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The social costs of intercity transportation: a review and comparison of air and highway

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This paper provides a comprehensive survey of the literature on the measures of social costs, providing an indication of the state of engineering and economic literature. We operationalize the new thinking about which externalities to consider in an analysis of the transportation system. We construct measures of each externality: noise, air pollution, accidents and congestion for the highway and air transportation modes, where possible as a function of the amount of output or use, rather than as simple unit costs. We find that noise is the dominant cost of air travel, followed by congestion, air pollution and accidents. For highway travel, accidents are the most significant cost, followed by congestion, noise and air pollution. The social costs of highway travel are about 15% of the full costs of a highway trip, while the smaller social costs of air travel are only 5% of the full costs of an air trip. A highway trip generates four to five times as much externality as an air trip.

1. Introduction

There has been a great deal of interest in the issue of the social or external costs of transportation (Keeler *et al.* 1975, Fuller *et al.* 1983, Quinet 1990, Mackenzie *et al.* 1992, INRETS 1993, Miller and Moffet 1993, Works Consultancy Services 1993, INFRAS/IWW 1995, IBI 1995). The passions surrounding social costs and transportation, in particular those related to the environment, have evoked far more shadow than light. At the center of this debate is the question of whether various modes of transportation are implicity subsidized because they generate unpriced externalities, and to what extent this biases investment and usage decisions. On the one hand, claims of environmental damages as well as environmental standards formulated without consideration of costs and benefits often result in slowing or stopping investment in new infrastructure. On the other hand, the real social costs are typically not recovered when financing projects and are rarely used in charging for their use.

This paper provides a comprehensive survey of the literature on the measures of social costs in transportation, providing an indication of the state of engineering and economic literature. We operationalize the new thinking about what externalities are appropriate to consider in an analysis of the transportation system for developing the full cost, without double counting or attributing to transportation costs what are really due to other economic sectors. We measure each significant externality: noise, air pollution, accidents and congestion for both highway and air transportation, as a function of output or use where possible, rather than as simple unit or average costs.

Before we can measure externalities, we must define them. Spulber (1989) states that '[a]n externality refers to a commodity bundle that is supplied by an economic

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agent to another economic agent in the absence of any related economic transaction between the two agents'. Rothengatter (1994) cites the definition: 'an externality is a relevant cost or benefit that individuals fail to consider when making rational decisions.' These definitions bring out the idea that, in addition to there being willing parties to transactions, there are also unwilling parties—parties subject to the externality. In our analysis, we are dealing with negative externalities, that is a commodity bundle or a cost which the receiving party would rather not receive without compensation.

Central to the definition and valuation of externalities is the definition of the agent in question. One way is to define agents as comprising each vehicle, which influences other vehicles (agents) by generating effects (such as congestion and increasing the risk of accident) largely contained within the transportation system, and which also influences unrelated agents by generating effects (such as noise and air pollution) not contained within the transportation system. Alternatively, the infrastructure operator may be selected as the agent, thereby internalizing the first set of effects. However, we choose the first definition, giving us a broader scope of externalities to examine.

Second, we must determine what 'commodity bundles' or externalities are appropriate to consider in this context. This depends on how we define the problem of intercity transportation. Overall, the intercity transportation system is open, dynamic and constantly changing. Some of the more permanent elements include airports, intercity highways and railroad tracks. The system also includes the vehicles using those tracks (roads, rails or airways) at any given time. Other components are less clear-cut: are the roads which access their airports, freeways or train stations part of the system? The energy to propel vehicles is part of the system, but is the extraction of resources from the ground (e.g. oil wells) part of the system? DeLucchi (1991) analyses them as part of his life-cycle analysis, but should we? Where in the energy production cycle does it enter the transportation system?

Any open system influences the world in many ways. Some influences are direct, some are indirect. The transportation system is no exception. Three examples may illustrate the point:

(*a*) *First order (direct) effect:* a road improvement increases demand and reduces travel time.
(*b*) *Second order (less direct) effect:* reduced travel time increases the amount of land development along a corridor; this is not direct because other factors may intervene to cause or prevent this consequence.
(*c*) *Third+ order (indirect) effect:* the new land development along a corridor results in increased demand for public schools and libraries.

As can be seen almost immediately, there is no end to the number or extent of third+ order (indirect) effects, which may follow in turn from second order (less direct) effects. While recognizing that the economy is dynamic and interlinked in an enormous number of ways, we also recognize that it is almost impossible to quantify anything other than proximate, first order, direct effects of the transportation system. Rather than building a structural model of the economy tracing the reverberations and interactions of all choices, decisions and outcomes, we rather rely on correlation between cause and effect, given that many effects have multiple causes which only influence the outcome probabilistically. If the degree to which 'cause' (transportation) and 'effect' (negative externality) are correlated is sufficiently high, then we consider the effect direct; the lower the probability of effect following from the single (transportation) cause, the less direct is the effect. The question of degree of correlation is fundamentally empirical, and the appropriate level of correlation to use contains an element of arbitrariness.

Several costs are excluded because they are outside the strictly defined intercity transport sector. In order to evaluate costs, borders must be drawn around the system we are considering, otherwise one is drawn into a full evaluation of the entire economy. First, we exclude pecuniary externalities, the effect on other markets due to changes in price associated with changes in demand. For a limited project, for instance a single corridor, it is unlikely prices in most commodity markets will change noticeably. Some researchers ascribe a fraction of US defense costs to the transportation sector, since much of that defense is of the Middle East, an oil producing region, which would not otherwise be defended. The links are tenuous, and certainly outside the market. It is unclear whether such defense expenditures actually lower energy costs and they may be undertaken for a variety of geopolitical reasons. Others consider parking to be a cost associated with transportation. Parking is not 'free'; it is either charged directly to the consumer or subsidized by the provider (a shopping center or office building or the community which builds wider than necessary streets). Parking costs are not included since this research evaluates the differences in intercity transportation, and parking is a local cost which is unlikely to be avoided by switching intercity travel modes. Access costs, the costs to access the intercity transportation system (the airport, the interstate highway) are not considered as they are mainly local and would largely complicate the work, in addition to not being significantly different for the two modes. 'Sprawl' and increased costs of serving dispersed land uses are sometimes blamed on the automobile. Certainly automobility enables dispersed housing, but so do the telephone and any number of other technologies. It is at least a second order effect, and outside the intercity transport sector. There are also costs which have long been recognized but are seemingly impossible to accurately quantify, including things like 'social severance' or the cost of dividing communities with infrastructure, or 'ecosystem severance', the costs to the environment of driving a highway through local ecologies.

In this analysis, we divide the direct external costs (inputs) into four main categories: Noise (Quiet), Air Pollution (Clean Air), Accidents (Safety) and Congestion (Time), which are discussed sequentially in the following sections. Each section, in turn, describes the measurement of that externality, how much is generated as a function of transportation outputs, how that externality is valued and an integration of these two elements to arrive at the total cost of that externality. Further, this analysis is conducted for both highway and air. After reviewing the full cost of each externality, we compare them across modes. The paper concludes by noting that the value of externality varies with modal use, and despite all of the research, we still lack a knowledge on the true economic costs of externalities. The challenge is not simply measuring the externality, but also valuing it, a bridging of the fields of engineering and economics.

2. Noise

2.1. *Measurement*

Noise is usually defined as unwanted sound. Sound is most commonly measured by the decibel (dB), which is defined as follows (Starkie and Johnson 1975):

$$dB = 10\log_{10}\,(P^2/P_{ref}) \tag{2.1}$$

where P is the pressure in newtons per square meter and $P_{ref} = 0.00002\ \text{N m}^{-2}$, which is the quietest audible sound.

The frequency of sound is measured in cycles per second (hertz), the range from 20–16 000 H can be heard by the human ear. Generally, sound measures are weighted to reflect what is perceived as 'loudness'. The most common weight, the A scale, gives the measure dB(A), where the number of decibels is weighted by sound at various frequencies to give equivalent loudness.

