), using the figures above and the mobile source emission factors (Tables 2 to 5) The results are fairly approximate due to the relative uncertainty in some of the emission factors (particularly for N_2O, FCs and PM), the magnitude of the indirect effects, and the dependence of emissions on operating conditions (such as ambient temperature) However, when valuing impacts of emissions in economic terms (for example, as part of a transport reform assessment), the uncertainties associated with assigning costs to a particular level of air pollution would far outweigh the inaccuracy of the emission inventory

Table 6 Life-cycle emission inventory for Australian transport and mobile equipment, for 1993

Source Category	Estimated emissions (*10^9 grams*)								
	CO_2	**CH_4**	**N_2O**	**NO_x**	**CO**	**NMVOCs**	**SO_x**	**FCs**	**PM**
Domestic Aviation	4260	0.3	0.1	16	97	3	1	na	0.1
Road Transport	64047	23.6	2.8	364	3666	480	20	2.3	25.1
Cars	*40985*	*19.2*	*2.3*	*230*	*2875*	*363*	*7*	*1.8*	*6.4*
Rail Transport	3883	0.3	0.1	96	33	7	5	na	2.5
Domestic Marine	3452	0.4	0.1	69	146	44	34	na	4.0
Domestic Civil Transport	75643	24.60	3.2	546	3941	534	60	2.3	31.7
International Aviation	5927	0.04	0.18	23	4	0.4	1	na	0.2
International Shipping	2024	0.09	0.06	54	4	2.0	31	na	2.4
International Civil Transport	7951	0.13	0.23	77	8	2.4	33	na	2.5
Military Transport	1212	0.1	0.03	9	10	1	1	na	1.5
Other Mobile Engines	10490	1.1	0.30	175	153	52	12	na	12.8
Pipeline	205	7.2	0.01	0.3	0.1	1	0.0	0	0.0
Total	95500	33.1	3.7	807	4110	590	105	2.3	48.5

na not available, and assumed negligible when calculating totals.

Notes:

1. Columns may not add to totals due to rounding.
2. Figures for international transport relate to emissions due to international passenger and freight movements accomplished using fuel purchased in Australia.

Sources: Authors' estimates based on Bush et al. (1993), Apelbaum (1993), DME (1990), Wilkenfeld (1991) and Tables 2 to 5.

For most gases, cars account for over half of the life-cycle emissions due to the domestic transport sector (Table 6) Based on the work of Cosgrove (1992), the contribution of domestic civil transport to total Australian (human-sourced) emissions is of the order of 27 per cent for CO_2, 1 per cent for CH_4, 2 per cent for N_2O, 50 per cent for NO_x, 25 per cent for CO, 50 per cent for NMVOCs, 10 per cent for SO_x, 25 per cent for FC species and 2 per cent for PM. Note that for *urban* air pollution, the transport share of noxious emissions is considerably higher. In cities, motor vehicles emit over 90 per cent of the carbon monoxide, 80 per cent of nitrogen oxides and 50 per cent of particulates, the national averages for CO and PM being much lower due to high output from the combustion of plant material (such as wood fires and controlled savanna burning)

3. SOCIAL COSTS OF EMISSIONS

National greenhouse gas emission inventories have been developed recently for a variety of human activities (including transport), primarily to fulfil Australia's international environmental reporting obligations (under the United Nations Framework Convention on Climate Change) They form the starting point for estimating the value of reducing emission levels, and provide a basis for the development of climate change response strategies Since our knowledge of the amount of damage caused by various emissions is currently limited, we are unable to provide accurate estimates of the value of emission abatement at this time However, a number of hypothetical examples are presented here to illustrate the possible uses of emission inventories and to indicate the need for further research in the emissions area

As an example of the roles that emission inventories have in transport assessments, this section derives rough (order of magnitude) estimates for the costs of environmental damage caused by transport emissions. Approximate costs imposed on society per kilogram of gas emitted have been adapted from the literature (primarily RCNPT 1992, EPAV 1994) for some of the main air-borne pollutants generated by transport (and are presented in Table 7). Such rates ($/kg) are derived by identifying the groups at risk (for example, asthma sufferers), estimating the responses of the groups to certain levels of ambient air pollution (for example, laboratory studies on the relationship between toxic doses and effects on health), and estimating the values of these responses (for example, medical expenses)

Where possible, the values used in this paper (for environmental damage) were based on studies that derived costs using surveys on willingness-to-pay (WTP) for certain levels of air quality In general, WTP estimates are preferable when valuing qualities such as human health since they allow for more effects than just direct monetary costs (such as hospital expenses) In theory, WTP values also reflect concerns about the disutility of symptoms (such as pain or restricted movement), lost leisure time, changes in life expectancy, and risks of dying. However, the damage costs per unit emission in Table 7 were generally based on a combination of direct cost methods (such as expenses due to lost wages, replacement of degraded building materials, and loss of productivity from crops or livestock) and contingent valuation methods (such as surveyed WTP for reductions in the risk of illness, loss of heritage buildings and damage to forests)

