The External Damage Cost of Noise Emitted from Motor Vehicles

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ABSTRACT

With a detailed model of the cost of motor vehicle noise in the United States in 1990, we estimate that the external damage cost of this noise could range from as little as \$100 million per year to as much as \$40 billion per year, although we believe that the cost is not likely to exceed \$5 billion (1991\$). Our base-case estimate is \$3 billion. The wide range is due primarily to uncertainty regarding 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.

INTRODUCTION

In many urban areas, noise is a serious problem. Noise disturbs sleep, disrupts activities, hinders work, impedes learning, and causes stress (Linster 1990). Indeed, surveys often find that noise is the most common disturbance in the home, and motor

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vehicles usually are the primary source of that noise (OECD 1988).[1]

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 1978; Hall and Welland 1987; O'Byrne et al. 1985). 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.[2] This dollar-per-decibel measure, multiplied by the average value of homes, the number of homes exposed to noise above a threshold, and the amount of motor vehicle noise above a threshold, will tell us the external "damage cost" of motor vehicle noise in and around the home. The cost of noise in and around the home then can be scaled by the ratio of time spent in all activities affected by motor vehicle noise to time spent in or around the home, to produce the total external damage cost of motor vehicle noise.

In this paper, we present such a model of the total external damage cost of noise emitted from motor vehicles in the United States. Because of considerable uncertainty in the value of several key parameters, we are able to estimate only the order of magnitude of the cost. Indeed, we find that the cost could range from as little as $100 million per year to approximately $40 billion per year, although we believe that the cost is not likely to exceed $5 billion (1990 data, 1991$). (This range does not include the external damage cost of noise from activities related to motor vehicle use, such as highway construction or the cost of controlling noise.) Our base-case estimate is $3 billion. In sensitivity analyses presented at the end of the paper, we show that this wide range is due primarily to uncertainty regarding the cost of noise per decibel (dBA) 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 NEED FOR THIS ANALYSIS

We performed this analysis because there is no detailed, comprehensive, up-to-date estimate of the cost of motor vehicle noise in the United States. Indeed, it appears that in the past 20 years, there has been but one original analysis of the cost of motor vehicle noise in the United States (Fuller et al. 1983), the results of which have been cited in virtually every review of the social costs of transportation in the United States. Fuller et al. calculated the dollar cost of motor vehicle noise in residential areas as the product of three factors: 1) the number of housing units in each of up to three distance/noise bands along roads; 2) dBA of noise in excess of a 55 dBA threshold; and 3) a valuation parameter of $152/excess-dBA (1977$).

Fuller et al. used a 1970s-vintage noise-generation equation to delineate the distance/noise bands. They assumed that throughout each band the noise level was equal to the value calculated at the middle of the band. They made other simplifying assumptions as well: they used national-average data on housing density, housing value, and traffic volume; they ignored noise barriers; and they ignored noise costs away from the home.

Our analysis improves, expands, and updates the work of Fuller et al. (1983) in several ways:

1. We used the latest noise-generation equation—the Federal Highway Administration's (FHWA's) recently developed Traffic Noise Model (TNM) (formerly called the STAMINA model) (Anderson 1995). The new TNM is based on recent measurements of noise from motor vehicles, and has parameters that account for noise attenuation due to intermediate obstructions, noise absorption by soft ground, and noise emitted by

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[1] OECD (1988) states that "transport is by far the major source of noise, ahead of building or industry, with road traffic the chief offender" (pp. 43–44). They estimate that in the early 1980s, 37% of the U.S. population was exposed to road traffic noise of 55 decibels (dBA) or greater (outdoor level, 24-hour *Leq*), 18.0% to 60 dBA or greater, 7.0% to 65 dBA or greater, 2.0% to 70 dBA or greater, and 0.4% to 75 dBA or greater (percentages are cumulative, not additive). They estimate that in most countries in Europe, a larger percentage of the population than in the United States is exposed to each noise level.

[2] One also can estimate the cost of noise on the basis of preferences stated in contingent valuation surveys. See, for example, Vainio (1995).

accelerating vehicles (Anderson 1995; Rilett 1995; Jung and Blaney 1988). The Fuller (1983) noise-generation equation was based on noise measurements made in the 1970s, and did not include parameters for obstructions, ground cover, or acceleration.

2. Rather than delineate three noise bands and then take the average in each of three discrete noise bands, we integrated the updated noise-generation equation over the entire area of land exposed to noise above a threshold. (In essence, we had an infinite number of distance/noise bands.)
3. We calculated noise costs in detail, for several different types of road and traffic conditions, in each of 377 urbanized areas[3] and 1 aggregated rural area of the United States. We used urbanized-area-specific data on miles of roadway, traffic volume, housing density, and housing value, rather than nationally aggregated data.
4. We accounted for the noise reductions provided by noise barriers, as a function of the height and length of the barrier.
5. We accounted (crudely) for the noise-reflection characteristics of the ground, and for noise shielding due to intervening structures.
6. We used time-activity data to extend the analysis to include the cost of noise damages to activities in commercial, industrial, and municipal areas.
7. We estimated marginal costs for light-duty automobiles, medium-duty trucks, heavy-duty trucks, buses, and motorcycles, on six different types of roads.
8. We estimated a base case, a low-cost case, and a high-cost case, and performed sensitivity analyses on several key variables.

In the following sections, we develop our noise-cost model, and document the base-case parameter values.

THE MODEL

General Noise Cost Model

As outlined in the introduction, our general cost model is conceptually straightforward: the external damage cost of noise emitted from motor vehicles is equal to dollars of damage per excess decibel (HV), multiplied by the annualized value of housing units exposed to motor vehicle noise above a threshold (P), multiplied by the density of housing units exposed to motor vehicle noise above a threshold (M), multiplied by the amount of motor vehicle noise over a threshold (AN), multiplied by a scaling factor to account for costs in nonresidential areas ($(T_o+T_i)/T_i$). We do this multiplication for each of six types of roads in each of 377 urbanized areas (plus 1 aggregated rural area). Formally:

$$C_n = \Big(\sum_u \Big(\sum_r \Big(\sum_h AN_{u,r,h}\Big)\Big) \cdot M_u \cdot P_u\Big) \cdot HV \cdot \frac{T_o + T_i}{T_i} \qquad (1)$$

$$AN_{u,r,h} = \frac{L_{u,r,h}}{5280} \cdot \Big(\Big(\int_{d_e}^{d_{t^*}} Leq(d)_{u,r,h}\Big) - ANB_{u,r,h}\Big)$$

where:

C_n = the total external damage cost of motor vehicle noise in the United States in 1990 (1991$);

subscript u = geographic area (377 urbanized areas plus 1 aggregated rural area; we use u rather than a because most of the areas are urbanized areas);

subscript r = type of road (the six types used by FHWA are: Interstate, other freeway, principal arterial, minor arterial, collector, and local);

subscript h = height class of noise barriers along the road (none, low, medium, or high);

$AN_{u,r,h}$ = the motor vehicle "area-noise" level (we will explain this below; see also figure 1) in area u along road type r with noise barrier of height-class h (zero height if no noise barrier) (dBA-mi^2);

$ANB_{u,r,h}$ = the motor vehicle "area-noise" level below the noise-damage threshold t^* in area u along road type r with noise barrier of height-class h (dBA-ft);

M_u = the density of housing units exposed to motor vehicle noise above a threshold in area u (number of housing units exposed to motor vehicle noise above threshold t^* divided by total land area exposed to motor vehicle noise above threshold t^* [units/mi^2]);

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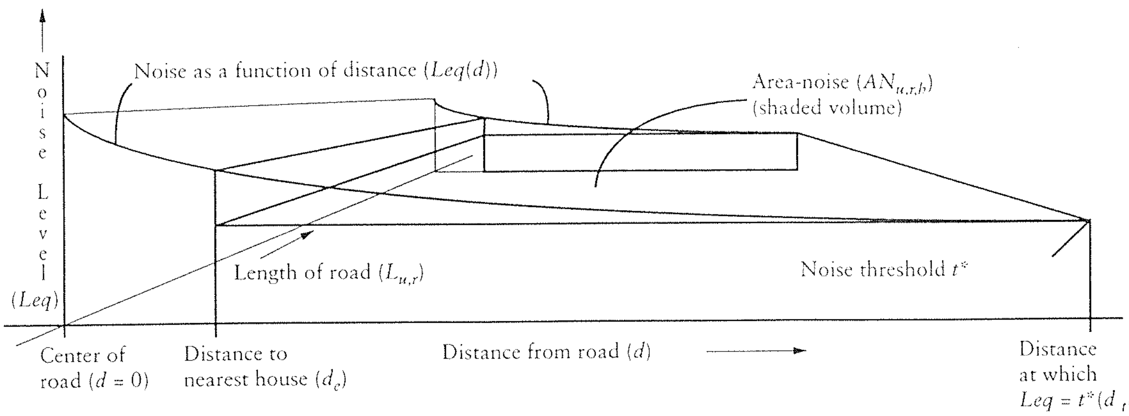
[3] The U.S. Census Bureau uses the term *urbanized area* to represent a geographic area consisting of one or more central cities and a penumbra of suburbs and satellite cities. It is typically smaller than what the Census Bureau defines as a standard metropolitan statistical area.

FIGURE 1 Noise Fall Off with Distance from the Road



P_u = the median annualized value of housing units exposed to motor vehicle noise above a threshold in area u (\$/unit);

HV = the percentage of annualized housing value lost for each decibel of noise over the threshold level t^*;

T_i = the average amount of time spent in or around one's home (minutes);

T_o = the average amount of time spent away from one's home in places where motor vehicle noise can be a problem (minutes);

$L_{u,r,h}$ = the total length of road type r in area u with noise barrier of height-class h (zero height if no noise barrier) (mi);

d_{t^*} = the "equivalent distance" (defined below) from the roadway to the point at which traffic noise drops to the threshold level (ft);

d_e = the equivalent distance from the roadway to the closest residence (ft);

t^* = the threshold noise level below which the damage cost is presumed to be zero (dBA);

$Leq(d)_{u,r,h}$ = motor vehicle noise (dBA) as a function of distance d from the road edge, for type of road r in area u with noise barrier of height-class h. This function is integrated from the point e, at the closest residences, up to the point at which the noise level drops off to the threshold level t^* (see figure 1). The units of the integrated equation are dBA-ft.

