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Climate Change Emission Valuation for Transportation Economic Analysis

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Climate change threatens to reduce opportunities for snow play, as well as ecological stability, species survival, and human security.

Abstract

This paper describes climate change impacts and costs, presents methods for quantifying and monetizing (measuring in monetary units) these impacts, summarizes published unit cost estimates, and explains the values used in the report, *Transportation Cost and Benefit Analysis*. Climate change emission valuation depends on many factors including the range of impacts considered, the methods used to quantify impacts, and emission reduction targets. Recent studies predict that damage costs are potentially very high if atmospheric greenhouse gas levels exceed critical thresholds, while emission control costs are $20-50 per tonne of carbon dioxide equivalent (CO_2e). Some transportation emission reduction strategies have relatively low costs when co-benefits such as consumer savings, congestion reductions and safety are considered.

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Introduction

Climate change (also called *global warming* and *the greenhouse effect*) refers to Earth climate changes caused by emission of gases (called *greenhouse gases* or *GHGs*) that increase atmospheric solar heat gain. Climate change gasses such as carbon dioxide (CO_2) are like salt in a soup: a certain amount is desirable but too much is unpleasant and harmful. Many experts believe that anthropogenic (human caused) increases in atmospheric greenhouse gasses pose significant *costs* (damages) and *risks* (possible future damages). In response, many jurisdictions, industries and consumers are committed to reducing their emissions. These often involve economic trade-offs, such as higher prices for more efficient equipment, or reduced consumption of energy-intensive goods such as air travel.

To *optimize* such decisions it is useful to establish *monetized* (measured in monetary units) climate change emissions, assigning cost values such as cents-per-gram or dollars-per-tonne. These are useful for decisions such as evaluating specific strategies, determining optimal emission reduction policies, and for setting appropriate emission prices and taxes (Litman, 2008). This is important for transportation economics because transport activities are a major and growing source of climate change emissions, and transport system changes can involve various costs and benefits, as described in *Transportation Cost and Benefit Analysis*.[1]

Transportation professionals often classify difficult-to-quantify impacts as *intangibles* (impacts that cannot be perceived by the senses) and exclud them from quantitative analysis. As a result, easy-to-measure impacts (such as project costs, vehicle operating expenses, and travel time savings) often receive more consideration than relatively difficult-to-measure social and environmental impacts, and concentrated, short-term impacts receive more consideration than dispersed, long-term impacts. This biases decision-making in various ways. For example, it tends to favor economic objectives (because they involve market resources) over social and environmental objectives; industries (which have more financial transactions) over communities (which involve more non-market transactions); wealthier people (because they purchase more market goods) over poorer people; and the current generation over future generations.

This paper provides an overview of these issues and describes the climate change emission values used in the 2009 update of *Transportation Cost and Benefit Analysis* (Litman, 2009). It summarizes information on climate change *costs* and *risks*, discusses methodologies for quantifying and monetizing these impacts, and reviews current climate change emission unit cost values.

[1] Todd Litman (2009), *Transportation Cost and Benefit Analysis: Techniques, Estimates and Implications*, Victoria Transport Policy Institute (www.vtpi.org/tca).

Climate Change Science

Atmospheric concentrations of climate change gasses such as carbon dioxide (CO_2) are increasing rapidly. Prior to the industrial revolution, CO_2 levels were 260 – 280 parts per million by volume (ppmv). During the last century they have increased to about 36% to 380 ppmv and are projected to continue rising due to human activity, particularly fossil fuel consumption.

A growing body of scientific evidence has indicated that climate change imposes significant costs and risks. Although scientists tend to be cautious, among related disciplines (climatology, geology, ecology, etc.) there is virtual consensus that anthropogenic climate change is occurring and imposes significant environmental, social and economic costs and risks (Pew Center on Global Climate Change, 2006). For example, the *Intergovernmental Panel on Climate Change* (IPCC, 2007a), 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." The United Nations Environmental Program's *2007 Global Environment Outlook* emphasizes the need for action to reduce these risks (UNEP, 2007). Although some organizations argue the evidence is inconclusive or that climate change provides as many benefits as costs (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 (Sourcewatch, 2008).

As experts gain more understanding of climate change impacts they have become more concerned about its costs and risks, including possible catastrophic damages due to thresholds and positive feedback loops. For example, a detailed study lead by respected economist Sir Nicholas Stern called attention to the threat of 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" (Stern et al., 2006). In 2008 Stern stated that his earlier evaluation, mainly based on the IPCC's 2001 report, underestimated potential damages:

> *"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." (Adam, 2008)*

The Australian Government's Garnault Climate Change Review, released in late 2008, provides an updated review of climate science and economics. 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 (Garnault et al., 2008). A 2008 study by some of the world's leading climate scientists argues that deep and rapid emission reductions are needed to avoid catastrophic damage:

> *"If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO2 will need to be reduced from its current 385 ppm to at most 350 ppm . . . If the present overshoot of this target CO2 is not brief, there is a possibility of seeding irreversible catastrophic effects."* (Hansen et al., 2008)

Measuring Climate Change Emissions

Climate change emission analysis can be challenging. Emissions are measured in various units, including grams, pounds, kilograms, tons, and metric tonnes. This report generally uses *metric tonnes of carbon dioxide equivalent* (tonnes CO_2e). A frequent source of confusion is the distinction between *carbon* (an element) and *carbon dioxide* (CO_2, a gas consisting of one carbon and two oxygen atoms). A unit of carbon equals 3.67 units of carbon dioxide. Table 1 shows greenhouse impact equivalency factors of various gases.

Table 1 **Greenhouse Gas Carbon Dioxide Equivalencies** (CO2 Equivalent)[2]

Name	Chemical Formula	Lifetime (years)	Global Warming Potential		
			20 years	*100 years*	*500 years*
Carbon dioxide	CO_2	Variable	1	1	1
Methane	CH_4	12	72	25	7.6
Nitrous oxide	N_2O	114	289	298	153
CFC-12	CCl_2F_2	100	11,000	10,900	5,200
HFC-134a	CH_2FCF_3	14	3,830	1,430	435
HCFC-22	$CHClF_2$	12	5,160	1,810	549

This table indicates the climate change impacts of various gases.

Table 2 indicates the total climate change emission impacts of various fuels, including carbon dioxide and other greenhouse gas emissions (total CO_2 equivalent values).

Table 2 **Tailpipe Carbon Dioxide Equivalencies** (Grams Per Liter)[3]

Fuel Type	CO_2	CH_4	N_2O	Total CO_2 Equivalent	
CO_2 Equivalent Factor	*1*	*21*	*310*	*Grams Per Liter*	*Grams Per US Gallon*
Gasoline	2,360	0.2273	0.3358	2,469	9,345
Diesel	2,730	0.0605	0.2	2,793	10,572
Ethanol 10	2,124	0.2273	0.3358	2,233	8,452
Ethanol 85	531	0.2273	0.358	640	2,422
Conventional Aircraft Fuel	2,330	2.19	0.23	2,447	9,262
Jet Fuel	2,550	0.08	0.25	2,629	9,951

This table indicates the climate change impacts of various transportation fuels.

In addition, transport activities have these climate change impacts (IPCC WG III, 2007b):

- Vehicle air conditioning refrigerants cause about 4.9% of transport climate change emissions.
- Nitrous oxide (N_2O) cause 2.0 to 2.8% of transport emissions.
- Methane (CH_4) emissions cause 0.1 to 0.3% of transport emissions.
- High altitude jet emissions have much greater impact than the same gases emitted at ground level.

[2] IPCC Working Group I, 2007, p 212; at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_Ch02.pdf.
[3] FHIO (2003), *Greenhouse Gas Table of Conversion Factors*, Canada Federal House in Order Office.

Table 3 indicates conversion factors for calculating transportation emissions and unit costs.

Table 3 **Conversion Factors** (http://en.wikipedia.org/wiki/Carbon_tax)

Fuel	CO_2 Emissions		Cost Per $10 per ton of CO_{2e}	
	Pounds Per Gallon	Grams Per Liter	Per Gallon	Per Liter
Gasoline	19.564	2344.3	$0.0978	$0.0258
Diesel	22.384	2682.2	$0.1119	$0.0296
Jet fuel	21.095	2527.7	$0.1055	$0.0279

This table indicates the quantity of CO_2 produced and the climate change emission costs per gallon and per liter for various fuels. For example, if climate change emissions are valued at $50 per tonne of CO_{2e}, emission costs per gallon of gasoline are 5 x $0.0978 = 49¢ per gallon, or about 2.4¢ per mile for 20 mile-per-gallon vehicles.