When performing noise–cost studies, sound, which varies over the course of time, must be averaged to give an effective perceived noise level, which is the continuous energy mean equivalent of the noise level measured in dB(A) over a specific period. This is further translated into an index such as the Noise Exposure Forecast (NEF), which is defined as follows for highways:

$$\text{NEF} = L_{epn} + 10\log_{10} N - 88 \tag{2.2}$$

where L_{epn} is the effective perceived noise level (loudness) measured in dB(A) and N is the number of events (e.g. vehicles per hour, or number of flights per daytime, night-time).

Measures for air are similar, though the number of events is stratified between daytime and night-time flights and weighted accordingly (night-time flights are 16.67 times more onerous than daytime flights). It is important to note that due to the logarithmic scale of noise measurement the amount of noise measured is not linearly additive with the number of vehicles. For instance, one truck may generate 80 dB(A) noise, but two trucks will only generate 83 dB(A).

2.2. *Generation*

Next we need to measure the amount of noise generated by a vehicle interacting with its infrastructure. Factors which influence this include background flow, the size of the vehicles, their speed and materials of the pavement surface. In addition, the propagation of the noise over distance is influenced by ground cover, obstruction, barriers, the grade of the road or slope of take-off, the grade of surrounding land and presence of buildings. Complex models and analyses using site-specific data can more precisely account for variations due to those effects. For this exercise, it will be assumed that propagation is simple, over an unobstructed plain, since we are attempting to obtain a general result for comparison purposes, not to site or mitigate a specific facility.

For highways, rather than measure the noise associated with each car, the noise is generally associated with the overall flow. The basic noise level measured is L_{10}, the amount of noise exceeded 10% of the time (UK DoT 1988). The 1 hour basic noise level is given by equation (2.3), and the additive corrections both for mean traffic speed and heavy vehicles (C_{pv}) and for the adjustment for distance from the edge of the roadway (C_d) are given in equations (2.4) and (2.5), respectively:

$$L_{10} = 42.2 + 10\log Q_h\,\text{dB(A)} \tag{2.3}$$

$$C_{pv} = 33\log_{10}\,(V + 40 + 500/V) + 10\log_{10}(1 + 5\,p_{hv}/\text{V}) - 68.8\,\text{dB(A)} \tag{2.4}$$

$$C_d = -10\log_{10}(\text{d}/13.5)\,\text{dB(A)} \tag{2.5}$$

where V is the mean traffic speed in kilometers per hour; P_{hv} is the percentage of heavy vehicles; Q_h is the hourly traffic flow; and d is the shortest slant distance from the effective source (in meters).

Noise due to aircraft can be associated with airports and with aircraft flying overhead, not in the process of take-off or landing. Most research in this domain has dealt with noise around airports. While it is the aircraft that actually generate the noise, it is the airport, the most convenient point of complaint, that is held responsible.

The annoyance caused by noise is due to a number of unique factors, including individual preferences, socio-economics, environmental conditions, local topography, specific flight paths and number of flights. Aircraft noise production is tied to the 'stage' of the aircraft, its level of technology, which is related to its age and size. The technology determines total engine thrust needed, and is thus an influence in noise production.

2.3. *Valuation*

The damages caused by noise include the loss of sleep, lower productivity, discomfort and annoyance. These are hard to quantify, but because they are associated with a place, the amount of damage is often viewed as resulting in lower property values. This provides a basis for establishing a value for noise (quiet). A number of studies have been performed over the years to measure the decline in residential property value due to noise and its associated vibration. This has not been done for non-residential (commercial and public) buildings, however, where abatement measures are more cost-effective. Tables 1 and 2 summarize empirical findings of noise damage by roads and airports from hedonic models of housing collected by Nelson (1982a,b), Modra and Bennett (1985) and others. These studies use a noise depreciation index (NDI), the percentage reduction of house price per dB(A) above ambient noise. The average NDI for all of the airport noise surveys since 1967 (excluding the first three) is 0.62, the same value as for highways.

2.4. *Integration*

In order to translate noise production rates into economic damage costs, we must estimate total residential property damage costs per linear kilometer of a roadway or around airports. A model was developed and run through a number of scenarios to develop simplified average (and marginal) cost functions by applying the equations in the earlier subsections. Application of the noise model under certain assumptions gives us an average cost curve for the noise damage associated with each passenger kilometer traveled, depending on the number of vehicles per hour (Q_h).

The model is solved by dividing the area on each side of the roadway into 10 meter strips (s) parallel to the road. Each 10 meter by one kilometer strip has a number of housing units (H_s) depending on the density. The total damage for each strip is computed based on multiplying the homes by the value (HV) of each home by the noise depreciation index (NDI) by the net increase in the NEF (after (NEF_a) – before (NEF_b)). The total damage as a present cost (PV) is summed over all the ten meter strips for a one kilometer stretch:

$$PV = \sum_{s} (H_s)(\mathrm{HV})(\mathrm{NDI})(\mathrm{NEF}_a - \mathrm{NEF}_b) \tag{2.6}$$

Because of the logarithmic shape of the noise curves, the higher the level of background noise, the smaller the percentage increase in noise production, but

Table 1. Noise depreciation near highways.

Researcher	Site	NDI	Year
Towne	Seattle, WA	negligible	1968
Diffey	London, UK	0	1971
Gamble *et al.*	all 4 areas	0.26	1970
	N. Springfield, VA	0.21	1970
	Bogata, NJ	2.22	1970
	Rosedale, MD	0.42	1970
	Towson, MD	0.26	1970
Anderson and Wise	all 4 areas	0.25	1970
	N. Springfield, VA	0.14	1970
	Towson, MD	0.43	1970
Hammar	Stockholm, Sweden	1.4	1972
Vaughn and Huckins	Chicago	0.65	1974
Nelson	Washington, D.C.	0.87	1975
Langley	No. Springfield, VA	0.32	1977
Bailey	No. Springfield, VA	0.30	1977
Abelson	Sydney, NSW	0.56	1977
Hall *et al.*	Toronto, ON	1.05	1977
Langley	No. Springfield, VA	0.40	1980
Palmquist	Kingsgate, WA	0.48	1980
	N. King Co., WA	0.30	1980
	Spokane, WA	0.08	1980
Allen	No. Virginia	0.15	1980
	Tidewater	0.14	1980
Taylor *et al.*	Southern Ontario	0.5	1982
Holsman and Bradley	Sydney, NSW	0.72	1982
Pommerehne	Berlin, Germany	1.2	1985
Hall and Willard	Toronto/Vic. Park	0.335	1987
	Toronto/Leslie St.	2.10	1987
	Toronto/Etobicoke	0.39	1987
	pooled	0.70	1987
Soguel	Neuchâtel, Switzerland	0.91	1989
Streeting	Canberra, Australia	0.90	1989
Swiss (X)	Basle, Switzerland	1.26	
	Average	0.62	

Sources: Nelson (1982b); Modra and Bennett (1985); the present authors.

individual sensitivity to noise arises nonlinearly with increases in noise. The costs are linear with respect to density, home value, noise depreciation index and the number of passengers (as determined by capacity and load factor). It is nonlinear with respect to speed and number of vehicles per hour.

Because there are a number of complex assumptions in the noise model, and we are interested in a typical case with a range of flows, the model was estimated in reduced form when we assume a speed of 100 km/h and 10% heavy vehicles, a discount rate of 7.5% to calculate the present value of the reduction in the price of a home due to a long-term noise phenomenon (a new highway), a noise depreciation index of 0.62, an average home value of $250 000 and a typical suburban density of 360 houses per square kilometer. For automobile travel, the integrated highway noise model gives a range of between $0.0000/vkt and $0.0060/vkt average cost, depending on flow.

Table 2. Noise depreciation near airports.