5,280 = feet/mile.

Note that we calculated the cost of noise from motor vehicle traffic on all roads in all 377 urbanized areas of the United States. We were able to do this because we had detailed data—on housing value, housing density, road mileage, traffic volume, etc.—for each of the 377 urbanized areas.

Unfortunately, we did not have detailed data for rural (non-urban) areas, and as a result could not model noise costs along rural roads in the same way that we modeled noise costs in urban areas. If we are to estimate costs for rural areas at all, it must be on the basis of assumed average characteristics. The difficulty here is that rural situations can run the gamut from small towns situated on noisy roads to essentially depopulated open spaces. For simplicity, we parsed the continuum into rural towns in which traffic noise is a problem, and rural towns in which it is not, and assumed that traffic noise is a problem only in those towns in which at least one federally funded noise barrier has been built.

FHWA (USDOT 1990) lists the length and height of over 400 noise barriers in 92 non-urban towns. On the basis of these data, we estimated the extent of the entire road network in all 92 towns. We then estimated the average housing density, housing value, vehicle speed, and so on, in the 92 towns. Having thus in effect characterized a single, aggregated rural area, we applied our noise-damage model to estimate the cost of motor vehicle noise in this area. Our estimates and assumptions are detailed in Delucchi and Hsu (1996).

Because there are only 92 small towns with federally funded noise barriers, our estimated total noise damages are trivial (less than \$10 million in the base case). It is clear, though, that costs are not zero in rural towns without noise barriers,[4] and that as a result we underestimate noise costs in rural areas, perhaps significantly.

Motor Vehicle Area-Noise Submodel ($AN_{u,r,h}$; $Leq(d)_{u,r,h}$)

The calculation of $AN_{u,r,h}$ the area-noise levels, is the core of the general model presented above. In this section, we derive an expression for $AN_{u,r,h}$ in terms of the data available to us.

Continuous noise, such as noise from motor vehicle traffic is represented by a measure known as the "equivalent sound level," denoted *Leq* (NCHRP 1976). The *Leq* gives the average sound level over a given period, such as an hour, day, or year. The sound intensity usually is reported in "A-weighted" decibels. This weighting favors the medium and high frequencies to which the human ear is most sensitive (Linster 1990). Hence, a sound level of 55 dBA (24-hr *Leq*) means a 24-hour average sound level of 55 A-weighted decibels. In this analysis, the main noise parameters—the threshold level (t^*), the noise from motor vehicles (*Leq*), and the cost of a decibel of noise (*HV*)—are expressed on a daily or annual average basis, the two being the same because we assume the daily average is the same for every day of the year.

FHWA's Traffic Noise Model calculates the equivalent hourly noise level from motor vehicles as a function of traffic volume, truck percentage, average speed, distance to the highway, shape of the road, ground cover, height of the roadway, environmental factors such as wind, and many other parameters. In this analysis, we used a simplified version of the TNM model (Anderson 1995; Jung and Blaney 1988), with our addition of a noise-barrier-reduction term, B_h:

$$Leq(d)_{u,r,h} = 10 \cdot \log_{10}\left\{0.0296\,\frac{\Phi'}{180} \cdot V_{u,r,h} \cdot K_{u,r} \cdot \left(\frac{50}{d}\right)^{1+\alpha}\right\} - B_h \qquad (2)$$

$$V_{u,r,h} = \frac{Dvmt_{u,r,h}}{24 \cdot L_{u,r,h}}$$

$$K_{u,r} = \sum_{v} Kv_{u,r}$$

$$Kv_{u,r} = f\left(Sv_r,\ Fv_{u,r},\ FCv_r,\ Cv_r\right)$$

where:

$Leq(d)_{u,r,h}$ = the equivalent sound level (dBA) (equation from Anderson 1995);

Φ' = the equivalent subtending angle, used to model the decrease in the noise level caused by intermediate obstructions; this is a function of the subtending angle Φ and the site parameter α (Delucchi and Hsu 1996; Jung and Blaney 1988);

$V_{u,r,h}$ = traffic volume (vehicles/hour) in urban area *u* on road type *r* with noise barrier of height class *h*;

$K_{u,r}$ = the total noise-energy emissions from different vehicle classes in urban area *u* on road type *r*;

d = the "equivalent distance," equal to $\sqrt{dn \cdot df}$ where d_n is the distance from the middle of the near lane to the noise recipient, and d_f is the distance from the middle of the far lane to the noise recipient[5] (feet);

50 = the reference distance (feet);

α = the site parameter, or ground-cover coefficient (unitless); used to model the decrease in noise due to different types of ground cover;

Φ = the subtending angle, used to model shielding due to intervening structures: it is the angle between two lines emanating toward the road from the noise receptor; one line drawn perpendicular to the axis of the roadway, the other drawn from the noise receptor to the edge of the obstruction (e.g., house, hill) along the roadway (our formulation assumes that the subtending angle is the same on either side of the perpendicular);

B_h = the reduction in noise level provided by a noise barrier of height-class *h* (zero height and zero reduction if no noise barrier) (dBA);

$Dvmt_{u,r,h}$ = daily vehicle-miles of travel (VMT) in

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[4] We expect that in many rural areas, traffic volume and housing density, and hence noise exposure, are relatively low. The sensitivity to noise, however, might be higher in these situations.

[5] The equivalent distance is defined slightly differently for roads that have a noise barrier. However, the difference is unimportant, and for modeling simplicity, we assumed that the equivalent distance for roads with barriers was the same as the equivalent distance for roads without.

urban area u on road type r with a noise-barrier of height class h;

24 = hours in a day;

$Kv_{u,r}$ = the noise-energy emissions from vehicle-type v in urban area u on road type r (the actual equation and parameter values are from FHWA's TNM, and are shown in Delucchi and Hsu (1996));

Sv_r = average speed of vehicle type v (mph) on road type r;

$Fv_{u,r}$ = the fraction of total VMT by vehicle-type v in urban area u on road type r;

FCv_r = the fraction of vehicle type v cruising at constant speed, on average, on road type r (the remaining fraction is assumed to be accelerating);

Cv_r = the weighted average of the exponent for cruising and the exponent for accelerating, for vehicle type v on road type r (exponent values from the TNM);

vehicle types v: light-duty autos (LDAs) (a), medium-duty trucks (MDTs) (m), heavy-duty trucks (HDTs) (h), buses (b), and motorcycles (c).

Our approach is to integrate equation (2) with respect to the distance d, in order to obtain the true noise level over the entire area subjected to excessive motor vehicle noise. The result is an expression that has the units dBA-ft. When the evaluated integral of equation (2) is converted to dBA-miles and multiplied by the length, in miles, of roads of type r in area u with noise barriers of height h, the result is a quantity with the units dBA-mi^2, which can be described as the area of land subjected to some true average noise level. We refer to this quantity, which is unique for road type r in area u with noise barriers of height-class h (zero height if no noise barrier), as the Area-Noise Level, $AN_{u,r,h}$. Figure 1 illustrates this area.

The integration of equation (2) results in the following expression for $AN_{u,r,h}$ (Delucchi and Hsu, 1996):

$$AN_{u,r,h} = \frac{L_{u,r,h}}{5280} \cdot \Big[(d_{t^*} - d_e) \cdot (4.34294\, log_e\{0.0001644 \cdot \Phi' \cdot 50^{1+\alpha} \cdot V_{u,r} \cdot K_{u,r}\} - B_h - t_*) - 4.34294\,(1+\alpha) \cdot (d_{t^*} \cdot (log_e\{d_{t^*}\} - 1) - d_e \cdot (log_e\{d_e\} - 1))\Big] \tag{3}$$

Equation (3), which is expressed in terms of miles of roadway, vehicle volume, a "K" parameter, which is a function of vehicle-type mix and vehicle speed, and distance from the road, is the full form used in the model. The integral is evaluated from the distance of the closest housing unit (the point d_e) to the distance at which the noise drops to the threshold level (d_t^*).

Simplifying Assumptions Underlying the Motor Vehicle Area-Noise Submodel

Although we accounted for a number of important factors, including traffic volume, traffic speed, the fraction of vehicles accelerating at any one time, the distance from the road, noise absorption by the ground, noise reduction due to intermediate obstructions, and the extent and height of noise barriers, we also omitted or simplified several important factors. For example, we assumed that all vehicles travel on smooth, level roads—we did not estimate the effects of rough roads and potholes. We did not include noise from horns, sirens, skidding cars, or starting or revving engines. Our treatment of noise attenuation due to ground cover and intermediate obstructions, while explicit, was crude. In addition, we estimated the cost of motor vehicle noise averaged over 24 hours of the day, rather than the cost of the actual hourly noise profile.[6]

In reality, of course, motor vehicle noise is a more complex phenomenon than we have modeled. It depends on topography, wind, temperature, the condition of the road, the relative heights of the road and the receptors, the orientation of the road, the arrangement and size of structures and hills, the specific characteristics of ground cover, and other factors (NCHRP 1976). We left these other

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[6] Recall that the FHWA noise model used here estimates the equivalent hourly noise level based on the hourly traffic volume. We input to this model the 24-hour average traffic volume, equal to the reported average daily volume divided by 24 hours in a day. Thus, we assumed that the traffic volume is constant. (Note that as a result, the estimated 1-hour *Leq* is the same for every hour of every day, and hence equal to the 24-hour—and the annual—*Leq*.) Of course, in reality the traffic volume is not constant: usually, it is much lower between 12:00 am and 6:00 am than at other times. It would be better to estimate average hourly volumes for different periods of the day (say, daytime, evening, and late night), and set different noise thresholds for each period, and then estimate exposure and damages for each period. However, we do not have the data to do this.

parameters out of our model because it was not easy to get values for them for every urbanized area in the United States.

