External Costs of Transport in the U.S.

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Overview of chapter

In this chapter we report estimates of the external costs of transport in the United States.[1] Generally, we cover road, rail, air, and water transport; passenger transport and freight transport; and congestion, accident, air pollution, climate change, noise, water pollution, and energy-security costs. However, we were not able to find estimates for all cost categories; in particular, there are fewer estimates for freight transport than for passenger transport, fewer estimates for water transport than for other modes, and fewer estimates of water pollution costs than of other costs. Table 1 summarizes the quality of estimates in each category.

In our review, negative externalities are the *unaccounted for* or *unpriced* costs of an action. This means that they are the result of individual decisions or actions, such as whether to drive or take a train, or freight something by ship or plane, and are related to the explicit prices and unaccounted-for costs of those choices.

Estimates of the external costs of transport may be used for several purposes: as a guide to more economically efficient pricing (given that the optimal price is equal to the private market price plus the estimated marginal external costs); as a guide to allocating research and development funds to mitigate the largest external costs; as part of a cost-benefit analysis of optimal investment in transportation modes and infrastructure; and as part of historical or comparative analyses.

As indicated in Table 1, the available estimates do not fully characterize all costs for all modes. Moreover, the wide variations in estimation methods, data, and assumptions among even the “good” estimates confound the comparison of estimates across modes. As a result, we are able to make only general comparisons among modes and general statements about total costs of transport.

In the following sections we review recent estimates of external costs by mode in the U. S. In each section we first review methods and issues in the estimation of the cost, and then present estimates of the costs. For each cost category (e.g., congestion delay, accidents) we summarize estimates of the cost by mode and study. Presenting the estimates in this way indicates where more research and analysis is needed.

[1] Estimates of the external costs of transport in Europe can be found in Janic (2007), Bickel et al. (2006), Link (2005), Quinet (2004), and Nash et al. (2001).

Table 1. Quality of estimates of external costs by transport mode and cost category

	Road		Rail		Air		Water	
	Pass.	*Freight*	*Pass.*	*Freight*	*Pass.*	*Freight*	*Pass.*	*Freight*
Congestion delay	good	good	poor	poor	poor	n.e.	n.e.	n.e.
Accident	good	good	n.e.	poor	poor	n.e.	n.e.	n.e.
Air pollution, health	good	good	fair	fair	fair	fair	fair	fair
Air pollution, other	good	good	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Climate change	good	good	good	good	fair	fair	fair	good
Noise	good	good	poor	poor	fair	n.e.	n.e.	n.e.
Water pollution	poor	poor	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Energy security	fair	fair	fair	fair	fair	n.e.	n.e.	fair

Pass. = passenger; n.e. = not estimated.

Congestion delay costs

Brief Review of Methods and Issues

The congestion caused by additional travel generates a number of external costs, including opportunities foregone due to travel delay, the discomfort of crowding, and the impact of travel-time uncertainty on the reliability of arrival and delivery times. Table 2 provides a comprehensive classification of the external costs of congestion, by mode, with a qualitative indication of the likely magnitude of the externality.

Most analyses have focused on the opportunity cost of activities foregone due to travel delay due to road congestion; there has been less work on the external costs of congestion for other modes, or on the other kinds of external costs of road congestion, such as the impact on the reliability of arrival and delivery times. In this review we consider only those impacts of congestion that are properly considered externalities, as we define the term above. Thus, we do not count for example congestion at freight train yards or at airport terminals used by a single carrier, because in both instances the full cost of the congestion is recognized by the entities making the travel decisions.

Table 2. Qualitative classification of congestion externalities by mode.

Marginal travel by→ External effect on ↓	**Road**	**Rail**	**Air**	**Water**	*Remarks*
Travel time underway (opportunity cost of time)	++	0	0	0?	Additional drivers and vehicles slow down other vehicles on the road, but additional passengers, trains, or planes do not slow down other trains or planes while underway, because for safety reasons rail and air lanes en route are not permitted to become congested. It might be possible for some short-haul shipping lanes to become crowded.
Crowding, comfort of passenger travel	+	+	+	0?	Highway congestion can make drivers anxious. Crowding on trains can make people stand, which can be uncomfortable. While passengers on plane have a reserved seat, crowded flights are less comfortable because there is less room to "stretch out," less overhead luggage space, etc.
Reliability of arrival time (passenger, freight)	++	0	+	0	The greater the variation in delay times the greater the uncertainty about arrival times (Small et al., 1999). Congestion can occur at airports due to too many incoming and outgoing flights (Poole and Dachis, 2007).
Boarding or disembarking time	n.a.	+	+	0	Large crowds can cause minor delays in boarding trains and planes, increase dwell time at stations, and slow disembarkation.
Time spent at garage/station/terminal/ port (opportunity costs, comfort costs, reliability costs)	+?	0	++	+?	Road congestion can result in extra search time for parking spaces. Passenger rail lines have one train per station per track on fixed schedules, and although freight trains can experience crowding at rail yards, the costs are faced by the operator. At airports with different carriers and limited terminal capacity, additional flights can cause significant airport delays for all other flights (Brueckner, 2002).
Cars and trucks waiting at rail or raised-bridge crossings.	n.a.	+	0	+	Additional train cars increase the time that cars and trucks must wait at rail crossings. Additional ships can increase the time that cars and trucks wait at raised-bridge crossings.
Energy use	+	0	+	0	Idling due to congestion on highways or at airport terminals increases energy use per ton-mile or passenger mile.
Accidents	+	0	0	0	Changes in average vehicle speed can affect the frequency and severity of accidents.
Vehicle wear and tear	+	0	0?	0	Driving in congested conditions increases vehicle wear and tear

Notes: ++ = large effect; + = small effect; 0 = no effect; n.a. = not applicable, At the simplest level, congestion delay costs on the road are equal to hours of delay multiplied by the value of opportunities foregone during an hour of delay. Hours of delay are estimated on the basis of the difference between the average speed in a baseline travel situation and the average speed in a scenario with increased travel; this difference, in turn is based on empirical relationships between average speed and travel volume, which in the case of road traffic can be fairly complex. The value of an hour of delay depends on the type and value of the activity being displaced and the conditions of the delay. If it is possible to work or relax during the delay, the opportunity time "cost" may be small. (See Lyons et al. [2007] for a discussion of this for rail passengers in Britain.) Accordingly, analysts often distinguish displacement of unpaid activities from displacement of paid work, and estimate the value of travel time as a function of the income of the persons affected and the "amenity" conditions of the travel per se. (See Small et al. [1999] for a general discussion of valuing travel time and predictability.)

We do not consider here what are sometimes referred to as "scarcity" costs, which are related to infrastructure capacity. Maibach et al. (2007) write that "scarcity costs denote the opportunity costs to service providers for the non-availability of desired departure or arrival times" (p. 23). Although it is true that there is a cost to expanding (or failing to expand) capacity, it is not clear that this ought to be viewed as an *external* cost of individual travel choices, because the individual fares charged by service providers ideally are supposed to include capacity fees. Thus, in our review, congestion externalities for, say rail travel are related to the actual delays and disamenities caused by crowding per se, or to the delay in road traffic caused by road crossings (Table 2), but do not include scarcity/capacity effects. Put another way, for privately operated non-road modes, there is in theory nothing to prevent the carrier from figuring out the optimal capacity assuming full-cost prices and then charging the passengers those full-cost prices; in this situation, there is no externality (see e.g., Gorman [2008, p.7]) . We hasten to add, however, that a complete social cost-benefit analysis of transport modes, as opposed to a study of the external costs of transport, certainly would include all actual infrastructure and capacity costs as well as congestion delay costs.

Because there has been considerable research on all of the factors in the estimation of road delay, and because the theory is relatively well developed and most of the parameters (e.g., traffic volumes, average speed, and personal income) are relatively easy to estimate (compared, for example, with the estimation of parameters in the calculation of climate-change externalities), estimates of national average-annual delay costs for roads tend to be relatively robust. For more information on estimates of the cost of travel time, see Zhang et al. (2004), Calfee and Winston (1998), Morrison and Winston (1989), and Small et al. (1999). For more information on estimates of hours of delay on highways in the U. S., see reports by the Texas Transportation Institute (Schrank and Lomax, 2007).