Researcher	Study area	Range of noise level	Range of NDI	Best NDI (NEF)	Year	Average house value
			%	%		
Paik	New York	20–40	1.9–2.0	1.9	1960	$16656
Paik	Los Angeles	20–40	1.8–2.0	1.8	1960	$19772
Paik	Dallas	20–40	2.3–2.6	2.3	1960	$18011
Emerson	Minneapolis	20–50	0.4	0.58	1967	$19683
Dygert	San Francisco	25–45	0.5–2.0	0.50	1970	$27600
Dygert	San Jose	25–45	0.1–1.5	0.70	1970	$21000
Price	Boston	25–45	0.6	0.83	1970	$13000
Mieszkowski	Toronto/Etobicoke	20–35	0.3–1.3	0.50	1969–73	
De Vany	Dallas	20–55	0.2–0.8	0.58		
Nelson	Washington, D.C.	20–35	1.0–1.1	1.10	1970	$32724
	Rochester		0.55	0.55	1980	
	Sydney/Marrickville		0.50	0.50	1980	
	Edmonton		0.50	0.50	1980	
	London		0.68	0.68	1980	
O'Byrne	Atlanta					
Pennington	Manchester	27–40		0.47	1990	£30886
Gillen and Levesque	Toronto	0–40		0.18	1990	C195809
	Average			0.62		

Sources: Nelson (1982a); the present authors.

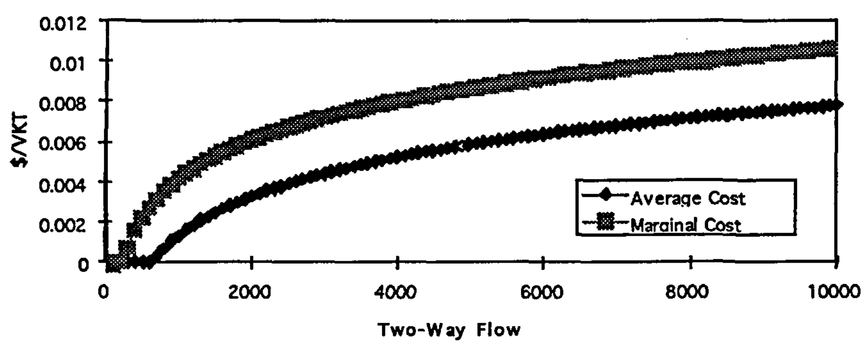

Figure 1. Highway noise: average and marginal costs.

A graph of the average cost of highway noise (AC_{hn}) (in \$/vkt) versus flow is shown in figure 1, and the equation is given in (2.7) ($r^2 = 0.92$). However, this value is extremely sensitive to assumptions. At an auto occupancy of 1.5 and flow of 6000 vehicles per hour, this converts to \$0.0045/pkt:

$$AC_{hn} = [-0.018 + 0.0028 \ln(Q_h)] f_D \times f_H \times f_C \qquad (2.7)$$

where AC_{hn} is the average cost of highway noise; f_d is the density/360 (default = 1); f_H is the house value/\$250 000 (default = 1); and f_c is the cost per dB(A)/0.0062 (default = 1).

To compare, INFRAS/IWW (1995) gives noise estimates from Europe of \$0.0058/pkt for automobiles, about the same for buses (\$0.0054/pkt) and \$0.0163/tkt (tonne km traveled) by truck. For cars, Miller and Moffet (1993) report a range from \$0.0008/pkt to \$0.0013/pkt, in 1990 US dollars. For buses, they take \$0.0003/pkt as an acceptable value.

Table 3 shows the estimated noise costs per passenger kilometer traveled generated by air travel in eight countries. The average value for these results is *\$0.0043/pkt* which is used here. For two reasons those numbers should be expected to be higher in Europe than in the United States. First, noise standards are not as strict on aircraft engines; and second, population densities (and thus impacted populations) are higher.

An alternative approach would require conducting economic engineering studies around the specific airports. In principle, the methodology would be similar to that used for highways. However, specific details about the noise generation of aircraft using each airport, flight paths, airline schedules, land uses and topography would be required. This would provide the effective perceived noise level and noise exposure forecast for specific geographical zones. For each zone, a hedonic model could be applied to estimate the reduction in property value due to air traffic noise. This capitalized value would need to be allocated to specific aircraft, and then to passengers and passenger kilometers based on flight lengths.

A third approach would use the implied value of noise damage resulting from damages awarded by courts settling lawsuits. A given award would be taken to be damages which, again, would need to be allocated to aircraft, passengers and passenger kilometers.

3. Air pollution

3.1. *Measurement*

Probably the most difficult external cost to establish is that of air pollution. Determining the quantity of pollutants emitted from an automobile, airplane or train is, in principle, a relatively straightforward engineering task, though it depends on vehicle type, model year, vehicle deterioration, fuel type, speed, acceleration and deceleration, and other factors. However, traditionally, emission rates are determined by tests in laboratory, rather than actual conditions, so to some extent

Table 3. Noise costs generated by air travel.

Country	Average cost (\$/pkt)
Canada	0.0039
Germany	0.0049
Italy	0.0079
Holland	0.0099
Sweden	0.0014
Switzerland	0.0017
France	0.0030
United Kingdom	0.0018
Average	0.0043

Note: All values converted to \$US, 1995.
Sources: Quinet (1990); IBI (1995).

these rates underestimate the amount of actual emissions, particularly due to super-emitters, or poorly maintained vehicles (Small and Kazimi 1995). Determining the damage done is more difficult still, depending on the place and time of emission, density and distribution of the population, the climate and topography. This section synthesizes earlier studies to develop cost estimates.

As used here, the types of air pollution fall into four main categories: photochemical smog, acid deposition, ozone depletion and global warming, though it is only the first and last for which significant research into transportation costs have been undertaken. However, there are several criteria pollutants which the EPA regulates, each of which is associated with health damages and are addressed in later subsections. There is considerable scientific controversy surrounding all of these categories, and there is no direct translation from pollutant emitted to damage inflicted. We describe the problems in some more detail:

(*a*) *Photochemical smog* occurs low in the atmosphere and at ground level, and results in health, vegetation and material damages. Seasonal in nature and peaking in the summertime in most areas, smog's principal cause is tailpipe emissions from automobiles. Ozone, formed in the atmosphere by a reaction between volatile organic compounds (VOCs), nitrogen oxides (NO_x) and water in the presence of sunlight, is the main cause of smog.

(*b*) *Acidic deposition* (acid rain), most prevalent in eastern North America and Europe, is found in the troposphere. Acid rain is formed when sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) react with H_2O to form sulfuric and nitric acid. The principal source of SO_2 is fixed source burning of fuels, particularly coal, such as in electricity generation.

(*c*) *Stratospheric ozone depletion*—Ozone (O_3) is formed when oxygen molecules (O_2) are combined with oxygen atoms photodissociated from other oxygen molecules. The layer of ozone in the atmosphere reflects ultraviolet radiation bombarding the earth. Due to man-made pollutants, particularly chlorofluorocarbons (CFCs), the layer has become thinner over time. The Montreal Protocol required the phasing out of damaging CFCs, such as used as refrigerants for air conditioners.

(*d*) *Global warming* (Greenhouse Effect) is a result of trace gases in the troposphere absorbing heat emitted by the earth and radiate some of it back, thus warming the global atmosphere. The Intergovernmental Panel on Climate Change concludes that man-made pollutants are increasing the amount of heat retained by the earth, with possible long-term consequences including raising the average planetary temperature, resulting in a slight melting of polar ice-caps and a consequent rise in the sea level. The impacts on global weather patterns are not well understood; some areas may benefit, but others are sure to lose. There is considerable dispute in the scientific community on the magnitude of changes caused by man-made pollution. In particular, little is understood about feedbacks within the environmental system; for instance, a rise in temperature may increase cloud cover, which will cause more sunlight to be reflected rather than reaching the earth, thereby mitigating the temperature rise. Other feedbacks may make the problem worse. The economic and ecological effects of such changes are unknowable with certainty, although attempts have been made at estimating these costs (Nordhaus 1994).