Analysis should generally reflect lifecycle emissions. Emissions occur *upstream*, during fuel extraction and processing, vehicle manufacturing, facility construction (particularly cement production), as well as tailpipe emissions. Table 4shows lifecycle emissions for various transport modes calculated by Chester and Horvath (2008). This indicates that tailpipe emissions represent only about 64% of lifecycle emissions for typical automobiles and 75% for typical bus transport. Gagnon (2006) found similar results, estimating that tailpipe emissions represent about 60% of total emissions.

Table 4 **Lifecycle Climate Change Emissions** (Grams of Greenhouse Gas Equivalent)[4]

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*

[4] The study also provides energy and emission rates for various forms of rail and commercial aviation.

Quantifying and Monetizing Climate Change Emission Costs

Although most experts agree that climate change imposes significant costs and risks, these impacts are difficult to *quantify* (measure in physical units) and *monetize* (measure in monetary units) for various reasons discussed below.

Climate change impacts are *indirect* (there are several steps between the release of a gas and its ultimate climatic effects), *long-term* (climatic impacts may take decades or centuries to fully occur) and *uncertain* (current models cannot predict with certainty the magnitude of all possible future effects). Climate change imposes a wide range of damages and risks, including ecological damages, species extinctions, increased storm severity, seawater rise, increased tropical diseases, drought, reduced agricultural productivity, higher air conditioning costs, and population displacements. Many impacts are *non-market* (involving goods not commonly traded in a competitive market so their monetary value must be determined indirectly). In addition, there are likely to be some *benefits*, including reduced heating costs and increased productivity for some agriculture. Both ecological and human systems may respond in ways that reduce some costs.

Climate change impacts are not necessarily linear, there may be thresholds beyond which impacts and resulting damages become catastrophic (Hansen, 2008). A 2008 European Commission report notes that some studies have particularly high upper-bound damage cost estimates "in the light of possible non-linear dramatic events" (Maibach, et al., 2008, p. 267). Some damages, such as increased diseases and reduced agricultural productivity, may have multiple causes so it is difficult to determine the share of costs caused by climate change emissions. Because much of the damages involve ecological resource and will occur generations into the future, their valuation must reflect assumptions about factors such as *existence value* (the inherent value of a person or ecological resource), *legacy value* (the value of providing resources to future generations) and *intergenerational equity* (fair treatment of future generation) that are based on ethical judgments.

For this type of analysis it is useful to categorize costs and risks according to their ease of quantification and monetization. For example, the Australian Government's Garnault Climate Change Review divides impacts into four categories (Garnault et al., 2008, 1.3):

- Currently measurable market impacts.
- Market impacts that could not be quantified in time for the review, but which are theoretically amenable to monetization.
- The insurance value of mitigation against extreme events, based in part on expert judgment since probabilities cannot be known from past experience.
- Non market impacts based on the values people place on factors such as environmental amenity, and their willingness to forego some consumption to preserve these amenities.

Monetization Techniques

Various techniques can be used to monetize non-market values (Litman, 2009, Chapter 4; EC, 2005; Zhang, et al, 2005). Transportation economists use these techniques to monetize accident costs, travel time and air pollution damages. Similar techniques can be used to monetize climate change emissions. Two basic approaches are used:

- *Damage costs* refers to the value of resources damaged or lost, such as land (due to sea level rise), agricultural productivity (due to hydrologic changes), hurricane damages, and lost species (due to habitat loss).
- *Control costs* (also called *avoidance* or *mitigation costs*) refers to the costs of avoiding a particular damaging impact, such as the costs of reducing emissions, protection against threats such as sea level rise, carbon sequestration (storage), or the cost of compensating people harmed by impacts such as sea level rise and additional hurricane damages.

Economic valuation should generally reflect the lower of these two approaches since it would be irrational to spend more on control costs than the value of avoided damages, nor accept damages if control costs are cheaper. If climate change damages are considered small and emission reductions are costly it is best to accept risks so valuation would be based on damage costs, but if climate change damage costs are considered high and control costs relatively cheap, it is rational to reduce risk, so valuation is based on control costs. However, damage costs can be used to reflect higher-bound costs for sensitivity analysis.

Economic valuation should generally reflect marginal impacts, that is, the costs or benefits of the next unit of consumption. Marginal damage costs tend to increase as atmospheric concentrations of climate change gases rise, and are not necessarily linear since damage costs and risks may increase exponentially due to threshold and positive feedback effects.

Marginal control costs tend to increase with increased emission reductions, since it is rational to implement the most cost effective (considering all costs and benefits) strategies first, requiring higher unit cost strategies to be implemented to achieve larger reductions. For example, some low cost (or even negative cost, that is, they provide net benefits) emission reduction strategies probably exist, such as cost effective vehicle fuel efficiency technologies, and transportation policy reforms that provide co-benefits such as congestion and accident reductions (Litman, 2007). However, once all lower-cost strategies are implemented, more costly strategies must be deployed to further reduce emissions.

Control cost estimates should reflect *net costs*, that is, all costs minus all benefits, including indirect and non-market impacts. Many transportation emission reductions strategies provide significant co-benefits, such as consumer savings, local air pollutant reductions, and economic benefits from reduced fuel imports. Emission reduction strategies that reduce total vehicle travel tend to provide additional benefits such as congestion reductions and improved mobility options for non-drivers. Costs may include the incremental costs of additional equipment or infrastructure (such as more efficient vehicles or building insulation), and reduced consumer value (such as reduced mobility, smaller and less powerful vehicles, cooler buildings during winter and warmer buildings during summer).

Table 5 **Range of Impacts (Costs and Benefits)**

	Costs	Benefits
Direct	Implementation costs Reduced consumer value Transition costs (costs of change) Transaction costs (costs of collecting and paying fees).	User financial savings (such as fuel cost savings) Additional user benefits (such as improved convenience, comfort and reliability) Transport system efficiency (reduced congestion, parking costs, accidents)
Indirect	Industrial transition costs (such as contraction of domestic vehicle production). Less agricultural productivity that would occur if ambient temperatures and CO_2 concentrations increase.	Reductions in other pollutants (local air pollution, noise, etc.) Economic benefits of reduced energy imports Environmental benefits from reduced energy production (such as avoided strip mines and petroleum leaks)

Control costs should reflect net costs, which are all cost minus all benefits. Emission control strategies often involve various costs and benefits, including many indirect impacts.

Transportation energy conservation programs are sometimes criticized as being economically harmful, particularly if they involve higher fuel taxes or reductions in automobile purchases, but these are really economic transfers (costs to one part of the economy and benefits to others). For example, higher fuel taxes provide revenues that can be used to reduce other taxes or provide additional investments, while reductions in automobile purchases leave consumers with more money to spend on other goods, increasing employment in other industries. Improved energy efficient and reduced petroleum imports tend to be very beneficial to the economy overall ("Economic Development Impacts," VTPI, 2008).

Some monetization debates involve *burden of proof* issues. For example, decision-makers can either assume that climate change damages can be ignored unless demonstrated beyond a doubt, or that climate change risks are significant unless demonstrated otherwise. Increasingly, the *precautionary principle* is applied to such issues, which assumes that a reasonable effort should be made to mitigate (prevent or offset) uncertain risks, particularly if damages are potentially catastrophic.

Damage Cost Estimates

As discussed earlier, climate change damage cost analysis is challenging due to the diversity of damages and risks, the numerous steps between an emission and its ultimate damages, the global nature of impacts, and the large range of values different people place on these damages (Stern, 2006, p. 23). Some published climate change emission valuations lack detailed explanation of the assumptions used (Hohmeyer, 2006).

Table 6 summarizes various climate change impacts. Economic analysis often focuses on anthropocentric impacts (effects on humans) such as increased cooling costs, hurricane damage, sea level rise, reduced agricultural productivity and lost recreation opportunities. Climate change cost estimates tend to increase when ecological values are added, such as the inherent value of maintaining ecological systems and species, either for their own sake (existence value) or because of often unappreciated service they provide people, now and in the future, such as production of clean air and water, and as a bank for potentially valuable genes. Because climate change threatens a large number of species and ecological systems, damage costs are potentially very large. For example, applying even a modest value of a few million dollars to each threatened species' existence-year could result in huge costs to activities that stimulate extinctions.

Table 6 **Climate Change Impacts**

Direct Effects	Secondary impacts
Higher ambient temperatures and more heat waves	Discomfort, illnesses and deaths, increased cooling costs.
Ecosystem disruption and species extinction	Loss of productive habitats (clean air and water, fish and game), genetic resources (for pharmaceuticals and agricultural products), recreation opportunities (bird watching), aesthetic values (beautiful landscapes and plants) traditional lifestyles and traditions (hunting and gathering).
Sea level rise	Lost land, habitat and farmland productivity, and protection costs. Refugees from disrupted areas.
Hydrologic change (droughts, flooding, reduced snowpack, reduced river flows)	Increased water supply costs, reduced agricultural productivity, reduced hydroelectric production.
More tropical diseases	Human illnesses and deaths. Threats to agricultural productivity.
Reduced snow and ice	Lost recreation activities, cultural traditions and lifestyles.