The net effect of our simplifications and omissions is not obvious. Although some of the omissions result in an underestimation of noise—tires are noisier on rough and pot-holed roads than on smooth roads, and sirens, horns, starts, skids, and so on add to normal engine and tire noise—other omissions and simplifications might have the opposite effect.

BASE-CASE VALUES OF PARAMETERS IN THE MODEL (URBANIZED AREAS)

Limits of Integration of Noise Equation

Equation (3), the expression for area-noise level, is the product of $L_{u,r,b}$ and an integration of Leq from $d = e$ (the equivalent distance from the roadway to the closest housing unit) to $d_t{}^*$, which is the equivalent distance from the road to the point at which the noise level has dropped to the threshold level.

Because the equivalent distance d is defined with respect to the center of the near and far lanes, we estimated the number and width of lanes, the width of dividers and shoulders, and the distance from the closest housing unit to the road edge, for each type of road. Table 1 shows our assumptions for the base case, low-cost case, and high-cost case, and the calculation of the equivalent distance to the closest residence in the base case. Generally, we assumed that housing units can be built up to the edge of the road right-of-way, but not in the right-of-way. On the presumption that barriers usually are built along roads that are relatively close to housing areas, we have assumed that houses typically are closer to roads that have barriers than to roads that do not.

The value of d at $Leq = t^*$ is obtained by solving equation (2) for d at $Leq = t^*$, for each value of

TABLE 1 Calculation of the "Equivalent Distance" from the Noise Source to the Noise Recipient
(In feet, except as noted)

	Interstate	Other freeway	Principal arterial	Minor arterial	Collector	Local road[1]
Distance, pavement edge to first house, roads without barriers[1]	50/65/80	40/50/60	30/35/45	25/25/38	20/20/30	20/20/30
Distance, pavement edge to first house, roads with barriers[1]	50.0	40.0	30.0	25.0	20.0	20.0
Width of right shoulder of road[1]	10.0	10.0	5.0	4.0	4.0	4.0
Width of a lane[2]	12.0	12.0	11.5	11.3	11.1	10.9
Number of lanes[3]	5.4	4.5	3.4	2.5	2.1	1.8
Width of dividers plus left shoulders[4]	20.0	10.0	5.0	2.0	0.0	0.0
Equivalent distance, roads without barriers[5]	*111.6*	*88.2*	*59.9*	*43.1*	*35.1*	*33.5*
Equivalent distance, roads with barriers[5]	*95.7*	*77.8*	*54.7*	*43.1*	*35.1*	*33.5*

[1] Our assumptions. Numbers separated by a slash are high-cost case/base case/low-cost case.

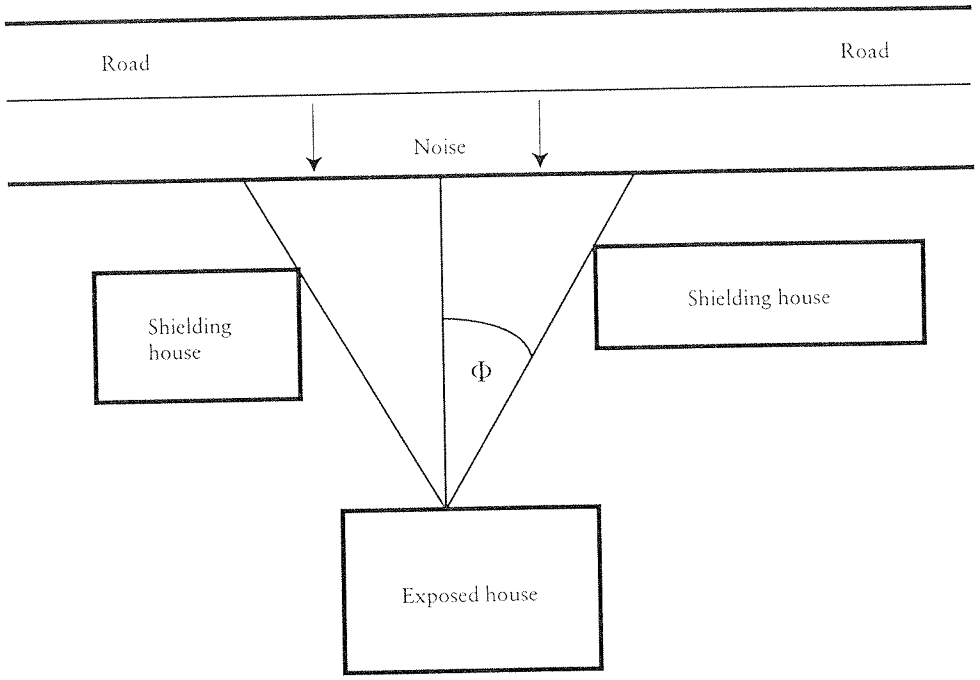
[2] FHWA (USDOT 1992) reports miles of roadway by width of lane and amount of vehicle traffic for Interstates, other freeways, major arterials, minor arterials, and collectors (but not local roads) in urban areas in 1991. With these data, we estimated a mileage-weighted average lane width for each of the five types of roads just mentioned. The estimate for local roads is our assumption.

[3] FHWA (USDOT 1992) reported miles and lane-miles of roadway for Interstates, other freeways, major arterials, minor arterials, and collectors in urban areas in 1991. With these data, we back-calculated the number of lanes of each type of road. FHWA estimated lane-miles of local roads using data derived not from the actual number of lanes of local roads, but rather from the assumption that all local roads average two lanes. We felt that this was too high, and instead have assumed that local roads average 1.8 lanes.

[4] Our assumptions, based partly on FHWA (USDOT 1992) data on miles of divided road in each road-type category.

[5] Equal to: $\sqrt{dn \cdot df}$, where dn is the distance from the middle of the near lane to the noise recipient, and df is the distance from the middle of the far lane to the noise recipient (Jung and Blaney 1988). Results are shown for the base case only.

FIGURE 2 Noise Shielding by Intervening Structures
(As represented by the subtending angle Φ)



S_r, $V_{u,r,h}$, and B_h. There is a different d_t^* for each of the six roadway types r in each of the 377 urbanized areas (plus 1 aggregated rural area) u and for each height class h. Where d_t^* is less than e, we assumed that there were no noise damages in that urbanized area along road type r at height class h.

Subtending Angle (Φ) (Shielding Due to Intervening Structures)

Houses, trees, hills, and other objects close to a road shield housing units further back from some of the road noise. The noise attenuation provided by this shielding depends on the location, size, height, and other characteristics of the intervening "shields" and the shielded houses. The FHWA Traffic Noise Model includes a relatively sophisticated calculation of the attenuation due to shielding (Blaney 1995). However, it is not possible to model shielding in detail in every area in the United States. Instead, we adopted a much simpler approach, and used the subtending-angle parameter in the Jung and Blaney (1988) equation to model the effect of shielding.

In our formulation, the subtending angle is one-half the angle of sight framed by intervening objects. Figure 2 shows a house in the second row of houses back from a road, partially shielded from road noise by houses in the first row. The angle created by the gap between the two houses in the front row, from the point of observation of the house one row back, is double the subtending angle. Where there are no obstructions at all, the subtending angle is 90°, or one-half of 180° (Jung and Blaney 1988).

The subtending angle is meant to model the noise field at a single receptor, not the "average" noise field over a complex arrangement of structures. Nevertheless, we had no other way to account formally but simply for attenuation due to shielding. We assumed in our base case that average "line of sight" to the road, or open noise path to the road, throughout an exposed residential area, is a sweep of 60°, or 30° on either side of the perpendicular, so that $\Phi = 30$.

We emphasize that this is just a best guess at the value of a crude parameter. The "true" national-average value of F could be slightly less or somewhat more than 30°. We assumed a value of 20° in our low-cost case, and 40° in our high-cost case.

Ground-Cover Coefficient (α) (Noise Reflection)

The ground-cover coefficient, α is a unitless coefficient (between 0.0 and 1.0) meant to account for the noise attenuation caused by ground cover between the noise source and the receptor. Jung and Blaney (1988) describe the range of values of α:

- 0.00 represents perfectly reflective surfaces, such as pavement;
- 0.25 represents moderately reflective surfaces, such as bare soil, or partially paved surfaces;
- 0.50 represents moderately absorptive ground cover, such as lawns or soft soil fields;
- 0.75 represents very absorptive ground cover, such as fields with large trees; and
- 1.0 represents perfectly absorptive ground cover.

On the basis of this description, and recognizing that in large areas of central cities most of the ground is hard (Anderson 1995), we assumed in our base case that $\alpha = 0.375$. (Blaney (1995) reports a value of 0.66 in an analysis for Ontario, but this was chosen to be high in order to compensate for overestimated noise emissions from motor vehicles.)

Of course, this is merely our best guess. The "true" national-average value of the ground-cover coefficient (α) might range from as little as 0.25, which is the value for relatively hard and reflective ground, to 0.50, which is the value for moderately soft and absorptive ground. It is not likely to be less than 0.25 or higher than 0.50, because in urban areas the average must be some mix of hard and soft ground—leaning, we believe, slightly toward the hard side. We assumed a value of 0.50 for our low-cost case, and 0.25 for our high-cost case.[7]

Threshold Noise Level Below Which Noise has No Cost (t^*)

It is widely agreed that in most situations there is a nonzero threshold noise level below which most people will not be annoyed and above which most will be annoyed, although as the Organization for Economic Cooperation and Development (OECD) emphasizes, the threshold is different for different people and in different places (OECD 1986). Our literature review indicated that the threshold is around 55 dB.