Air pollution emissions come primarily from the excess by-product of burning of a fuel, though there are other sources, including evaporation and leakage of feedstocks and finished energy resources, and venting, leaking and flaring of gas mixtures. There are a number of stages in the fuel cycle (DeLucchi 1991). Though transportation changes will obviously influence all of the stages in the fuel cycle, we are making the assumption in this paper that aside from the 'end-use' transportation stage, all other stages are in functioning markets for which pollution externalities have already been captured. This is the problem of the 'first best' and 'second best'. The idea of the first best solution which we adopt suggests that we optimize the system under question as if everything else were optimal. The second best solution recognizes that other systems are also suboptimal. Clearly, other systems are suboptimal to some extent or another. However, if we make our system suboptimal in response, we lessen the pressure to change the other systems. In so doing, we effectively condemn all other solutions to remaining second best.

3.2. *Generation*

Despite many simplifications, the science of emissions estimation remains an extremely complicated subject. Models such as the EMFAC series (California Air Resources Board 1991) and the MOBILE series (Environmental Protection Agency 1988) have been developed which characterize emissions generation by a number of factors including fleet mix (size and age of vehicles), fuel usage, the environment (temperature) and travel characteristics. For instance, light-duty trucks pollute about 20% more than autos, medium-duty trucks (with catalytic converters) pollute about two times as much as autos on HC and NO_x and the same on CO. Rates for heavy-duty trucks are also about two times auto pollution rates for HC and CO, and five times for NO_x. Furthermore, older cars pollute more than newer—a 1972 model year is about ten times more noxious than a 1992 car, though most improvements came from standards implemented between 1972 and 1982. It has been noted from studies of pollution in more realistic situations that the rates proposed above may err on the low side. Small and Kazimi (1995), after reviewing considerable technical

Table 4. Emissions factors (gm/pkt).

	Jets (1)	Highways	Gasolinecar (2)	Light-duty diesel truck (2)	Heavy-duty diesel truck (2)
Passenger km traveled	5.8×10^{11}	5.4×10^{12}			
Pollutant:					
CO	0.28	6.053	8.125	1.000	5.828
VOC	0.093	0.95	2.348	0.226	1.472
NO_x	0.13	1.11	0.787	0.933	9.801
SO_x			0.038	0.076	0.360
PM10			0.024	0.247	1.474
C	100	46			

Note: pkt = passenger kilometer traveled; data for 1989: VOC = volatile organic compounds, CO = carbon monoxide, NO_x = nitrous oxides, SO_x = sulfur oxides, PM10 = particulate matter, C = carbon.

Sources: (1) GAO (1992), Bureau of Transportation Statistics (1994) *Annual Report*, carbon information from Energy Information Administration (1994, p. 102); (2) Small and Kazimi (1995), 1992 fleet average, (gm/km) from EMFAC7F, updated for VOC underestimate by 2.1.

research, developed corrected emission factors shown in the rightmost three columns in table 4, which we adopt. We caution that even these numbers may be lower than actual emissions (Harley 1996).

Overall, estimates of pollution from aircraft are significantly smaller than from cars. Combining the total emissions with an estimate of passenger kilometers traveled by jets in the United States produces an estimate of pollution per unit output shown in the left two columns in table 4. However, this ignores some of the joint cost aspects of both air and highway travel, where freight is shipped along with passengers. This suggests that, on a per distance basis, aircraft are cleaner than automobiles by about a factor of 10. While these are clearly macroscopic estimates, the highway emissions calculated here are in the same range as those suggested by the adjusted EMFAC7F rates after considering both running and cold-start emissions and age of the fleet. We can compare the microscopic and macroscopic estimates in table 4: for CO 8.1 gm/pkt (micro) versus 6.1 gm/pkt (macro); for HC (VOCs) 2.3 gm/pkt (micro) versus 0.95 gm/pkt (macro), while NO_x are 0.79 gm/pkt (micro) versus 1.1 gm/pkt (macro). The more precise (and from a damage estimate, the more expensive) microscopic estimates from the EMFAC7F models, as adjusted for underestimation by Small and Kazimi (1995), are used for the auto mode.

EMFAC and MOBILE models only provide data on criteria pollutants, that is pollutants for which standards have been set for health reasons. Greenhouse gases (principally carbon dioxide and methane) do not have such standards. The carbon data of table 4 is extracted from emission factors developed by the Energy Information Agency (1994). To compare, Pickrell (1995) reports emissions rates which convert to approximately 62 gm/pkt, which is of the same order of magnitude as our macroscopic estimate of 46 gm/pkt. British researchers have produced estimates which can be compared for our purposes. Wootton and Poulton (1993) convert fuel liters of gasoline to CO_2 by multiplying by a factor of 23.51 accounting for fuel density and the molecular weight of CO_2. Their estimates of CO_2 emissions in gm/km range from 162 to 228 depending on the size of the vehicle. Converting grams of CO_2 into grams of carbon (dividing by 3.6667) gives, at an occupancy of 1.2, 42 gm/pkt, which is broadly consistent with our estimates.

3.3. *Valuation*

We divide the valuation of pollution damages into three components: health effects of local pollution, material and vegetation effects of local pollution and global

Table 5. A comparison of estimates of health, material and vegetation effects ($/kg).

Pollutant	Health damage			Materials damage		Vegetation damage	
	Fuller	Ottinger	Small and Kazimi	Fuller	Ottinger	Fuller	Ottinger
CO	n.a.	n.a.	n.a.	$0.0063	n.a.	n.a.	n.a.
$VOC+NO_x$	$1.22	$1.64	$3.04	$1.19	$0.03	$0.025	$0.03
SO_x	$0.84	$4.61	$13.82	$1.60	$0.31	$0.0019	$0.00
PM10	$1.20	$0.94	$12.85	$1.03	$0.00	n.a.	$0.00

Source: Fuller *et al.* (1983), updated to 1995 US dollars using medical care inflation rates: Pace (1990), updated from 1990 Canadian to 1995 US dollars; Small and Kazimi (1995), in 1995 US dollars, Los Angeles region; $2.7 M Value of Life.

effects. Clearly the damages of the local pollution depends on where it occurs—pollution in Los Angeles is more costly than pollution in a rural area.

Some recent work on the costs of air pollution from cars comes from Small and Kazimi (1995) analyzing the Los Angeles region. They review recent evidence on mortality and morbidity and its association with pollutants (VOC, PM10, SO_x, NO_x) and they combine various exposure models of the Los Angeles region with health costs. Their findings, shown in table 5, suggest that particulate matter (PM10) is a primary cause of mortality and morbidity costs, followed by morbidity due to ozone. Of course, costs in densely populated areas, such as the Los Angeles basin, should be higher than in rural areas as the exposure rate is far higher. They also assume a value of life of $4.87 million in their baseline assumptions, though they test other scenarios; we report their estimate using a $2.7 million value of life for consistent comparison with the accident data.

In table 5, we also compare the Small and Kazimi results with health cost estimates from Fuller *et al.* (1983) and Pace (1990) (updated to 1995 dollars). The estimates are most similar on the ozone producing NO_x and HC, and vary widest for the particulate problems due to PM10 and SO_x.

Fuller *et al.* (1983) and Pace (1990) also estimate materials damage; again, the numbers vary, this time Fuller's estimates are significantly higher than Ottinger's. Finally, Fuller *et al.* estimate vegetation damage from air pollution. Both Fuller and Ottinger agree, in general, that NO_x is the primary source of vegetation damage, and their estimates of $0.02–$0.03/kg are close. These results are shown in the right-hand four columns of table 5.

The use of macro-economic/global climate model to estimate a 'carbon tax' which would be the price of damages from pollution has been attempted by Nordhaus (1994). He used a model which would estimate the appropriate tax at a given point of time to optimize the amount of pollution, trading off economic costs of damages due to greenhouse gases and the damages due to imposing the tax. He estimates the appropriate tax at $5.29 in tons of carbon equivalent for the 1990s.

