5.10 Air Pollution

This chapter describes vehicle air pollutants including greenhouse gasses, describes emission rates of different vehicles, factors that affect emission rates, and vehicle air pollution costs.

5.10.1 Chapter Index

5.10.2 Definitions

Air Pollution Costs refers to harm caused by motor vehicle air emissions, including damages to human health, ecological health and esthetic conditions. These include *exhaust emissions* from tailpipes, *non-exhaust emissions* (NEE) from tire and break wear, and *lifecycle emissions* that also include air emissions from fuel extraction and refining, vehicle manufacturing, and transportation facility construction.

5.10.3 Discussion

Motor vehicles produce various harmful air emissions, as summarized in Table 5.10.3-1. Some impacts are localized, so where emissions occur affects their costs, while others are regional or global, making location less important. Emission control technologies have reduced emission rates of some but not all of these pollutants.

Table 5.10.3-1 **Vehicle Pollution Emissions**[1]

Emission	Description	Sources	Harmful Effects	Scale
Carbon dioxide (CO_2)	A product of combustion.	Fuel production and tailpipes.	Climate change	Global
Carbon monoxide (CO)	A toxic gas caused by incomplete combustion.	Tailpipes.	Human health, climate change	Very local
CFCs and HCFC	A class of durable chemicals.	Air conditioners and industrial activities.	Ozone depletion, climate change	Global
Fine particulates (PM_{10}; $PM_{2.5}$)	Inhaleable particles.	Tailpipes, brake lining, road dust, etc.	Human health, aesthetics	Local and Regional
Road dust (non-tailpipe particulates)	Dust particles created by vehicle movement.	Vehicle use, brake linings, tire wear.	Human health, aesthetics	Local
Lead	Element used in older fuel additives.	Fuel additives and batteries.	Human health, ecological damages	Local
Methane (CH_4)	A flammable gas.	Fuel production and tailpipes.	Climate change	Global
Nitrogen oxides (NOx) and nitrous oxide (N_2O).	Various compounds, some are toxic, all contribute to ozone.	Tailpipes.	Human health, ozone precursor, ecological damage.	Local and Regional
Ozone (O_2)	Major urban air pollutant caused by NOx and VOCs combined in sunlight.	NOx and VOC	Human health, plants, aesthetics.	Regional
Sulfur oxides (SOx)	Lung irritant and acid rain.	Diesel vehicle tailpipes.	Human health and ecological damage	Local and Regional
VOC (volatile organic hydrocarbons)	Various *hydrocarbon* (HC) gasses.	Fuel production, storage & tailpipes.	Human health, ozone precursor.	Local and Regional
Toxics (e.g. benzene)	Toxic and carcinogenic VOCs.	Fuel production and tailpipes.	Human health risks	Very local

This table summarizes various types of motor vehicle pollution emissions and their impacts.

[1] USEPA (2000), *Indicators of the Environmental Impacts of Transportation*, Center for Transportation and the Environment (www.itre.ncsu.edu/cte); ORNL, *Transportation Energy Data Book* ORNL (www.ornl.gov).

Health Effects

Numerous studies using various methodologies indicate that motor vehicle air pollution contributes to various health problems including cancer, cardiovascular and respiratory diseases, and perinatal mortality.[2]

Table 5-10.3-2 **Human Health Effects of Common Air Pollutants**[3]

Pollutant	Quantified Health Effects	Unquantified Health Effects	Other Possible Effects
Ozone	Mortality Respiratory RAD* Minor RAD Hospital admissions Asthma attacks Changes in pulmonary function Chronic sinusitis and hay fever	Increased airway responsiveness to stimuli Centroacinar fibrosis Inflammation in the lung	Immunologic changes Chronic respiratory diseases Extrapulmonary effects (changes in the structure or function of the organs)
Particulate matter / TSP/ Sulfates	Mortality Chronic and acute bronchitis Minor RAD Chest illness Days of work loss Moderate or worse asthma status	Changes in pulmonary function	Chronic respiratory diseases other than chronic bronchitis Inflammation of the lung
Carbon monoxide	Mortality Hospital admissions– congestive heart failure Decreased time to onset of angina	Behavioral effects Other hospital admissions	Other cardiovascular effects Developmental effects
Nitrogen oxides	Respiratory illness	Increased airway responsiveness	Decreased pulmonary function Inflammation of the lung Immunological changes
Sulfur dioxide	Morbidity in exercising asthmatics: Changes in pulmonary function Respiratory symptoms		Respiratory symptoms in non-asthmatics Hospital admissions
Lead	Mortality Hypertension Nonfatal coronary heart disease Nonfatal strokes Intelligence quotient (IQ) loss	Neurobehavioral function Other cardiovascular diseases Reproductive effects Fetal effects from maternal exposure Delinquent and antisocial behavior in children	

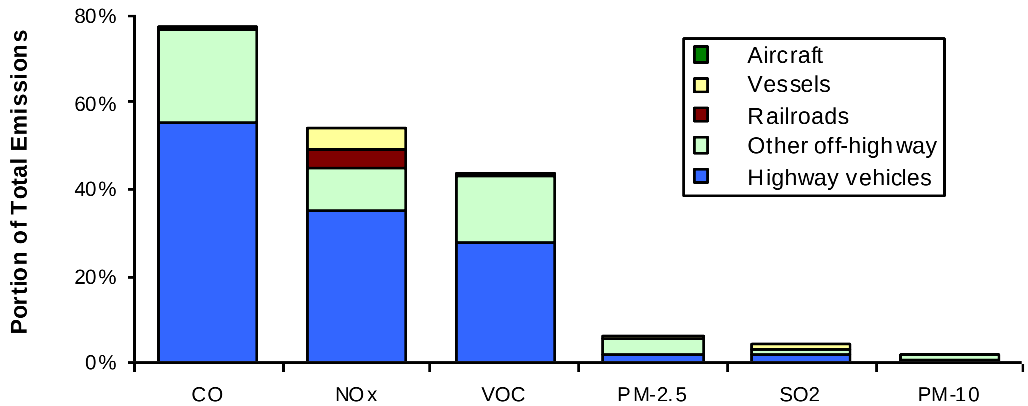
This table summarizes human health impacts of various air pollutants. (RAD = Reactive Airways Disease, a general term for various illnesses that cause breathing difficulties.)*

[2] HEI (2010), *Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects*, HEI Special Report 17, Health Effects Institute (www.healtheffects.org); at http://pubs.healtheffects.org/getfile.php?u=553.

[3] Ken Gwilliam and Masami Kojima (2004), *Urban Air Pollution: Policy Framework for Mobile Sources*, Prepared for the Air Quality Thematic Group, World Bank (www.worldbank.org); at www.cleanairnet.org/cai/1403/articles-56396_entire_handbook.pdf. Also see, *How Vehicle Pollution Affects Our Health*, Ashden Trust; at www.ashdentrust.org.uk/PDFs/VehiclePollution.pdf.

Figure 5.10.3-1 shows transport's share of major pollutants. This share is even higher in many areas were people congregate, such as cities, along highways and in tunnels. Emission control strategies significantly reduce per-mile emission rates of some pollutants (CO, SOx and VOCs), but some other pollutants are not easily reduced by technology, emission tests often underestimate actual emission rates, emission control systems sometimes fail, and reduced emission rates have been partly offset by increased travel. Because the easiest reduction strategies have been implemented, additional reductions will be more difficult. The harmful impacts of some emissions, such as fine particulates and air toxics, have only recently been recognized and so have minimal control strategies.[4,5] This research indicates that people who live or work near busy highways experience significant increases in lung disease, despite vehicle emission reduction technologies.[6]

Figure 5.10.3-1 **Transport Air Pollutant Shares (2002)**[7]



Transportation is a major contributor of many air pollutants. These shares are even higher in certain circumstances, such as in cities, along major roads and in tunnels.

Climate Change

Climate change (also called *global warming* and *the greenhouse effect*) refers to climatic changes caused by gases (called *greenhouse gases* or *GHGs*) that increase atmospheric solar heat gain.[8] Although some organizations argue the evidence is inconclusive or emission reduction economic costs exceed likely benefits (e.g. Center for the Study of Carbon Dioxide and Global Change), such groups generally have little climatic or ecological expertise, and often represent industries that benefit from continued climate change emissions.[9] Major scientific organizations consider anthropogenic (human caused) global warming a significant

[4] Doug Brugge, John Durant and Christine Rioux (2007), "Near-Highway Pollutants In Motor Vehicle Exhaust: Review Of Epidemiologic Evidence" *Environmental Health*, Vol. 6/23 www.ehjournal.net/content/6/1/23.

[5] HEI (2007), *Mobile-Source Air Toxics: A Critical Review of the Current Literature on Exposure and Health Effects*, Health Effects Institute (www.healtheffects.org); at http://pubs.healtheffects.org/view.php?id=282.

[6] *Community Assessment of Freeway Exposure and Health* (www.tufts.edu/med/phfm/CAFEH/CAFEH.html)

[7] ORNL (2005), *Transportation Energy Data Book*, USDOE (www.doe.gov), Table 12.1.

[8] Todd Litman (2009), *Climate Change Emission Valuation for Transportation Economic Analysis*, (www.vtpi.org); at www.vtpi.org/ghg_valuation.pdf.