According to a World Health Organization task group, daytime noise levels of less than 50 dBA *Leq* outdoors cause little or no serious annoyance in the community (OECD 1986). The task group considers daytime noise limits of 55 dBA *Leq* as a general health goal for outdoor noise in residential areas. However, they stated that "at night, an outdoor level of about 45 dBA *Leq* is required to meet sleep criteria" (OECD 1986, 37). Linster (1990) and OECD (1988) report that research in OECD countries indicates that outdoor levels should not exceed 55 dBA *Leq*.[8] Finally, in his analysis of the effect of noise on the Helsinki housing market, Vainio (1995) tested "different partially linear noise specifications," and found that "the cutoff level of 55 dBA *Leq* is supported by the data" (p. 163).

Based on these studies, we assumed a threshold value (t^*) of 55 dBA (daily and annual *Leq*) in our base case, and 50 dBA in our high-cost case. We found, however, that the threshold level is one of the most important parameters in our model. As we show below in our sensitivity analyses, a small change in the threshold level results in a very large change in calculated noise costs.

Road Mileage ($L_{u,r,h}$) and VMT ($Dvmt_{u,r,h}$) by Urbanized Area, Type of Road, and Height of Noise Barrier

We obtained values for these parameters by combining information from separate FWHA databases on roads, vehicle travel, and noise barriers. FHWA (USDOT 1991a, 1991b, 1991c) reports miles of roadway (L) and vehicle-miles of travel (D_{vmt}) on six classes of road (freeway, other limited-access highways, principal arterial, minor arterial, collector street, local road), in each of 377 urbanized areas. Another publication (USDOT 1990) reports the length, height, location, and name of road for each noise barrier built with federal funding, as of December 31, 1989 (the latest year for

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[7] One of the referees believes that these bounds are too wide—that neither 0.25 nor 0.50 are likely as national averages.

[8] For reference, a graph in Linster (1990) shows that a busy intersection produces about 80 dBA, and a quiet living room about 40.

which data were available). We used the information on noise barriers to determine, for each type of road in each urbanized area, the total mileage of roadway in each of four noise-barrier height classes: zero height (no barrier), low, medium, and high. (We were interested in the height of noise barriers because, as explained below, we assumed that the noise reduction provided by a barrier is a function solely of its height and length.) The method is described in Delucchi and Hsu (1996).

Traffic Speed by Type of Road (Sa_r, Sm_r, Sh_r, Sb_r, Sc_r)

We assumed that the speed of traffic varies from road type to road type, but otherwise does not vary among urban areas. The average speeds assumed in our analysis are listed in table 2. Our assumptions for Interstate freeways and other freeways are based on FHWA-reported national averages for these two types of road. For the other four types of road, we made what seemed to us to be reasonable assumptions.

It is possible that exposure-weighted average speeds are lower than we have assumed. For example, Fuller et al. (1983) assumed average speeds that were considerably lower than our assumed speeds. In our low-cost case, we assumed that speeds are 85% of those in the base case.

Truck, Bus, and Motorcycle Fractions ($Fm_{u,r}$, $Fh_{u,r}$, $Fb_{u,r}$, $Fc_{u,r}$)

Because trucks are much noisier than cars, motor vehicle traffic noise depends on the mix of cars and trucks in the vehicle stream. FHWA (USDOT 1991c) reported the MDT and HDT fractions of traffic volume ($Fm_{u,r}$ and $Fh_{u,r}$), by state, but not by urbanized area. We assumed that the state-level fractions apply to each urbanized area in the state (and to the aggregated rural area).

FHWA's TNM includes separate noise equations for buses and motorcycles (Anderson 1995). According to the model, buses are quieter than HDTs, and motorcycles are quieter than LDAs. Although buses and motorcycles constitute but a tiny fraction of total VMT, it still is worthwhile to treat them separately in the model, at least for the purpose of estimating marginal damages. FHWA (USDOT 1991, 1992) reported national VMT by

TABLE 2 Average Speeds in Urbanized Areas
(Miles per hour)

	Interstate	Other freeways	Principal arterials	Minor arterials	Collectors	Local roads	All roads
LDAs	59.6	58.2	37.0	30.0	25.0	20.0	34.4
MDTs	54.0	53.0	33.0	27.0	20.0	17.0	31.8
HDTs	50.0	49.0	28.0	22.0	17.0	14.0	33.6
Buses	45.0	44.0	22.0	18.0	15.0	10.0	21.0
Motorcycles	60.0	60.0	40.0	34.0	30.0	25.0	38.4
All vehicles[1]	58.6	57.6	36.4	29.6	24.6	19.9	n.e.

[1] Calculated as:
$$S_r = \frac{VMT_r}{\sum_{v} \frac{VMT_{v,r}}{S_{v,r}}}$$

where: S_r = the average speed on road type r; VMT_r = total VMT on road type r (USDOT 1991c); $VMT_{v,r}$ = VMT by vehicle type v on road type r (USDOT, 1991c, and our estimates); $S_{v,r}$ = average speed of vehicle type v on road type r (this table).

Key: LDA = light-duty automobile, including light truck; MDT = medium-duty truck; HDTs = heavy-duty truck; n.e. = not estimated.

Methods:
Interstates and other freeways: *Highway Statistics 1990* (USDOT 1991a) reports the average speed of all vehicles on highways with 55 miles per hour (mph) speed limits in 1990: 58.6 mph on urban Interstates, and 57.6 mph on other urban freeways. We picked average speeds by vehicle class, such that the calculated travel-weighted average speed by all vehicles was 58.6 mph on Interstates, and 57.6 mph on other freeways (bottom row of this table).
Other roads: The values for the other types of roads are our estimates of average speeds. We chose these values so that the calculated average speed on all roads, by vehicle class (far right column of the table), was consistent with other data on average speeds by vehicle class (see Delucchi 1996).

buses and motorcycles on urban Interstates and on all other urban roads. We disaggregated the VMT on all other urban roads into VMT on other freeways, principal arterials, minor arterials, collectors, and local roads, based on our judgment. We then assumed that this national distribution of VMT applies to every urban area.

The automobile fraction ($Fa_{u,r}$) is calculated as 1 minus the sum of the other fractions.

Fraction of Traffic Cruising Rather Than Accelerating (FCa_r, FCm_r, FCh_r, FCb_r, and FCc_r; and Ca_r, Cm_r, Ch_r, Cb_r, and Cc_r)

The noise from a motor vehicle engine depends in part on the speed of the engine: the higher the rpm, the greater the number of explosions per second, and hence the greater the noise from the engine. When a vehicle accelerates, the engine rpm increases rapidly. Consequently, accelerating vehicles are noisier than cruising vehicles.

The noise-energy equations in the TNM include an exponent that has one value for acceleration and another for cruising. In our model, we weighted the cruising exponent value by the fraction of vehicles that, on average at any given time, are cruising at a steady speed on road type r. We assumed that the remaining vehicles are accelerating, and so weighted the accelerating exponent value by 1 minus the cruising fraction.

On roads where vehicles start and stop a lot, and have a low average speed—such as on local roads—the cruising fraction will be relatively low. On roads where vehicles rarely stop and start, and cruise at a high average speed—such as on Interstates—the cruising fraction of course will be relatively high. Generally, we assumed that the cruising fraction is related to the average speed. In the low-cost case, we assumed lower cruising fractions. Our assumptions are shown in Delucchi and Hsu (1996).

Housing Unit Density in Areas Exposed to Motor Vehicle Noise Above the Threshold (M_u)

As shown in equation (1), the calculated cost of motor vehicle noise is directly proportional to the density of housing units in the areas exposed to this noise above the threshold t^* (i.e., the areas near roads). Data from the Bureau of the Census (USDOC 1990) allowed us to calculate the average density of housing units (*HUs*) in each urbanized area (let us call this M_u^*), but this is not necessarily the same as the average density of *HUs* exposed to motor vehicle noise above a threshold (the parameter M_u in the model). We estimated M_u by adjusting M_u^*, as follows:

$$M_u = M_u^* \cdot AD$$

$$M_u^* = H_u/A_u$$

where:

M_u = the density of *HUs* in areas exposed to motor vehicle noise above the damage threshold, within area u (*HUs*/mi^2);

M_u^* = the average density of *HUs* in area u (*HUs*/mi^2);

AD = the adjustment factor for *HU* density (discussed below);

H_u = the number of *HUs* in area u (USDOC 1990);

A_u = the total land area of area u (mi^2) (USDOC 1990).

Estimating the density adjustment factor AD. A priori, it was not clear if M_u is greater or less than M_u^*. Along some roads, the housing density is quite high; along others, it is zero, and it is not immediately obvious how these two opposing trends might play out.

Our approach was to find the AD that produces an M_u that is consistent with independent data on the number of houses near roads nationally. Specifically, we multiplied M_u^* by an adjustment factor AD chosen so that the resulting calculated total number of houses within 300 feet of a 4+ lane highway, in all urbanized areas, matched the Bureau of the Census' estimate of the number of houses within 300 feet of a 4+ lane highway, as reported in the *American Housing Survey for the United States in 1989* (USDOC and USHUD 1991). The adjustment factor AD is the same for all urbanized areas. The method is described in Delucchi and Hsu (1996) and the result is AD = 1.40. We assumed that this resulting M_u is uniform throughout the area of land exposed to motor vehicle noise above the threshold. In the low-high analysis, we considered density adjustment factors of 1.00 and 1.50 instead of 1.40.