Estimates of U.S. Costs by Mode & Intermodal Comparisons

Table 3 summarizes recent estimates of congestion delay costs by mode. Most authors focus on time-delay costs of road congestion, and estimate these to be in the range of 1 to 7 cents per mile (2006 $) on average. Of course, congestion costs on particular roadways can be much higher than this; for example, Ozbay et al. (2007) estimate that congestion costs on some routes in New Jersey can exceed 30 cents per mile.

We did not find a study that estimated congestion costs by water mode. (As indicated in Table 2, these primarily would be related to congestion at port terminals.) Maibach et al. (2007) suggest that presently congestion costs at seaports are small, but could become significant in the future, especially in North America where "capacity...is approaching its limits and...congestion at cargo handling and storage facilities is a priority issue" (p. 35).

Table 3. Estimates of congestion delay costs by mode (year-2006 cents).

	Road	Rail	Air	Water
Gorman et al. (2008)	0.22 to 0.54/tm[a] (freight)	0.03/gtm[b] (freight)	--	--
Lemp and Kockelman (2008)[c]	4.75/pmt	--	--	--
Parry et al. (2007)[d]	3.80 /pmt	--	--	--
Delucchi (2004a)[e]	1.93 to 7.46/pmt	--	--	--
Levinson et al. (1998)	0.88/pmt [f]	--	0.35/pmt [g]	--

Notes: pmt = passenger-mile of travel; gtm = gross ton-mile; vmt = vehicle-mile of travel; tm = ton-mile.

[a] Using forecasted year 2000 congestion costs due to trucks of $5.0 billion (year-1994 $) and 198,789 million vehicle miles for trucks reported by FHWA (1997, Tables 1 & 17), Gorman (2008, p. 7) assumes a 14.8-ton average payload and estimates $0.0022 per tm (year-2006 $). However, Gorman's payload estimate implies an unrealistically high 2,942 billion ton-miles for trucks in 2000. Using an estimate of 1,203 billion ton-miles for all trucks (Dennis, 2004, Figure 4), we estimate $0.0054 per tm (year-2006 $). We recognize that our estimate for ton-miles excludes certain categories, such as shipments by households, retail, service, and government establishments (including U.S. Mail); and certain non-commercial freight shipments, such as municipal solid waste (as discussed by Dennis, 2004, p. 9).

[b] This is an estimate of the delay to road traffic caused by freight trains crossing the road network. Gorman et al. (2008, p. 7-8) evaluate the frequency, duration and intensity of rail interaction with road transportation, and estimate a $465 million total congestion delay cost to road traffic, based on $20/delay-hour and 1.4 billion gross ton-miles of rail traffic.

[c] To estimate the delay caused per mile of additional travel by specific vehicle types, Lemp and Kockelman (2008) use a formula that predicts delay as a function of traffic volume, estimates of differences in delay caused by different vehicle types, and an assumption that travel time costs $8/vehicle-hour. Estimates appear to be in year-2006 $. We converted to PMT, assuming 1.6 passengers per vehicle (U.S. DOT, 2008, Table 4-22).

[d] Parry et al. (2007) report FHWA's (2000) estimate of the "weighted-average" marginal external delay cost at "5 cents per passenger mile" (p. 380). According to Parry et al. (2007), FHWA estimated marginal external costs for representative urban and rural roads at different times of day, and then weighted each estimate by its share of total VMT. However, in reviewing FHWA (2000, Table V-23) we found that the estimate is in terms of cents per vehicle-mile – not per passenger-mile – so we assumed cents per VMT here. Original estimate is in year-1994 $. We converted to PMT, assuming 1.6 passengers per vehicle (U.S. DOT, 2008, Table 4-22).

[e] Delucchi (2004a) estimates low and high external delay costs on the basis of low and high assumptions regarding the value of travel time by trip purpose, delay by trip purpose, and other factors. Estimates in year-1991 $.

[f] The estimate from Levinson et al. (1998, Table 12) appears to be in year-1995 $. We converted to pmt, assuming 1.6 passengers per vehicle.

[g] According to Levinson et al. (1998, p.235), this is consistent with data representing the San Francisco to Los Angeles trip by air plane. The estimated congestion arises due to airport use exceeding its capacity. Estimate appears to be in year-1995 $.

Accident costs

Brief Review of Methods and Issues

The estimated costs of accidents include medical costs, property damage, lost productivity, insurance administration, emergency services, and the nonmonetary costs of lost quality of life and pain and suffering as a result of death and serious injury. In the case of travel by road, the estimated cost of accidents is greater than every other social cost except travel time (Delucchi, 2004b). The threat of motor vehicle accidents also gives rise to "fear and avoidance costs" – e.g., the opportunity costs of making people afraid to walk (Newbery, 1998; Evans, 1994) – and to "extra attentiveness costs" (i.e., extra effort to avoid accidents) (Newbery, 1998; Edlin 2002; Steimetz, 2003; Hensher, 2006), but these are not included in the external-cost estimates reviewed here.

Although estimating the total costs of accidents can be relatively straightforward – the biggest challenge is the estimation of the value of non-monetary impacts such as pain and suffering and lost quality of life, but there is a large literature on this (See Riera et al. [2006] for a estimation of the value of statistical life in the context of motor-vehicle accidents) – estimating the *external* costs of accidents is difficult. The external costs of accidents are those that: 1) are inflicted on party *B* as a result of a trip made by party *A* (i.e., would not have occurred had party *A* not made the trip), and 2) are not accounted for, in any way, by party *A* in its trip-making decision.[2] Neither of these conditions is easy to estimate. Consider the first condition. It might seem that any time that car *A* is involved in an accident with car *B*, there is a potential externality, ignoring for now condition 2: if *A* hadn't been there, it appears at first glance that *B* would not have incurred costs. But although it is true that had *A* not made the trip, that *exact* accident involving *A* and *B* would not have occurred, it is possible that *B* or some other party would have gotten in an accident anyway. The relevant question is whether the trip by *A* affects the accident *risk* that all others face; if the accident risk is independent of *A's* travel, then *A's* trip does not generate external costs (Elvik, 1994; Jansson, 1994).[3] And the relationship between marginal trips and the overall accident rate for everyone else is not straightforward, in part because, as mentioned above, people may compensate for increased exposure by driving more carefully.[4]

As regards the second condition, the issue is the extent to which insurance liability payments, altruism, and the prospect of court-awarded damages together adequately reflect to party *A* the increased risk that *A's* actions impose on party *B.* One complication here is that it is not clear how much insurance liability payments, which may be made annually, influence daily trip-making decisions. If insurance rates do not

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[2] This conceptualization goes back at least to Vickrey (1968).

[3] This is analogous to the case of congestion: a congestion externality arises if an additional trip increases the average travel time for everyone else.

[4] To see the subtleties, consider the case of cars hitting pedestrians. It might seem that every additional car creates additional risk for pedestrians, and hence gives rise to potential external costs, but to the extent that pedestrians adjust to the increased exposure by being more careful, then part of the potential external cost is manifest as the cost of extra care rather than as the cost of more accidents.

affect driving decisions, then any change in overall risk resulting from additional driving is effectively unpriced and hence an externality.

The upshot is that estimates of the external portion of accident costs can be quite uncertain and can vary significantly from mode to mode. For example, accidents involving passenger transport by rail, air, or water can have large total *social* (private+external) costs, as noted by Levinson et al (1998), but typically the external-cost portion of the total is relatively small, because marginal travel by these modes does not appreciably increase the average risk for everyone – and as discussed above if the average risk doesn't change, there is no externality. The risk to persons and property not traveling on the mode is an externality if it is not reflected in insurance or insurance-like prices paid by the operator of the mode, but this presumably is a small fraction of the total accident cost. Thus, for all modes, improving estimates of external accident costs will require better models of accident rates as a function of travel, and better information on the magnitude and effect of liability insurance payments and related quasi-prices.

Finally, we note that accident costs and delay costs are inter-related. Accidents usually cause delay, and changes in vehicle speed and density due to congestion can affect the frequency and severity of accidents. Hensher (2006) discusses the inter-relationships in the context of speed limits in urban areas.

Estimates of U.S. Costs by Mode & Intermodal Comparisons

Table 4 summarizes recent estimates of external accident costs by mode. Again, we found relatively few estimates for rail and air, and no estimates for water. The estimates of the external costs of road accidents vary by about an order of magnitude or more, due mainly to differences in key valuation parameters, such as the value of life lost or of pain and suffering, and in the definition and estimation of externalities. Differences due to different base years are minor, because the accident rate per vehicle mile of travel has declined only modestly over the past 20 years; for example from 1996 to 2005 the fatality rate per vehicle mile traveled declined by 14% (Starnes, 2008), which is trivial compared with the roughly 1000% variation in the estimates.