[9] Sourcewatch (2008), *Global Warming Skeptics*, SourceWatch (www.sourcewatch.org); at www.sourcewatch.org/index.php?title=Climate_change_skeptics.

cost (actual damages) and risk (possibility of future damages).[10] For example, the Intergovernmental Panel on Climate Change, which consists of hundreds of scientists, concluded, "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level".[11] The United Nations Environmental Program's 2007 Global Environment Outlook emphasizes the need for action to reduce the costs and risks.[12]

A study published in the *Proceedings of the National Academy of Sciences* calculated the climate changing impacts of 13 economic sectors taking into account their global warming and global cooling emissions.[13] The analysis concluded that motor vehicles are the greatest contributor to atmospheric warming. Cars, buses, and trucks release pollutants and greenhouse gases that promote warming, while emitting few aerosols that counteract it.

Putting a value on GHG emissions is difficult due to uncertainty and differences in human values concerning ecological damages and impacts on future generations. In addition, climate changes impacts are not necessarily linear, many scientists believe that there may be thresholds or tipping points beyond which warming and damage costs could become catestrphic.[14]

Recent scientific studies indicate the risks are larger than previously considered. For example, the 2006 report by the economist Sir Nicholas Stern called attention to the threat of a permanent "disruption to economic and social activity, later in this century and in the next, on a scale similar to those associated with the great wars and the economic depression of the first half of the 20th century",[15] but two years later stated that his earlier evaluation greatly underestimated the potential costs:

> *"Emissions are growing much faster than we'd thought, the absorptive capacity of the planet is less than we'd thought, the risks of greenhouse gases are potentially bigger than more cautious estimates and the speed of climate change seems to be faster."[16]*

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[10] Pew Center on Global Climate Change (2006), *The Causes of Global Climate Change,* (www.pewclimate.com); at http://pewclimate.com/global-warming-basics/science-brief-092006.

[11] IPCC (2007) *Climate Change 2007: Synthesis Report - Summary for Policymakers* (www.ipcc.ch); at www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf

[12] UNEP (2007) *Global Environmental Outlook 4*, (www.unep.org); at www.unep.org/geo/

[13] Nadine Unger, et al. (2011), "Attribution Of Climate Forcing To Economic Sectors," *Proceedings of the National Academy of Sciences of the U.S.* (www.pnas.org): at www.pnas.org/content/early/2010/02/02/0906548107.abstract.

[14] James Hansen (2008) *Global Warming Twenty Years Later: Tipping Points Near - Briefing before the Select Committee on Energy Independence and Global Warming, U.S. House of Representatives*, Columbia University (www.columbia.edu); at www.columbia.edu/~jeh1/2008/TwentyYearsLater_20080623.pdf

[15] Sir Nicholas Stern (2006), *Stern Review on the Economics of Climate Change*, UK Office of Climate Change (www.occ.gov.uk); at www.sternreview.org.uk

[16] David Adam (2008) "I underestimated the threat, says Stern", *The Guardian* (www.guardian.co.uk), April 18 2008; at www.guardian.co.uk/environment/2008/apr/18/climatechange.carbonemissions

Factors Affecting Emission Costs
Various factors that affect air pollution cost estimates are discussed below.

Scope
Emission analysis can be narrow, only considering tailpipe emissions, or broader, including emissions from vehicle and fuel production, as indicated below. Chester and Horvath (2008) estimate that total emissions for a passenger car are 0.36 kg CO_2e per passenger mile, 57% higher than the 0.23 kg tailpipe emissions.[17] Research by the British Air Quality Expert Group indicate that non-exhaust emissions constitute 60% (by mass) of PM2.5 and and 73% of PM10 of road transport emissions, representing 7.4% and 8.5% of total UK PM2.5 and PM10 emissions, and are predicted to become more dominant in the future.[18]

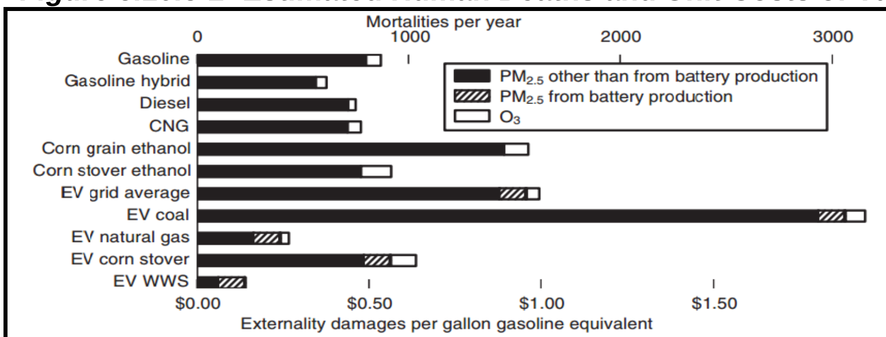
Table 5.10.3-3 **Scope of Emissions considered**

Scope	Description	Pollutants
Exhaust	Emissions from vehicle tailpipes	CO, CO_2, NOx, particulates, SOx, VOCs
Non-exhaust emissions	Includes non-tailpipe particulates from brakes, tire wear and road dust.	Particulates VOCs, air toxics, CFCs and HCFCs.
Lifecycle	Total emissions from vehicle and fuel production, facilities and use.	Those above, plus emissions during vehicle and fuel production, and roadway constructions and maintenance.

The scope of analysis may only consider tailpipe emissions, or it can include additional emissions.

Fuel Type
Various fuels can power vehicles. Their total (including "upstream" emissions during production and distribution) health and environmental impacts vary. Figure 5.10.3-2 illustrates estimated human deaths and health costs of various fuels, indicating that many alternative fuels have total air pollution costs comparable or larger than gasoline.

Figure 5.10.3-2 **Estimated Human Deaths and Unit Costs of Various Vehicle Fuels**[19]



This figure illustrates the estimated deaths and health damage costs per gallon of gasoline equivalent for various vehicle fuels, taking into account upstream as well as tailpipe particulate and ozone pollution emissions.

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[17] Mikhail Chester and Arpad Horvath (2008), *Environmental Life-cycle Assessment of Passenger Transportation: Detailed Methodology for Energy, Greenhouse Gas and Criteria Pollutant Inventories of Automobiles, Buses, Light Rail, Heavy Rail and Air*, UC Berkeley Center for Future Urban Transport, (www.its.berkeley.edu/volvocenter); at http://repositories.cdlib.org/its/future_urban_transport/vwp-2008-2.

[18] Air Quality Expert Group (2019), *Non-Exhaust Emissions from Road Traffic*, UK Department for Environment, Food and Rural Affairs; at https://bit.ly/2Ufin64.

[19] Christopher W. Tessuma, Jason D. Hillb and Julian D. Marshalla (2014), "Life Cycle Air Quality Impacts Of Conventional And Alternative Light-Duty Transportation In The United States," Proceedings of the National Academy of Science (www.pnas.org); at www.pnas.org/content/early/2014/12/10/1406853111.full.pdf.

Units of Measure

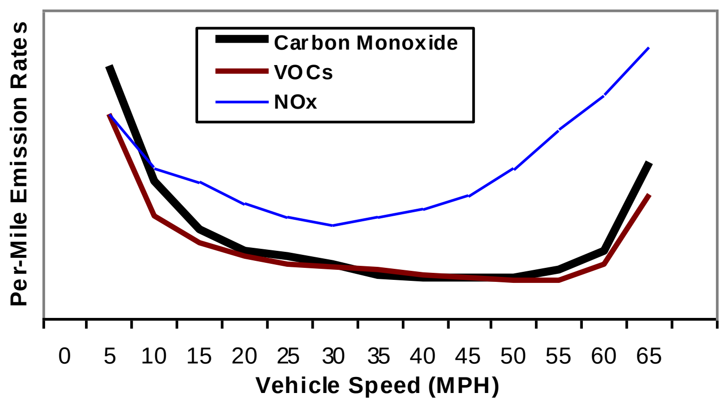
Emissions are measured in various units, including grams, pounds, kilograms, tons or tonnes.[20] For more information climate change emission measurement see the VTPI paper *Climate Change Emission Valuation for Transportation Economic Analysis.*[21]

Vehicle-mile Emission Rates

Vehicle emission models, such as MOBILE6 and its variants, can be used to predict vehicle emissions under various circumstances.[22] The following factors affect emission rates:[23]

- Vehicle type. Larger vehicles tend to produce more emissions.
- Vehicle age and condition. Older vehicles have less effective emission control systems. Vehicles with faulty emission control systems have high emissions.
- Driving cycle. Emission rates tend to be relatively high when engines are cold.
- Driving style. Faster accelerations tend to increase emission rates.
- Driving conditions. Emissions per mile increase under hilly and stop-and-go conditions, and at low and high speeds, as illustrated in Figure 5.10.3-3. As a result, energy consumption and emissions are likely to decline if roadway conditions shift from Level of Service (LOS) F to D, but are likely to increase with shifts from LOS D to A.[24]

Figure 5.10.3-3 **Vehicle Emissions by Speed**[25]



This figure shows how typical vehicle emissions are affected by speed.