Annualized Value of *HU* in Areas Exposed to Motor Vehicle Noise Above the Threshold (P_u)

The calculated cost of motor vehicle noise also is directly proportional to the median annualized value of housing units in areas exposed to motor vehicle noise above the threshold t^* (equation (1)). We estimated the annualized value of *HU*s near roads in each urban area by annualizing the full value of owner-occupied *HU*s in each urban area u, and then adjusting for the difference between the annualized cost of all *HU*s and the annualized cost of owner-occupied *HU*s, and for the difference between the value of *HU*s near roads and the value of *HU*s throughout the urban areas. Formally:

$$P_u = FVO_u^* \cdot \frac{i}{1\text{-}(1+i)^t} \cdot \frac{AHCUS}{AOCUS} \cdot AV \cdot V_{91/90}$$

where:

P_u = the annualized value of *HU*s exposed to noise above a threshold, in urban area u (as above);

FVO_u^* = the median value of owner-occupied *HU*s or houses for sale in each urbanized area u in 1990 (USDOC 1990);

i = the annual interest rate for investment in *HU*s (discussed below);

t = the term of the investment in *HU*s (years; discussed below);

$AHCUS$ = the median annual cost of all occupied *HU*s in all urban areas of the United States in 1991 (USDOC and USHUD 1991, 1995);

$AOCUS$ = the median annual cost of owner-occupied *HU*s in all urban areas of the United States in 1991 (USDOC and USHUD 1991, 1995);

AV = the housing-value adjustment factor: the ratio of the value of *HU*s near roads to the value of all *HU*s in urban areas (AV);

$V_{91/90}$ = the ratio of housing value in 1991 to housing value in 1990 (see Delucchi and Hsu 1996).

Interest rate (i) and annualization period (t). Partly on the basis of long-term trends in real interest rates, we assumed that the appropriate real annual interest rate for investment in housing is 4% to 7% per year. The lifetime of the investment probably is on the order of 30 to 40 years. We assume 4% and 40 years ($AF = 0.0505$) in the low-cost case, and 7% and 30 years ($AF = 0.0806$) in the high-cost case. For our base case, we assumed values halfway between the low and high: 5.5% and 35 years ($AF = 0.0650$).

The ratio of the value of HUs near roads to the value of all HUs in urban areas (AV). We believe that, in general, the disbenefits of being close to a major roadway (noise, pollution, safety, aesthetics) outweigh the benefit of accessibility, so that housing value declines the closer that one gets to a major roadway. However, what we wanted to know is not the worth of noise-devalued homes in areas of excess motor vehicle noise, but rather what the value of those homes would be were they exactly as they are *except* not devalued because of motor vehicle noise. We expected that, even if motor vehicles were perfectly quiet, housing value still would decline with proximity to major roads, on account of the danger, ugliness, and intrusiveness of the roads. Thus, we assumed that, if there were no noise from roads, the value of *HU*s near roads would be 5% less than the average value in the urban area ($AV = 0.95$). In our low-cost case, we assumed that $AV = 0.90$, and in our high-cost case, we assumed that $AV = 1.00$.

Diminution in Annualized Housing Value per Excess Decibel (*HV*)

Several studies (Nelson 1978; Hall and Welland 1987; O'Byrne et al. 1985; Vainio 1995) estimated the shadow price of noise in the housing market by regressing sales price or property value against noise and other explanatory variables, such as lot size, number of rooms, and number of bathrooms. The estimated effect of noise on housing value is expressed as a percentage of value lost per decibel of noise above a threshold level. These property-value (hedonic) studies, and the range of results from property-value studies cited in Verhoef (1994), Vainio (1995), and Maddison et al. (as reported by Maddison 1996), indicate that each decibel of noise above a threshold reduces the value of a home by 0.2% to 1.3%. However, a recent contingent-valuation (CV) study of willingness-to-pay (WTP) for residences at different hypothetical levels of airport noise estimated that homeowners value noise at 1.5% to 4.1% of housing value per decibel, depending in part on whether the bids of those who were unwilling to accept the noise at any price are included (Feitelson et al. 1996). Similarly, Verhoef (1994) notes that CV studies can yield estimates up to 15 times greater than those derived from hedonic price techniques. Feitelson et al. offer several reasons for this difference between the CV results and the property value results, the most important being that some property value studies estimate only the loss of market value (as the difference between market prices at different noise levels), and not the full loss of consumer value including surplus (as the area under a demand curve estimated in a "second-stage" hedonic analysis). Nevertheless, we are skeptical of valuations above 2.0%.

Note that the ranges cited above are the implicit valuations of home buyers only, not of all householders. It is likely that home buyers as a group value noise differently than do all households (renters plus owners) on average. For example, renters of a given income level might not be willing to pay as much to reduce noise as are home owners (of the same income level, and for the same noise reduction), perhaps because renters in general care less about amenities of home. Evidence that this is so comes from the Feitelson et al. (1996) CV study, which found that the parameter *HV* for renters was 25% to 40% less than the parameter *HV* for homeowners. Thus, the overall *HV* for the entire housing market probably is less than *HV* in the market for home buyers.

On the basis of the preceding discussion, we assumed a range of 0.2% (low-cost case) to 1.5% (high-cost case) of housing value, per decibel (daily and annual *Leq*) of noise. In our base case, we assumed a value halfway between the low and the high (0.85%). Note that the total calculated noise costs are directly proportional to this %-value/dBA parameter, so that it is straightforward to reestimate results for different parameter values.

Problems with the parameter HV. For several reasons, our use of the parameter *HV*, the estimated reduction in annualized housing value per decibel of noise above a threshold, might not yield an accurate measure of the total cost of motor vehicle noise.

(i) First, we assumed that the marginal cost of each decibel is the same—that is, the cost of noise is a linear function of the noise level—whereas theoretically we expect that the true cost function for noise is nonlinear. For example, it does not seem likely that the WTP for a 50 to 55 dBA change is equal to the WTP for a 75 to 80 dBA change. Nevertheless, not only do most studies use a linear functional form, most that have tried nonlinear forms found they are no better than linear forms (Hall and Welland 1987; Feitelson et al. 1996).[9] Because of this, and because nonlinear functions generally are not available, we assumed that the cost of noise is linearly related to the level, and hence the $/dBA cost is constant.

A related question is whether the fractional diminution in housing value per excess decibel depends on income or housing value. It is conceivable that wealthy people are willing to pay a greater *fraction* of their income to eliminate an excess decibel than poor people; or, put another way, that an excess decibel of noise causes a greater percentage reduction in the annualized value of expensive homes than in the annualized value of modest homes. However, we do not have data to evaluate this possibility, and so do not address it formally.

(ii) Some people might undervalue noise when they decide how much they are willing to pay to live in a quieter location. This will be the case if there are psychological and physiological effects of noise that are so subtle that people do not realize that they are caused by noise. We believe that noise has these kinds of subtle effects, but we were unable to quantify them.

(iii) The parameter *HV* is valid only over the range of noise problems experienced in the housing areas studied in the original hedonic price analyses. Therefore, if commercial and industrial areas experience significantly different noise problems from the residential areas analyzed in the hedonic price analyses, the function might not accurately represent the dollar cost of noise levels in these areas. We recognize this possibility, but lack the data to correct for it.

Effect of Noise Barriers (B_h)

Many roads have noise barriers that attenuate vehicle traffic noise and reduce total exposure to noise. In equation (2), we represent the reduction in noise, B_h, provided by a noise barrier, as a func-

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[9] However, at least one study (McMillan et al. 1980) used a logarithmic functional form.

tion only of the height of the barrier. Of course, in reality, the noise reduction is a function not only of the height of the noise barrier, but also of its thickness and construction, the distance from the source of the noise to the barrier, the distance from the barrier to the recipient of the noise, the height of the source of the noise and the recipient of the noise relative to the barrier, the extent of the barrier, the orientation of the barrier with respect to the roadway, and other factors (Jung and Blaney 1988; NCHRP 1976).

However, to keep the integration of equation (2) and the size of the analysis manageable, we used a very simplified model of the effect of noise barriers: we placed each noise barrier into one of three height categories, and assumed that the attenuation provided by a barrier is a function only of the height of the barrier. Our assumed reductions by height class (the parameter B_b), shown in table 3, are based on a 1976 study that analyzed the cost-effectiveness of various measures to reduce traffic noise damages (NCHRP 1976). We assumed that the dBA reductions in table 3 apply at every point along the noise trajectory emanating from the road, so that the effect is simply to shift the entire noise-distance curve down by a fixed amount (B_b) in equation (2) for stretches of road on which noise barriers were erected.

Although our assumptions regarding the effects of barriers are simplistic, a comparison of those assumptions with the results of the more sophisticated model in Jung and Blaney (1988) indicates that the assumptions are valid over a relatively wide range of conditions and distances (see Delucchi and Hsu 1996 for details). In any case, given that only a minor fraction of roads have noise barriers, the total error in our calculation due to using a simple model of the effect of noise barriers is small compared with the total estimates of the damage cost of motor vehicle noise.

TABLE 3 Assumed Reductions in Motor Vehicle Noise (dBA), by Barrier Height
(In feet)

	Reduction in noise provided by barrier (parameter B_b, in dBA)		
Height of noise barrier (feet)	Base case[1]	Low-cost scenario[2]	High-cost scenario[2]
Less than 12.5	8.4	10	7.0
12.5–17.5	10.8	14	9.0
More than 17.5	13.0	16	11.0

[1] These are NCHRP's (1976) estimates of the reduction provided by a 10-foot, 15-foot, and 20-foot noise barrier.
[2] Greater noise reduction results in a lower damage cost, and vice versa.

Time Spent in and Away from One's Home (T_i and T_o)

Traffic noise causes damages at places other than one's home or residential property. We accounted for these costs by extrapolating residential costs in proportion to the amount of time spent outside (T_o) versus in or around (T_i) one's home. Recall that we estimated the cost of noise on the basis of analyses of the value of noise implicit in the prices that people pay for houses. These housing price analyses considered the effect of noise on the value of the home only, and did not capture the effect of noise on activities away from one's home.[10]

In principle, the cost of noise depends on the physical characteristics of the noise, the length of time that people are disturbed by the noise, and what people are doing, or trying to do, when they are disturbed. These factors can vary greatly from place to place and time to time, and as a consequence the total cost of noise disturbance (per minute) in, say, the home might be quite different from the total cost of noise (per minute) away from the home—say, at the office. For example, the \$/dBA value of quiet in an office or in school may well exceed the \$/dBA value of quiet at home, whereas the value of quiet in a fast-food restaurant may be less.