This table summarizes climate change impacts.

It is possible that climate change may cause catastrophic events. For example, positive feedback cycles could lead to very high atmospheric and ocean temperatures, causing large changes in weather patterns, resulting in large reductions in food production, massive extinctions, spread of disease, huge loss of human life, greatly reduced economic productivity and degraded quality of life for most people. As a result, a reasonable upper-bound damage estimate is essentially infinite: too large to be worth counting, just as most rational people would consider their own lives and the lives of their family and friends to have infinite value, not for sale at any price.

Climate change valuation is sensitive to assumptions used in monetization. To illustrate this, Hohmeyer (2006) uses the example of the loss of 200 kg of crop productivity in Niger, which could be valued at the $80 market price, or based on the value of a human life lost. If this occurs 50 years in the future this loss could be valued as low as $0.70 ($80 discounted at 10% annually over 50 years), or as much as $3.3 million (a life lost without discounting), or any value in between. Which value is considered correct depends on assumptions and judgments made in the analysis.

Specific factors that affect damage cost valuation are discussed below.

a) Discounting Long-term Impacts

The effects of present day emissions will persist for centuries (Stern, 2006). Although global warming is already causing impacts, such as reduced snow pack and rainfall shifts, the most serious damages and costs are not expected until after 2050. Conventional economic analysis discounts future damage costs, which reduces the value of current emission reductions. This reflects the assumption that economic resources have investment value (their consumption can create economic resources that build value over time), and that future generations will be wealthier than current generations.

Discounting can significantly affect long-term analysis. For example, if a statistical life is valued at $1 million, the present value of a death a century in the future discounted at 8% is just $455, indicating what the current economy should rationally pay to reduce that risk. High discount rates can result in low costs for even catastrophic damages to future generations. Even a 0.5% discount rate has a large effect over two centuries as shown below.

Table 7 **Net Present Value of $1 million at Different Real Discount Rates**[5]

Annual Discount Rate	50 years in future	100 years	200 years
0.1%	$951,000	$905,000	$819,000
0.5%	$779,000	$607,000	$369,000
1.0%	$608,000	$370,000	$137,000
3.0%	$228,000	$52,000	$2,700
8.0%	$21,300	$455	$0.21

As discount rates increase the value assigned future impacts declines.

Most long-term economic analyses apply a *social discount rate*, which is calculated by adding the pure time preference discount rate and a forecast of future economic growth. For example, the Stern Review projections assume average world income will increase from about $7,000 in 2006 to about $100,000 in 2100; therefore "*a sacrifice of $70 per person (1 per cent of income) today would be justified if (and only if) it increased the income of our great-grandchildren in 2100 by at least $1,000*." (Quiggin, 2006). However, many economists consider the assumption of continued exponential economic growth and increased wealth for centuries into the future uncertain and overly optimistic (Nordhaus, 1997). Daly and Cobb (1994, p 154) say such discounting is often used "to convert a 'very large number' into a very small number under the cover of numerological darkness."

[5] Formularium (2008), *Discount: Net PresentValue* (www.formularium.org).

It is possible that future generations may value ecological integrity more than increased material wealth, or resource depletion and environmental degradation may reduce economic growth and future wealth (UNEP, 2007; Hirsch, Bezdek and Wendling, 2005; Diamond, 2005). Conventional discounting of ecological values reflects *weak sustainability*, which considers market goods substitutes for ecological goods, but many experts advocate *strong sustainability*, which considers market goods poor substitutes for ecological goods and therefore demands their preservation (Ayres, van den Bergh, and Gowdy, 1998). For example, weak sustainability would allow depletion of wild fish stocks provided that fish farming can produce equal economic value, but strong sustainability rejects this, assuming that wild fish stocks have unique ecological values that cannot be replaced by industrial production and so should be protected. These issues of uncertainty, or a demand for strong sustainability supports use of low or zero social discount rates for ecological and human health impacts, at least for sensitivity analysis (to define upper-bound values).

According to Quiggin (2006, p. 14), a discount rate of three percent or higher "…is tantamount to saying that the future (certainly anyone more than two generations away from us) can go to hell for all we care, since the welfare of our greatgrandchildren has about a tenth the weight we accord the current generation," although most people demonstrate a desire to provide a positive legacy to their descendants and future generations in general. U.S. government agencies frequently use 3% to 7% social discount rates. Some models use *parabolic discounting* (discount rates start high and decline over time) but this makes little practical difference if a high discount value is used for the initial period since "…all far-future costs and benefits [have been] discounted away to insignificance" (Ackerman and Finlayson, 2006).

The Stern and Garnault studies both used discounting while acknowledging its problems and expressing reservations. Some critics consider Stern's social discount rate of about 1.4%, too low.[6] Despite acknowledging that future generations might be no wealthier than present generations, the Garnault Review uses real discount rates of 1.35% and 2.65%.

In cost benefit analysis, higher discount rates can lead to conclusions that many people would reject on ethical or common sense grounds: that the current generation cares little about their descendants and future ecological conditions. Studies that discount long-term impacts should be used transparently, acknowledging the normative value judgements and economic assumptions behind the calculations.

[6] This is equivalent to a discount rate of about 1.3% plus pure time preference of 0.1% for a social discount rate of 1.4% (Ackerman, 2007). Early reports that Stern used a 0.1% discount rate were erroneous, based on only the pure time preference component of the social discount rate. Stern used various growth values in model runs to account for the possibility that climate change could reduce future economic growth.

b) Global Factors

Unlike local and regional impacts, which is largely borne by the population of one country, global warming is a global problem. Both the causes and consequences are unevenly distributed, with the greatest per capita emissions in wealthy countries and the greatest vulnerabilities in less wealthy countries. A full discussion of these issues is beyond the scope of this paper, but two items warrant brief examination:

Value of life

Premature loss of life is one of the largest elements of future GHG damage cost estimates, and the preservation of life is one of the largest benefits of mitigation. Lives lost, or years of life lost can be valued in many different ways. Since global warming impacts are expected to harm many lower-income regions, emission cost values will be lower if lives are valued using wealth-dependant indicators such as willingness to pay, and higher if a standard value of life is applied to everybody...

Value of a dollar

Assumptions used to incorporate economic growth into the valuation of future climate change impacts also apply to the geographic distribution of wealth. If a dollar is only worth half as much to a future person who is twice as wealthy, a dollar should also have a higher value in the hands of a low income person in our current time period. Stern (2006, p. 159) notes that regional economic analysis, which considers differences in the social welfare value provided by a given amount of money in different regions, would increase climate change damage costs, but due to time constraints ignored this factor, biasing the damage cost values downward.

c) Uncertainty

The uncertainties inherent in climate change science and economics pose particular challenges for economic analysis. Using a single cost value may give decision-makers a false sense of certainty. The *Stern Review* (p. 143) emphasizes the importance of revisiting past estimates and creating models that can deal with the possibility of much higher damages than covered by most previous studies. Further discussion of uncertainty and risk in climate change economics can be found in section 1.2 of the *Garnault Review*.

d) Non-Marginal, Non-Reversible Effects

Economic analysis of GHG emission damage costs must question common assumptions, such as that impacts are linear and economic growth will continue exponentially. Beyond a certain threshold, climate change emissions may create positive feedbacks with catastrophic results, leading to huge damage costs and reduced economic growth. These non marginal effects are not likely to be reversible as discussed in the *Stern Review*.

The Future of GHG Damage Cost Estimates

Recent scientific findings using increasingly sophisticated analysis that can account for more factors will likely "…increase cost estimates, and probably strongly." (Stern, p. 149). This is likely to increase climate change emission unit costs. However, for the reasons discussed above, the range of estimates is likely to remain wide.

Published Damage Costs Estimates

Table 8 summarizes several published estimates of climate change damage costs.

Table 8 **Monetized Damage 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 italicized. 2007 Values were converted to USD in the base year then adjusted for inflation by Consumer Price Index.[7]
* Assumes the currency year is the same as the publication year. ** From Maibach et al. (CE Delft) 2008.

These estimates vary widely due to factors such as the scope of impacts considered, discount rates and economic growth assumptions used in the analysis. They span more than three orders of magnitude, from slightly below zero (assuming net benefits) to more than £1000 per tonne of CO_{2e} (Ackerman and Finlayson, 2006; Watkiss and Downing, 2008). Studies that account for uncertainty produce positively skewed distribution of damages; that is, "…there is a higher probability of an extremely disastrous outcome than of a much more minor one" (Clarkson and Deyes, 2002). Many damage cost estimates are skewed toward the lower end of possible damages because they:

- Only consider a limited portion of all costs and risks, and ignore the possibility of catastrophic damage.
- Apply discounting to non-economic impacts that should not be discounted.
- Assume that economic growth will continue exponentially.