[20] *USEPA Transportation Tools* (www.epa.gov/climatechange/wycd/tools_transportation.html).
[21] Todd Litman (2009), *Climate Change Emission Valuation for Transportation Economic Analysis*, VTPI (www.vtpi.org); at www.vtpi.org/ghg_valuation.pdf.
[22] US EPA (2008) *MOBILE Model (on-road vehicles),* (www.epa.gov); at www.epa.gov/OTAQ/mobile.htm.
[23] USDOT (2005), *Sensitivity Analysis of MOBILE6 Motor Vehicle Emission Factor Model*, (www.dot.gov); at www.tdot.state.tn.us/mediaroom/docs/2005/emission_reductions.pdf.
[24] VTPI (2008), "Multi-Modal Level of Service" *TDM Encyclopedia*, at www.vtpi.org/tdm/tdm129.htm.
[25] TRB (1995), *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use*, TRB Special Report #345, National Academy Press (www.nap.edu); www.nap.edu/openbook.php?record_id=9676.

Per Capita Emission Rates

Various factors affect per capita annual emissions, including land use patterns, vehicle ownership rates, pricing, and the quality of alternative modes, such as walking, cycling and public transit.[26] Models such as URBEMIS (*www.urbemis.com*) can be used to predict the emission reduction effects of various mobility and land use management strategies.[27]

Exposure by Location and Travel Mode

Exposure refers to the amount of air pollution an individual inhales. *Local* pollutants such as carbon monoxide, air toxins and particulates, tends to concentrate adjacent to roadways. Air pollution costs (per ton of emission) are higher along busy roads, where population densities are high, and in areas where geographic and climatic conditions trap pollution and produce ozone, and in vehicles.[28] Car occupants are generally exposed to higher air pollutant concentrations than walkers, cyclists and public transport users, although along busy roadways pedestrians and cyclists may incur more harm because they inhale larger air volumes.[29] Emissions under conditions in which air pollution tends to concentrate due to geographic and weather conditions (such as in valleys during inversions) impose greater damages than the same emissions in less vulnerable locations. Jet aircraft emissions at high altitudes are believed to produce relatively large climate change impacts.[30]

A growing body of research is investigating how pollution exposure affects health, taking into account the distance between emission sources and lungs, and the amount of pollution that people actually inhale, as summarized in the box below.

Air Pollution Exposure Research

Doug Brugge, John L Durant and Christine Rioux (2007), "Near-Highway Pollutants In Motor Vehicle Exhaust: A Review Of Epidemiologic Evidence Of Cardiac And Pulmonary Health Risks," *Environmental Health 6*, No 23 (www.ehjournal.net/content/6/1/23).

Lawrence D. Frank, et al. (2011), *An Assessment of Urban Form and Pedestrian and Transit Improvements as an Integrated GHG Reduction Strategy*, Washington State Department of Transportation (www.wsdot.wa.gov); at www.wsdot.wa.gov/research/reports/fullreports/765.1.pdf.

Julian D. Marshall, Michael Brauer and Lawrence D. Frank (2009), "Healthy Neighborhoods: Walkability and Air Pollution," *Environmental Health Perspectives*, Vol. 117, No. 11, pp. 1752–1759; summary at www.medscape.com/viewarticle/714818.

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[26] VTPI (2005), "Land Use Impacts on Transportation," "Transportation Elasticities," and other chapters in the *Online TDM Encyclopedia*, Victoria Transport Policy Institute (www.vtpi.org); at www.vtpi.org/tdm.

[27] Nelson/Nygaard (2005), *Crediting Low-Traffic Developments: Adjusting Site-Level Vehicle Trip Generation Using URBEMIS*, Urban Emissions Model, California Air Districts (www.urbemis.com).

[28] *Community Assessment of Freeway Exposure and Health* (CAFEH) study (www.tufts.edu/med/phfm/CAFEH/CAFEH.html).

[29] NZTA (2011), *Determination of Personal Exposure to Traffic Pollution While Travelling by Different Modes*, The New Zealand Transport Agency (www.nzta.govt.nz); at www.nzta.govt.nz/resources/research/reports/457/docs/457.pdf.

[30] John Whitelegg and Howard Cambridge (2004), *Aviation and Sustainability*, Stockholm Environmental Institute (www.sei.se).

Unit Cost Values

Unit air pollution costs refers to estimated costs per kilogram, ton or tonne of a particular pollutant in a particular location (such as a particular city or country).[31] There are two basic ways to quantify these impacts: *damage costs* which reflect damages and risks, and *control* (also called *avoidance* or *mitigation*) *costs* which reflect the costs of reducing emissions. Studies, summarized in this chapter estimate unit costs of various pollutants using methods discussed in Chapter 4. Some estimates are several years old (for example, Wang, Santini and Warinner's study was completed in 1994). It is possible that health damage unit costs have decline over time as improved medical treatment reduces the deaths and illnesses caused by pollution exposure, but this is probably offset by increased urban population (which increases the number of people exposed) and the increased value placed on human life and health that generally occurs as people become wealthier. Unit costs are affected by:

- The mortality (deaths) and morbidity (illnesses) caused by pollutant exposure (called the *dose-response function)*.
- The number of people exposed.
- The value placed on human life and health (measured based on the *Value of a Statistical Life* [VSL], the *Value Of a Life Year* [VOLY], *Potential Years of Life Lost* [PYLL] and *Disability Adjusted Life Years* [DALYs]).[32]
- The range of additional costs and damages (such as crop losses, ecological degradation, acid damage to buildings, and aesthetic degradation) considered in the analysis.

[31] M. Maibach, et al. (2008), *Handbook on Estimation of External Cost in the Transport Sector*, CE Delft (www.ce.nl); at http://ec.europa.eu/transport/costs/handbook/doc/2008_01_15_handbook_external_cost_en.pdf

[32] *Potential Years of Life Lost* and *Disability Adjusted Life Years* take into account the relative age at which people die or become ill and therefore gives greater weight to risks to younger people.

5.10. 4 Estimates & Studies

This section summarizes various cost estimates. All values in U.S. dollars unless otherwise indicated.

Local and Regional Pollutant Summary

The table below summarizes the cost estimates of various studies described in this chapter and converts them to 2007 U.S. dollars.

Table 5.10.4-1 **Regional Pollution Studies Summary Table – Selected Studies**

Publication	Costs	Cost Value	2007 USD
			Per Vehicle Mile
CE Delft (2008)	Urban Car	0.0017 - 0.0024 €/km (2000)	$0.003 - 0.004
	Urban Truck	0.106 - 0.234 €/km	0.189 - 0.417
Delucchi et al (1996)	Light Gasoline Vehicle	$1990/VMT 0.008 - 0.129	0.013 - 0.205
	Heavy Diesel Truck	0.054 – 1.233	0.086 - 1.960
Eyre et al. (1997)	Gasoline Urban	$/VMT 1996 0.030	0.040
	Diesel Urban	0.074	0.098
FHWA (1997)	Automobiles	$/VMT 0.011	0.015
	Pickups/Vans	0.026	0.034
	Diesel trucks	0.039	0.051
			Per Tonne/Ton
AEA Technology (2005)	NH3 / tonne Europe	2005** €19,750	$26,061
	NOx	€7,800	$10,293
	PM2.5	€48,000	$63,339
	SO2	€10,325	$13,624
	VOCs	€1,813	$2,392
RWDI (2006)	PM2.5 / tonne	2005 Canadian $317,000	$277,359
	O3 Total	$1,739	$1,522
Wang, Santini & Warinner (1994), US cities	NOx	1989 $/ ton $4,826	$8,059
	ROG	$2419	$4,040
	PM 10	$6508	$10,868
	SOx	$2906	$4,853

More detailed descriptions of these studies are found below. 2007 Values have been adjusted for inflation by Consumer Price Index.[33] ** Currency year is assumed to be the publication year. ** Average of results, see details below. Later studies focus on very fine particles (PM 2.5).*

- CE Delft (2008) base on Clean Air for Europe (CAFE) Programme values.[34]

Table 5.10.4-2 **Air Pollution Costs** (2000 Euro-Cents/vehicle-km)

	Passenger Car	Heavy Duty Vehicle
Urban, petrol	0.17 (0.17 - 0.24)	
Urban, diesel	1.53 (1.53 - 2.65)	10.6 (10.6 - 23.4)
Interurban, petrol	0.09 (0.09 - 0.15)	
Interurban, diesel	0.89 (0.89 - 1.80)	8.5 (8.5 - 21.4)

[33] Note that CPI is not the only way to adjust for inflation and results can vary significantly with different methods, see: Samuel H. Williamson (2008), "Six Ways to Compute the Relative Value of a U.S. Dollar Amount, 1790 to Present," MeasuringWorth (www.measuringworth.com).
[34] M. Maibach, et al. (2008).