Table 4. Estimates of external accident costs by mode (year-2006 cents).

	Road	Rail	Air	Water
Lemp and Kockelman (2008)[a]	4.1 to 14.4/pmt (6.6/pmt weighted avg)			
Parry et al. (2007)[b]	1.9/pmt			
Delucchi (2004b)[c]	1.4 to 4.9/pmt $0.1/tm to $2.0/tm (freight)			
Forkenbrock (1999; 2001)	0.76/tm (freight)	0.22/tm[d] (freight)		
Miller (1997)[e]	1.9 to 4.0/pmt			

Notes: pmt = passenger-mile of travel; tm = ton-mile.

[a] To estimate external crash costs for different vehicle types, Lemp and Kockelman (2008) use data on national average crash rates, a model of crash severity by vehicle type (given a crash), and estimates of economic and non-economic costs by severity of injury (from the widely used work of Blincoe et al. [2002]). They assume that 50% of the costs are externalities. The variation pertains to different vehicle types. Estimates appear to be in year-2006 $. We converted to pmt, assuming 1.6 passengers per vehicle.

[b] The $ year of the estimate from Parry et al (2007) is unclear; we assume year-2005 $ is reasonable. We converted to pmt, assuming 1.6 passengers per vehicle.

c Delucchi (2004b, Tables 1-8 and 1-9a) estimates low and high external accident costs for the entire U. S. vehicle fleet in 1991 on the basis of low and high assumptions regarding the fraction of costs internalized by insurance liability premiums and other factors. We assume here that 10% of the total estimated by Delucchi (2004b) is attributable to heavy-duty freight trucks, and that 89.3% is attributable to light-duty passenger vehicles (based on Miller et al., 1998); the remaining 0.7% is attributable to buses, which we do not consider here. We then divide heavy-duty freight-vehicle costs by ton-miles of truck shipment in 1991 (low-cost estimate from Table 1-A5 of Delucchi [2004b], high-cost estimate from www.bts.gov/publications/national_transportation_statistics/html/table_01_46b.html), and divide light-duty passenger-vehicle costs by passenger miles of travel (equal to vehicle miles from Table 1-A5 of Delucchi [2004b] multiplied by 1.6 passengers per vehicle). Original estimates in year-1991 $.

[d] Forkenbrock (2001) explains his method: "In summary, Class I freight railroads were involved in accidents that cost society a total of $3,323,980,000 in 1994, and they paid a total of $1,263,000,000 in various kinds of compensation for accidents. The net uncompensated accident cost of freight rail operations in 1994 was therefore $2,060,980,000. Dividing this figure by the 1,200,701,000,000 Class I rail ton-miles in 1994…results in an uncompensated cost of 0.17 cent per ton-mile." (p. 330). Estimates in year-1994 $.

[e] Miller (1997) estimates that the external costs of road accidents in the U. S. in 1993 were $56 billion or $116 billion (in year-1995 $), depending on how insurance payments are treated. We divided these estimates by 2,296 billion vehicle miles in 1993 (www.fhwa.dot.gov/ohim/summary95/vm201.pdf) and then converted to pmt, assuming 1.6 passengers per vehicle.

Again, we did not find estimates of the external accident cost of passenger or freight transport by water for the U.S. Zhang et al. (2004) estimate accident costs for marine ferries in Canada, but they express the results per trip rather than per passenger-mile, and they classify all of the costs as "internal" rather than "external" (see their Table 4.22).[5] Maibach et al. (2007) write that "for inland waterways and maritime transport information on accident costs is almost entirely lacking" (pp. 36-37).

Air pollution costs: health impacts

Brief Review of Methods and Issues

All transportation modes emit significant quantities of air pollutants. Air pollution harms human health, damages materials, reduces visibility, and stresses crops and forests. In this paper we consider two categories: A) impacts on human health, and B) other impacts, on materials, visibility, crops, and forests. We make this distinction for two reasons. First, there has been much more research on the health impacts of air pollution than on the other impacts. Second, the value of the health impacts of air pollution markedly exceeds the value of the other impacts combined.

An extensive epidemiological literature indicates that air pollution causes a variety of effects including premature mortality, chronic illness, and hospital admissions for respiratory and cardiovascular illnesses Bascom et al, 1996; Cohen et al, 2005; Samet and Krewski, 2007). To quantify the health impacts of air pollutants due to emissions from transportation sources, the most detailed analyses proceed in four steps, which constitute the "damage function" approach (McCubbin and Delucchi, 1999; Muller and Mendelsohn, 2007):

1) Estimate the relationship between changes in transportation activity (e.g., vehicle miles of travel) and changes in emissions of air pollutants.

2) Estimate the relationship between changes in emissions and changes in air quality; this can be done with sophisticated 3-dimensional atmospheric chemistry models, or, more crudely, with simple functions relating air quality to emissions.

3a) Estimate the relationship between changes in air pollution and changes in human exposure to air pollution (see Brauer et al., 2008).

3b) Estimate the relationship between changes in exposure and changes in health impacts such as mortality, chronic illness, and asthma attacks. This step often is combined with step #3a, so that one estimates the relationship between changes in air pollution and changes in health impacts.

[5] Zhang et al. (2004) also estimate accident costs for air transport in Canada, but express the results per flight hour rather than per passenger-mile or ton-mile, and classify all of the costs as "internal."

4. Estimate the relationship between changes in health impacts and changes in economic welfare. This step typically is called "valuation," because the objective is to estimate the dollar value of the physical health impacts.

All of these steps are uncertain, but the last two are especially uncertain. For example, air quality models and emissions models probably have prediction errors of less than 50%,[6] but uncertainty in the relationships between air quality and human health, and in valuation, can be several-fold, or even an order of magnitude. The biggest potential health impact of air pollution – mortality related to particulate matter – is potentially very uncertain, for example, due to questions regarding the toxicity of different types of particulate matter (Reiss et al, 2007), and the value of an average statistical life based on, say, wage-risk studies can be an order of magnitude higher than the value of statistical life based on life-years lost if relatively few years are lost (Viscusi and Aldy, 2003; Leksell and Rabl, 2001).

Because there is no mechanism by which air pollution costs are transmitted to those whose activities cause the pollution (aside from the very small effect of one's own pollution on oneself), essentially all air pollution is reasonably regarded as an externality.

Estimates of U.S. Costs by Mode & Intermodal Comparisons

Table 5 summarizes several estimates of the health costs of air pollution, by mode. In this case there are estimates for all modes, although there are many more estimates for road than for the other modes. The estimates of damage costs span a very wide range, mainly because of different assumptions regarding key parameters such as the mortality impacts of pollutants, the value of mortality, and the base year of analysis. The base year is important in the case of air pollution because air-pollutant emissions have declined dramatically over the past 20 years due to improvements in engine design and fuel quality, and are projected to decline further over the next 20 years dues to regulatory changes both in the U.S. and internationally .

Combining data on national emissions from highway vehicles in the U. S. with total travel by highway vehicles in the U. S., we calculate that fleet-average per-mile emission rates declined by around 70% from 1990 to 2006.[7] (By comparison, on a per-mile basis oil use, GHG emissions, noise emissions, and accidents have changed much less.) Moreover, there can be a significant difference between fleet-average emissions in year *Y* and emissions from a new model-year *Y* vehicle. Thus, if the method of McCubbin and Delucchi (1999) was applied to new recent-model-year cars (as opposed to the 1991 fleet average), the estimates reported for them in Table 7 would be reduced by an order of magnitude. For these reasons, we suggest that researchers estimate air pollution damages from road transport by multiplying an estimate of the damages per kg emitted by the emission rate in kg/mi, rather than by using other analysts' estimates of the cost per mile.

Similarly, care should be taken with rail and water estimates because of recent regulatory changes in the U.S. (EPA, 2008) and likely implementation of more stringent international fuel standards for ocean-

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[6] Tesche (1988) found that ozone air quality models had prediction errors of 35% to 40%. More recent ozone air quality models are more accurate than this (Davidson et al., 2008; Hogrefe et al., 2008; Gilliland et al., 2008), but aerosol air-quality models are not yet as well developed, and the errors appear to be slightly larger than the errors in ozone air-quality models (Davidson et al., 2008; Fisher, 2008; Gilliland et al., 2008). The status of aerosol air-quality modeling is particularly relevant because aerosol levels are associated with premature mortality (e.g., Samet and Krewski, 2007).