Base cases (often called *business as usual* or *BAU*) should account for population and economic growth, which increases total future emissions and human costs. Estimated unit costs have tended to increase over time as scientists and economists learned more about damage costs and risks, and are often forecast to increase in real terms if atmospheric GHGs concentrations rise. For example, Stern estimates a range of damage unit costs that increase as atmospheric carbon dioxide rise (Maibach, et al., 2008, Table 130).[8]

[7] For more inflation adjustment methodologies 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).
[8] The report *Estimating the Social Cost of Carbon Emissions*, raises the value "£1/tC per year in real terms for each subsequent year to account for the increasing damage costs over time" (Clarkson and Deyes, 2002).

Control Costs

Unit emission costs can be calculated based on *control costs* (also called *mitigation* or *avoidance costs*), that is, the cost of reducing GHG emissions or removing GHGs from the atmosphere through carbon dioxide sequestration, and therefore reducing future climate change damages. Table 9 summarizes various estimates of these cost values.

Table 9 **Mitigation Cost Estimates – Selected Studies**

Publication	Cost Values	Cost Value/tonne CO2	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)	2008 EU CO_2 permit prices	€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
Maibach et al (2000)		€135	$150

Mitigation cost estimates vary considerably, but less than damage costs.
* Assumes the currency year is the same as the publication year. ** From Maibach et al. (CE Delft) 2008.

Unit costs vary depending on the size of emission reductions. Many emission reduction strategies individually experience economies of scale (unit costs decline as they expand), but eventually achieve an optimal size beyond which unit costs increase. For example, expanding commute trip reduction programs may be cost effective, but once they achieve their potential further expansion is inefficient, increasing costs but providing little additional emission reductions. Once the most cost effective strategies are implemented, more costly strategies must be deployed to achieve additional reductions. Emission control valuation therefore depends on the amount of emissions to be reduced, with higher unit costs for larger reduction targets. The most costly of the strategies implemented represents marginal emission reduction control costs.

Emission reduction valuation is sensitive to how indirect impacts are considered. This is particularly true of transportation emission reduction strategies since transport activity has so many indirect and non-market impacts (Litman, 2007). Energy conservation and some alternative fuels provide consumer savings, and often reduce other pollutant emissions. Petroleum conservation reduces oil import economic costs. Mobility management strategies that reduce vehicle travel (such as improvements to alternative modes, pricing reforms, and smart growth land use policies) can provide additional co-benefits including congestion reductions, road and parking facility cost savings, accident reductions, improved mobility for non-drivers, and increased public fitness and health. On the other hand, strategies that increase vehicle fuel efficiency (such as fuel efficiency standards) stimulate additional vehicle travel, exacerbating transportation problems (Litman, 2005). Table 10 compares the impacts of various transportation emission reduction strategies.

Table 10 **Comparing Strategies** (Litman, 2007)

Planning Objective	Alternative Fuels	Fuel Efficient Vehicles	Vehicle Travel Reductions
Consumer cost savings	?	✓	✓
Other pollution reduction	?	✓	✓
Reduced oil import costs	✓	✓	✓
Congestion reduction		✗	✓
Road and parking cost savings		✗	✓
Reduced traffic accidents		✗	✓
Improved mobility options		✗	✓
Land Use Objectives		✗	✓
Physical Fitness & Health			✓

✓ = helps achieve that objective. ✗ = contradicts that objective. **?** = impacts are variable.

Shifting to alternative fuels provides relatively few benefits. Increasing vehicle fuel efficiency provides energy conservation benefits, but by reducing vehicle operating costs tends to stimulate more driving, exacerbating other transportation problems such as congestion, accidents and sprawl. Strategies that reduce total vehicle travel (such as improving travel options, pricing reforms, smart growth land use policies) provide a wider range of benefits.

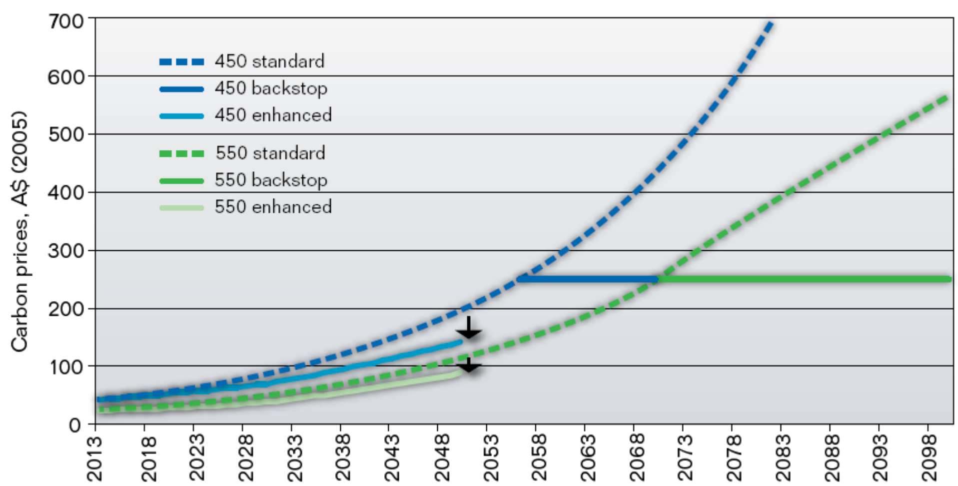
Many current emission reduction planning efforts ignore many indirect impacts (Gallagher, et al., 2007) or only mention them incidentally (McKinsey, 2007). Most only consider a limited set of co-benefits, such as pollution reduction health benefits and economic benefits of reduced oil imports, but ignore other significant benefits such as congestion reductions, roadway cost savings, and accident reductions. This exaggerates emission reduction costs and undervalues strategies that provide multiple benefits such as mobility management and smart growth. Some studies do assume that low-cost and negative cost (they provide net benefits) emission reduction strategies exist (Mees, 2000; Litman, 2007). The Stern Review estimates of 2050 GHG mitigation costs includes positive as well as negative values, implying that some emission reduction strategies provide net social benefits.

Emission control costs also depend on fuel prices. The Garnault Review (2008, p. 6) suggests that rising oil prices should reduce mitigation costs; the "higher the market prices of petroleum, coal and natural gas, the lower the costs of mitigation." Including resource external costs, such as oil import economic costs and coal mining environmental costs, also increases energy conservation values ("Resource Externalities," Litman, 2009).

Most forecasts predict that mitigation unit costs will increase over time as more costly strategies are implemented to achieve larger emission reduction targets. Some estimates assume that there is an upper limit to mitigation prices based on alternative fuels and carbon sequestration. For example, the Garnault Review includes a 'technological backstop' for carbon prices at $250 Australian dollars (about $200 US), which creates a plateau shown in the figure below. Garnault (2008, p. 526) suggests that faster technological innovation and rational government policies (such as shifting spending to public transit, automobile pricing reforms and smart growth land use policies) could reduce mitigation costs, illustrated with arrows on the graph below.

Figure 1 **Carbon Price Scenarios** (Garnault, et al, 2008, p. 251)

Figure 11.1 Australia's carbon prices under different mitigation scenarios and technological assumptions



Note: The rising carbon price paths are derived in GTEM and implemented in MMRF, except for the prices derived under the enhanced technology assumptions, which are implemented only in GTEM and reported up to 2050. The 450 and 550 price paths move on to the horizontal backstop path when they reach about $250/t CO_2-e. The two arrows show the extent to which the enhanced technology assumptions reduce the carbon price relative to the standard technology assumptions.

The Garnault review forecasts that mitigation costs and carbon prices will rise for a time and then plateau due to technological innovation. 2005Aus$1.00 = 2007US$0.81.

Emission Reduction Targets

Emission control costs can be valued by developing an emission reduction supply curve of the marginal cost of achieving specified targets.[9] For example, cost-effective strategies might achieve a 20% reduction for $1 per tonne, a second 20% reduction for $10 per tonne, a third 20% reduction for $50 per tonne, and a fourth 20% reduction for $150 per tonne. If society establishes a 40% emission reduction target then marginal control costs would be valued at $20 per tonne. If the target is 60%, the control cost is $50 per tonne.

Various organizations and jurisdictions have established specific emission reduction targets (UNFCCC, 2007).[10] A common initial target is to reduce emissions 20% below 1990 levels by 2020 or 2030, although more recent research on climate change costs suggests that this is inadequate and more aggressive targets are required, such as 40%, 60%, 80% or 90% reductions. For example, the *Western Climate Initiative* has a regional GHG target of 15% below 2005 levels by 2020. Canada's *Climate Change Accountability Act* mandates reductions of 25% below 1990 levels by 2020 and 80% by 2050.[11] The Garnault Review recommends a 90% reduction in Australia's emissions by 2050.