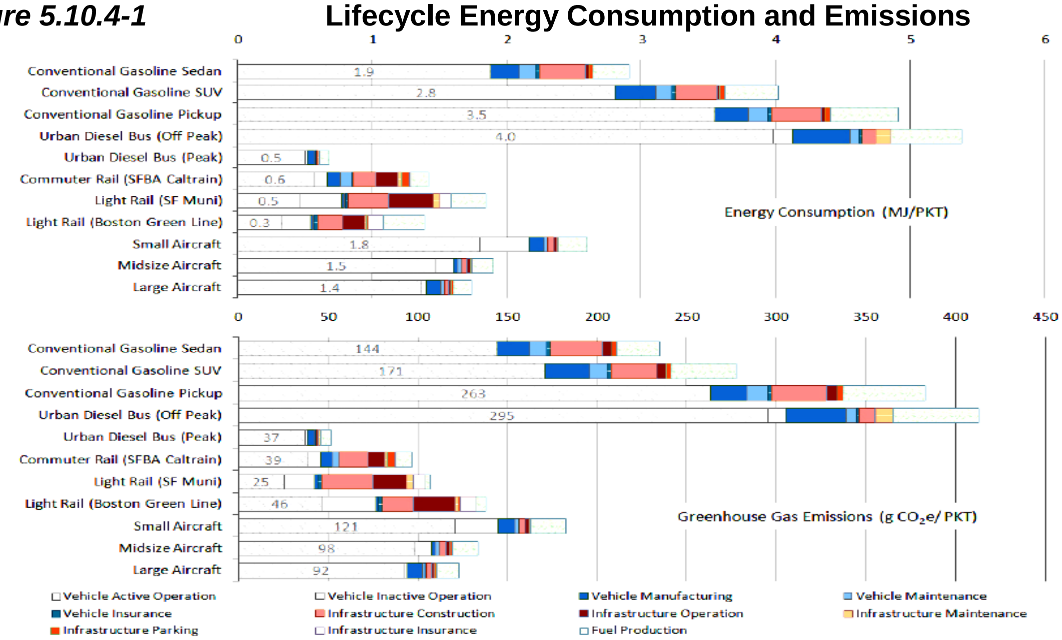
- Table 5.10.4-3 and Figure 5.10.4-1 show lifecycle emissions for various transport modes calculated by Chester and Horvath. Tailpipe emissions represent only about 64% of lifecycle emissions for typical automobiles and 75% for bus transport. Similarly, Gagnon estimated that tailpipe emissions represent about 60% of total emissions.[35]

Table 5.10.4-3 **Lifecycle Climate Change Emissions** (Grams CO_2 Equivalent)[36]

Vehicle Type	Sedan		SUV		Pickup		Bus-Average		Bus-Peak	
Avg. Occupancy	1.58		1.74		1.46		10.5		40	
	VMT	PMT	VMT	PMT	VMT	PMT	VMT	PMT	VMT	PMT
Operations	370	230	480	280	480	330	2,400	230	2,400	59
Manufacture	45	29	71	41	48	33	320	31	320	8.1
Idling	0	0	0	0	0	0	80	7.6	80	2
Tire production	7.2	4.5	7.2	4.1	7.2	4.9	2.5	0.24	2.5	0.064
Maintenance	17	11	19	11	19	13	45	4.2	45	1.1
Fixed Costs	5.6	3.6	5.7	3.3	5.8	4.0	14	1.4	14	0.35
Roadway const.	52	33	52	30	52	36	52	4.9	52	1.3
Roadway maint.	0	0	0	0	0	0	210	20	11	0.27
Herbicides/Salting	0.37	0.24	0.41	0.23	0.41	0.28	0.37	0.036	0.37	0.0094
Roadway lighting	13	8.5	14	7.8	14	9.4	4.9	0.47	4.9	0.012
Parking	8.5	54	8.5	49	8.5	58	0	0	0	0
Fuel production	59	38	98	56	100	71	260	24	260	6.4
Totals	*578*	*412*	*756*	*482*	*735*	*560*	*3,389*	*324*	*3,190*	*79*
Operations/Total	*0.64*	*0.63*	*0.63*	*0.65*	*0.65*	*0.65*	*0.75*	*0.76*	*0.75*	*0.75*

***VMT** = Vehicle Miles Traveled;* ***PMT** = Passenger Miles Traveled;* ***Operations** = tailpipe emissions*

Figure 5.10.4-1 **Lifecycle Energy Consumption and Emissions**



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[35] Luc Gagnon (2006); *Greenhouse Gas Emissions from Transportation Options*, Hydro Quebec; at www.hydroquebec.com/sustainable-development/documentation/pdf/options_energetiques/transport_en_2006.pdf.

[36] Mikhail Chester and Arpad Horvath (2008), *Environmental Life-cycle Assessment of Passenger Transportation*, UC Berkeley Center for Future Urban Transport (www.its.berkeley.edu/volvocenter).

- The UK Department for Environment, Food and Rural Affairs publishes *Air Quality Economic Analysis: Damage Costs by Location and Source*, which provides a list of damage costs per tonne of NOx and PM emissions by location and source, for policy and project evaluation, as summarized in Table 5.10.4-4.

Table 5.10.4-4 **Damage Costs By Location and Source** (£2017/tonne)[37]

Pollutant	Central Value	Low Sensitivity Area	High Sensitivity Area
NOx	6,199	634	23,153
SO2	6,273	1,491	17,861
NH3	6,046	1,133	18,867
VOC	102	55	205
PM2.5	105,836	22,588	327,928

This table summarizes air pollution unit costs used for economic evaluation in the UK. For more information see www.gov.uk/guidance/air-quality-economic-analysis.

- The U.S. FHWA published a detail study of future freight transport emissions under various conditions, indicating that emission rates of most pollutants will decline significantly between 2002 and 2020, as indicated in the table below.

Table 5.10.4-5 **Arterial Truck Emission Factors (grams/mile)**[38]

Truck Class	Year	VOC	CO	NOX	PM-10 Total	PM-10 Exhaust Only
Single-Unit Truck – Gasoline	2002	2.29	59.87	7.18	0.13	0.11
	2010	0.61	14.24	4.95	0.09	0.07
	2020	0.21	9.00	1.92	0.05	0.03
Single-Unit Truck – Diesel	2002	0.59	2.86	15.34	0.42	0.38
	2010	0.37	1.41	6.18	0.17	0.13
	2020	0.26	0.30	1.01	0.07	0.03
Combination Truck – Diesel	2002	0.61	3.18	17.02	0.41	0.37
	2010	0.39	1.47	6.38	0.17	0.13
	2020	0.28	0.33	1.03	0.07	0.03

- The report, *Non-Exhaust Emissions from Road Traffic*, indicate that particles from brake, tire and road surface wear currently constitute 60-73% (by mass) of PM2.5 and PM10 road transport emissions, contribute 7.4% and 8.5% of fine particulat emissions, and will become more dominant in the future.[39] NEEs are especially important in urban environments due to frequent braking, and on major highways due to high travel speeds. Field testing found that a typical car emits 5,760mg/km of tyre wear emission, about 1,000 more than the 4.5mg/km exhaust emission limits.[40]

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[37] DEFR (2019), *Damage Costs by Location and Source, Air Quality Economic Analysis*, UK Department for Environment, Food and Rural Affairs (https://uk-air.defra.gov.uk); at https://bit.ly/33xcQfu.
[38] ICF Consulting (2005), *Assessing the Effects of Freight Movement on Air Quality at the National and Regional Level*, US Federal Highway Admin. (www.fhwa.dot.gov); at https://bit.ly/33A9acV.
[39] Air Quality Expert Group (2019), *Non-Exhaust Emissions from Road Traffic*, UK Department for Environment, Food and Rural Affairs (https://uk-air.defra.gov.uk); at https://bit.ly/2Ufin64.
[40] EA (2020), *Tyres not Tailpipes*, Emissions Analystics (www.emissionsanalytics.com); at https://bit.ly/3bctOCp.

- Several studies compare lifecycle climate emissions of various vehicle types.[41] These comparisons are complex and depend on vehicle size, how embodied energy and fuel-economy are estimated, how emissions are calculated, assumed driving patterns, and even regional climate. No single estimate applies everywhere. In most cases electric vehicles produce far lower emissions than conventional gasoline or diesel vehicles, and somewhat lower emissions that hybrid vehicles. Their benefits are large in areas with renewable electicity, but small or insignificant in areas with coal-intensive generation.

- Henderson, Cicas and Matthews compare the energy consumption and pollution emission rates of various freight modes.[42] They find that truck transport consumes about 15 times as much energy and produces about 15 times the pollutant emissions per ton-mile as rail, water and pipeline transport.

- A major study evaluated the effects of proximity to major roads on human coronary artery calcification (CAC).[43] The results indicate that reducing the distance between the residence and a major road by half was associated with a 7.0% increase in CAC.

- A major National Research Council study provided an extensive review of energy consumption external costs.[44] It estimated emissions of criteria (conventional air pollution) and climate change gases (CO_2-equivelent per vehicle-mile), and their unit costs (per vehicle-mile and gallon of fuel) for various vehicle fuels and time periods. It provided the following estimates of motor vehicle fuel exernal costs:
  - Aggregate national non-climate change damages costs are approximately $36 billion for the lightduty vehicles in 2005 and $56 billion including heavy vehicles.
  - Non-climate change costs from transportation energy use average 1.2¢ to >1.7¢ per vehicle-mile for the current U.S. vehicle fleet, plus 0.15¢ to >0.65¢ climate change emissions at $10 per tonne of CO_2-equivelent; 0.45¢ to >2.0¢ at $30 per tonne of CO_2-eq; and 1.5¢ to >6.0¢ at $100 per tonne of CO_2-eq. The table below summarizes these estimates. This suggests that external energy costs range from about 1.4¢ to 7.7¢ per vehicle mile in 2007 dollars.