However, environmentalists propose much higher carbon taxes; proposals range from $5.80/tonne to $179.40/tonne (IBI 1995). These values are significantly higher than that recommended by Nordhaus, which we use. Nordhaus's results already factor in the optimization required to compare the costs of damages to that of prevention, developing an equilibrium solution, while the other estimates consider only the cost of damage (and a high estimate at that), disregarding the economic burden imposed by the new tax or the changes in behavior required to obtain equilibrium. Clearly, this value is subject to a significant amount of controversy and the consensus of estimated damage, if one is arrived at, is likely to change over time.

3.4. *Integration*

Combining the data in tables 4 and 5 (summarized in table 12), the cost of air pollution caused by air travel (basically the health damages from particulates, sulfur oxides, hydrocarbons, carbon monoxide and nitrogen oxides, plus the greenhouse damages due to carbon) is $0.0009/pkt, or for a 1000 km trip, approximately 89 cents, which at $49 per trip is 1.8% of the fare. For cars, we have a cost of $0.0052/vkt, ($0.0035/pkt) or $5.20 for a 1000 km trip. By our calculation, air travel is less environmentally damaging than car travel.

Miller and Moffet (1993) calculate car and light-truck pollution costs to be about $0.024/pkt to $0.042/pkt. This is almost ten times higher than our estimate. Their

Table 6. Costs of air pollution, comparison of studies.

Mode	Hansson/ Markham	Kageson/ T&E†	Planco	Swiss MoT	INFRAS/ IWW
Cars	0.43–1.44	0.47–1.86	2.26	0.15	0.35–1.33
Trucks	1.03–1.71	0.50–0.71	1.48	1.69	0.52–2.77
Passenger rail	0.17–0.37	0.08	0.13	0.00	0.08–0.44
Freight rail	0.22	0.08	0.20	0.00	0.03–0.15
Air	1.08	0.70	–	–	0.18–1.09
Shipping	0.20	–	0.22	–	0.15–0.91

Note: All costs, 1995 US cents per pkt or per tkt.
Source: IBI (1995), exhibit 3.4.
†T&E = Study for Ministry of Transport and Environment.

estimates for the cost of carbon dioxide emissions are almost 20 times more than ours. Other pollutant cost estimates were higher, and more pollutants were priced, including CFCs, which are being phased out.

Our estimate of $0.0049/pkt by automobile (excluding the cost of carbon emissions and greenhouse effects) is near the low end of estimates in table 6 (IBI 1995). However, our estimate of $0.0003/pkt by air travel (again excluding carbon) is lower than the lowest estimate provided. Our estimates of costs of carbon were $0.0005/pkt for air travel and $0.0003/pkt by car. The automobile estimates are significantly lower than some European and other US estimates. INFRAS/IWW (1995) estimates the external cost of climate change for cars at E0.0066/pkt (ECU), E0.0027/pkt for buses and E0.01066/tkt for trucks. Also E0.0030/pkt for passenger rail, E0.0011/tkt for freight rail, E0.0098 for passenger air and E0.0505/tkt for air freight. The principal cause of the difference is the $52.80/tonne proposed carbon tax in Europe (with the higher year 2000 estimates using a $123.20/tonne carbon tax), as compared with $5.80/tonne carbon tax for 1995 (based on Nordhaus 1994) used in our study. The Miller and Moffet (1993) study assumed an even higher carbon tax, $82.80/tonne to $179.40/tonne.

An important point is the consequences of changes in emission factors. The total estimates of damage in a region are divided by an estimate of total emissions to obtain a cost per kilogram of emittant. If the rate of emission is increased, but the total damage is constant, the the economic damage per unit of emission declines.

4. Accidents

4.1. *Measurement*

There is some debate as to whether accidents are properly considered social costs, since they are generally borne within the transportation sector. However, the consequences of multi-party accidents are clearly in part external to the individual or vehicle which causes it. For that reason, rather than for any attempt at purity in a definition of externalities, we include them here. However, to include the cost of accidents as a social cost means defining the cost of insurance as a transfer. Accident costs and insurance costs are not additive in an estimate of the full cost of transportation.

There are a number of sources recording highway accidents. The National Highway Traffic Safety Administration has two databases: NASS, the National Accident Sampling System, and FARS, the Fatal Accident Reporting System. In

Table 7. US civil aviation accidents, deaths and death rates.

Carrier type	Accidents total	Accidents fatal	Deaths, no.	Rate/ MVH total	Rate/ MVH fatal	Rate/ MVK total	Rate/ MVK fatal
Large airlines	25·8	5·6	141·0	0·0219	0·0046	0·0033	0·0024
Commuter airlines	19·4	5·0	31·2	0·0884	0·0227	0·0300	0·0080

Note: MVH = million aircraft hours flown; MVK = million vehicle kilometers.
Source: National Safety Council (1993, p. 96), average 1988–1992.

addition, each state keeps records, as does the insurance industry with its National Council on Compensation Insurance DCI (Detailed Claims Information) database. Accidents and injuries are typically classified by their degree of severity (Killed/fatal injury, Incapacitating injury, Non-incapacitating injury, Possible injury, Property damage). Only a small proportion of accidents results in death or incapacitating injury. A similar classification is given by the National Transportation Safety Board (1992) for major air carriers (Fatal, Serious injury, Minor injury, No injury). However, the annual variance in the number of deaths in the air transportation system is quite high (for large carriers, 285 fatalities in 1988 versus 53 in 1992, as shown in table 7); a single accident can result in hundreds of deaths, therefore any developed accident rate should be based on a multi-year sample.

4.2. *Generation*

Aviation accident statistics are collected by the National Transportation Safety Board. Table 7 compares average accident rates for large airlines and commuter airlines over the 1988 to 1992 period. There are no clear trends over time for the years 1988–1992.

While accidents are often assumed to occur at a fixed rate, this 'linearity' conjecture should not be assumed to be true. Some work has been attempted to estimate the rate of accidents as a function of traffic. A relevant study was conducted by Sullivan and Hsu (1988), who estimate a model of freeway accidents in California with the dependent variable equal to the square root of the total number of annual accidents in the section during the peak periods 5.00–9–30 a.m. or 3.00–7.30 p.m. This model is a total accident rate (TAR_h) model, given in equation (4.1). It can be converted to an average accident rate (AAR_h) by dividing by Q_h or a marginal accident rate (MAR_h) model by taking the first derivative with respect to Q_h. We define the variable 'a' as a constant reflecting all the variables multiplied by their respective coefficients other than Q_h (the variable NONE, in theory, may depend on Q_h, but we will assume for now that the section has been designed sufficiently with no queueing, so that NONE equals one):

$$\mathrm{TARh} = (\mathrm{a} + 0.000143\, Q_h)^2 \tag{4.1}$$

$$\mathrm{AARh} = \mathrm{TARh/Qh} = (\mathrm{a} + 0.000143\, Q_h)^2/Q_h \tag{4.2}$$

$$\mathrm{MARh} = \partial\mathrm{TAR}/\partial\mathrm{Qh} = (0.000286)(\mathrm{a}) + (2)\, 0.000143^2\, Q_h \tag{4.3}$$

$$a = 0.19\, L \times N + 1.92\,\mathrm{IRAMP} - 0.98\,\mathrm{ARAMP} - 0.017\,\mathrm{NONE} \tag{4.4}$$

where $L \times N$ is the section length (L) in miles times the number of travel lanes (N) (excluding auxiliary lanes); IRAMP is the average number on-ramps per mile; ARAMP = IRAMP if there are auxiliary lanes, and 0 if there are no auxiliary lanes in the section; Qh is the average hourly traffic volume in all lanes during the peak period; and NONE is the average percentage of time during the peak period when no queue exists in the freeway section.

4.3. *Valuation*

The method presented here uses a comprehensive approach which includes valuing years lost to the accident, as well as direct costs. Several steps must be

Table 8. Estimated value of life, by type of study.