[9] See for example, McKinsey, 2007, exhibits A and B.
[10] *Urban and Regional Carbon Management* (www.gcp-urcm.org); *Cities for Climate Protection* (www.iclei.org); Pew Center for Global Climate Change (www.pewclimate.org/states-regions).
[11] *Bill C-377: Climate Change Accountability Act*, House of Commons of Canada (www.parl.gc.ca)

Transportation is a significant source of climate change emissions. Although some studies suggest that other sectors have lower-cost emission reduction options, or that transport emission reductions should focus on improving vehicle fuel economy and fuel type (McKinsey, 2007; Gallagher, et al., 2007), several studies indicate that, if co-benefits are considered, the transport sector offers significant cost effective emission reductions (Litman, 2007; Robèrt and Jonsson, 2006). A European Union report concluded that vehicle travel reductions will be needed to achieve emission reduction targets (EEA, 2008). Washington State's Climate Action Team reached a similar conclusion:

> "While new technologies and cleaner fuels are vital to reducing GHG emissions, as long as annual vehicle miles traveled (VMT) continues to grow, we'll never be able to meet the state's 2020, 2035, and 2050 goals. Reduction of vehicle miles traveled – through a partnership between the state, regional, and local level – is critical." (WSCAT, 2007, p. 16)

Emissions Trading

Emission trading involves creating an emission reduction market through which businesses can buy and sell emission credits (or bid on a fixed quantity of credits in some proposals). These credits are supposed to represent a net reduction in emissions compared with what would otherwise occur. Examples of GHG emissions markets include the *European Union Emissions Trading Scheme*,[12] created in conjunction with the Kyoto Protocol, and the *International Carbon Bank and Exchange.*[13]

Such markets should be able to identify and implement the most cost effective emission reduction strategies, minimizing total economic costs to society. For example, if a particular company or technology can reduce emissions for $1 per tonne it should be able to sell cheaper credits than a company or technology that costs $2 per tonne reduced.

Carbon credit prices can be considered to reflect marginal control costs. However, such markets have been criticized for various problems (Burke, 2007; Kanter, 2008; WWF, 2007), such as a lack of accountability (whether the promised actions really occur) and *additionality* (whether the actions result in overall net reductions compared with what would otherwise occur). Emission trading also tends to be biased in favor of easy-to-predict and easy-to-implement strategies, which places mobility management programs at a disadvantage. Emission markets are currently small in scale and so reflect the cheapest set of emission reduction strategies; prices are likely to increase over time as more costly strategies must be used to achieve much larger targets.

[12] http://ec.europa.eu/environment/index_en.htm.
[13] www.icbe.com.

Global Units – Stern's Damage to Mitigation Ratio

The Stern Review calculates the ratio between GHG reductions (mitigation) costs and damage costs without mitigation. This can be a useful framework for understanding the consequences of various strategies.

The *Stern Review* treatment of control costs (and possible benefits) is based on the net social costs measured in percentage of consumption excluding any benefit from global warming damage avoided. Their analysis uses Gross Domestic Product (GDP) as an indicator of the scale of cost or benefit from various strategies in per capita consumption. It includes both the potential for lost productivity (such as reduced agricultural output due to declining rainfall) and adaptation costs (for example the cost of building flood control systems in the face of sea level rise) in the social costs of business as usual emissions. Therefore, a 20% GDP loss might consist of a 15% productivity loss plus a 5% diversion of productivity to adaptation measures, reducing available economic output for consumption 20% in total (more comprehensive indicators such as the Genuine Progress Indicator might provide an even more useful indication of social benefits and costs).

Their estimate of mitigation costs is "1% of GDP, +/- 3%" (2006, p. 240). The range of values from –2% to +4% is important to consider in the transportation sector; as it raises the possibility that climate change mitigation could have an overall positive social value rather than a net cost in at least some sectors, even without considering the benefits of reducing GHG emissions. As discussed earlier, many emission reduction strategies provide co-benefits, particularly mobility management strategies that reduce transportation problems such as congestion and accidents, so significant reductions are possible with net social benefit (Litman, 2009). In contrast, global warming under business as usual emissions was forecast to have a social cost of 5 to 20%, with possible costs as high as 35% when non-market impacts are considered (Stern, et al., 2006, Figure 6.5d).

Taking Stern's most likely cost of 1% for mitigation and the range of social costs (and therefore the benefit of avoiding these costs) from 5 to 20% gives values analogous to a benefit cost ratio range of 5:1 to 20:1. This can be considered a rough indication of the net benefits of mitigation estimated in the Stern Review,[14] although it probably represents a lower-bound estimate since Stern uses relatively low damage cost estimates that exclude ecological existence values, and a relatively high social discount rate, and does not consider all co-benefits from emission reduction strategies. Alternative damage estimates, discount rates and control cost estimates could produce benefit cost ratios of 100:1 or even higher.[15]

[14] Not all damage costs can be avoided as the planet will continue to warm due to already released emissions (which tend to decrease the benefit side of the ratio). The 2006 Stern report was mainly based on the now outdated 2001 IPCC report (updating the damage estimates would greatly increase the benefit side particularly since damages are happening sooner and Stern uses a substantial social discount rate).

[15] For example, adopting a near zero social discount rate might well result in such a ratio on its own if damages over the next several centuries were considered. Of course, if the social cost of mitigation was near zero this ratio could be much higher.

Valuation Estimates

This section summarizes various estimates of climate change emission reduction unit costs.

- A team of economists headed by Sir Nicholas Stern, Head of the U.K. Government Economics Service, performed a comprehensive assessment of climate change impacts, costs and risks (Stern, et al., 2006). Using the results from formal economic models this study estimated 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, damage estimates can rise to 20% of GDP or more. In 2008 Stern stated that new scientific findings show that his 2006 evaluation greatly underestimated the potential threat and costs of GHG emissions (Adam, 2008). The Stern Review estimated the social cost of carbon (SCC) for various levels of atmospheric carbon emission. Table 11 shows three scenarios of greenhouse gases concentrations (expressed in parts-per-million of carbon dioxide equivalent, ppm CO2e).

Table 11 **Social Cost of Carbon** (Stern, 2006)

Scenario	Year 2000 $/tC	Year 2007 $/tCO2e
Business-as-usual (baseline climate)	$309.50	$371.40
650ppm CO2e stabilization	$143.65	$172.38
550ppm CO2e stabilization	$115.70	$138.84
450ppm CO2e stabilization	$89.20	$107.04

This table summarizes emission cost values for various atmospheric carbon dioxide concentrations.

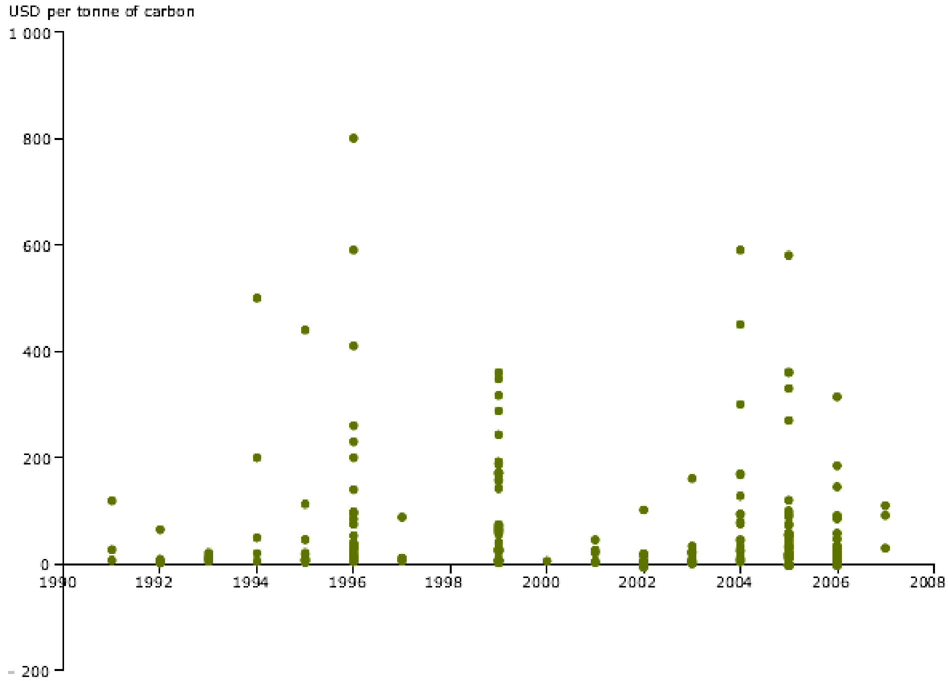
- The Congressional Budget Office (CBO, 2008) estimates that climate change emissions limits in the proposed *America's Climate Security Act* (S. 2191),[16] would result in CO_2 emissions permit prices of about $23 tonne in 2009 and about $44 in 2018, raising gasoline prices about 20¢ per gallon in 2009 and 40¢ per gallon in 2018. Larger emission reductions proposed by the Stern Report and the Intergovernmental Panel on Climate Change (IPCC) are predicted to require permit prices of $80 per tonne by 2030, and $191 per tonne by 2050, adding roughly $0.70 to $1.70 per gallon to gasoline prices over the next four decades. With these additional fees, US gasoline prices would still be lower than they currently are in Europe.