	$10/Tonne CO_2-Eq	$30/Tonne CO_2-Eq	$100/Tonne CO_2-Eq
Non-climate change	$0.012- >0.017	$0.012- >0.017	$0.012- >0.017
Climate change	$0.0015- >0.0065	$0.045- >0.020	$0.015- >0.060
Total	*$0.0135->0.0235*	*$0.057- >0.037*	*$0.027->0.077*

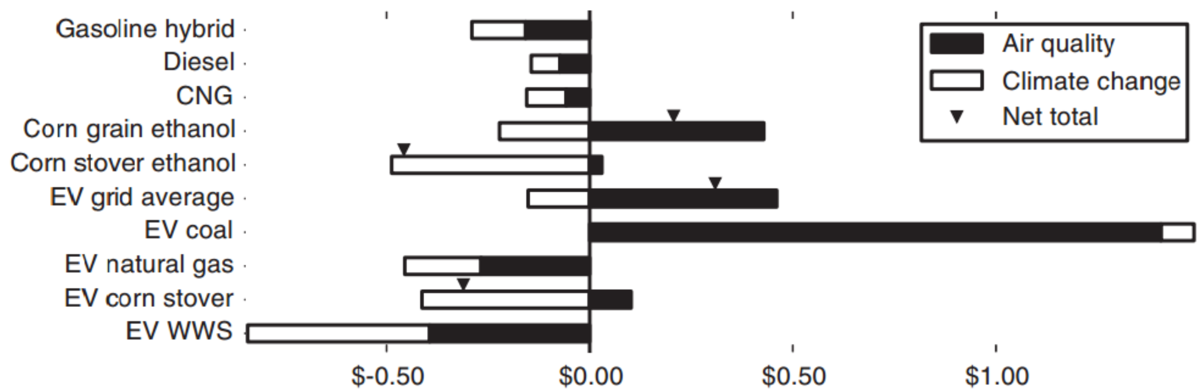
[41] Zeke Hausfather (2019), *Factcheck: How Electric Vehicles Help to Tackle Climate Change*, Carbon Brief (www.carbonbrief.org); www.carbonbrief.org/factcheck-how-electric-vehicles-help-to-tackle-climate-change.
[42] Chris Hendrickson, Gyorgyi Cicas and H. Scott Matthews (2006), "Transportation Sector and Supply Chain Performance and Sustainability," *Transportation Research Record 1983* (www.trb.org), pp. 151-157.
[43] B. Hoffmann, et al. (2007), "Residential Exposure to Traffic Is Associated With Coronary Atherosclerosis," *Circulation*, July 31, 2007 (www.circulationaha.org); at www.precaution.org/lib/traffic_and_atherosclerosis.070717.pdf.
[44] NRC (2009), *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*, Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption; National Research Council, National Academy of Sciences (www.nap.edu/catalog/12794.html).

- Electric vehicles and grid-dependent hybrid vehicles showed somewhat higher damages than many other technologies for both 2005 and 2030. Although operation of the vehicles produces few or no emissions, electricity production at present relies mainly on fossil fuels and, based on current emission control requirements. In addition, battery and electric motor production added up to 20% to the damages from manufacturing.
- Depending on the extent of projected future damages and the discount rate used for weighting them, the range of estimates of marginal damages spanned two orders of magnitude, from about $1 to $100 per ton of CO_2-eq, based on current emissions. Approximately one order of magnitude in difference was attributed to discount-rate assumptions, and another order of magnitude to assumptions about future damages from emissions. At $30/ton of CO_2-eq, motor vehicle climate change damage costs begin to approach the value of non-climate damages.

- Shindell used a multi-impact economic valuation framework called the Social Cost of Atmospheric Release (SCAR) that considers a variety of of pollutants and impacts, including climate change and human health impacts.[45] The results suggest that efforts to mitigate atmosphere-related environmental damages should target a broad set of emissions including CO2, methane and aerosol/ozone precursors. Illustrative calculations indicate environmental damages are $3.80 (−1.80/+2.10) per gallon of gasoline and $4.80 (−3.10/+3.50) per gallon of diesel.

- Tessuma, Hillb and Marshalla estimate that upstream and tailpipe particulate and ozone emissions cause human deaths valued at about 50¢ per gallon or 2.5¢ per vehicle-mile for gasoline, with different costs for other fuels as illustrated in the figure below.

Figure 5.10.3-2 **Externality Damages Per Gallon Equivalent to Gasoline**[46]



- van Essen, et al describe various method that can be used to calculate air pollution costs, and summarize monetized estimates of various pollutants.[47] They recommend the Impact Pathway Approach (IPA) developed by the ExternE-project.

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[45] Drew Shindell (2015), "The Social Cost of Atmospheric Release," *Climate Change*, (http://link.springer.com/article/10.1007/s10584-015-1343-0).

[46] Christopher W. Tessuma, Jason D. Hillb and Julian D. Marshalla (2014), "Life Cycle Air Quality Impacts Of Conventional And Alternative Light-Duty Transportation In The United States," Proceedings of the National Academy of Science (www.pnas.org); at www.pnas.org/content/early/2014/12/10/1406853111.full.pdf.

- Wang summarizes various air pollution reduction unit cost studies in dollars per ton of reduction.[48] He describes factors that affect such cost estimates, including perspective (individual or social), emissions considered, emission rates calculations, baseline assumptions, geographic and temporal scope, and how program costs are calculated. Ignores cobenefits (congestion reduction, road and parking savings, crash reductions, etc.) from mobility management.

- The Clean Air for Europe (CAFE) Programme developed monetized damage costs per tonne of pollutant for each European Union country (excluding Cyprus) and for surrounding seas. The analysis provides a range of estimates based on various input values. The table below summarizes overall average values. Emissions occurring at sea impose 50-80% of the damage of the same emissions occurring on land.

Table 5.10.4-6 **Average Damages Per Tonne of Emissions** (2005)[49]

Assumptions				
PM mortality	VOLY median	VSL median	VOLY mean	VSL mean
O3 Mortality	Mortality	VOLY median	VOLY mean	VOLY mean
Health Care?	Included	Included	Included	Included
Health sensitivity?	Not included	Not included	Included	Included
Crops	Included	Included	Included	Included
O3/health Metric	SOMO 35	SOMO 35	SOMO 0	SOMO 0
European Land Areas				
NH_3	€11,000	€16,000	€21,000	€31,000
NOx	€4,400	€6,600	€8,200	€12,000
$PM_{2.5}$	€26,000	€40,000	€51,000	€75,000
SO_2	€5,600	€8,700	€11,000	€16,000
VOCs	€950	€1,400	€2,100	€2,800
European Area Seas				
NOx	€2,500	€3,800	€4,700	€6,900
$PM_{2.5}$	€13,000	€19,000	€25,000	€36,000
SO_2	€3,700	€5,700	€7,300	€11,000
VOCs	€780	€1,100	€1,730	€2,300

This table summarizes air pollution unit cost values from a major study sponsored by the European Union. The full report provides a variety of cost values reflecting various assumptions, with individual values for each country reflecting their specific geographic situation. (VOLY = *"Value Of a Life Year";* VSL = *"Value of a Statistical Life";* SOMO = *"Sum of Means Over 35 ppbV")*

[47] van Essen, et al (2004), *Marginal Costs of Infrastructure Use – Towards a Simplified Approach*, CE Delft (www.ce.nl); in Vermeulen, et al (2004), *Price of Transport: Overview of the Social Costs of Transport*, CE Delft; at www.rapportsysteem.nl/artikel/index.php?id=181&action=read.

[48] Michael Q. Wang (2004), "Examining Cost Effectiveness of Mobile Source Emission Control Measures," *Transport Policy*, Vol. 11, No. 2, (www.elsevier.com/locate/tranpol), April 2004, pp. 155-169.

[49] AEA Technology Environment (2005), *Damages Per Tonne Emission of PM2.5, NH3, SO2, NOx and VOCs From Each EU25 Member State*, Clean Air for Europe (CAFE) Programme, European Commission (www.cafe-cba.org); at www.cafe-cba.org/reports.

Climate Change Emissions

This section describes climate change unit costs. For more information see "Climate Change Emission Valuation for Transportation Economic Analysis."[50]

Table 5.10.4-14 summarizes climate change *damage cost* unit values from various studies, with their values converted to 2007 U.S. dollars.

Table 5.10.4-14 **Climate Change Damage Cost Estimates**

Publication	Description	Cost Value/tonne CO_2	2007 USD/t CO_2
Tol (2005)**	Minimum	-4 Euro (2000)	$-4.43
	Central	11	**$12**
	Maximum	53	$59
DLR (2006)**	Minimum	15 Euro (2000)	$17
	Central	70	**$78**
	Maximum	280	$310
Jakob, Craig & Fisher (2005)	Damage	NZ $270 (2003)	**$178**
Hohmeyer & Gartner (1992)	Damage	$220 *	**$326**
Bein (1997)	Recommended	$1,000 Canadian*	**$917**
	Maximum	$4,264	$3,910

*Central or recommended values are shown in bold. 2007 Values were converted to USD in the base year then adjusted for inflation by Consumer Price Index. *Assumes the currency year is the same as the publication year. ** From Maibach et al. 2008. For a graphic comparison of cost values see Figure 4.1 in* Climate Change: The Cost of Inaction and the Cost of Adaptation *(EEA, 2006).*

Table 5.10.4-15 summarizes climate change *control cost* unit values from various studies, with their values converted to 2007 U.S. dollars.