We stress that the derived costs are very approximate, and further research is needed in this area Typically, the values in Table 7 are simply average unit costs (total costs divided by total emissions), and marginal damage costs could be quite different In fact, the value given for CO_2 emissions (2 cents per kilogram) is only a proxy for the damage costs of global warming It is a control cost that relates to the costs (per kilogram of CO_2 sequestered) of establishing and maintaining a forested area capable of absorbing CO_2 emissions Not only is the magnitude of the control cost uncertain (for example, the costs of purchasing and afforesting land will vary markedly from place to place and from year to year), but control costs can be quite unrelated to potential damage costs The costs associated with global warming are very difficult to assess and are largely unknown The approximate costs per unit emission (for each gas) are used here simply to illustrate how the consideration of environmental damage by transport emissions can be incorporated into comparisons of transport options

Table 7 Costs per kilogram of environmental damage by air-borne pollutants

Emission response	Estimated environmental damage[a] (*$/kg*)							
	CO_2	CH_4 & N_2O	NO_x[b]	CO	NMVOC	SO_x	FCs	PM
Health loss	na/ns	na/ns	1 00	na/s	0 40[c]	5 30	na/ns	10.00
Buildings and materials corrosion	na/ns	na/ns	0 03	na/ns	na/s	0 36	na/ns	na/s
Water acidity	na/ns	na/ns	na/s	na/ns	na/ns	na/s	na/ns	na/s
Crops and vegetation damage	na/ns	na/ns	0 03	na/ns	na/s	na/s	na/ns	na/s
Impaired visibility	na/ns	na/ns	0 51	na/s	na/s	0 41	na/ns	2 48
Damage to ecosystems	na/ns	na/ns	na/s	na/s	na/s	na/s	na/ns	na/s
Stratospheric ozone depletion	0 00	na/ns	na/s	na/ns	na/ns	na/ns	na/s	na/ns
Global warming	0.02[d]	na/s	na/s	na/s	na/s	na/s	na/s	na/ns
Total[e]	0.02	na/s	1.58	na/s[f]	0.40	6.07	na/s	12.48

na/ns not available, probably not significant

na/s not available, probably significant

a 1993 Australian dollars per kilogram of gas emitted

b Assumes the rate of formation of ozone is proportional to the level of NO_x emissions This is very approximate, since ozone levels depend non-linearly on ambient concentrations of NO_x, CO and NMVOCs

c Based on estimates of increased incidence of cancers due to air-borne toxics

d The estimated control cost of sequestering CO_2 by planting trees

e Disregarding, at this stage, the not available values

f Data given by Quinet (1994) implies the environmental damage costs of CO emissions could be of the order of $0 01/kg

Sources: Authors estimates based on RCNPT (1992) and EPAV (1994)

Table 8 Order of magnitude costs for annual environmental damage by transport emissions, 1993

Domestic transport mode	Costs of environmental damage ($ million)[a]					
	CO_2	NO_x	NMVOCs	SO_x	PM	Total
Aviation	88	25	1	6	1	122
Road	1326	574	192	121	313	2527
Car	*848*	*363*	*145*	*43*	*80*	*1479*
Rail	80	151	3	30	31	296
Maritime	71	109	18	206	50	454
Total	1566	860	214	364	396	3399

a 1993 Australian dollars, disregarding the not available values in Table 7

Damage costs calculated using Table 7 will tend to be conservative, since not only are costs for known environmental impacts (such as the greenhouse potential of N_2O and CH_4, damage to ecosystems and stratospheric ozone depletion) unavailable, there also remain many chronic effects of air pollution yet to be fully understood Using the transport inventory (Table 6) and the unit emission costs (Table 7) gives an estimated $3.4 billion as the cost of environmental damage due to Australian domestic transport emissions in 1993 (see Table 8)

The values given in Table 8 are very approximate, not only due to the uncertainty surrounding the costs per kilogram (from Table 7), but also from simplifying assumptions made in their calculation The estimates do not make full allowance for:

- atmospheric dispersion or the chemical transformation of emission species;
- the distribution of emission sources (emissions in non-urban areas will generally have less impact than those in urban areas) or pollution thresholds for certain effects; and
- the formation of low-level ozone (the principal constituent of smog) depending on a complex series of reactions involving NO_x, CO and NMVOC pollution

Though very approximate, the costs derived here are in rough agreement with international estimates of the social costs of transport emissions Quinet (1994) has summarised the results of 25 overseas studies on the costs imposed by noxious transport emissions The estimated damages due to transport emissions vary from country to country, between 0.03 per cent to 1.2 per cent of the gross national product (GNP) of each country, with an average result of about 0.4 per cent of GNP. In comparison, the non-CO_2 component of the costs presented in Table 8 are equivalent to around 0.45 per cent of Australian gross domestic product (for 1993)