Type of study	Value of life ($) (1995 dollars, millions)
Average of 49 studies	2.9
Average of 11 auto safety studies	2.7
Study type	
Extra wages for risky jobs (30 studies)	2.5–4.4
Market demand versus price:	
Safer cars	3.4
Smoke detectors	1.6
Houses in less polluted areas	3.4
Life insurance	3.9
Wages	2.7
Safety behavior:	
Pedestrian tunnel use	2.7
Safety belt use (2 studies)	2.6–4.0
Speed choice (2 studies)	1.7–2.9
Smoking	1.3
Surveys:	
Auto safety (5 studies)	1.6–3.6
Cancer	3.4
Safer job	2.9
Fire safety	4.7

Note: Value in millions of after-tax dollars ($1995 = $1988 × 1.3).
Source: Adapted from Miller (1992).

Table 9. Comprehensive costs, by severity of accident.

Accident severity	Cost per person	Cost per crash
K—fatal	$3 110 564	$3 529 312
A—incapacitating	220 357	297 138
B—evident	43 195	62 832
C—possible	22 138	32 874
O—property damage	2 254	5 835
Unreported	2 081	5 387
A–B–C reported nonfatal	60 261	90 469
K–A–B–C reported injury	100 298	150 497

Note: 1995 dollars, assumes 4% discount rate ($1995 = $1988 × 1·3.
Source: Miller (1992, p. 39).

undertaken: converting injuries to years of life, developing a value of life and estimating other costs. Placing a value on injury requires measuring its severity. Miller (1992) describes a year of functional capacity (365 days/year, 24 hours/day) as consisting of several dimensions: Mobility, Cognitive, Self-care, Sensory, Cosmetic, Pain, Ability to perform household responsibilities and Ability to perform wage work.

Central to the estimation of costs is an estimate of the value of life. Numerous studies have approached this question from various angles. Jones-Lee (1990) provides one summary, with an emphasis on British values from revealed and stated preference studies. The FAA (1989) provides another summary. He finds the range of value of life to vary by up to two orders of magnitude (a factor of 100). Miller's (1992) summary is reproduced in table 8, with numbers updated to 1995 dollars.

After converting injuries to functional years lost, combining with fatality rates, and value of life, a substantial portion of accident costs have been captured. But this data must be supplemented by other costs, including hospitalization, rehabilitation and emergency services. Taking the comprehensive costs, they can be allocated to the various accident categories by severity, as shown in table 9. Based on California accident data, we have estimated the cost of urban accident at $70 000 and a rural accident of $120 000. While there are more urban accidents, they are at lower speed and less likely to result in serious injury or death.

4.4. *Integration*

Application of the accident model developed above will provide us an estimate of the accident cost per passenger kilometer traveled. The average annual accident rate per hour at a level Qh = 6000 vph and $a = 0.61$ (when the following conditions prevail: 1 km section, 4 lanes wide, 0.12 intersections per km, no queueing) is 0.00036. Dividing by 365 (days per year), and then multiplying by 33% (the proportion of four and half hour peak period traffic in the peak hour), we get the probability of an accident per hour per vehicle is 0.000 000 32. Multiplying this by the cost of an accident, we calculate $0.038/vkt for rural travel (which have higher fatality rates) or $0.022/vkt for urban travel. Clearly the value resulting depends

Table 10. Estimates of accident costs.

Study	$/pkt
Levinson *et al.* (1996) rural	0.026
Levinson *et al.* (1996) urban	0.015
Insurance costs (24.000 km/yr)	0.025
Insurance costs (16.000 km/yr)	0.038
US DoT (1975)	0.014
Keeler *et al.* (1975) rural	0.013
Keeler *et al.* (1975) urban	0.016
Erickson (1982)	0.002
Gordon (1990)	0.02
Jones-Lee (1990)	0.018
Vernbergg and Jagger (1990)	0.014
US Department of Commerce (1990)	0.036
Konheim and Ketcham (1991) rural	0.028
Konheim and Ketcham (1991) urban	0.0552

Sources: NRDC (1993); the present authors.

upon the assumptions made. Taking the rural travel cost and converting from vkt to pkt (at 1.5 person per vehicle) gives \$0.026/pkt while the urban cost is \$0.015/pkt, with a central value around \$0.020/pkt. This and previous estimates are given in table 10.

These results are consistent with, though not identical to, international studies. Australian data (ABTC 1992) shows an average cost per accident of \$AU10 378. This result is significantly lower than American figures, principally due to a lower value of life in the Australian method, which is not as comprehensive as in the United States. INFRAS/IWW (1995) compute costs of accidents using a macroscopic methodology, computing national estimates of fatality and injury costs. Their European average was in European Currency Units, E0.032/pkt for cars, E0.009/pkt for buses, E0.022/tkt for trucks, E0.0019/pkt for passenger rail and E0.0009/tkt for freight rail. Given the variation of exchange rates, these figures are consistent with our estimate.

A similar calculation could be performed for air travel. However, because the accidents are fewer, and vary a great deal in magnitude, accident rates are not stable on a yearly basis. Similarly, it is difficult to establish with confidence any costs beyond loss of life using the value of life idea discussed above.

If, for large airlines we have 0.005 fatal accidents per million aircraft km, an average number of passengers per flight of 100, an average of 25 deaths per fatal crash, and a value of life of \$2.7 million, then the cost for accidents on large aircraft is \$0.00054/pkt. Taking more conservative values of life and including non-life costs (injury and medical, accident clean-up, etc.), and assuming a higher number of fatalities, could quadruple the estimate to \$0.0022/pkt.

This range of estimates is consistent with Canadian estimates of accident costs: \$0.001/pkt (CAN94) (IBI 1995). Australian data (ABTC 1992) show an estimate of \$1 259 000 (AU88) total cost per fatal accident, multiplied by the US accident rate gives a cost of \$AU0.0006/pkt, which is also within the same order of magnitude as our estimates. However, given the experience with Australia's highway estimates, their estimate is probably better seen as a lower bound.

5. Congestion

5.1. *Measurement*

The time which a trip takes can be divided into two components: uncongested and congested times. The uncongested time is a simple function of distance and uncongested speed. Congested time depends on the number of other vehicles on the road, as well as numerous random factors (the weather, drivers' attention, local design conditions). In this research, we look only at recurring congestion, due to a flow in excess of capacity, rather than at incidents. Certainly incidents and other non-recurring congestion are a significant cost. While the uncongested time is clearly an internal cost, congestion, like accidents, but unlike the other externalities, is both internal to the transportation system and external to the individual traveler (Nijkamp 1994). As the system approaches 'capacity', a vehicle imposes an increasing amount of delay on all other vehicles in the system, which has ramifications both within and outside the transport sector. The increased cost of transportation rebounds in the productive sectors of the economy, reducing the amount of time and money that can be spent in other activities and on other goods. In our analysis, congestion is considered an externality on the basis of the proposition that it is external to the vehicle.

In this paper, both highway and air transportation are considered subject to congestion effects. It is important to recognize that volume–delay relationships are nonlinear, so the marginal congestion cost imposed by each vehicle depends on the number of vehicles. For limited access highways, the point of maximum throughput typically has a speed which is one-half of the free-flow speed. For signalized highways, the relationships are much more complex, and must consider delay at intersections caused by traffic on other links; however, since we limit ourselves to intercity transportation, this complexity is ignored. Most of the congestion delay associated with air travel occurs at and around airports. In both cases, for highways and airports, the amount of delay depends on both supply and demand.

5.2. *Generation*

The exact relationship between volume and delay can be best determined by a detailed, site-specific engineering study. For highways, the *Highway Capacity Manual* (TRB 1985) provides some estimates. For a segment with a 112 kph design speed, under ideal conditions the capacity is taken to be 2000 passenger cars per hour per lane (pcphpl). The following equation for limited access freeways is derived from the *Highway Capacity Manual*, table 3.1 (TRB 1985).

$$\mathrm{AD}_{\mathrm{ht}} = 0.2 \times (Q_{\mathrm{h}}/Q_{\mathrm{ho}})^{10} \tag{5.1}$$

where AD_{ht} is the average delay per vehicle kilometer (min); Q_{h} is the flow per unit time (e.g. vehicles/h); and Q_{ho} is the capacity per unit time.