Table 5.10.4-15 **Climate Change Control Cost Estimates – Selected Studies**

Publication	Costs	Cost Value/tonne CO_2	2007 USD/tonne
BTCE (1996)	Social Cost of Transportation Measures	Includes measures with less than zero social cost	Includes less than zero
Bloomberg News (2007)	2007 price of EU CO_2 permits for 2008	€21.45	$29
SEC (2008)**	2010	€14	$16
	2020	€38	$42
	2030	€64	$71
	2050	€120	$133
Stern (2006)**	2015	€32 – 65 (2000)	$35 – 72
	2025	€16 – 45	$18 – 50
	2050	€-41 – 81	$-45 – 90
Markus Maibach et al (2000)		€135	$150

*Mitigation cost estimates vary considerably, but less than damage costs. * Indicates that the currency year is assumed to be the same as the publication year. ** Indicates that the data is cited from Maibach et al., 2008.*

[50] Todd Litman (2009), *Climate Change Emission Valuation for Transportation Economic Analysis.* (www.vtpi.org); at www.vtpi.org/ghg_valuation.pdf.

- A team of economists headed by Sir Nicholas Stern, Head of the U.K. Government Economics Service, performed a comprehensive assessment of evidence on the impacts of climate change, using various techniques to assess costs and risks. Using the results from formal economic models the Review estimates that the overall costs and risks of inaction on climate change will be equivalent to at least 5% of global GDP, and if a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more.[51] This study supports the development of international emission trading, which would establish a monetized unit value of greenhouse gas emissions. In 2008 Stern stated that new scientific findings show that his 2006 evaluation greatly underestimated the potential threat and costs of GHG emissions.[52]

- The Australian Government's Garnault Climate Change Review (2008) provides an updated review of climate science and economics, particularly in light of the IPCC's 2007 reports. It indicates that current emission trends have almost 50% chance of increasing global temperatures 6 degrees Centigrade by 2100, much higher than the 3% risk estimate made in 2007 based on older studies such as the IPCC's 2001 reports.[53]

- A 2006 study of Canadian greenhouse gas emissions from transportation estimates that transportation accounts for 31% of total emissions if only tailpipe emissions are counted, but over 50% if the full lifecycle of transportation is counted.[54]

- The European Commission *ExternE* program monetized energy production external costs for 14 countries. The table below summarizes estimates of global warming unit costs.

Table 5.10.4-16 **Greenhouse Gas Damage Costs**[55]

Emission	Units	Low	Mid Point	High
Carbon Dioxide	tonne carbon	€74	€152	€230
Carbon Dioxide	tonne CO_2	€20	€42	€63
Methane	tonne CH_4	€370	€540	€710
Nitrous Oxide	tonne N_2O	€6,800	€21,400	€36,000

[51] Sir Nicholas Stern (2006), *Stern Review on the Economics of Climate Change*, HM Treasury (www.sternreview.org.uk).
[52] David Adam (2008) "I underestimated the threat, says Stern", *The Guardian* (www.guardian.co.uk), April 18 2008; at www.guardian.co.uk/environment/2008/apr/18/climatechange.carbonemissions
[53] Ross Garnault et al. (2008) *The Garnault Climate Change Review:Final Report,* Australian Government Department of Climate Change (www.climatechange.gov.au); at www.garnautreview.org.au
[54] Luc Gagnon (2006); *Greenhouse Gas Emissions from Transportation Options,* Hydro Quebec (www.hydroquebec.com); at www.hydroquebec.com/sustainable-development/documentation/pdf/options_energetiques/transport_en_2006.pdf . This data includes all domestic transportation, but not international flights or shipping.
[55] EC (1998), *ExternE; Newsletter 6*, European Commission ExternE Project (www.externe.info), March 1998.

- CE Delft (2008) reviews a number of damage and avoidance cost studies. They base their recommended values on avoidance costs in the short term (2010 and 2020) and on estimated damage costs after 2020. The escalating values recommended are shown in the table below.[56] The recommended per Km value for urban gasoline powered cars is 0.67 Euro cents per km, with a range of 0.19 to 1.20 Euro cents per km (based on tailpipe emissions only and the 2010 values shown below).

Table 5.10.4-17 **External Costs of GHG Emissions** (€/tonne CO_2)

Year	Lower value	Central value	Upper value
2010	7	25	45
2020	17	40	70
2030	22	55	100
2040	22	70	135
2050	20	85	180

`Both avoidance and damage cost estimates increase over time in this study

- The Intergovernmental Panel on Climate Change estimates the costs of mitigating climate change impacts at US $0.10 to $20 per-ton of carbon in tropical regions and US $20 to $100 elsewhere. It also finds that GDP losses in the OECD countries of Europe would range from 0.31% to 1.5% in the absence of international carbon trading, and with full trading the GDP loss would fall to between 0.13% and 0.81%.[57]

- A 2000 report for the International Union of Railways uses a shadow value of 135 Euro per tonne CO_2 based on avoidance costs, with a range from 70 to 200 Euro.[58]

- Point Carbon, an emission trading consulting firm, has developed Certified Emissions Reductions (CER) contracts, with prices that vary depending on how risks are distributed between seller and buyer, and the nature of the projects. The table below indicates price ranges prior to 2006, in Euros per tonne of carbon dioxide equivalent (t CO_2e).

Table 5.10.4-18 **Carbon Emission Credit Prices**[59]

Description	Price Range (EURO/t CO_2e)
Non-firm volume. Buyer buys what seller delivers even if emissions reductions turn out not to qualify as CERs.	€3-6
Non-firm volume. Contract contains preconditions, e.g. that the underlying project qualifies for the CDM.	€5-10
Firm volume. Contract contains preconditions (as above). Usually strong force majeure clauses and high credit rating requirements.	€9-14
Firm volume. No preconditions. Forward spot trades will fit this category.	€12-14

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56 M. Maibach, et al. (2008), *Handbook on Estimation of External Cost in the Transport Sector*, CE Delft (www.ce.nl); at http://ec.europa.eu/transport/costs/handbook/doc/2008_01_15_handbook_external_cost_en.pdf
57 IPCC (2001), *Climate Change 2001: Synthesis Report*, Intergovernmental Panel on Climate Change (www.ipcc.ch).
58 Markus Maibach et al (March 2000) *External Costs of Transport*. INFRAS (www.infras.ch) / IWW Universitaet Karlsruhe (www.iww.uni-karlsruhe.de).
59 Point Carbon (2006), *Carbon 2006 Towards a Truly Global Market*, (www.pointcarbon.com).

- A July 2007 media report notes EU carbon dioxide permits for 2008 were trading at €21.45, or $29.22, a tonne, 47 percent more than the price of 2008 UN credits, called certified emission reductions.[60]

- A U.S. government study concludes that aviation emissions are potentially a significant and growing contributor to climate change, particularly because high-level emissions may have much greater impacts than emissions lower in the atmosphere.[61]

5.10.5 Variability

Vehicle air pollution costs vary depending on vehicle, fuel and travel conditions. Larger, older and diesel vehicles, and those with ineffective emission controls have higher emission costs. Emissions rates tend to be higher for short trips. Urban driving imposes greater air pollution costs than rural driving. Climate change, ozone depletion and acid rain emissions have costs regardless of where they occur. Climate change costs estimates tend to increase with time and depend on the emissions scenario being considered.

5.10.6 Equity and Efficiency Issues

Air pollution emissions are an external cost, and therefore inequitable and inefficient. Lower-income people tend to have relatively high emission vehicles, so emission fees or restrictions tend to be regressive, but many lower-income people experience heavy exposure to air pollutants, and so benefit from emission reduction strategies.

Global warming is inequitable on a global scale since the people with the least responsibility for the problem (lowest incomes and lowest GHG emissions) are the most susceptible to the damage caused.

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[60] Bloomberg News (July 3, 2007), "Price difference between EU and UN carbon credits offers 'huge' profit opportunity" *International Herald Tribune (*www.iht.com); at www.iht.com/articles/2007/07/03/business/carbon.php

[61] GAO (2000), *Aviation and the Environment; Aviation's Effects on the Global Atmosphere Are Potentially Significant and Expected to Grow,* U.S. General Accounting Office (www.gao.gov), Feb. 2000.

5.10.7 Conclusions

Air pollution cost estimates other than GHGs are based on studies described in this chapter, reflecting only tailpipe emissions. It excludes "upstream" emissions that occur during fuel production and distribution, and the pollution associated with vehicle manufacturing and roadway construction, as these costs are captured in chapter 5.12. However, full lifecycle climate change emissions are included in the estimates below.

Greenhouse gas cost estimate

The greenhouse gas emission values are based on the studies summarized in tables 5.10.4-14 and 5.10.4-14. A control cost estimate is used to calculate the default values and damage costs are provided as an upper bound and for sensitivity analysis, as discussed in the VTPI report *Climate Change Emission Valuation for Transportation Economic Analysis*.[62]

Studies by leading experts indicate that climate change may impose significant economic, social and environmental costs. These damages could be catastrophic, far beyond what is considered acceptable and rational, so the upper-bound estimate of damage costs could be virtually infinite. Even more moderate damage predictions imply significant costs that justify significant action to avoid these impacts. Control costs tend to be significantly lower than damage costs. Several recent studies suggest that emission control costs will remain $20-50 per tonne of CO_2e for some time, although this may increase to achieve larger emission reductions. A value of $35 per tonne is used as the default value.