[7] We used emissions data from: www.epa.gov/ttn/chief/trends/ and highway travel numbers from: www.fhwa.dot.gov/policy/ohpi/qftravel.cfm.

going ships (McCarthy, 2008). Ships have historically used fuel with extremely high sulfur levels and have generated significant global health impacts that have been estimated only recently (Corbett et al, 2007).

Table 5. Estimates of air-pollution health costs by mode (year-2006 cents).

	Road	Rail	Air	Water
Author estimates using COBRA[a]	LDGV: 0.91/pmt HDDV: 1.55/tm	0.35 /tm	0.39/pmt 1.88/tm	1.74/tm
Lemp and Kockelman (2008)[b]	0.11 to 1.53/pmt			
Parry et al. (2007)[c]	1.29/pmt			
Zhang et al. (2004)[d]	car: 0.09/pmt (intercity) car: 0.87/pmt (urban) bus: 0.10/pmt (intercity) transit: 0.34/pmt (urban) truck: 0.52/tm (freight)	0.49/pmt (intercity) 0.18/tm (freight)	0.01/pmt 0.003/tm (freight)	1.13/pmt 0.08/tm (freight)
Forkenbrock (1999; 2001)[e]	0.10/tm (freight truck)	0.01 to 0.03/tm (freight)		
McCubbin and Delucchi (1999)[f]	LDGV: 0.50 to 6.66/pmt HDDV: 1.04 to 19.35/tm			
Levinson et al. (1998)[g]	0.71/pmt		0.18/pmt	
Small & Kazimi (1995)[h]	1977 car: 5.61/pmt Tier II car: 0.24/pmt ULEV: 0.21/pmt 2000HDDT: 8.08/tm			

Notes: pmt = passenger-mile of travel; gtm = gross ton-mile; vmt = vehicle-mile of travel; tm = ton-mile; ULEV = ultra-low-emission vehicle; 2000HDDT = heavy-duty diesel truck, fleet average in the year 2000; Tier II car =

automobile meeting U. S. government Tier II emission standards; LDGV = light-duty gasoline vehicle; HDDV = heavy-duty diesel vehicle.

[a] COBRA refers to the Co-Benefits Risk Assessment (COBRA) Screening Model (Abt Associates, 2006). We ran the model in late 2008. COBRA estimates the value of health damages due to changes in fine particulate matter (PM) air quality due to changes in emissions in PM precursors, including SO_2, NO_2, and NH_3. "Built into COBRA are emissions inventories, a simplified air quality model, health impact equations, and economic valuations ready for use, based on assumptions that EPA currently uses as reasonable best estimates" (Abt Associates, 2006, p. 4). Estimates are in 2006 $. To produce estimates in dollars per unit of activity, we divided by estimates of total activity data for 2010: VMT by vehicle class from the EPA (2005, Table 3, p. G-8), and air, rail, and water ton-miles of shipment from the Bureau of Transportation Statistics (BTS) (Dennis, 2007, Figure 4). (The BTS shows data through 2005; we have projected data for 2010 assuming the rate of change from 2000 to 2005.) We assume that all rail effects are due to freight; and we assume that 90% of air travel effects are due to passenger travel and 10% due to freight, based on ton-weighted departures (FHWA, 2005, Table 2-4). We calibrated the rail and water estimates to be consistent with the emission inventory reported by EPA (2008) for the Locomotive & Marine Diesel rule, and we assumed that 5% of emissions were due to foreign ships not included in the BTS domestic ton-mile estimates.

b Lemp and Kockelman (2008) multiply vehicle emission rates, which they get from U.S. EPA emission indices, by unit health damage costs from Ozbay and Berechman (2001), for specific models of light-duty vehicles. The variation is due to different emission levels for different vehicles. Estimates appear to be in year-2006 $. We converted to pmt, assuming 1.6 passengers per vehicle.

c Parry et al (2007, Table 2) appear to report their estimate in year-2005 $. We converted to pmt, assuming 1.6 passengers per vehicle.

d Zhang et al. (2004) calculated the increases in mortality and morbidity cases due to the change in the concentration of each pollutant, and then estimated the monetary valuation of different impacts due to air pollution. Data from Table 6.22 of Zhang et al. (2004). Estimates are in year-2002 Canadian $. We converted to US $ using a typical year 2002 US/Canadian exchange rate (C$1.55=US$1.00), and then updated to year-2006 $.

e Forkenbrock's (2001, Table 9; 1999, p. 515) estimates are based on the work of Haling and Cohen (1995), who use results of National Economic Research Associates (NERA, 1993) to assign costs of air pollution in 2233 rural US counties in various states. NERA's estimates include impacts on health, materials, agriculture, and aesthetic quality. NERA's estimates of health costs include mortality and nonfatal effects ranging from minor irritations to more serious ailments that require medical treatment. Estimates are in 1994 $.

f McCubbin and Delucchi (1999, Table 4) use a detailed damage-function approach to estimate the health effects of air pollution from the on-road vehicle fleet in every county in the U. S. in 1990. Only emissions from motor vehicles themselves are included here; emissions from petroleum refineries and emissions of road dust are reported in McCubbin and Delucchi (1999) but not included here. The low-high range reflects uncertainty in emissions, air quality, health impacts, and valuation. Estimates are in 1991 $/vmt. We converted to pmt, assuming 1.6 passengers per vehicle; and for trucks we converted to ton-miles assuming 5.8 tons per truck, based on year 2000 VMT (FHWA, 2000, Table VM-1) and ton-miles (Dennis, 2007, Figure 4).

g Levinson et al. (1998, Table 12) synthesized earlier studies to develop cost estimates of air pollution caused by air travel, considering the health, material, and vegetation damages from particulates, sulfur oxides, hydrocarbons, carbon monoxide and nitrogen oxides, plus the greenhouse damages due to carbon. Estimates are in 1995 $. We converted to pmt, assuming 1.6 passengers per vehicle.

h Small and Kazimi (1995) estimate air pollution costs by pollutant and vehicle type in Los Angeles. Their baseline results, which are presented here, use a $4.87 million value of life, the geometric average of the high and low particulate mortality coefficients, the geometric average of two ozone morbidity figures with the costs equally attributed to NOx and VOC, and the only particulate morbidity figure. Estimates are in 1992 $. We converted to pmt, assuming 1.6 passengers per vehicle and 5.8 tons per truck (as noted in footnote f).

Air pollution costs: other impacts (visibility, agriculture, materials, forestry)

Brief Review of Methods and Issues, and Estimates of Costs

There have been very few recent estimates of visibility, agriculture, materials, and forestry costs of transportation air pollution in the U. S. As mentioned above, Forkenbrock's (1999; 2001) estimates are based on studies that include impacts on materials, agriculture, and "aesthetic quality," but his estimates are not disaggregated by type of impact. The air-pollution damage estimates of Levinson et al. (1998) also are based on studies that include damages to materials and vegetation, but like Forkenbrock, Levinson et al. (1998) do not disaggregate their results by type of impact.

We have found one set of estimates of the costs of the other (non-health) impacts of transportation air pollution in the U. S., and another set pertaining to all air pollution in the U. S. Delucchi et al. (2002) estimate the visibility cost of motor-vehicle air pollution, and Murphy et al. (1999) estimate the agricultural cost of motor-vehicle air pollution. These estimates, along with much less detailed estimates of the materials and forestry cost of motor-vehicle air pollution, are summarized in Delucchi (2000). On the basis of the information presented in Delucchi (2000), we can estimate the cost of the non-health impacts as a percentage of the cost of health impacts, for road. This is shown in Table 6.

Muller and Mendelsohn (2007) estimate air pollution damages to health, visibility, materials, and agricultural, from all sources of emissions in the U. S. in the year 2002. Table 6 includes their estimates. They estimate smaller damages from non-health impacts relative to health impacts than does Delucchi (2000), though both studies find that health impacts dominate. We suspect that in a table like this constructed for rail, air, and water modes, the costs of non-health impacts, in total, generally will be much less than the estimated health damages.