The cost of damages by emissions may then be accounted for along with other costs involved with transport activities. For example, consider Australian expenditure on roads, which totals around $6 billion per annum A change to the transport system that served to reduce the need for road maintenance (more commuter cycling?) may be assessed as uneconomic if environmental costs are ignored For example, the implementation costs for the policy measure may be significantly greater than the reduced road expenditure However, the measure could be assessed worthwhile if the benefits from reducing emissions were also valued

As a further illustration, consider the hypothetical situation of imposing a *carbon tax* (that is, a tax on fuels that is proportional to their carbon content) to reduce carbon dioxide emissions from transport. Cosgrove and Ironfield (1990) estimated deadweight losses (measures of the losses to society as a whole, externalities such as air pollution aside, arising from some economic action) for various scenarios in which hypothetical carbon taxes replaced the existing state and federal fuel excise charges It was assumed that the extra tax revenue raised would be transferred back to consumers, so the welfare change in the economy was measured by the deadweight loss in the fuel market Conceptually, it would include the costs incurred by consumers from less discretionary travel, reduced convenience (for example, shifting from private to public transport), restricted choice (for example, smaller cars may be required) and greater capital expenditure (such as to replace an inefficient vehicle)

Using the results of Cosgrove and Ironfield's analysis (a partial equilibrium welfare measurement of the impacts of increasing fuel prices, using constant long-term own-price elasticities of fuel demand), it is estimated that a hypothetical carbon tax of 50 cents per litre (applied to all transport fuel) could result in Australian transport fuel use by 2005 falling to around that in 1988, with a consequent annual deadweight loss to society of the order of $1 4 billion However, the emission reduction following this reduced level of fuel use could yield a benefit of the order of $1 8 billion (based on a proportional change in the environmental damage costs from Table 8) If the calculation is repeated for a hypothetical carbon tax of 1 dollar per litre, 2005 transport fuel consumption is projected to fall to around 20 per cent below that of 1988, with a deadweight loss of around $3 7 billion For this more drastic fuel price scenario, the proportional reduction in the environmental damage costs would be approximately $2.4 billion

As a final example of the uses for emission inventories, environmental damage costs per unit transport task can be derived (from Table 8) for aggregate transport activities Using the task estimation methods outlined by Cosgrove and Gargett (1992) gives national average rates for environmental damage from vehicle emissions of around $7 50 per thousand passenger-kilometres for cars and $3.90 for buses For freight transport, a similar analysis yields approximate emission damage rates of $10 70 per thousand tonne-kilometres for road transport and $4 90 for rail transport Such aggregate rates are of course only indicative, and do not necessarily reflect on the performance of any particular road or rail transport operator However, they do highlight the need to account for the damage costs of transport emissions when conducting transport assessments

4. CONCLUSION

Though the values (derived in the previous section) for environmental damage costs due to transport are very approximate, they at least serve to illustrate the magnitude of air pollution problems that policies may have to address.

Further research is needed in the area of costing emissions, especially in quantifying the environmental damage costs due to different levels of transport emissions. As shown in Table 8, transport emissions impact on ecosystems (airborne damage to flora and fauna, and acidic deposits in aquatic habitats) and the global atmosphere (stratospheric ozone depletion and the greenhouse effect). However, the costs associated with such environmental damage are largely unknown.

The calculation of emission inventories forms an integral part of efforts to include the costs of emissions in economic assessments of transport options. Other research topics essential for improving the estimates of the damage costs include:

- the relationship between the level of emissions emanating from vehicles and the final concentration and distribution of the pollutants in the environment;
- the value of environmental damage (such as the loss of native species or the increased incidence of human cancers), the share attributable to air pollution, and how the damage varies with the atmospheric concentration of the particular pollutants;
- the level of indirect emissions due to transport (such as from vehicle manufacture); and
- the derivation of vehicle emission rates that are current, task specific and reflect actual operating conditions (for example, by regularly conducting emission tests on vehicle fleets).

Should more detailed information (concerning the environmental consequences of transport emissions) become available, then we may be able to properly test the validity of the view put forward by Quinet (1994): that the costs associated with reducing CO_2 emissions to a stable level are likely to be balanced by the savings in reduced damage to the human and natural environment due to a consequent reduction in noxious air pollution.

5. REFERENCES

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ABS	Australian Bureau of Statistics
ACS	Australian Customs Service
ADIPG	Australian Draft Inventory Preparation Group
AEC	Australian Environment Council
AGPS	Australian Government Publishing Service

AIP	Australian Institute of Petroleum
BTCE	Bureau of Transport and Communications Economics
CEPA	Commonwealth Environment Protection Agency
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DASET	Department of the Arts, Sport, the Environment and Territories
DME	Department of Minerals and Energy of New South Wales
DPIE	Department of Primary Industries and Energy
ECMT	European Conference of Ministers of Transport
ERDC	Energy Research & Development Corporation
EPAV	Environment Protection Authority of Victoria
IPCC	Intergovernmental Panel on Climate Change
OECD	Organisation for Economic Co-operation and Development
RCNPT	Royal Commission on National Passenger Transportation.

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