Given that the range of damage cost estimates is from $19 to $917 per tonne, selecting the most appropriate value to use for sensitivity analysis is a difficult task. The value used is 33% of $917 rounded to $300 per tonne CO_2e. This value is well above many damage values used in the past, but these lower values must be re-assessed in light of the most recent scientific findings discussed in section 5.10.3 and 5.10.4.

To calculate the per mile value of GHG emissions, the total 2006 US greenhouse gas emissions from the transportation sector was multiplied by the percentage of petroleum use in road transportation (2.010 billion tonnes X 84.1%) for 1.690 billion tonnes of tailpipe emissions.[63] To convert to lifecycle emissions, including automobile manufacturing, roadway construction and maintenance, and upstream emissions from petroleum extraction and refining, values from the Canadian study *Greenhouse Gas Emissions from Transportation Options* are used indication overall transportation emissions at 1.68 times tailpipe emissions.[64] However, as air conditioning emissions are included in the original figures which would bring the factor down to 1.58, and since there is some uncertainty about applying Canadian data to the US and other countries, a more conservative factor of 1.4 is used. This results in a lifecycle emissions estimate of 2.366 billion tonnes. Divided by 3000

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62 Todd Litman (2009), *Climate Change Emission Valuation for Transportation Economic Analysis.* (www.vtpi.org); at www.vtpi.org/ghg_valuation.pdf

63 ORNL (2008), Transportation Energy Data Book, Oak Ridge National Laboratory (www.ornl.gov), Tables 1.16 & 11.4; at http://cta.ornl.gov/data/index.shtml

64 Luc Gagnon (2006); *Greenhouse Gas Emissions from Transportation Options*, Hydro Quebec (www.hydroquebec.com); at www.hydroquebec.com/sustainable-development/documentation/pdf/options_energetiques/transport_en_2006.pdf (52%/31%=1.68)

billion annual miles results in estimated emissions of 0.00079 tonnes per mile (0.79 kg) per mile (including heavy trucks).[65] Average car emissions are estimated at 0.49 kg per mile, which is about 15% lower than the lifecycle automobile emissions estimate in the 2008 report, *Environmental Life-cycle Assessment of Passenger Transportation.*[66] Multiplied by $35 per tonne gives an average cost of $0.028 per vehicle mile or $0.017 for an average car.

Summary & Allocation of Costs

Urban Peak local air pollution is estimated to cost about 5¢ per average automobile mile. Urban Off-Peak costs are estimated at a slightly lower 4¢ per VMT to account for smoother road conditions. Rural driving air pollution costs are estimated to be an order of magnitude lower at 0.4¢ per VMT.

Greenhouse gas emissions are estimated at 1.7¢ per mile for an average car and 2.4¢ per mile for light trucks, as shown below in table 5.10.7-2. The upper bound value for greenhouse gas emissions is represented by damage costs of $300 per tonne or about 15¢ per mile for an average car and 20¢ per mile for light trucks, as shown below in table 5.10.7-3.

Compact cars are estimated to have local emissions 10% lower than an average car, and 20% lower global warming costs. Although electric vehicles produce no tail-pipe emissions, and reduce brake emissions through regenerative braking, their electicity production produces air pollution, and due to their battery weight, they produce high tire and road wear emissions, and so are estimated to produce 25% of local emissions and 25% of global warming costs based on the fact that electric vehicles produce brake, tire and road dust particulates comparable to gasoline vehicles. Vans and light trucks are estimated to produce 80% more local air pollution than an average car. Motorcycles are estimated to produce twice the local air pollution and half the climate emissions of an average car.

Each rideshare passenger imposes an air pollution cost 2% of a van based on a 20% emission increase for 10 passengers. Older buses produced relatively high local air pollution costs due to high pollution output of diesel engines, but this is decreasing with new standards and technologies, so current and near future local emission costs are estimated to be 2.5 times greater than an average automobile, and greenhouse gas costs are 5 times higher based on fuel consumption. Electric trolleys and urban buses are estimated to have air pollution five times greater than an electric car, and GHG emissions 1/3rd that of a diesel bus. Bicycling, walking, and telecommuting are estimated to have negligible air pollution costs.

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[65] This is significantly higher than results obtained using EPA fuel efficiency ratings, but real world fuel consumption and emissions are considerably higher that rated mileage. E.g. Jeremy Korzeniewski (Aug. 2 2008) *Cars.com calculates the real CAFE numbers with True Mileage Index!* (www.cars.com); at www.autobloggreen.com/tag/true+mileage+index/ ; EWG (2006) *Putting the Truth in Your Tank*, Environmental Working Group (www.ewg.org); at www.ewg.org/reports/realmpg.

[66] This report estimates lifecycle emissions for a Camry sedan at 0.36 kg per passenger mile or 0.57 kg per vehicle mile. Mikhail Chester and Arpad Horvath (2008), *Environmental Life-cycle Assessment of Passenger Transportation: A Detailed Methodology for Energy, Greenhouse Gas and Criteria Pollutant Inventories of Automobiles, Buses, Light Rail, Heavy Rail and Air v.2*, UC Berkeley Center for Future Urban Transport, (www.its.berkeley.edu/volvocenter/), Paper vwp-2008-2; at http://repositories.cdlib.org/its/future_urban_transport/vwp-2008-2.

Table 5.10.7-1 Estimate **Non-GHG Air Pollution Costs** (2007 US Dollars per VMT)

Vehicle Class	Urban Peak	Urban Off-Peak	Rural	Average
Average Car	0.062	0.052	0.004	0.040
Compact Car	0.051	0.042	0.003	0.031
Electric Vehicles	0.016	0.013	0.001	0.010
Van/Light Truck	0.112	0.094	0.007	0.071
Rideshare Passenger	0.002	0.002	0.000	0.001
Diesel Bus	0.185	0.160	0.013	0.129
Electric Bus/Trolley	0.078	0.065	0.005	0.050
Motorcycle	0.106	0.086	0.006	0.061
Bicycle	0.000	0.000	0.000	0.000
Walk	0.000	0.000	0.000	0.000
Telecommute	0.000	0.000	0.000	0.000

These only include tailpipe emissions. Other air pollution costs are covered in chapter 5.12.

Table 5.10.7-2 Estimate **Greenhouse Gas Control Costs** (2007 USD per VMT)

Vehicle Class	Urban Peak	Urban Off-Peak	Rural	Average
Average Car	0.019	0.017	0.015	0.017
Compact Car	0.014	0.013	0.012	0.013
Electric Vehicles	0.005	0.004	0.004	0.004
Van/Light Truck	0.026	0.024	0.021	0.024
Rideshare Passenger	0.000	0.000	0.000	0.000
Diesel Bus	0.094	0.086	0.077	0.086
Electric Bus/Trolley	0.031	0.028	0.026	0.028
Motorcycle	0.009	0.009	0.008	0.009
Bicycle	0.000	0.000	0.000	0.000
Walk	0.000	0.000	0.000	0.000
Telecommute	0.000	0.000	0.000	0.000

These control costs are the default values used for analysis. Damage cost values shown in the table below reflect an upper bound for use in sensitivity analysis. These reflect lifecycle emissions including emissions during petroleum extraction and refining, vehicle manufacturing and maintenance, as well as roadway construction and maintenance.

Table 5.10.7-3 Estimate **Greenhouse Gas Damage Costs** (2007 USD per VMT)

Vehicle Class	Urban Peak	Urban Off-Peak	Rural	Average
Average Car	0.161	0.147	0.132	0.147
Compact Car	0.121	0.110	0.099	0.110
Electric Vehicles	0.040	0.037	0.033	0.037
Van/Light Truck	0.222	0.202	0.181	0.202
Rideshare Passenger	0.004	0.004	0.004	0.004
Diesel Bus	0.806	0.733	0.660	0.733
Electric Bus/Trolley	0.269	0.244	0.220	0.244
Motorcycle	0.081	0.073	0.066	0.073
Bicycle	0.000	0.000	0.000	0.000
Walk	0.000	0.000	0.000	0.000
Telecommute	0.000	0.000	0.000	0.000

These damage costs are upper bound values for use in sensitivity analysis. These reflect lifecycle emissions.

Automobile Cost Range

The minimum value estimate is based on the lower range of estimates described. The maximum is based on the higher end range of the estimates described.

	Minimum	Maximum
Local Air Pollution	$0.002	$0.10
GHG Emissions	$0.009	$0.15

5.10.8 Resources

Resources on vehicle emissions and emission reduction strategies are listed below.