- The UK Department for Environment, Food and Rural Affairs (DEFRA, 2007) published guidance on the recommended carbon shadow price for application in project evaluation. It established a value of £25/tCO2e in 2007, or about US$39.00 based on the Stern Report. Dietz (2007) criticizes this as too low, based on the degree of uncertainty concerning damage costs and greenhouse gas concentration levels, while Newbery (2007) criticizes this as too high, based on lower potential abatement costs (such as substituting alternative fuels for coal).

[16] The cap starts at 4% below the 2005 emission level in 2012 and decline annually at a constant rate, such that it reaches 19% below the 2005 emissions level in 2020 and 71% below the 2005 emissions level in 2050.

- The European Environment Agency study, *Climate Change: The Cost of Inaction and the Cost of Adaptation* (EEA, 2007) discusses factors to consider when evaluating climate change emission costs, and describes and evaluates previous studies. Figure 2 illustrates that study's comparison of various carbon cost estimates.

Figure 2 **Carbon Emission Cost Estimates** (EEA, 2007, Figure 4.1)



This figure graphically illustrates the range of estimated climate change costs.

- The European Commission's *ExternE* program monetized energy production external costs for 14 countries (EC, 2005). This study estimated global warming damage costs at €9/tCO_2, using a medium discount rate and only considering damages that can be estimated with a reasonable certainty, so it excluded impacts such as extended floods and more frequent and damaging hurricanes. This is used as a lower-bound cost value. Avoidance costs are used to estimate a central value of €19/ tCO_2, based on €5 to €20 per tCO_2 to achieve Kyoto targets, and tradable CO_2 permits that ranged from about €18 to €24/ tCO_2 in 2005. More stringent reduction targets, such as the EU target of limiting global warming to 2°C above pre-industrial temperatures, may lead to marginal abatement costs as high as €95/ tCO_2, but because they consider such an ambitious goal politically unacceptable they use an intermediate target, using the Dutch value of €50/ tCO_2 as an upper-bound for sensitivity analysis.

- A 2005 New Zealand study recommends a value of NZ$270 per tonne CO_2 as the best available estimate (Jakob, Craig and Fisher, 2005).

- Kuik, Brander and Tol (2008) performed a meta-analysis of recent studies of the costs of greenhouse gas mitigation policies that aim toward the long-term stabilization of these gases in the atmosphere. They find that reducing atmospheric carbon dioxide concentrations to 350 parts per million is predicted to cost €70-350 per tonne of CO_2.

- Maibach et al (2008) estimated climate change emission reduction unit costs based on an extensive review of previous studies. They base their recommended values on avoidance costs in the short term (2010 and 2020) and on estimated damage costs after 2020. These escalating values are shown in the table below. The recommended value is €0.67 per km for urban gasoline powered cars, with a range of €0.19 to €1.20 per km (based on tailpipe emissions only and the 2010 values shown below).

Table 12 **Emission Cost Values, €/tonne CO_2** (Maibach, et al. 2008)

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

This study estimates that costs will increase over time.

- The Intergovernmental Panel on Climate Change (IPCC, 2001) estimates climate change mitigation costs 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%.

- Point Carbon (www.pointcarbon.com), an emission trading consulting firm, developed *Certified Emissions Reductions* (CER) contracts, with prices that vary depending on how risks are distributed between seller and buyer, and the type of projects. The table below indicates price ranges prior to 2006.

Table 13 **Carbon Emission Credit Prices** (Point Carbon, 2006)

Description	Price Range (€/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).	€9-14
Firm volume. No preconditions. Forward spot trades will fit this category.	€12-14

This table indicates 2006 carbon credit prices.

- Tol (2005) summarized estimates of the marginal damage costs of carbon dioxide emissions from 28 previously published studies by 18 independent teams of scholars that produced 103 total estimates. Combining all studies, the mode is $2 per tonne of carbon (tC), the median $14/tC, the mean $93/tC, and the 95 percentile is $350/tC. The analysis found that studies with a lower discount rate have higher estimates and much greater uncertainties, studies that use equity weighing have higher estimates and larger uncertainties, and studies that are peer-reviewed have lower estimates and smaller uncertainties. Concludes that using standard assumptions about discounting and aggregation, marginal damage costs are unlikely to exceed $50/tC.

- A July 2007 media report notes EU carbon dioxide permits for 2008 were trading at €21.45, or $29.22, a tonne, 47% more than the price of 2008 UN Certified Emission Reduction credits (Bloomberg News, July 3, 2007).

- A comprehensive (535-page) Australian study estimates full social costs of various GHG control strategies (BETC, 1996). This study identified some pricing and transit strategies as *no regrets strategies* with zero or negative social costs (they provide overall benefits even without considering the value of reduced GHG emissions) when congestion reduction, safety and other secondary benefits are considered. No regrets measures identified include:
  - Reduced urban public transport fares.
  - City-wide parking charges.
  - Metropolitan road user charges.
  - Labeling of new cars to inform buyers of their fuel efficiency.
  - Shifting freight from road to rail.

Emission Cost Summary

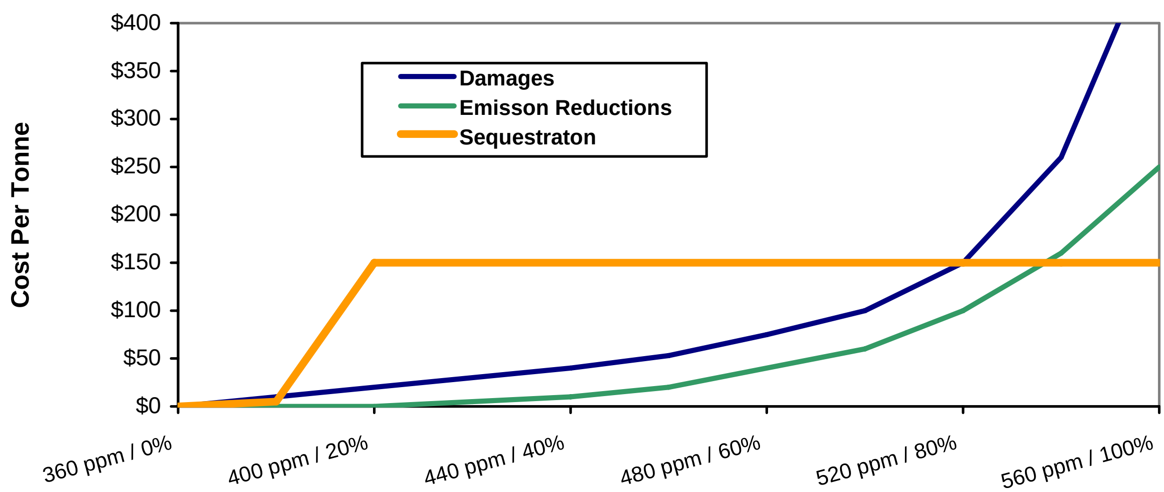
At this time it is impossible to predict with certainty future climate change damage or control costs, but available information provides useful guidance for emission valuation. Damage costs depend on the concentration of atmospheric climate change gases and various assumptions about the range of damages considered (particularly whether ecological systems and species are considered to have existence value) and the methods used to value future damages. Using reasonable assumptions suggests that total damage costs could be very high if atmospheric carbon concentrations exceed 550 ppm.

Some emission reductions, perhaps 20-40%, are free or provide net benefits because their costs are offset by future benefits including energy savings, economic benefits from energy efficiency and reduced petroleum imports, and co-benefits such as reductions in other pollutant emissions, traffic congestion and traffic accidents. Net benefits depend on whether the most optimal policies (such as carbon taxes and other pricing reforms) are implemented, and technological progress. Unit costs tend to increase to achieve greater emission reduction targets.

Carbon sequestration (carbon dioxide capture and storage) is inexpensive for the relatively small portion of emissions that can be captured by tree planting, but costs are likely to increase to $100-200 per tonne for industrial sequestration, although the exact cost is uncertain and may create ecological risks (CBO, 2007).