Table 6. The costs of the non-health impacts of motor-vehicle air pollution as a percentage of the cost of the health impacts

Non-health impact	Delucchi (2000), motor-vehicle air pollution low-damage case to high-damage case [a]	Muller and Mendelsohn (2007), all air pollution in U.S.
Visibility	19% to 10%	4%
Agriculture	17% to 2%	2%
Materials	5% to 3%	~0%
Forestry	1% to 1%	~0%
All	**43% to 15%**	**6%**

[a] In Delucchi (2000), percentages are the ratio of visibility + agricultural + materials + forestry damages to health damages excluding damages from "upstream" emissions (e.g., at petroleum refineries) and from road-dust emissions. The range is the low-damage case to the high-damage case. Estimates are based on 1990-1991 U. S. emission levels.

Climate change costs

Brief Review of Methods and Issues

All transportation modes emit pollutants that can affect global climate. These climate-forcing pollutants, sometimes called "greenhouse gases" (even though some of the pollutants are aerosols rather than gases), include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), nitrogen oxides (NO_2), ammonia (NH_3), sulfur oxides (SO_2), volatile organic compounds (VOCs), chlorofluorocarbons (CFCs), and various forms of particulate matter (PM). The Intergovernmental Panel on Climate Change (IPCC) provides an exhaustive review of research on the effects of GHGs on global climate (IPCC, 2007).

The climate change costs of transport can be estimated as the product of the two factors: CO_2-equivalent emissions of GHGs (in kg/ton-mile, kg/passenger-mile, or kg/vehicle-mile), and the damage cost of a unit of GHG emissions (in \$/kg-CO_2). Ideally, CO_2-equivalent emissions are estimated for the entire lifecycle of a transportation mode, where "lifecycle" refers to all of the activities directly or indirectly involved in transportation, including for example the production and transport of the fuel used by the transport mode and the production and transport of finished materials used by the transport mode. "CO_2-equivalency" means that one gram of emission of non-CO_2 GHG *P* is expressed as the number of grams of CO_2 that have an effect equivalent to that of one gram of *P*, where "equivalency" ideally is in terms of the damages from climate change (Bradford, 2001; Manne and Richels, 2001). The Lifecycle Emissions Model (LEM) (Delucchi, 2003) and the widely used Greenhouse-gases, Regulated Emissions, and Energy-use in

Transportation (GREET) model (Wang, 1999) estimate lifecycle, CO_2-equivalent emissions from transport modes except air.

The cost of a unit of GHG emissions has been estimated in numerous studies. Delucchi (2004c), Pearce (2003), Tol (2003), Wahba and Hope (2006), and Anthoff et al. (2009) review or develop original estimates of the marginal damage cost of CO_2 emissions. Anthoff et al. (2009) show that damage estimates can span several orders of magnitude, depending on the pure rate of time preference (a component of the social discount rate), the relationship between changes in consumption (or income) and changes in welfare (also known as equity weighting), and the per-capita income level to which the results are normalized. This wide range makes it difficult even to establish reasonable upper and lower bounds.

Estimates of U.S. Costs by Mode & Intermodal Comparisons

Table 7 shows estimates of the climate change cost. Not included in Table 7 are studies that estimate GHG emissions and radiative forcing changes due to transport modes but do not value the changes in dollars (Capaldo et al., 1999; Sausen et al., 2005; Eyring et al., 2005; Fuglestvedt et al., 2008). Eyring et al. (2005) summarize the emissions from international shipping over the past several decades. Capaldo et al. (1999) use a global chemical transport model to estimate that the emissions from international shipping can be a dominant contributor to atmospheric sulfur dioxide concentrations, and that particulate matter emissions from ships result in a global radiative forcing of $-0.11 Wm^{-2}$, due to cloud effects. Sausen et al. (2005) estimate that in the year 2000, aviation had a radiative forcing of 77.8 mW/m^2, including the effect of cirrus clouds induced by aviation. Fuglestvedt et al. (2008) calculate the global mean net radiative forcing due to each transport sector in the year 2000 relative to preindustrial times: 175 mW/m^2 for the road sector, about 5 mW/m^2 for the rail sector, 70 mW/m^2 for aviation, and -70 mW/m^2 for shipping. Shipping has a negative radiative forcing because of relatively high emissions of sulfur dioxide, due to the high sulfur content of marine fuel oil.[8]

The estimates developed for this paper, shown as “Author estimates” in Table 7, span the range of the other estimates presented in Table 7. The nearly 100-fold difference between our low and high results is due entirely to the uncertainty in the $/kg damage cost of GHG emission, as discussed above. Note that our estimates include the full lifecycle, and a wide range of GHGs, whereas the other estimates in Table 7 include only end-use emissions of CO_2.

[8] Our “author estimates” in Table 7 also account for the high emissions of sulfur from shipping and the negative radiative forcing effect of sulfate.

Table 7. Estimates of climate-change damage costs by mode (year-2006 cents).

	Road	Rail	Air	Water
Author estimates[a]	car: 0.06 to 4.78/pmt (26 mpg) scooter: 0.02 to 1.23/pmt mini-bus: 0.02 to 1.47/pmt city bus: 0.04 to 3.46/pmt truck: 0.03 to 2.74/tm (freight)	0.02 to 1.68/pmt (intracity rail transit) 0.006 to 0.47/tm (freight)		0.002 to 0.23/tm (freight)
Lemp & Kockelman (2008)[b]	0.84 to 3.81/pmt			
Parry et al. (2007)[c]	0.19/pmt			
Zhang et al. (2004)[d]	car: 0.06/pmt (intercity) car: 0.12/pmt (urban) bus: 0.01/pmt (intercity) transit: 0.04/pmt (urban) truck: 0.06/tm (freight)	0.07/pmt (intercity) 0.01/tm (freight)	0.08/pmt 0.45/tm (freight)	0.16/pmt (passenger ferry) 0.01/tm (freight – presumably a large cargo ship)
Forkenbrock (1999; 2001)[e]	0.19/tm (freight)	0.03/tm (freight)		

Notes: pmt = passenger-mile of travel; tm = ton-mile.

[a] We multiply estimates of lifecycle CO_2-equivalent emissions, in grams/passenger-mile or grams/ton-mile, by an assumed GHG global damage cost of $\$1.0/10^6$-g-$CO_2$-equivalent (low-cost case) to $\$80/10^6$-g-$CO_2$-equivalent (high-cost case) (\$0.91/ton to \$73/ton). The estimates of lifecycle emissions are from an updated version of the model documented in Delucchi (2003), and include the CO_2 equivalent of CH_4, N_2O, CO, NO_2, SO_2, VOCs, PM, and CFCs. The damage cost estimates are based on our review of Delucchi (2004c), Pearce (2003), Tol (2003), Wahba and Hope (2006), and Anthoff et al. (2009). Estimates in year-2006 \$.

[b] Lemp and Kockelman (2008) multiply end-use (not lifecycle) emissions of CO_2 (not including other GHGs), estimated on the basis of the carbon-content of the fuel and the fuel economy, by an assumed damage value of

$50/ton-$CO_2$, for specific models of light-duty vehicles. Estimates appear to be in year-2006 $. We converted to pmt, assuming 1.6 passengers per vehicle.

[c] Parry et al (2007, Table 2) multiply end-use (not lifecycle) emissions of CO_2 (not including other GHGs) by an assumed damage value of $14/ton-$CO_2$, (They consider a range of $5.50/ton to $82/ton.) They appear to report their estimate in year-2005 $. We converted to pmt, assuming 1.6 passengers per vehicle.

[d] Zhang et al. (2004) multiply end-use (not lifecycle) emissions of CO_2 (not including other GHGs) by an assumed damage value of $5.50/ton-$CO_2$ (year 2002 Canadian $), which they derived starting with a value of $3.50/ton-$CO_2$ in 1990 US $. Original estimates are in year-2002 Canadian $. We converted to US $ using a typical year 2002 US/Canadian exchange rate (C$1.55=US$1.00), and then updated to year-2006 US $.

[e] Forkenbrock (1999, p. 516; 2001, Table 7) multiplies end-use (not lifecycle) emissions of CO_2 (not including other GHGs) by an assumed damage cost of $10 per ton of CO_2. Estimates are in 1994 $.

Noise costs

Brief Review of Methods and Issues

In many urban areas, noise is a serious problem. Roadways with large volumes of high-speed traffic, high-speed rail lines, and airports can be very noisy. This noise can disturb sleep, disrupt activities, hinder work, impede learning, and cause stress. As a result, homes near major roadways and airports have less value than similar homes further away.