Emission Calculators

Below are various tools for calculating the emissions of various activities and goods:

- *CarbonCounter* (www.carboncounter.org). Carboncounter.org is an individual carbon dioxide emissions calculator generated by The Climate Trust.
- *Density Effects Calculator* (www.sflcv.org/density). Indicates how neighborhood density impacts the environment (land, materials, energy and driving).
- *EPA's Personal Online Greenhouse Gas Calculator* (www.epa.gov/climatechange/emissions/ind_calculator.html).
- *MetroQuest* (www.envisiontools.com). Evaluates different long-term planning strategies.
- *Personal* CO_2 *Calculation* (www3.iclei.org/co2/co2calc.htm). This worksheet determines yearly direct personal carbon dioxide emissions. Results include yearly personal carbon dioxide emissions and a per capita comparison chart to other industrialized countries.
- *SafeClimate Carbon Dioxide Footprint Calculator* (http://safeclimate.net/calculator). Calculates "carbon footprints" by tracking residential and transportation energy consumption and greenhouse gas emissions in the U.S., Canada and 36 other countries.
- *Tool For Costing Sustainable Community Planning* (www.cmhc-schl.gc.ca/en/inpr/su/sucopl/index.cfm) by the Canadian Mortgage and Housing Corporation allow a user to estimate the major costs of community development, particularly those that change with different forms of development (e.g., linear infrastructure), and to compare alternative development scenarios.
- Travel Matters Emissions Calculators *(www.travelmatters.org). TravelMatters! from the Center for Neighborhood Technology that provides interactive emissions calculators, online emissions maps, and a wealth of educational content that emphasize the relationship between more efficient transit systems and lower greenhouse gas emissions.*

Other Resources

Michael Brauer, Conor Reynolds and Perry Hystad (2013), "Traffic-Related Air Pollution And Health In Canada," *Canadian Medical Association Journal*, Vol. 185, No. 18, pp. 1557-1558; at www.cmaj.ca/content/185/18/1557. Also see (2012), *Traffic-Related Air Pollution and Health: A Canadian Perspective on Scientific Evidence and Potential Exposure-Mitigation Strategies*, Simon Fraser University (www.sfu.ca) for Health Canada; at www.sfu.ca/clearstudy/Documents/2012-03-01%20Traffic%20and%20Health%20FINAL.pdf.

Tufts University (2011), *Community Assessment of Freeway Exposure & Health Study*, http://now.tufts.edu/articles/every-breath-you-take. This major, multi-faceted study investigates roadway air pollution and its effects on residents' health.

Mikhail Chester and Arpad Horvath (2008), *Environmental Life-cycle Assessment of Passenger Transportation: A Detailed Methodology for Energy, Greenhouse Gas and Criteria Pollutant Inventories of Automobiles, Buses, Light Rail, Heavy Rail and Air v.2*, Paper vwp-2008-2, UC Berkeley Center for Future Urban Transport (www.its.berkeley.edu/volvocenter), at www.sustainable-transportation.com.

Mikhail Chester, Stephanie Pincetl, Zoe Elizabeth, William Eisenstein and Juan Matute (2013), "Infrastructure And Automobile Shifts: Positioning Transit To Reduce Life-Cycle Environmental Impacts For Urban Sustainability Goals," *Environmental Research Letters*, Vol. 8, pp. (2013) (doi:10.1088/1748-9326/8/1/015041); at http://iopscience.iop.org/1748-9326/8/1/015041/pdf/1748-9326_8_1_015041.pdf.

Mark Delucchi (2005), *The Social-Cost Calculator (SCC): Documentation of Methods and Data, and Case Study of Sacramento*, Sacramento Area Council of Governments (SACOG) and the Northeast States for Coordinated Air-Use Management (NESCAUM), UCD-ITS-RR-05-37, (www.its.ucdavis.edu); at www.its.ucdavis.edu/publications/2005/UCD-ITS-RR-05-18.pdf.

DfT (2009), *Transport Analysis Guidance: 3.3.5: The Greenhouse Gases Sub-Objective*, Department for Transport (www.dft.gov.uk); at www.dft.gov.uk/webtag/documents/expert/unit3.3.5.php.

DEFR (2015), *Damage Costs by Location and Source, Air Quality Economic Analysis*, UK Department for Environment, Food and Rural Affairs (http://bit.ly/1hur2Ij); at www.gov.uk/government/uploads/system/uploads/attachment_data/file/460398/air-quality-econanalysis-damagecost.pdf.

EDRG (2007), *Monetary Valuation of Hard-to-Quantify Transportation Impacts: Valuing Environmental, Health/Safety & Economic Development Impacts*, NCHRP 8-36-61, National Cooperative Highway Research Program (www.trb.org/nchrp); at www.statewideplanning.org/_resources/63_NCHRP8-36-61.pdf.

Environmental Valuation Reference Inventory (www.evri.ca) is a searchable storehouse of empirical studies on the economic value of environmental benefits and human health effects.

Caroline Evans, et al. (2015), *Updating Environmental Externalities Unit Values*, Austroads (www.austroads.com.au); at www.onlinepublications.austroads.com.au/items/AP-T285-14.

GHG Assessment Tools (www.slocat.net/?q=content-stream/187/ghg-assessment-tools) describes various methods used to quantify transport sector greenhouse gas emissions, and the impacts of emission reduction strategies.

Sarath Guttikunda (2011), *Urban Air Pollution & Co-Benefits Analysis in India*, UrbanEmissions (www.UrbanEmissions.Info); at www.cgrer.uiowa.edu/people/sguttiku/ue/simair/SIM-air-Brochure.pdf.

Intergovernmental Panel on Climate Change (www.ipcc.ch) includes many publications on climate change impacts and costs.

ITDP (2010), *Manual for Calculating Greenhouse Gas Benefits of Global Environmental Facility Transportation Projects*, Institute for Transportation and Development Policy, for the Scientific and Technical Advisory Panel of the Global Environment Facility (www.thegef.org); at www.thegef.org/gef/GEF_C39_Inf.16_Manual_Greenhouse_Gas_Benefits.

ITDP and CAI-Asia Center (2010), *Transport Emissions Evaluation Models for Projects (TEEMP)*, Clean Air Initiative for Asian Cities (www.cleanairinitiative.org) and the Institute for Transportation and Development Policy (www.itdp.org); at www.cleanairinitiative.org/portal/node/6941. These Excel-based TEEMP models were developed for evaluating the emissions impacts of Asian Development Bank's transport projects (www.adb.org/Documents/Evaluation/Knowledge-Briefs/REG/EKB-REG-2010-16/default.asp) and were modified and extended for the for Global Environmental Facility (www.thegef.org) Scientific and Technical Advisory Panel (STAP). Also see *Manual for Calculating Greenhouse Gas Benefits of Global Environmental Facility Transportation Projects* (www.thegef.org/gef/GEF_C39_Inf.16_Manual_Greenhouse_Gas_Benefits).

Todd Litman (2009), "Evaluating Carbon Taxes As An Energy Conservation And Emission Reduction Strategy," *Transportation Research Record 2139*, Transportation Research Board (www.trb.org), pp. 125-132; based on *Carbon Taxes: Tax What You Burn, Not What You Earn*, Victoria Transport Policy Institute (www.vtpi.org); at www.vtpi.org/carbontax.pdf.

M. Maibach, et al. (2008), *Handbook on Estimation of External Cost in the Transport Sector*, CE Delft (www.ce.nl); at http://ec.europa.eu/transport/sustainable/doc/2008_costs_handbook.pdf.

Yeganeh Mashayekh, et al. (2011), "Costs of Automobile Air Emissions in U.S. Metropolitan Areas," *Transportation Research Record 2233*, Transportation Research Board (www.trb.org), pp 120-127, DOI 10.3141/2233-14; at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.933.2176&rep=rep1&type=pdf.

ORNL (annual reports), *Transportation Energy Data Book*, Oak Ridge National Laboratory, USDOE (http://cta.ornl.gov/data), provides annual energy price, supply and consumption.

Drew Shindell (2015), "The Social Cost of Atmospheric Release," *Climate Change*, (http://link.springer.com/article/10.1007/s10584-015-1343-0).

Niklas Sieber and Peter Bicker (2008), *Assessing Transportation Policy Impacts on the Internalization of Externalities of Transport*, Transport & Mobility Leuven for the European Commission; at www.tmleuven.be/project/refit/d3-3.pdf.

NRC (2009), *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*, Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption, National Research Council (www.nap.edu); at www.nap.edu/catalog/12794.html.

Transportation Air Quality Center, USEPA (www.epa.gov/otaq) provides information on vehicle emissions, emission reduction strategies, and tools for evaluating the emission impacts.

Travel Matters (www.travelmatters.org) is a website with interactive emissions calculators, on-line emissions maps and other information resources to help examine the relationships between transportation decisions and greenhouse gas emissions.

Urban Emissions Information (http://urbanemissions.info) is a website that promotes the sharing of knowledge base on air pollution analysis and management, particularly in developing countries. The *SIM-air Working Paper Series* (http://urbanemissions.info/simair/simseries.html) includes various technical papers concerning air pollution analysis and control.

USEPA Transportation Tools (www.epa.gov/otaq/stateresources/tools.htm) provides links to sources of information on transport activities, emissions and emission reductions.

Arthur Winer, Yifang Zhu and Suzanne Paulson (2014), "Carmageddon or Carmaheaven? Air Quality Results of a Freeway Closure," *Access 44*, Spring, pp. 10-16; at http://www.uctc.net/access/44/access44.pdf.

Anming Zhang, Anthony E. Boardman, David Gillen and W.G. Waters II (2005), *Towards Estimating the Social and Environmental Costs of Transportation in Canada*, Centre for Transportation Studies, University of British Columbia (www.sauder.ubc.ca/cts), for Transport Canada; at www.sauder.ubc.ca/cts/docs/Full-TC-report-Updated-November05.pdf.