There have been some studies of airport delay, perhaps the most widely used approach is that of the FAA (1983). Using a methodology similar to the *Highway Capacity Manual*, each airport, based on runway designs and other physical factors, has a rated capacity (annual service volume). Delay per aircraft depends on the usage (in operations) of the airport relative to its capacity. The following average delay per aircraft (in min) was estimated using the FAA graphs:

$$\mathrm{AD}_{\mathrm{at}} = 0.19 + 2.33\,(Q_{\mathrm{a}}/Q_{\mathrm{ao}})^{6} \tag{5.2}$$

where $\mathrm{AD}_{\mathrm{at}}$ is the average delay per aircraft; Q_{a} is the aircraft operations per year; and Q_{ao} is the annual service volume.

5.3. *Valuation*

The value of time depends on a number of factors (Hensher 1995). Among them are the mode of travel, the time of day, the purpose (business, non-business) of the trip, the quality or level of service of the trip (including speed) and the specific characteristics of the trip-maker, including income. Furthermore, the value of time saved probably depends on the amount of time saved — 60 people saving 1 min may not be worth the same as 1 person saving 60 min. Time in motion is valued differently than time spent waiting. Similarly, schedule delay — the amount of time between when one wants to depart and the next scheduled service (bus, train, plane) — also has a value associated with it. Unexpected delays are more costly than the expected, since those are built into decisions. All of these factors would need to be considered in a detailed operational analysis of the costs of travel time and congestion.

There are a number of approaches for valuing travel time, ranging from utility theory to theories of marginal productivity (FAA 1989). Economic theory holds that a firm in a competitive market will be in equilibrium when the marginal revenue product of a factor of production equals its price. In other words, the last good which is produced still earns money, but the next one won't. If labor is taken to be an input to the firm, the firm will pay salaries up to the point that the worker adds marginal revenue to the firm, this is his earning rate. Given those assumptions, some take the value of time for the business traveler to be the wage rate, since travel substitutes for work. Of course, this ignores any differences in the quality of the trip, the fact that work can be done while traveling, that much business travel occurs on the employee's rather than the employer's time and a number of other factors. It also creates problems for valuing the time of non-business travel.

The extension to non-business travel assumes that the consumer values non-business activities the same at equilibrium (otherwise they would expend more time on the activity with the higher value). Since one of those equilibrium activities to which the consumer is indifferent is work, it is plausible to value non-business travel at the wage rate as well. Extending the household production theories of Becker (1965), it can be assumed that households perform activities which maximize utility, including expenditures of both time and money. Since travel itself is an intermediate activity, and thus provides no utility, the time saved in travel (for instance, due to an improvement) can be spent either consuming leisure activities or earning income. Therefore the value of time in travel must be compared with its time at work and at home. Thus the value of time saved can be greater or less than the wage rate depending on the value of time in travel (is it positive or negative?), as well as the valuation of work, and the wage rate cannot be assumed to be the only factor used in estimating the value of time.

A large number of studies have estimated the value of travel time (FAA 1989). These studies use several approaches, often grouped under the willingness to pay rubric. A number of studies calculate elasticity of demand to estimate how much money people pay to save time. Early studies were based on regression analysis, more recently multinomial logit has been used. Miller and Fan (1992) have collected estimates of value of time from a variety of studies of intercity transportation, shown in table 11.

5.4. *Integration*

Estimates of the average delay depending on the use (demand) of highway and airport facilities were derived in earlier sections. Microeconomic theory suggests that in an efficient and competitive system, prices are at marginal cost, as this maximizes profits and consumer benefits, and thus total welfare for society.

Recall the delay expression from above, this average delay is the average cost in minutes per mile or minutes per kilometer, composed of two parts, a fixed portion reflecting the uncongested time to travel, which is a private cost, and the variable portion which is a function of volume, which is the result of an externality from other drivers.

The total delay ($\mathrm{TD_{ht}}$) is simply the average cost multiplied by the total number of users (Q), while the marginal delay ($\mathrm{MD_{ht}}$) is simply the derivative of the total delay:

$$\mathrm{TD_{ht}} = 0.32 \times (Q_{\mathrm{h}})^{11}/(Q_{\mathrm{ho}})^{10} \tag{5.3}$$

$$\mathrm{MD} = \partial \mathrm{TD_{ht}}/\partial Q_{\mathrm{h}} = 3.5 \times (Q_{\mathrm{h}}/Q_{\mathrm{ho}})^{10} \tag{5.4}$$

The above equations can be monetized by multiplying the cost, which is given above in minutes per mile by a value of time. The delay results graphed in figure 2, these can

Table 11. Value of time business and non-business trips (\$/h).

Study	Air	Car	Currency
Business trips			
Koppelman	\$20–60	\$20–60	US77
Compass/Tri-State	\$65–67	\$37–47	US90
RPI/Cole Sherman New York	\$51	\$26	US90
Horizons: Ontario–Quebec	\$58	\$25	US90
British Rail/Illinois	\$54	\$23	US90
CRA Texas (linehaul, access)	\$35, 24	\$20, 13	US90
Non-business trips			
Koppelman	\$15–45	\$15–45	US77
Compass/Tri-State	\$34–42	\$16–37	US90
RPI/Cole Sherman New York	\$32	\$26	US90
Horizons: Ontario–Quebec	\$32	\$18	US90
British Rail/Illinois	\$19	\$13	US90
CRA Texas (linehaul, access)	\$28, 19	\$9, 6	US90

Source: Adapted from Miller and Fan (1992).

Table 12. Intermodal comparison of long-run average costs.

Cost category	Air system (\$/pkt)	Highways (\$/vkt)	Highways (\$/pkt)
Noise	0.0043	0.0068	0.00045
Air pollution			
CO	0.0000018	0.000049	0.000033
VOC	0.0001530	0.003850	0.0026
NO_x	0.0001700	0.001000	0.00067
SO_x	—	0.000315	0.00021
PM10	—	0.000085	0.000057
Carbon	0.0005800	0.000260	0.00017
Subtotal	0.00090	0.0056	0.0037
Accidents	0.0005	0.03	0.0200
Congestion	0.0017	0.0069	0.0046
Total	0.0073	0.0492	0.0328

Note: Vehicle occupancy—highways, assume 1.5 passengers per car.

easily be multiplied by a value of time (for instance, \$10/h) to obtain costs at different congestion levels.

To compare, Miller and Moffet (1993), while recognizing the problematic nature of a general cost, estimate a national average of \$0.0021/pkt spread across all drivers. This is within our broad range of marginal costs of \$0.00/pkt when uncongested ($Q_h/Q_{ho}<0.75$) to \$0.60/pkt at capacity of \$10/h. For comparison purposes, we select a value \$0.005/pkt. This estimate is consistent with the idea of approximately free-flow travel for five of the seven-hour automobile trip such as between San Francisco and Los Angeles and a 10 kph reduction in speed for the other two hours.

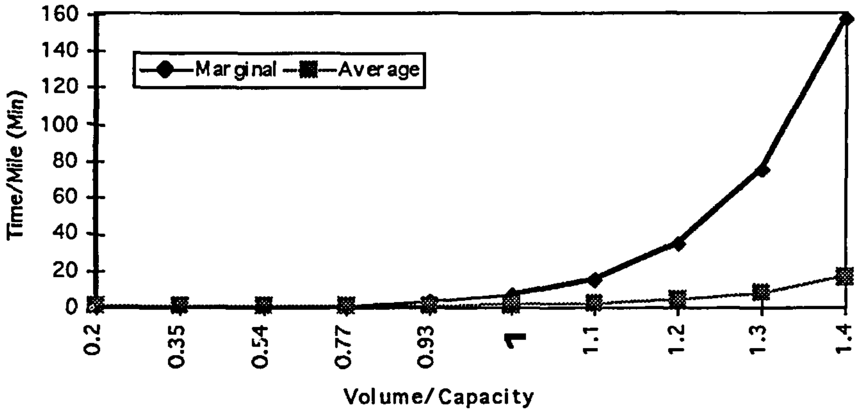

Figure 2. Congestion: average versus marginal delay of highway travel.