Figure 3 illustrates idealized climate change damage, control and sequestration cost curves. Marginal unit costs are likely to rise with increased total emissions (from 360 to 560 parts per million) and emission reduction targets (from 0% to 100% reduction). Most studies conclude that damage costs are much higher than control costs, justifying aggressive emission reduction targets, although exact costs and benefits are uncertain.

Figure 3 **Idealized Damage, Control and Sequestration Cost Curves**

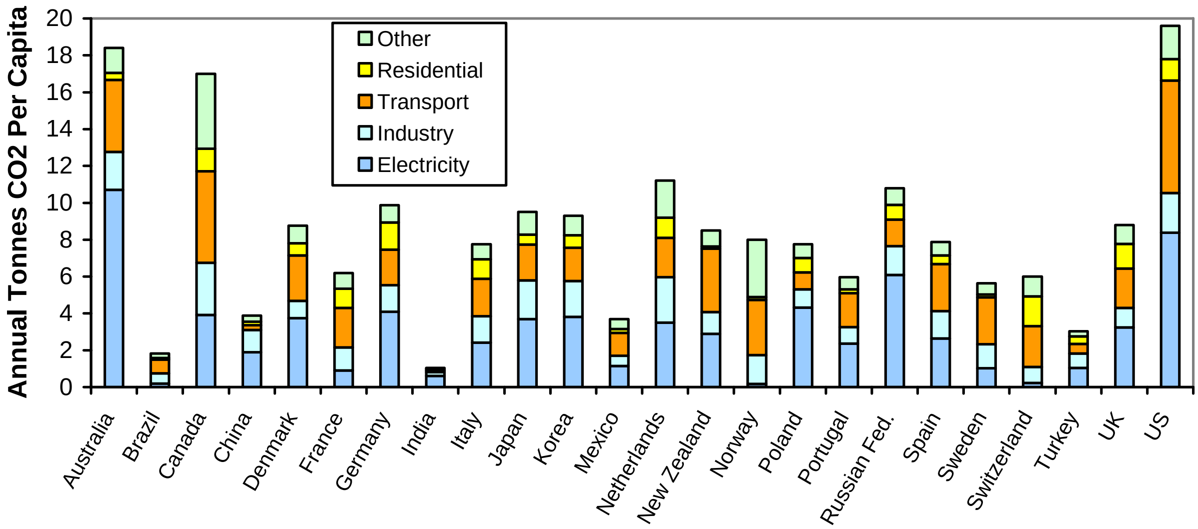


Marginal damage costs increase as atmospheric GHGs rise from 360 to 560 ppm, and control costs increase as targets rise from 0% to 100% reduction. Most analyses conclude that damage costs are higher than control costs justifying aggressive emission reduction efforts.

Transportation Emissions

According to the Intergovernmental Panel on Climate Change (IPCC, 2007c), in 2004 transport produced 23% of world energy-related GHG emissions with about three quarters coming from road vehicles, and this sector's GHG emissions have increased at a faster rate than any other energy using sector (Ribeiro, et al., 2007). Per capita emission rates vary significantly between countries, as indicated in Figure 4.

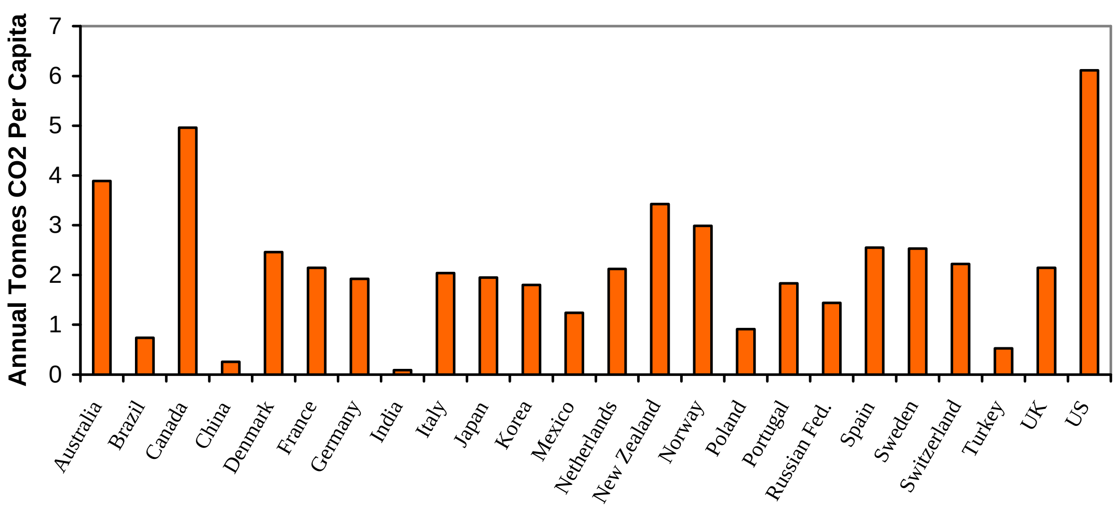
Figure 4 **Carbon Emissions Per Capita** (OECD, 2007, Page 22)



Total carbon dioxide emissions per capita vary significantly between countries.

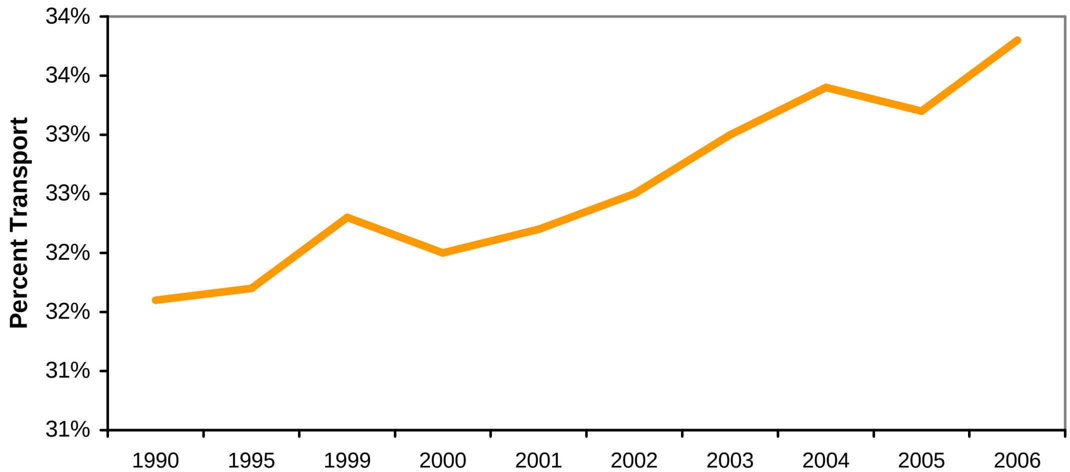
Similarly, per capita transportation emissions vary significantly due to differences in geography, economics and public policies, as illustrated in Figure 5. Even countries with similar levels of wealth differ significantly in their emission rates.

Figure 5 **Transport Carbon Emissions Per Capita** (OECD, 2007, Page 22)



Transport carbon dioxide emissions per capita vary significantly between countries.

Figure 6 **Transport Carbon Emissions** (USDOE, 2008, Table 11.5)



Transportation carbon emissions are increasing in total and as a portion of total emissions.

Transportation activity produces about a third of total fossil fuel carbon emissions and this portion is growing, as illustrated in Figure 6. About 80% of these emissions are generated by highway transport, of which about 75% are by personal transport and 25% by freight and other commercial vehicle use, as indicated in Table 14. Aviation currently produces about 9% of fossil fuel emissions but this is growing rapidly.

Table 14 **U.S. Transport Energy Use** (ORNL, 2008, Table 2.12)

Major Category	Mode	Trillion BTUs	Percent Total
Highway (80%)	Cars & motorcycles	9,256	33.5%
	Light trucks	7,518	27.2%
	Medium & heavy trucks	5,188	18.8%
	Buses	196	0.7%
Non-Highway (20%)	Air	2,496	9.1%
	Water	1,455	5.3%
	Pipeline	842	3.0%
	Rail	670	2.4%
Total		*27,621*	*100%*

This table summarizes total energy consumption by mode, indicating their carbon emissions.

Various factors affect per capita and per vehicle-mile emission rates, including land use patterns, vehicle ownership rates, pricing, and the quality of alternative modes, such as walking, cycling and public transit (VTPI, 2008). Models such as URBEMIS (www.urbemis.com) can be used to predict the emission reduction effects of various mobility and land use management strategies (Nelson/Nygaard, 2005). Vehicle emission models such as MOBILE6 can be used to predict total emissions under various circumstances (USEPA, 2008).