The external cost of noise from transport includes the value of the damages from excess noise experienced plus the cost of any defensive actions or avoidance behavior, although this second factor (defensive/avoidance behavior) rarely is estimated. To estimate damages from excess noise from a particular transport mode, one needs a model of noise generation from the source, a method for estimating exposure to the noise, and a method for valuing the damages of exposure above a threshold. Noise generation and exposure models have been developed for all modes; see Miedema and Oudshoorn (2001) for a review of models of annoyance due to exposure to noise from road, air, and rail transport, and Delucchi and Hsu (1998) for an application of noise-generation models to road noise and the resultant damages. Noise damage values generally are estimated on the basis of "hedonic" price analyses, which are discussed next.

As mentioned above, noise is a prominent enough problem that it measurably affects the value of homes. Econometric or "hedonic" price analyses measure this effect by estimating the sales price of a house as a function of a number of important characteristics, including the ambient noise level or distance from a major noise source (Nelson, 2008). If such an analysis does not omit important determinants of sales price, it can tell us how much an additional decibel of noise (above a certain threshold) reduces the value of a home. This reduction in value per decibel, multiplied by the average value of homes, the number of homes exposed to noise above a threshold, and the amount of noise above a threshold, will tell us the external "damage cost" of transport noise in and around the home. (See Nelson [2008] for a comprehensive discussion of issues in hedonic property value studies of noise from aircraft and road traffic.)

In the estimation of noise damages from transport a number of factors are uncertain. Delucchi and Hsu (1998) show that in the case of road-noise damages, the primary uncertainty regards the cost of noise per decibel above a threshold, the interest rate, the amount of noise attenuation due to ground cover and intervening structures, the threshold level below which damages are assumed to be zero, the density of housing alongside roads, average traffic speeds, and the cost of noise away from the home. The case of noise from air travel may be less complicated, because exposure is not attenuated by structures in complex ways.

Estimates of U.S. Costs by Mode & Intermodal Comparisons

Table 8 presents several estimates of noise damage costs. Most studies focus on noise from highway vehicles or airplanes, because noise from trains and ships generally is thought to be relatively minor. For example, Andersson and Ögren (2007) state that several studies have shown that individuals perceive noise from road traffic as more annoying than from rail traffic, and Bickel et al. (2006, p. 397) assume that ship noise is negligible.

Note that the studies of Table 8 estimate damages from each transport mode under the assumption that the mode is the only source of noise. Because noise from different sources does not simply add up, the net effect of "marginal" noise from a particular transport mode can depend on the magnitude and characteristics of other sources of noise (Moore, 1978).

Table 8. Estimates of noise damage costs by mode (year-2006 cents).

	Road	Rail	Air	Water
Forkenbrock (1999; 2001)	0.05/tm (freight)	0.05/tm (freight)[a]		
Delucchi and Hsu (1998)[b]	LDVs: 0.00 to 3.45/pmt HDTs: 0.00 to 5.48/tm			
Levinson et al. (1997, 1998)	0.87/pmt [c]	0.52/pmt to 0.89/pmt [d]	0.88/pmt [e]	

Notes: pmt = passenger-mile of travel; tm = ton-mile; LDV = light-duty vehicle; HDT = heavy-duty truck.

[a] Forkenbrock (2001) looked at the external costs of freight rail in rural areas in US. He argued that in sparsely settled rural areas, exposure to rail noise is similar to exposure to noise from trucks operating on highways, and that both are small. Accordingly, he assumed for rail noise the same cost per ton-mile he estimated for trucks in Forkenbrock (1999, p. 518). Original estimates are in year-1994 $.

[b] See discussion of Delucchi and Hsu (1998) in the text. Range is damages from travel on local roads, in the low-cost case, to damages from travel on interstate freeways, in the high-cost case. (Note that Delucchi and Hsu [1998] consider the high-cost case to be unlikely.) Estimates are in year-1991 $. We converted to pmt, assuming 1.6 passengers per vehicle; and for trucks we converted to ton-miles assuming 5.8 tons per truck, based on year 2000 vehicle miles traveled (FHWA, 2000, Table VM-1) and ton-miles (Dennis, 2007, Figure 4).

[c] Levinson et al. (1998, Table 12) use a noise-generation model to estimate the cost of motor-vehicle noise. They assume that there is zero background noise (Levinson et al, 1997, p. 209). Estimates are in year-1995 $. We converted to pmt, assuming 1.6 passengers per vehicle.

[d] Levinson et al. (1997, p. 210) analyzed the noise costs caused by high-speed rail for two train speeds: 125 mph and 200 mph. The $ year is unclear; we assume year-1994 $.

[e] Levinson et al. (1998, Table 3) review estimates of noise damage costs from air planes in Europe, and then assume that the average value applies to the U. S. (Zhang et al. [2004] make the same assumption.) Estimates are in year-1995 $.

Water pollution

Brief Review of Methods and Issues

Fuels and chemicals from transportation modes can spill and leak into oceans, rivers, lakes and groundwater. This water pollution can harm human health, injure and kill wildlife, corrode materials, and despoil scenic recreation areas (see Freeman [2000] for a discussion of the costs and benefits of water pollution policy). Transportation modes also can cause water pollution indirectly: emissions of nitrogen oxide from fuel combustion can eventually deposit as nitrate and cause nitrogen pollution in aquatic systems (see Galloway et al. [2004] for a comprehensive discussion of the nitrogen cycle).

In general there has been much less research on the dollar cost of the impacts of water pollution than on the dollar cost of the impacts of air pollution. A few studies have quantified the economic cost of oil spills (e.g., Grigalunas et al., 1986; Carson et al, 2004), but there is essentially no systematic research on the costs of the other impacts of water pollution. Gaffield et al. (2003) estimate that gastrointestinal illnesses due to water pollution (apparently from storm runoff) cost $2 to $14 billion per year (2002 dollars), but it is difficult to apportion to this to transportation. In any event, quantifying the cost of water pollution is a relatively low priority, because it appears to be small compared to the other external costs of transport (see Table 9).

Estimates of U.S. Costs by Mode & Intermodal Comparisons

We found in the peer-reviewed literature one relatively recent estimate of water pollution damage costs from road transport. This estimate is presented in Table 9.

Table 9. Estimates of water-pollution costs by mode (year-2006 cents).

	Road	**Rail**	**Air**	**Water**
Delucchi (2000, 2004b)[a]	0.014 to 0.051/pmt $0.003/tm to $0.051/tm (freight)			

Notes: pmt = passenger-mile of travel; tm = ton-mile.

[a] Equal to Delucchi's (2000) estimate of damages from oil spills, leaking storage tanks, and urban runoff due to oil use by all highway vehicles in the U. S. in 1990/91 ($0.4 to $1.5 billion), allocated between light-duty vehicles and heavy-duty vehicles according to fuel use in 1991 (78.1% LDVs, 21.2% HDVs, 0.7% buses; Table 1-A5 of Delucchi [2004b] for LDVs and HDVs and www.fhwa.dot.gov/policy/ohpi/qftravel.cfm for buses), then divided by pmt for LDVs and ton-miles for HDVs per Table 4 note *c* . Original estimates are in 1991 $.

Note that the estimates in Table 9 do not include the costs of the water-quality impacts of highway de-icing, which can disintegrate pavement, corrode vehicles and bridges, pollute groundwater, and harm vegetation (Vitaliano, 1992; EPA, 1996; Granato et al., 1996). Murray and Ernst (1976) estimated that in the U.S. in the 1970s, the environmental impacts of highway de-icing, including pollution of water supply and damage to human health, damage to vegetation, and corrosion of vehicles and infrastructure cost $2.9 billion/year (1973-74 $). Vitaliano (1992) also estimates the social costs of highway de-icing, and although he does not report national totals, his estimates of damages per ton of salt appear to be similar to Murray and Ernst's (1976). We do not include de-icing water-quality costs here because they either are not externalities at all (in the case of vehicle corrosion costs), or in any case are not external costs of marginal travel. However, these costs should be included in full social cost-benefit analyses of transportation investments.

Our estimate also excludes indirect water pollution impacts, such as NOx/nitrate pollution of aquatic ecosystems, as mentioned above. These are marginal external costs of transport fuel use, but as far as we know they have not been quantified.