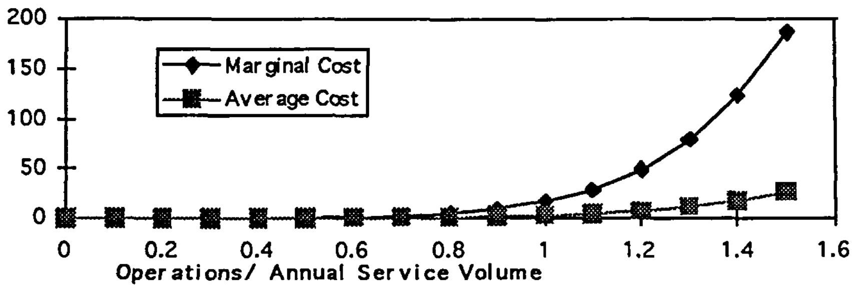

Figure 3. Congestion: average versus marginal costs of airport delay.

For airport delay, we can undertake a similar exercise, graphed in figure 3. Again, the average delay equation is simply the average cost in units of minutes, as a function of operations and capacity (annual service volume) as described above, the total delay (TD_{at}) and marginal delay (MD_{at}) are given below in units of minutes:

$$TD_{at} = AD_{at} \times Q_a = 0.19\ Q_a + 2.33\ Q_a^7/Q_{ao}^6 \tag{5.5}$$

$$MD_{at} = \partial TD_{at}/\partial Q_a = 0.19 + 16.31\ (Q_a/Q_{ao})^6 \tag{5.6}$$

Again, the issue of double counting needs to be addressed. Because congestion costs depend on volume, and volume depends on fares (and thus costs), the two should be solved simultaneously if any attempt is made to internalize this cost. As before, the above delay measures can be monetized by multiplying by a value of time. For comparison with other modes, we use a typical congestion cost of \$0.017/pkt, which is consistent with data representing the San Francisco—Los Angeles air trip.

6. Summary and conclusions

In the previous sections we calculated the noise, air pollution, accident and congestion costs for intercity highway and air travel; a summary of the long-run average costs of externalities is shown in table 12.

Our estimates of the cost of noise for highway and air travel are approximately equal, at about $0.004–0.005/pkt for both. However, we have reason to believe that over the long term the cost by air will decline relative to that by highway. In the case of air, we have not taken into consideration the upcoming switch to stage III aircraft which is mandated as of the year 2000. With the advent of stage III aircraft, one can expect at least a halving of the cost of airport noise at current airport utilization rates. The aircraft noise cost estimates are further based on a broad cross-section of estimates from other countries. The location of major airports in the United States are in areas of somewhat lower density than elsewhere, and more important, have approach and depature flight paths which can often be located over water, which further reduces the noise externality.

Our estimates of air pollution are probably the most subject to challenge. There is considerable debate about the magnitude of health damages associated with criteria pollutants. Moreover, we have placed no value on the environment for the sake of the environment. It is clear that the pollution damage by auto is significantly higher than by airplane. The cost of global climate change due to carbon emissions is an equally slippery area. There is a more than tenfold range in the estimates of these costs; we have chosen what we believe a reasonable estimate, though others will surely disagree.

Accidents are the highest social cost of intercity highway travel, and the lowest of air travel, indicative of the difficult levels of safety of each. Much of the accident costs are borne by travelers in the form of insurance, and some by society covering the uninsured, particularly health costs. While we have made little effort to attribute incidence in this paper, accident costs fall mostly wihtin the travel sector, even if not borne by the individual who causes the accident.

Congestion costs are another difficult area, in that congestion levels are facility specific, and depend on traffic flows on highways and at airports. We have estimated congestion levels comparing a typical intercity corridor. Los Angeles to San Francisco, assuming a relatively low value of time of $10 per hour. If the congestion costs were to be charged to travelers in the form of marginal cost pricing, we would have to be careful to avoid double counting, as demand depends on the toll and vice versa. The appropriate toll needs to be solved simultaneously with the demand in order to make an accurate estimate. In the final analysis, the optimal pricing strategy depends on optimizing the trade-off between expanding supply (capacity) and constricting demand, through pricing or some other mechanism, and potentially accepting some amount of delay as being less costly than mechanisms to reduce it.

Given their small magnitude, it should be noted that social costs play a relatively minor role in the comparison of total costs across modes; they are about 5% of the full cost of air travel and 15% of the full cost of highway travel (Levinson *et al.* 1996). The relatively high social cost of highway transportation is primarily due to the cost of accidents, an externality which is largely absent in air travel. The accident and congestion externalities are already partially internalized to travelers making decisions, as the accident externality generates higher insurance costs while congestion increases travel time. The most relevant externalities are therefore air pollution and noise. Air pollution and noise have approximately equal costs in the case of highway transportation, while for air travel, noise appears to be the major source of social costs.

Appendix

There are alternative classification schemes for external costs. Some are described below.

Verhoef (1994) divides external costs for transportation into social, ecological and intra-sectoral categories, which are caused by vehicles (in-motioin or non-in-motion) and infrastructure. To the commonly recognized externalities (noise, congestion, accidents, pollution), he adds the use of space (e.g., parking) and the use of matter and energy (e.g. the production and disposal of vehicles and facilities). Button (1994) classes externalities spatially, considering them to be local (noise, lead, pollution), transboundary (acid rain, oil spills) and global (greenhouse gases, ozone depletion). Gwilliam (1994) combines Verhoef's and Button's schemes, looking at a Global, Local, Quality of life (Social) and Resource utilization (air, land, water, space, materials) classification.

Rothengatter (1994) views externalities as occurring at three levels: individual, partial market and total market, and argues that only the total market level is relevant for checking the need of public interventions. He excludes pecuninary effects, activities concerning risk management and activities concerning transaction costs. Externalities are thus public goods whose effects cannot be internalized by private arranagements. Rietveld (1994) identifies temporary effects and non-temporary effects occurring at the demand side and supply side. Maggi (1994) divides the world by mode (road and rail) and medium (air, water, land) and considers noise, accidents and community and ecosystem severance. Though not mentioned above, to all of this might be added the heat output of transportation, clearly a major factor in the 'urban heat island' effect.

Button (1994) develops a model relating ultimate economic causes through physical causes, and symptoms to negative external effects. Neither users nor suppliers take full account of their environmental impacts, leading to excessive use of transport. He argues that policy tools are best aimed at economic causes, though actual measures have targeted all of the stages.

Coase (1992) argues that the problem is that of actions of economic agents have harmful effects on others. His theorem is restated from Stigler (1966) as '. . . under perfect competition, private and social costs will be equal'. This analysis extends and controverts the argument of Pigou (1920), who argued that the creator of the externality should pay a tax or be liable. Coase (1992) suggests the problem is lack of property rights, and notes that the externality is caused by both parties, the polluter and the receiver of pollution. In this reciprocal relationship, there would be no noise pollution externality if no one was around to hear. This theory echoes the Zen question: 'If a tree falls in the woods and no one is around to hear, does it make a sound?' Moreover, the allocation of property rights to either the polluter or pollutee results in a socially optimal level of production because in theory, the individuals or firms could merge and the external cost would become internal. However, this analysis assumes zero transaction costs. If the transaction costs exceed the gains from a rearrangement of activities to maximize production value, then the switch in behavior won't be made.

There are several means for internalizing these external costs. Pigou identifies the imposition of taxes and transfers and Coase (1992) suggests assigning property rights, while government most frequently uses regulation. To some extent, all have been tried in various places and times. In dealing with air pollution, transferable pollution rights have been created for some pollutants. Fuel taxes are used in some countries to deter the amount of travel, with an added rationale being compensation for the air pollution created by cars. The US government establishes pollution and noise standards for vehicles, and requires noise walls be installed along highways in some areas.

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