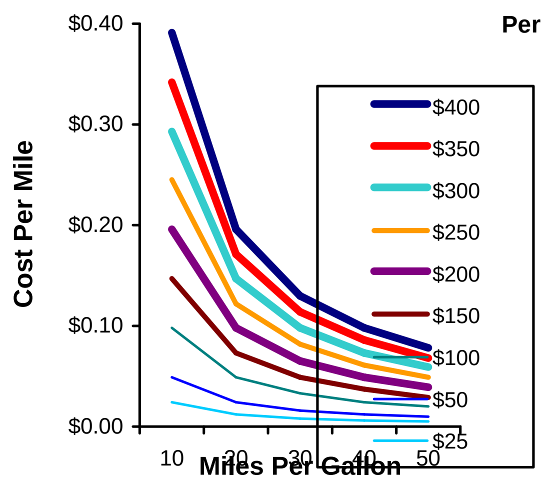
Table 15 compares typical emission rates per passenger-kilometer for various modes. Actual rates vary depending on load factors, vehicle fuel efficiency, and vehicle operating conditions. Public transit tends to be more fuel efficient than automobile travel, particularly if implemented with policies that result in high occupancy rates, efficient operation (such as grade separated transit ways) and transit oriented development (so most destinations are located close to transit stations).

Table 15 **Typical Emissions By Mode** (IPCC, 2007c, Table 5.4)

Mode	Load factor (average occupancy)	CO_2-eq emissions per passenger-km (full energy cycle)
Car (gasoline)	2.5	130-170
Car (diesel)	2.5	85-120
Car (natural gas)	2.5	100-135
Car (electric)	2.0	30-100
Scooter (two-stroke)	1.5	60-90
Scooter (four-stroke)	1.5	40-60
Minibus (gasoline)	12.0	50-70
Minibus (diesel)	12.0	40-60
Bus (diesel)	40.0	20-30
Bus (natural gas)	40.0	25-35
Bus (hydrogen fuel cell)	40.0	15-25
Rail Transit	75% full	20-50

Figure 7 illustrates climate change costs per vehicle-mile for various carbon dioxide equivalent unit costs and vehicle fuel efficiencies. Only if relatively high climate change cost values are applied (over \$150 per tonne, which equals \$1.47 per gallon of gasoline or about 7¢ per mile for a 20 mpg vehicle) does climate change become a significant factor in vehicle operating costs.

Figure 7 **Emission Costs Per Vehicle-Mile**



This figure shows emission costs per vehicle-mile for various values per tonne and fuel efficiencies.

Incorporating Emissions Costs in Economic Analysis

Economic analysis (also called *economic evaluation* or *appraisal*) refers to methods for determining the value of a policy, project or program. It is useful for identifying optimal emission reduction strategies, particularly for transportation projects that involve various benefits and costs. Incorporating climate change emission values into transportation economic evaluation can help identify truly optimal transport policies. For example, it can help evaluate various emission reduction strategies, incorporate climate change emission reduction targets into regular transport planning, and avoid policies that contradict climate protection goals. The IPCC Working Group III asserts that if "…the cost of CO2 emissions has a relatively important weight in these assessments, investments in unnecessarily carbon-intensive projects might be avoided. Strategic CBA [Cost-Benefit Analysis] can further make transport planning and policy carbon-efficient by extending CBA to cover multimodal investment alternatives". (IPPC, 2007b, p. 368)

The following factors should be considered when incorporating climate change emission unit cost values into the economic analysis of transport policies and programs:

- Most scientific experts consider climate change to have significant costs and risks. Economic analysis should reflect this scientific consensus, for example, by applying the precautionary principle to favor transportation strategies that conserve energy and reduce emissions over those that increase total energy consumption and emissions.
- Climate change may be non-linear and non-reversible beyond a certain threshold, so current emissions may have high costs and current emission reduction strategies have high marginal benefits.
- Climate change emission unit cost estimates vary widely, covering approximately three orders of magnitude due to uncertainty about impacts and the use of various assumptions and evaluation methods.
- Damage cost values are affected by factors such as the scope of analysis and the discount rate used, so results are determined by assumptions incorporated into the analysis. Selecting a value implies accepting normative judgments in the analysis.
- More recent studies tend to take into account a wider range of impacts and risks, and so tend to have higher damage cost estimates.
- Control cost estimates are in a narrower range than damage costs, but still cover a range from a net social benefit to more than $100 per tonne.
- Marginal control costs rise with increased emission reductions. Some emission control strategies have negative or zero costs because their implementation costs are offset by direct savings and indirect co-benefits.
- Transportation economic evaluation depends on the range of impact considered. Taking into account co-benefits such as congestion reduction, facility cost savings, and accident reductions increases the value of mobility management, and taking into account emission impacts reduces the estimated value of roadway expansion projects.
- Some transportation emission reduction strategies may be financed through carbon offsets. For example, transport agencies could establish special funds to help finance projects and programs that help reduce emissions.

VTPI Climate Change Cost Values

This report provides background information on the climate change emission values used in *Transportation Cost and Benefit Analysis* (Litman, 2009). As with the Stern Review, separate values are provided for damage and control costs. The control cost value, from sources in Table 8, is $35 per tonne, slightly higher than recent EU emission permit prices, since these are likely to increase over time to achieve larger emission reduction targets. The damage cost value, from sources in Table 7, is $300 per tonne, which is higher than many other sources for the following reasons:

- Scientific findings released since the Stern Review point towards higher damage costs.
- A rejection of higher discount rates.
- The resulting damage-to-control-cost-ratio of 8.6:1 is consistent with the 5:1 to 20:1 range by Stern and supported by other sources.

Table 16 compares these with other costs for an average automobile, as estimated in *Transportation Cost and Benefit Analysis*. Control costs of $35 per tonne CO_{2e} equal about 34¢ per gallon of gasoline or 2¢ per vehicle-mile, ranking it 11th and representing about 1% of total costs. Damage costs of $300 per tonne CO_{2e} equal about $2.93 per gallon or 15¢ per mile, ranking it third and representing about 11% of total costs.

Table 16 **Control and Damage Costs Compared** (Litman, 2009)

	Control $35 Per Tonne			Damage $300 Per Tonne		
Rank	Cost Category	Per mile	Percent	Cost Category	Per Mile	Percent
1	Total Vehicle Cost	$0.44	37%	Total Vehicle Cost	$0.44	34%
2	Time	$0.15	13%	Time	$0.15	12%
3	Total Crash	$0.14	12%	**Damage Costs: $300/$CO_{2e}$**	**$0.15**	**11%**
4	Total Parking	$0.13	11%	Total Crash	$0.14	11%
5	Land Use	$0.07	6%	Total Parking	$0.13	10%
6	Air Pollution	$0.04	3%	Land Use	$0.07	5%
7	Resource Use	$0.04	3%	Air Pollution	$0.04	3%
8	Congestion	$0.04	3%	Resource Use	$0.04	3%
9	Land Value	$0.03	3%	Congestion	$0.04	3%
10	Roads	$0.02	2%	Land Value	$0.03	3%
11	**Control Costs: $35/$CO_{2e}$**	**$0.02**	**1%**	Roads	$0.02	2%
12	Barrier Effect	$0.01	1%	Barrier Effect	$0.01	1%
13	Water	$0.01	1%	Water	$0.01	1%
14	Traffic Services	$0.01	1%	Traffic Services	$0.01	1%
15	Noise	$0.01	1%	Noise	$0.01	1%
16	Diversity	$0.01	1%	Diversity	$0.01	1%
17	Waste	$0.00	0%	Waste	$0.00	0%
	Total	*$1.16*	*100%*	*Total*	*$1.29*	*100%*

This table compares climate change emission costs with other costs for a typical automobile.

Conclusions

This paper discusses climate change impacts, how these impacts can be quantified and monetized, summarizes current cost estimates, and discusses how these values can be incorporated into transport economic analysis. It describes how climate change emission costs were estimated for the report, *Transportation Cost and Benefit Analysis.*

Climate change imposes significant costs and risks. It is important to include these in transport planning. A useful way to do this is to incorporate monetized unit cost values into economic evaluation, typically measured as cents-per-kilogram or dollars-per-tonne of carbon dioxide equivalent (CO_2e).

Damage costs are usually estimated to be significantly higher than control costs. Several recent studies suggest that emission control costs will remain $20-50 per tonne of CO_2e for the foreseeable future, although this may increase to achieve larger emission reductions. The costs of larger emission reductions will depend on several factors, including whether the most optimal policies are implemented, the speed of implementation, technological progress, people's acceptance of change, and the magnitude of emission reductions needed.

Many transportation emission reduction strategies provide significant co-benefits and so become more cost effective as more impacts are considered. There is a need for comprehensive economic analysis in order to accurately incorporate climate change emission impacts into transport planning, and to incorporate transport planning factors into emission reduction evaluation.

Climate change values described in this report reflect current understanding of this issue, which is likely to change over time. Our results are consistent with those of other studies, such as the Stern Review. These values provide a workable method for incorporating climate change emission impacts into transportation project economic analysis.

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