Ideally, then, we would estimate the exposure to and cost of noise in each location away from one's home. Unfortunately, we did not have data for this ideal estimation. So, instead, we used a simple binary classification: in every away-from-home location, the exposure to and \$/dBA of motor vehi-

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[10] For example, if a buyer has accepted a job in a given region, and is looking for a home in the region, then exposure to noise at work will not affect the choice between homes—because the exposure will be the same regardless of which house is chosen—and hence will not show up in the value of noise implicit in the price of a home.

TABLE 4 Time Spent in Various Locations, and the Impact of Noise

Place	Affected by noise?[1] (scenario assumptions in parentheses)	Time spent (minutes)[2]
Home (parameter T_i)	Yes	921.1
Office	Yes[3]	70.1
Plant	No	34.9
Grocery store	No (Yes)	12.4
Shopping mall	No	33.8
School	Yes	40.4
Other public place	No (Yes)	13.2
Hospital	Yes	14.4
Restaurant	Yes	28.1
Bar/nightclub	No	8.0
Church	Yes	6.3
Indoor gym	No	4.2
Other's home	Yes	60.6
Auto repair/ gas station	No	10.5
Playground/park	Yes	12.3
Hotel/motel	Yes	6.7
Dry cleaners	No	0.4
Beauty parlor	No (Yes)	2.0
Other locations	No (Yes)	1.9
Other indoor	Yes	11.7
Other outdoor	No (Yes)	33.2
In transit	No (Yes)	111.4
Total for T_o[4]	*n/a*	*250.6 (424.7)*

[1] Our assumptions. In areas that are not impacted by noise, the cost of noise is zero. In areas that are impacted, the amount and \$/dBA value of noise exposure per minute are assumed to be the same as the amount and \$/dBA value of noise exposure in one's home.

[2] From Wiley et al. (1991).

[3] In a survey of businesses and residences in England, 37% to 59% of business respondents and 25% to 48% of householders were disturbed indoors frequently or all of the time by noise from road traffic (Williams and McCrae 1995). Thus, motor vehicle traffic noise disturbed a greater fraction of business persons than householders.

[4] The sum of minutes in all places away from one's home that are negatively impacted by noise, as indicated by a "yes" in column 2. The value in parentheses is a scenario analysis, accounting for the additional "yeses" in parentheses in column 2.

cle noise per minute away from home either is zero or is the same as the exposure to and \$/dBA cost of motor vehicle noise per minute at one's home. The basis of this classification, which is shown in table 4, is our judgment. For example, it seems reasonable to assume that motor vehicle noise can be a problem in offices, schools, and churches, but not at nightclubs or shopping malls. In those locations impacted by noise, we assumed that the total cost of the noise was proportional to the amount of time spent in that location divided by the amount of time spent in one's home.

Table 4 shows the amount of time that adults in California spend in various locations every day, on average. In an average day in California, people spend 921.1 minutes at home (T_i), and 250.6 minutes at places other than home (T_o), where in our judgment motor vehicle noise might be a problem. In the high-cost case, we assumed that motor vehicle noise also disturbs those in transit (111.4 minutes; see following discussion) and those participating in various indoor and outdoor activities (an additional 62.7 minutes), so that the parameter T_o = 424.7 minutes.

Noise costs while in transit. It is important to accurately characterize noise experienced while in transit, because people spend, on average, 111.4 minutes per day in transit (see table 4), right at the source of the motor vehicle noise. There are at least three ways to approach this:

1. We can assume that the noise exposure in a vehicle is the same as that in a house located, for example, five feet from the edge of the road, and that noise costs per excess decibel per minute in transit is the same as in a home. However, these assumptions result in damages of the same order of magnitude as damages in the home, which seems implausible to us. It is likely that, contrary to our second assumption, the noise cost per excess decibel per minute in transit is much less than in a home. Also, the first assumption might overstate exposure.
2. Noise costs while in transit can be ignored on the admittedly weak grounds that the noise level inside vehicles does not generally disturb the occupants. Noise disrupts sleeping, reading, and conversation, none of which occur in vehicles as much as they do in homes. We adopted this approach in our base case.
3. The 111.4 minutes in transit can be included in the "T_o" of the $(T_o+T_i)/T_i$ scaling factor, treating it like an office or school exposed to motor vehicle noise, at the effective average distance of houses from the road. This will result in greatly reduced damages compared with the first

approach, because the effective average distance from the road is much more than the five feet assumed in the first approach. We adopted this approach in the high-cost case.[11]

TOTAL EXTERNAL DAMAGE COST OF NOISE EMITTED FROM MOTOR VEHICLES

Base Case, Low-Cost Case, and High-Cost Case

Table 5 summarizes the results of the analysis. Our base-case estimate is that the external damage cost of noise from motor vehicle traffic in 1990 is on the order of $3 billion per year (1991$), which seems to be a reasonable figure. However, there is considerable uncertainty in many of the parameter values, and this uncertainty compounds by a factor of 400 into a huge difference between our low-cost and high-cost cases: less than $100 million to more than $40 billion. Although the low-cost case, in which all parameters are at their low values simultaneously, and the high-cost case, in which all parameters are at their high values, might be unlikely combinations, it also is possible that some key parameters, such as the housing value lost per decibel, or the subtending angle, might be even lower or higher than our assumed low or high values. Thus, the huge range between the low and high cases may not misrepresent the uncertainty in the analysis.[12] Still, we believe that noise damages do not exceed $5 or $10 billion annually.

Sensitivity Analyses

In table 6 we show the sensitivity of the total external noise costs to changes in the value of each of the key parameters. The sensitivities are the percentage change in the total cost, relative to the base-case cost of table 5, given a change in each parameter value from its base-case value to its low

TABLE 5 The Cost of Motor Vehicle Noise
(Millions of 1991$)

	Urbanized areas			Rural areas[1]			All areas		
Noise at home	Base	Low	High	Base	Low	High	Base	Low	High
Interstates	944	32.2	12,121	3.7	0.1	52.7	948	32.3	12,174
Other freeways	552	19.9	6,942	0.7	0.0	9.7	552	19.9	6,952
Principal arterials	311	8.4	5,381	0.7	0.0	15.9	312	8.4	5,397
Minor arterials	144	4.5	2,977	0.2	0.0	7.0	145	4.5	2,984
Collectors	2.5	0.0	467	0.0	0.0	1.4	2.5	0.0	468
Local roads	0.0	0.0	14.6	0.0	0.0	0.0	0.0	0.0	14.6
Subtotal at home[2]	*1,953*	*64.9*	*27,903*	*5.3*	*0.1*	*86.7*	*1,959*	*65.0*	*27,990*
Total away from home[3]	531	17.7	12,865	1.4	0.0	40.0	533	17.7	12,905
Total at and away from home[4]	2,485	83.0	40,768	6.7	0.2	127	2,492	83.0	40,895

[1] As explained in the text, we calculated costs in rural areas in which a noise barrier had been built.
[2] The sum of costs in and around the home.
[3] As explained in the text, we assumed that the cost of noise away from one's home is proportional to the amount of time spent away from home.
[4] Total costs in and around the home plus total costs away from home.

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[11] At this point, we should distinguish noise of one's own vehicle, which is not an externality, from noise of other vehicles. However, because this is a high-cost case and the method is crude, we have not done so.

[12] Ideally, we would have treated uncertainty in individual parameter values formally, so that we would have been able to estimate the overall probability of the results. However, for most if not all of the important parameters, there was no objective basis for establishing a probability distribution. Moreover, for two reasons, we did not think it meaningful to formalize our judgment regarding the low and high parameter values. First, for some parameters, such as the national-average subtending angle, we have essentially no basis for setting bounds, and in fact cannot really say whether the low or high is more or less probable than any value in between. Second, we did not always set lows and highs independently; in some cases, we picked the bounds with an eye toward the reasonableness of the overall effect of our assumptions for all parameter values. Nevertheless, we believe that future work should attempt to find a basis for treating uncertainty more formally.

TABLE 6 Sensitivity Analyses

Parameter (units) (symbol)[1]	Parameter input values[2]			Sensitivity[3]	
	Base	Low	High	Low	High
Ratio of housing value in 1991 to housing value in 1990 ($V_{91/90}$)	1.047	1.047	1.047	0.0%	0.0%
Value of all *HUs* ÷ value of owner-occupied *HUs* (*AHCUS/AOCUS*)	0.95	0.95	0.95	0.0%	0.0%
Time spent at home (min) (T_i)	921.1	921.1	921.1	0.0%	0.0%
Time spent away from home in places impacted by noise (min) (T_o)	250.6	250.6	424.7	0.0%	14.9%
Change in house value per dBA (*HV*)	0.0085	0.0020	0.0150	–76.5%	76.5%
HU-value adjustment factor (*AV*)	0.95	0.90	1.00	–5.3%	5.3%
Effective annual interest rate (*i*)	0.055	0.04	0.07	–17.5%	18.9%
Years of investment in the home (*t*)	35.0	40	30	–4.1%	5.9%
HU-density adjustment factor (*AD*)	1.40	1.00	1.50	–28.6%	7.1%
Subtending angle, rural areas (deg) (*f*)	40	30	50	–0.1%	0.1%
Ground–cover coefficient, rural areas (*a*)	0.50	0.60	0.30	–0.0%	0.1%
Threshold noise level (dBA) (t^*)	55	55	50	0.0%	219.3%
Subtending angle, urban areas (deg) (*f*)	30	20	40	–36.2%	34.2%
Ground-cover coefficient, urban areas (*a*)	0.375	0.50	0.25	–21.6%	32.5%
Equivalent distance to road (ft) (d_e)	see Table 1			–8.1%	4.5%
Vehicle speed (mph) (*S*)	see Table 2			–33.3%	0.0%
Fraction of vehicles cruising (*FC*)	see Delucchi & Hsu (1996)			2.6%	0.0%
Noise barrier reduction (dBA) (B_b)	see Table 3			–0.5%	0.6%

[1] See text for a discussion of the parameters and their values.