Energy security/oil-importing costs

Brief Review of Methods and Issues

The U. S. consumes about a fourth of the world's petroleum, and imports nearly 60% of its own consumption (Davis et al., 2008). Over two thirds of U. S. oil consumption goes to the transportation sector, which with the exception of some electric rail systems is fueled entirely by petroleum.

The heavy use of imported oil by the transportation sector gives rise to several kinds of economic costs that are not reflected in the price of oil: the cost of the Strategic Petroleum Reserve, defense expenditures to protect U. S. oil interests, macro-economic disruption/adjustment costs due to price volatility, and pure wealth transfers from U. S. consumers to foreign producers. These external costs ultimately derive from the concentration of large amounts of oil in relatively unstable regions of the world, in particular the Persian Gulf.

Strategic Petroleum Reserve (SPR). The SPR is meant to buffer the effects of sudden supply shortfalls or sudden price spikes (www.fe.doe.gov/programs/reserves/index.html). The cost of the SPR includes the annualized construction costs, ongoing maintenance and repair costs, and costs related to changes in the value of oil over the period it is stored. Delucchi (2007) estimates the total cost of the SPR is very small, and so consequently we do not include it in our quantitative estimates here.[9]

[9] Delucchi (2007) probably underestimates the future price of oil in his low-cost case, but the higher the future price, the higher the present value of future oil sales, and hence the lower the cost of holding oil for future use.

Defense Expenditures. A substantial fraction of the U. S. defense goes towards protecting U. S. interests in Middle East – interests that center mainly on oil (Delucchi and Murphy, 2008a). Delucchi and Murphy (2008a) attempt to quantify the relationship between the size of the defense budget and various aspects of U. S. oil interests in the Middle East. Because there is little real information on which to base this quantification, the estimates of Delucchi and Murphy (2008a) span a wide range (see Table 10).

Macroeconomic adjustment costs. The inability of the macro economy to adjust efficiently to rapid changes in the price of oil can cause a real decrease in economy-wide output, manifest as a reduction in Gross Domestic Product (GDP). This "macroeconomic adjustment cost" (MEAC) is a function of the total level of petroleum consumption, the magnitude of the price change, the substitutability of oil in the economy, and other factors. To the extent that the MEAC is a real resource cost, a function of oil consumption, and not reflected in the price of oil, it is a marginal external cost of oil use. Jones et al. (2004) review research from 1996 to 2004 on the relationship between oil price shocks and the macroeconomy, and conclude that a one percent change in oil price causes a -0.055% change in GDP. Leiby (2007) provides the best recent estimate of the external macro-economic adjustment cost. The most important factors in the estimate of this external cost are the size of the U. S. economy, the level of imports, the world oil price, the likelihood of a disruption, and the responsiveness of regional oil supply and demand.

Wealth transfer cost. Because the world price of oil generally is well above the long-run marginal production costs of most of the major oil exporters, consumers of imported oil generally transfer a large amount of wealth to oil exporters. Greene and Ahmad (2005) estimate that from 1970 to 2004 this oil/wealth transfer cost exceeded one trillion dollars. However, because this cost is a transfer among nations we do not count it as an external cost here.

Estimates of U.S. Costs by Mode & Intermodal Comparisons

Few analyses estimate the external costs of oil importing. For this paper we have made original estimates by multiplying the energy-use intensity of different modes by the oil-importing damage cost. Table 10 shows the estimates; details are given in the notes to the table.

Table 10. Estimates of energy-security/oil-importing costs by mode (year-2006 cents).

	Road	Rail	Air	Water
Author estimates[a]	car: 0.20 to 0.75/pmt light truck: 0.22 to 0.84/pmt transit bus: 0.23 to 0.89/pmt freight truck: 0.22 to 0.84/tm	passenger: 0.15 to 0.58/pmt freight: 0.02 to 0.07/tm	passenger: 0.18 to 0.69/pmt	freight: 0.03 to 0.11/tm
Parry et al. (2007)[b]	0.39/pmt			

Notes: pmt = passenger-mile of travel; tm = ton-mile; MEAC = macroeconomic adjustment/disruption cost; EIA = Energy Information Administration.

[a] Oil importing damage cost. Leiby (2007) estimates the MEAC in the U. S. to be $2.10 to $7.40 per bbl of imported oil (2005 $) and reports that imported oil is 58.6% of total oil demand, which results in $1.20 to $4.30/bbl of all oil demanded in the U. S. We update to 2006 $ using the GDP implicit price deflator (Table 1.1.9 of the National Income Product Accounts from the Bureau of Economic Analysis [www.bea.gov/national/nipaweb/index.asp]), and then multiply the high value by a factor of 1.2 to account for the MEAC due to use of domestic oil, which as Leiby (2007) suggests is less than the cost of imported oil but not zero. The result is $1.27/bbl-oil to $5.36/bbl-oil.

Delucchi and Murphy (2008a) estimate that the military cost of consuming Persian-Gulf oil in the U. S. in 2004 was $13.4 billion to $47.0 billion, or $1.80/bbl to $6.20/bbl of all oil supplied in the U. S. in 2004 (given 7.6 billion bbl of crude and products supplied in 2004 [EIA, 2008]). Updating to 2006 dollars using the GDP implicit price results in a range $1.88/bbl-oil to $6.59/bbl-oil.

Leiby (2007) also estimates "monopsony" or demand-related wealth-transfer costs, but because these are transfers from U. S. consumers to foreign producers we ignore them here. We ignore the annualized cost of the Strategic Petroleum Reserve because it is trivial (Delucchi, 2007).

The MEAC and the military cost total $3.15/bbl to $11.95/bbl. Multiplying the total by 1-bbl-crude-oil/1.063-bbl-products and 1-bbl-product/5.353·10^6-BTU-product (higher heating value) in 2006 (both conversions from the EIA [2008]) gives a range $0.55/10^6$-BTU-product to $2.10/10^6$-BTU-product in the U. S. in 2006 $.

Energy intensities by mode. We assume the following end-use (not lifecycle) energy intensities (based on higher heating values, using the same energy conversion factors that the EIA uses):

Mode	Energy intensity		Source and notes
cars	3,571	BTU/pmt	Davis et al. (2008) Table 2.13, year 2005
personal trucks	~4,008	BTU/pmt	Our estimate for year 2005 based on Davis et al. (2008)
transit bus	4,235	BTU/pmt	Davis et al. (2008) Table 2.13, year 2005
air travel	3,264	BTU/pmt	Davis et al. (2008) Table 2.14, year 2005
passenger rail	2,759	BTU/pmt	Approximate weighted average of intercity rail, rail transit, and commuter rail, in Davis et al. (2008) Table 2.14, year 2005 (uses weights based on year 2006 energy use)
water (freight)	514	BTU/tm	Davis et al. (2008) Table 2.14, year 2005
rail (freight)	337	BTU/tm	Davis et al. (2008) Table 2.14, year 2005
road (freight)	4,009	BTU/tm	Energy use of medium/heavy trucks divided by ton-miles of freight hauled by trucks, Davis et al. (2008) Tables 2.7 and 5.12, year 2002

[b] Parry et al (2007, Table 2) appear to report their estimate in year-2005 $. We converted to pmt, assuming 1.6 passengers per vehicle.

Because a single national damage cost per energy unit applies to all modes, differences in damages among modes depend entirely on differences in energy consumption per mile (on the assumption that all modes use petroleum). As shown in the notes to Table 10, all passenger transport modes have roughly similar energy intensities per passenger mile, at current average occupancies, but freight shipment by road is an order of magnitude more energy intensive than shipment by water or rail.

Other costs (not estimated here)

The construction and use of transportation modes can create "external" or non-market costs beyond those estimated here. For example, all modes create unsightly infrastructure and waste, which presumably have an aesthetic cost. Surveys have found, not unexpectedly, that the general public feels that the world would be prettier without roads (Huddart, 1978), and the unsightliness of scrapped autos and junkyards has been formally condemned by the courts (Woodbury, 1987).