[2] Because estimated damages in rural areas are so small, we did not specify low–cost or high–cost values for or perform sensitivity analyses on most of the parameters for rural areas.

[3] For each parameter *P*, the percentage that represents the sensitivity is equal to: $\left(\frac{Cn_P}{Cn_B}-1\right)\cdot 100$, where Cn_P is the total cost of motor vehicle noise given all parameters except *P* at their base–case values, and Cn_B is the total cost of motor vehicle noise given all parameters at their base–case values (see table 5).

or high value, keeping all other parameters at their base-case values.

Note that we did not estimate low and high values for parameters whose base-case values were likely to be correct ($V_{91/90}$, *AHCUS/AOCUS*, and T_i), or for most of the parameters for rural areas, because estimated damages in rural areas are so much smaller than damages in urban areas (see table 5). (We remind the reader, however, that we estimated damages only along rural roads that have a noise barrier, and hence have underestimated damages in all rural areas.)

Parameters related linearly to costs: the change in house value per dBA (HV), the HU density adjustment factor (AD), and the HU value adjustment factor (AV) (a linear parameter in P_u). As one can see from the structure of the general model (equation (1)), total external noise costs C_n are proportional to the parameters *HV*, M_u, and P_u. Because M_u is proportional to *AD*, and P_u is proportional to *AV*, total costs are proportional to *AD* and *AV* as well as to *HV*. In our view, there is relatively little uncertainty regarding the values of *AD*, *AV*, and P_u. However, there is order-of-magnitude uncertainty regarding the parameter *HV*, and this results directly in order-of-magnitude uncertainty in the total costs.

Time spent away from home in places impacted by noise (min) (T_o). As one can see from the structure of the general model (equation (1)), away-from-home damages are proportional to the amount of time in away-from-home activities susceptible to noise. If motor vehicle noise disturbs more activities away from home than in our base case, such that the parameter "T_o" increases to 424.7 minutes (see table 4), the total costs increase by about 15% (see table 6).

Effective annual interest rate (i), and years of investment in the home (t). These parameters determine the annualization factor AF, which converts the change in the total value of a house into the change in the annual value over the life of the house at prevailing interest rates. As shown in table 6, external costs are moderately sensitive to plausible variation in i, the interest rate, but insensitive to plausible variation in t, the life of the home. This is because the annualization factor itself is relatively insensitive to the parameter t when t is over 30 years.

Threshold noise level (dBA) (t^*). The threshold level below which damages are assumed to be zero is perhaps the single most important parameter in the model. As shown in table 6, if t^* is only 50 dBA rather than 55 dBA, the estimated cost of noise more than triples.

As can be gleaned from figure 1, a drop in the threshold has two effects: it increases the number of *HU*s exposed to noise above a threshold, and it increases the amount of noise to which they are exposed. In the base case, some 6.9 million *HU*s (out of a national total of roughly 100 million) are exposed to noise above the 55 dBA threshold. In the high-cost case, 19.1 million *HU*s are exposed to noise above the 50 dBA threshold. Thus, the main effect of lowering the threshold is to increase the number of *HU*s exposed.

As we discussed above, most studies have assumed a threshold of 55 dBA, and we are reasonably confident that this is an appropriate value. Nevertheless, one should be aware that the results are extremely sensitive to this parameter. The extreme sensitivity of this parameter suggests that the linear form of the damage function does not accurately represent the marginal damage caused by an extra decibel of noise, since it seems implausible that an extra five decibels could treble damages. Ideally, one would estimate a nonlinear damage function in which there is no threshold, but damages rapidly approach zero below 55 dBA. Unfortunately, the data to estimate such a nonlinear damage function are not available.

Ground-cover coefficient (α) and subtending angle (ϕ) in urban areas. Because the subtending angle and the ground-cover coefficient are relatively simple representations of very complex noise-attenuation phenomena, our base-case values for Φ and α are merely plausible starting points, not elaborate calculations, and as a result the true implicit national-average values of these parameters (i.e., the combination that would replicate the results of a detailed physical model of every road in the country) could be considerably different from our base-case values.

As shown in the sensitivity analysis in table 6, this uncertainty has a significant effect on the calculated damages. For example, noise costs are roughly proportional to the subtending angle, such that if the angle is doubled, costs roughly double.

In scenario analyses not shown here, we tested the effect of jointly varying α from 0.2 to 0.6, and Φ from 20° to 50°, holding everything else constant. The cost results spanned an order of magnitude. These sensitivities demonstrate that uncertainty in the attenuation due to buildings, hills, and ground cover make it difficult to estimate precisely the cost of motor vehicle noise nationally.

Equivalent distance to road (ft) (d_e). The narrower the assumed right-of-way and the closer the houses are to the road, the greater the noise damages to residences. As shown in table 6, however, modest variation in this parameter (see table 1) changes the base-case costs by less than 10%.

Vehicle speed (mph) (S). Average vehicle speed is an important parameter in the calculation of the external damage cost of noise: if vehicle speed is somewhat lower than in our base case (see table 2), costs drop by over 30%.

In separate scenarios, not presented in table 6, we varied the speed of medium and heavy trucks relative to the base-case LDA speed. When we assumed that trucks travel at the same average speed as passenger cars, noise costs increased by approximately 10%. When we assumed that MDTs and HDTs travel at 80% and 60% of the average speed of LDAs, respectively, noise costs decreased by less than 10%. Thus, the results are not quite as sensitive to our assumptions regarding the speed of trucks relative to the speed of cars.

Fraction of vehicles cruising (FC). It is possible that we have overestimated the fraction of time that vehicles are cruising, and hence have overestimated the amount and cost of noise. However, reasonable variation in this parameter does not significantly affect the estimated costs: as shown in table 6, lower assumed cruising fractions increase the total cost of noise by less than 5%.

Noise barrier reduction (dBA) (B_b). We also tested the sensitivity of our results to different assumptions regarding the attenuation provided by noise barriers. The variations are shown in table 3, and the results are shown in table 6. The affect in B_b affect the results by 1% or less. Thus, uncertainty in the parameter B_b is unimportant.

B_b is unimportant in the aggregate because so few roads have noise barriers that it does not matter, nationally, how effective they are. Of course, if the costs of a particular project with and without noise barriers are analyzed, then the effectiveness of the barriers (B_b) might be very important. In that case, though, one would want to use a more sophisticated model of the effects of noise barriers than we have used here.

Comparison with Other Estimates

Verhoef (1994) and Rothengatter (1990) reviewed nearly 20 studies of the cost of traffic noise in Europe and the United States from 1975 to 1991. The studies used a wide variety of valuation techniques, including loss of property values, productivity losses, expenditures for medical care, loss of asset values, expenditures for vehicle noise reduction, and expenditures on house construction for noise reduction. In most of the studies, the cost of noise was estimated to be between 0.02% and 0.2% of Gross National Product (GNP), although a few studies estimated values as high as 0.5% to 2%. (The higher values generally resulted from assuming a very low damage threshold.) Our results are similar: about 0.002% to 0.8% of GNP with a base case of about 0.05% (table 5 results divided by 1990 GNP of about $5.5 trillion).

In the analysis of Fuller et al. (1983), the bulk of damage occurred along arterials. In our study, most damage occurs along Interstates and other freeways (see table 5). Fuller et al. found that damages on local roads were very small but not zero; we found them to be zero.

Marginal Cost of Noise from Different Types of Vehicles on Different Types of Roads (Urbanized Areas)

The cost of noise from an additional mile of vehicle travel depends on the type of vehicle and the type of driving. All else being equal, trucks are much noisier than cars, high-speed freeways are noisier than low-speed roads, and roads close to houses cause more disturbance than roads further from houses. Thus, an additional mile of travel by a truck on a high-speed road in a densely populated area will cause much more noise damage than will an additional mile of travel by an automobile on a local road in a sparsely populated area. In this section, we quantify these differences.

In table 7, we show the marginal cost of noise per 1,000 vehicle-miles of travel for each combination of the five types of vehicles and the six types of roadways, in urbanized areas. The values shown are calculated for a 10% increase in VMT for each vehicle-and-road combination, all else being equal. (Because of nonlinearities in the noise model, the cost/VMT will be different for a 10% increase than a 20% increase or a 10% decrease.)

As we expected, on a given type of road, HDTs cause the most damage per mile and LDAs the least. The difference between HDTs and LDAs is most pronounced on low-speed roads, where engine noise is more significant than speed-related tire noise. In fact, on collectors and presumably local roads, HDTs cause nearly two orders of magnitude more damages per mile than do LDAs.

As noted above, all else being equal, roads with high-speed traffic generate more noise than roads with low-speed traffic, and roads close to houses cause more disturbance than roads further from houses. However, roads with high-speed traffic usually are further from houses than are roads with low-speed traffic, and as a result, marginal damage costs by type of road do not vary systematically. For example, in table 7, damages do *not* decline uniformly going from Interstates down to local roads, because the effect of lower speed is at least partially offset by the proximity to houses. We do see that damages on other freeways always exceed damages on Interstates, because we assume that the speeds on other freeways are about the same as the speeds on Interstates, but these roads are clos-

TABLE 7 The Marginal Cost of Noise from a 10% Increase in VMT, for Different Types of Vehicles on Different Types of Roads, in Urbanized Areas

(In 1991$/1,000 VMT)

A. Base case

	Interstate	Other freeways	Principal arterials	Minor arterials	Collectors	Local roads
LDAs	2.96	4.25	1.18	0.57	0.07	0.00
MDTs	8.50	13.20	7.02	5.37	1.05	0.00
HDTs	16.69	30.80	20.07	29.93	4.93	0.00
Buses	6.36	9.77	7.18	6.42	1.22	0.00
Motorcycles	17.15	27.03	8.71	4.67	0.56	0.00

B. Low-cost case

	Interstate	Other freeways	Principal arterials	Minor arterials	Collectors	Local roads
LDAs	0.11	0.18	0.04	0.01	0.00	0.00
MDTs	0.40	0.66	0.32	0.18	0.01	0.00
HDTs	0.81	1.62	1.22	1.77	0.06	0.00
Buses	0.35	0.58	0.38	0.22	0.00	0.00
Motorcycles	0.66	1.13	0.27	0.09	0.00	0.00

C. High-cost case

	Interstate	Other freeways	Principal arterials	Minor arterials	Collectors	Local roads
LDAs	40.11	56.02	16.20	9.35	6.04	0.44
MDTs	114.76	173.38	96.05	84.93	78.84	12.13
HDTs	225.61	404.82	269.27	414.17	319.22	92.04
Buses	86.15	128.60	98.66	105.33	108.00	12.84
Motorcycles	232.47	355.73	119.64	76.65	50.08	2.73

Key: VMT = vehicle-miles of travel; LDAs = light-duty autos; MDTs = medium-duty trucks; HDTs = heavy-duty trucks.

Note: $/1,000 VMT for vehicle type v on road r is calculated by increasing VMT by vehicle type v on road type r by 10%, and then dividing the resultant increase in total dollar noise costs in urbanized areas by the amount of the increase in VMT in urbanized areas.

er to homes. However, no other generalizations are possible, because the marginal damages depend on vehicle speed, proximity to the road, and the noise-generation function of each vehicle type.

Other Components of the Social Cost of Noise Related to Motor Vehicle Use

Note that ours is an estimate of external damage cost of noise emitted directly from motor vehicles. This external damage cost, of course, is not the same as the total social cost of noise related to motor vehicle use. The total social cost of noise related to motor vehicle use is equal to the external damage cost of noise emitted directly from motor vehicles (which is what we have estimated here), plus the external damage cost of noise from "indirect" or "upstream" activities related to motor vehicle use (e.g., highway construction) and the cost of controlling noise related to motor vehicle use.

Indirect sources of noise. Button (1993), citing a 1975 report, states that "extremely high levels of noise are also often associated with the construction of transportation infrastructure—up to levels of 110 dB when piles are being driven" (p. 25). For want of data, we did not estimate the magnitude or cost of construction noise, or of noise from any other activity indirectly related to motor vehicle use. However, we observe that some of these indirect sources of noise, such as highway construction equipment, are scattered and intermittent, and others, such as petroleum refineries, are relatively remote. As a result, indirect noise probably is much less damaging, in the aggregate, than is direct noise from motor vehicles.

Costs of mitigating exposure to motor vehicle noise. There are at least four ways to mitigate exposure to traffic noise: insulate vehicles, build noise barriers, insulate buildings, and avoid noise.

(i) The cost of insulating vehicles against their *own* noise is not an external cost of motor vehicle use. However, the cost of insulating against noise from other vehicles, if such insulation is additional, arguably is a defensive expenditure and an externality. In any case, we do not know the cost of insulating vehicles against motor vehicle noise, or the cost of reducing noise from vehicles.

(ii) Although the cost of noise barriers is a real social cost of motor vehicle noise, and moreover might not be optimal (because the marginal investment cost might not equal the marginal noise-mitigation benefit), it is not a marginal cost of motor vehicle use in the way that irritation due to noise is, and probably is best classified as a public-sector investment cost, like the cost of the roads themselves. Indeed, the cost of noise barriers along highways is included in FHWA estimates of capital expenditures related to highways (USDOT annual). Given this classification, it is worth noting—as a matter of equity, not a matter of marginal-cost pricing—that to the extent that highway user fees cover the cost of highways, the cost of noise barriers is not a "subsidy" to motor vehicle users. In any case, the cost is relatively small, on the order of $50 million per year, and we do not include it in our estimate here of external damage costs.

(iii) In principle, the implicit valuation of noise estimated by hedonic-price analysis includes the cost of *prospective* mitigation measures—those that homeowners, who paid the prices sampled in the hedonic-price analyses, expected at the time of purchase to have to undertake later. However, the matter of mitigation measures already in place when a house goes on the market is more complicated. If a hedonic-price analysis assumes that noise is at the pre-mitigation level, then it will underestimate the cost of noise, because the mitigation measures already in place will have reduced the differences in observed sales prices, but not, in this case, the *assumed* differences in noise levels. (We suspect that the problem is minor.)

(iv) The personal cost of having to avoid noise (e.g., leave a noisy room or place) presumably is considered by the home buyers whose implicit valuation of the noise levels in different residential areas is estimated by the hedonic-price analyses used to establish the value of the parameter HV in this analysis.[13] If this is so, then avoidance costs are included in HV and hence in our estimates of the external cost of noise from motor vehicles.

Cost of Motor Vehicle Noise Given Noise from Other Sources

We have estimated the cost of traffic noise as if traffic were the only major source of noise; we have not estimated the cost of traffic noise when there also is noise from, say, airplanes, trains, public events, or construction equipment. It is not possible to do a general, national analysis of the cost of motor vehicle noise when there are other sources of noise, because it is neither possible to identify and quantify all of the other noise sources, nor can noise from one source be added in a straightforward manner to noise from another source.

The additive properties of two simultaneous noise sources depend on their frequency structures. If the two noises are of wide frequency range and equal in intensity, they add in such a way as to increase the noise level by 3 dB.[14] For two noise sources with a difference of 1 dB, the additive effect is to increase the louder noise by 2.5 dB. As the difference increases, the additive effect of the lower noise source becomes smaller, and when the difference in noise level reaches 10 dB, the louder noise source dominates the quieter one (Moore 1978).

We can use these additivity rules to illustrate how the marginal contribution of motor vehicles to noise above a threshold depends on the noise level

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[13] To the extent that buyers of homes in noisy areas do not realize initially that they might have to change their behavior because of the noise, and then find out later that they have to and that it is annoying, the hedonic-price analysis will underestimate the cost of noise.

[14] Two *pure* tones exactly in phase and of equal intensity combine to increase the noise level by 6 dB over the level due to one tone by itself. Pure tones out of phase and of equal intensity cancel one another.

of the other sources and the level of noise relative to the threshold (see table 8).

In this analysis, we estimated the quantity shown in column d, the contribution of motor vehicles to noise above a 55 dB threshold assuming that there is no other noise. This can be compared with the quantity shown in column e, the incremental contribution of motor vehicles to noise above a 55 dB threshold if there is in fact another source of noise. We see that if noise from each source is at the level of the noise threshold (case #1), then the contribution of motor vehicles alone (column d) underestimates by 3 dB the incremental contribution of motor vehicles when there are other noise sources (column e). This 3 dB is the maximum possible underestimation. In fact, if the noises are approximately equal in intensity and each more than 3 dB above the threshold (case #2), then the contribution of motor vehicles alone *overestimates* the incremental contribution when there is other noise.

If noise from motor vehicles exceeds the threshold, but is dominated by noise from other sources (case #3), then the contribution of motor vehicles alone again overestimates the incremental contribution, which in this case is zero. Finally, if noise from motor vehicles dominates noise from other sources (cases #4 and #5), then the contribution of motor vehicles alone overestimates the incremental contribution, except when the noise from the other source is less than or equal to the threshold level (case #5).

Although it might be tempting to conclude from the foregoing that our analysis overestimates the incremental contribution of motor vehicle noise, something like case #1 might not be that uncommon. Consequently, we do not speculate about how an analysis of the cost of incremental motor vehicle noise, given other sources of noise, might differ from our analysis. Also, we remind the reader that, as mentioned in the introduction, it appears that traffic is the main source of noise in most people's lives.

CONCLUSION

The range of external motor vehicle noise damages suggested by our analysis is less than $100 million to over $40 billion per year (1990 data, 1991$). However, we think it unlikely that damages greatly exceed $5 billion to $10 billion annually.

The considerable uncertainty in our analysis is due mainly to variability in the following parameters: the subtending angle (Φ), which represents noise attenuation due to intervening buildings, hills, and so on; the ground-cover coefficient (α), which represents sound attenuation over different types of ground cover; the percentage of housing value lost for each decibel of excess noise (HV); the annualization factor for housing value (AF); the noise threshold (t^*) below which damages are assumed to be zero; average vehicle speeds (S); the cost of noise away from the home (T_o); and the housing density in areas exposed to motor vehicle noise (determined by the adjustment factor AD). Assumptions about noise barriers are unimportant at the national scale.

TABLE 8 Marginal Contribution of Motor Vehicles to Noise Above a Threshold
(In decibels)

#	Motor vehicle noise alone	Other noise alone	Motor vehicle + other noise	Contribution of motor vehicles to noise above a 55 dB threshold if there is: No other noise	Other noise
	(a)	(b)	(c)	(d)	(e)
1.	55	55	58	0	3
2.	65	65	68	10	3
3.	60	70	70	5	0
4.	80	70	80	25	10
5.	75	55	75	20	20

We emphasize, too, that we have estimated the cost of noise under the assumption that motor vehicles are the only source of noise. The net effect of motor vehicle noise can depend quite strongly on the magnitude and characteristics of other sources of noise.

The estimated uncertainty is so great that the only recommendation we have to researchers is to:

- perform extensive econometric analyses of the relationship between housing value (HV) and noise, in which the parameter HV is a continuous nonlinear function of noise levels, and there is no threshold t* (the function might be asymptotic, however);
- collect primary data on vehicle speeds (S), housing density (Mu), and housing value (Pu), by type of road, in each urban area;
- use different parameters and a different model structure to account for the noise attenuation (parameters F and a); and
- model motor vehicle noise in the presence of other sources of noise.

The last two will not be easy. As mentioned above, it will be very difficult to model motor vehicle noise and other sources of noise jointly. Similarly, it will be difficult to develop a model in which noise attenuation due to ground cover and intervening objects is a function of parameters that can be measured and aggregated at the national level. In both cases, of course, the difficulty is that noise depends in a complex way on the particular characteristics of each site. In light of this, our estimates here are merely an indication of the order of magnitude of the external cost of motor vehicle noise.

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