Poorly designed and thoughtlessly placed transportation infrastructure can divide communities, impede circulation, and create barriers to social interaction.[10] Indeed, the "freeway revolts" that began in the late 1960s and shut down freeway projects in several cities in the U. S. – the dead-end Embarcadero Freeway in San Francisco, torn down after the 1989 Loma Prieta earthquake, is perhaps the most famous example – were spawned in part by these sorts of negative social impacts. Soguel (1995) cites a study by Appleyard that shows that "residents of San Francisco with light volumes of traffic have three times as many local friends and twice as many acquaintances as those on heavily traveled streets" (p. 302).[11]

Transportation infrastructure also can fragment sensitive environmental habitat and thereby disturb and possibly even eliminate plants and other (non-human) animals. Van Bohemen (1995, p. 133) distinguishes four kinds of fragmentation: destruction, disturbance, barrier action, and collisions with vehicles. Valuing these impacts is a complex undertaking (see Nijkamp et al. [2008] for a review issues in estimating the economic value of biodiversity). Willis et al. (1998) review studies of the "wildlife value" and "landscape value" of land used for roads in Britain. They report a very wide range of values, from less than £10/ha/yr to more than £10,000/ha/yr, depending, naturally, on the type of land (forest, meadow, farm, etc.), and the type of values solicited (use value, option value, existence value, etc.).

Finally, taxes and fees paid by users of transportation modes and transportation fuels may be considered to be insufficient or excessive with respect to some standards of equity or social-cost accounting. Delucchi (2007) and Delucchi and Murphy (2008b) review these issues and offer estimates of various financial "subsidies" to motor vehicle use in the U. S.[12] We do not include financial subsidies here because generally they are matters of equity rather than economic efficiency and hence do not constitute externalities as we define them.

Summary and conclusion

Table 11 presents the low and high estimates of the external cost of each of the impacts reviewed here. We can draw three general conclusions from this review. First, per passenger-mile or per ton-mile, the road mode generally has higher external costs than do the other modes. This is due to the relatively high energy intensity of road travel, the relatively close proximity of road vehicles to people, and to individuals operating the vehicles. Second, accident and congestion costs generally are the largest, followed by air pollution and climate change costs. Third, there is a great deal of uncertainty in many of the estimates,

[10] Along these lines, some researchers suggest that roads and cars cause urban "sprawl" and that sprawl has external costs (not paid by transportation users), such as higher infrastructure costs and reduced social interaction. However, Brueckner and Largey (2008) find that the effect of low density on social interaction actually is *positive*, or beneficial, rather than negative: as density decreases, social interaction *increases*.

[11] Soguel (1995) surveyed residents in the Swiss town of Neuchâtel (population 32,000) and found that they were willing to pay $1.9 to $2.6 million per year, or $58 to $82/person/year, to divert traffic on five urban streets to underground bypasses (for a total of 750 meters), in order to provide unimpeded access to the city center.

[12] A related issue is whether unpriced (free) parking is an external cost. The answer to this depends in part on considerations of the size of transaction costs and the "efficiency" of bundling, and partly on how one views environmental and congestion externalities that are indirectly related to parking supply. See Button (2006), Feitelson and Rotem (2004), and Shoup (2005) for a discussion of some of the issues; see Shoup (2005) for a discussion of the costs and impacts of "free" parking. This issue receives considerable attention because the total annualized cost of unpriced parking is at a minimum several tens of billions dollars per year (Delucchi, 2004b).

often having to do with the step of valuing physical impacts. Ongoing research will reduce this uncertainty.

Table 11. Summary of estimates of external costs by transport mode and cost category (year-2006 cents).

	Passenger (per passenger-mile)				Freight (per ton-mile)			
	Road	*Rail*	*Air*	*Water*	*Road*	*Rail*	*Air*	*Water*
Congestion delay	0.88 - 7.5	n.e.	0.35	n.e.	0.54	0.03	n.e.	n.e.
Accident	1.4 - 14.4	n.e.	n.e.	n.e.	0.11 – 2.0	0.22	n.e.	n.e.
Air pollution, health	0.09 - 6.7	0.49	0.01 - 0.39	1.1	0.10 - 18.7	0.01 - 0.35	0.0 - 1.9	0.08 – 1.7
Air pollution, other	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Climate change	0.06 - 4.8	0.02 - 1.7	0.08	0.16	0.02 - 5.9	0.01 - 0.47	0.45	0.00 - 0.23
Noise	0.0 - 3.5	0.52 - 0.89	0.88	n.e.	0.0 - 5.3	0.05	n.e.	n.e.
Water pollution	0.01 - 0.05	n.e.	n.e.	n.e.	0.003 to 0.05	n.e.	n.e.	n.e.
Energy security	0.20 - 0.84	0.15 - 0.58	0.18 - 0.69	n.e.	0.22 - 0.84	0.02 - 0.07	n.e.	0.03 - 0.11

n.e. = not estimated.

We have presented here estimates of the external costs of transport per passenger-mile and per ton-mile for recent years in the U. S. It also is interesting to ask what the *total* external costs of transport, as opposed to the costs per mile, might be in the future. Total external costs are the product of the total activity (e.g., passenger-miles of travel) and the average external cost per unit of activity (e.g., cost per passenger-mile of travel). We therefore conclude this chapter with discussions of trends in activity levels and costs per unit of activity, for the major external costs of road transportation.

<u>Congestion.</u> By any measure, road congestion has increased rapidly and dramatically over the past two decades (Schrank and Lomax, 2007). The dramatic rise in congestion is due to increases in vehicle-miles of travel and reductions in vehicle speeds. In the case of congestion -- unlike in the cases of accidents and air pollution -- there has been no reduction in impacts per mile to offset the increases in total miles driven.

Constraints on adding road capacity and the difficulty of discouraging or re-directing motor-vehicle use make large, widespread decreases in travel unlikely, although recent transportation planning efforts focused on better matching of origins and destinations may dampen VMT growth in some areas of the U.S. More promising are efforts to reduce congestion impacts per mile by re-allocating travel over time and space. (Congestion impacts per mile also can be reduced by making vehicles smaller, but the prospects for this seem unlikely.) Travel can be re-allocated by traffic control or by pricing; in the U. S., policy makers appear to favor pricing. The federal government and several states are developing congestion-pricing programs (Congressional Budget Office, 2009; Federal Highway Administration, 2008), including some designed to ease truck congestion at ports (Mani and Fischer, 2009).

Accidents. The fatality and injury rate per mile of vehicle travel have declined steadily for many years, due to reduced involvement of alcohol, increased use of seatbelts, improved vehicle safety, and other factors (Blincoe et al., 2002; Starnes, 2008). However, these reductions have been offset by growth in vehicle miles of travel, with the result that total road fatalities have remained roughly constant. Absent substantial changes in travel or traffic safety patterns, these trends are likely to continue in the near term.

Air pollution. Dramatic reductions in emissions per mile from motor vehicles, due to improved emission-control technology spurred by tougher emission standards, have outpaced the growth in total vehicle travel, with the result that total emissions of all air pollutants from the highway transportation sector in the U. S. have declined dramatically since 1990 (www.epa.gov/ttn/chief/trends/index.html). However, damage-cost trends may not have followed these emissions trends exactly, because the exposed population and the value of impacts have increased.

In the future, continued reductions in emissions per mile, particularly from diesel vehicles -- which emit the most damaging pollutants (PM, SO_X, and NO_X) -- may result in sharp decreases in total transportation-related air pollution damages, in spite of increasing travel and greater exposed population. Note that as vehicular air pollution is reduced, air-pollution-damage costs will become less important compared with accident, congestion, climate-change, and energy-security costs.

Climate change and energy security. Motor-vehicle energy use, petroleum use, and greenhouse-gas emissions have been increasing since 1970 because VMT has increased steadily while fuel use per mile has declined only modestly. Since the mid-1990s, petroleum use has increased with VMT, which implies that fuel-use per mile has remained constant (Davis et al., 2008). Oil-importing "energy-security" costs have increased since the 1990s because of increasing petroleum use, increasing oil imports, higher oil prices, and more regional conflicts over oil (Leiby, 2007). Similarly, climate-change costs have increased with petroleum use, population, and income.

In the near term, these trends in climate-change and energy-security costs are likely to continue. The middle term is uncertain, because of uncertain prospects for fuel-economy improvements and fuel substitution, and uncertainty about oil prices. In the long run (at least 30 years hence) we expect to see the energy-security and climate-change costs of transportation mitigated greatly by the widespread use of non-petroleum fuels.

We conclude that safety and congestion costs will remain large until there are very broad changes in transportation activity. The mitigation of energy-security costs and climate-change costs depends on the pace of introduction of non-petroleum fuels, which is difficult to predict. Air pollution costs are likely to be of diminishing importance.

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