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THE EXTERNAL DAMAGE COST OF DIRECT NOISE FROM MOTOR VEHICLES

Report #14 in the series: *The Annualized Social Cost of Motor-Vehicle Use in the United States, based on 1990-1991 Data*

UCD-ITS-RR-96-3 (14)

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REPORTS IN THE SOCIAL-COST SERIES

There are 20 reports in this series. Each report has the publication number UCD-ITS-RR-96-3 (#), where the # in parentheses is the report number:

Report 1: The Annualized Social Cost of Motor-Vehicle Use in the U.S., 1990-1991: Summary of Theory, Methods, Data, and Results (M. Delucchi)

Report 2: Some Conceptual and Methodological Issues in the Analysis of the Social Cost of Motor-Vehicle Use (M. Delucchi)

Report 3: Review of Some of the Literature on the Social Cost of Motor-Vehicle Use (J. Murphy and M. Delucchi)

Report 4: Personal Nonmonetary Costs of Motor-Vehicle Use (M. Delucchi)

Report 5: Motor-Vehicle Goods and Services Priced in the Private Sector (M. Delucchi)

Report 6: Motor-Vehicle Goods and Services Bundled in the Private Sector (M. Delucchi, with J. Murphy)

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Report 14: The External Damage Cost of Direct Noise from Motor Vehicles (M. Delucchi and S. Hsu) (with separate 100-page data Appendix)

Report 15: U.S. Military Expenditures to Protect the Use of Persian-Gulf Oil for Motor Vehicles (M. Delucchi and J. Murphy)

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LIST OF ACRONYMS AND ABBREVIATIONS AND OTHER NAMES

The following are used throughout all 20 reports of the series, although not necessarily in this particular report

AER = *Annual Energy Review* (Energy Information Administration)
AHS = *American Housing Survey* (Bureau of the Census and others)
ARB = Air Resources Board
BLS = Bureau of Labor Statistics (U. S. Department of Labor)
BEA = Bureau of Economic Analysis (U. S. Department of Commerce)
BTS = Bureau of Transportation Statistics (U. S. Department of Transportation)
CARB = California Air Resources Board
CMB = chemical mass-balance [model]
CO = carbon monoxide
dB = decibel
DOE = Department of Energy
DOT = Department of Transportation
EIA = Energy Information Administration (U. S. Department of Energy)
EPA = United States Environmental Protection Agency
EMFAC = California's emission-factor model
FHWA = Federal Highway Administration (U. S. Department of Transportation)
FTA = Federal Transit Administration (U. S. Department of Transportation)
GNP = Gross National Product
GSA = General Services Administration
HC = hydrocarbon
HDDT = heavy-duty diesel truck
HDDV = heavy-duty diesel vehicle
HDGT = heavy-duty gasoline truck
HDGV = heavy-duty gasoline vehicle
HDT = heavy-duty truck
HDV = heavy-duty vehicle
HU = housing unit
IEA = International Energy Agency
IMPC = Institutional and Municipa Parking Congress
LDDT = light-duty diesel truck
LDDV = light-duty diesel vehicle
LDGT = light-duty gasoline truck
LDGV = light-duty gasoline vehicle
LDT = light-duty truck
LDV = light-duty vehicle
MC = marginal cost
MOBILE5 = EPA's mobile-source emission-factor model.

MSC = marginal social cost
MV = motor vehicle
NIPA = National Income Product Accounts
NO_x = nitrogen oxides
NPTS = Nationwide Personal Transportation Survey
OECD = Organization for Economic Cooperation and Development
O_3 = ozone
OTA = Office of Technology Assessment (U. S. Congress; now defunct)
PART5 = EPA's mobile-source particulate emission-factor model
PCE = Personal Consumption Expenditures (in the National Income Product Accounts)
PM = particulate matter
PM_{10} = particulate matter of 10 micrometers or less aerodynamic diameter
$PM_{2.5}$ = particulate matter of 2.5 micrometers or less aerodynamic diameter
PMT = person-miles of travel
RECS = Residential Energy Consumption Survey
SIC = standard industrial classification
SO_x = sulfur oxides
TIA = *Transportation in America*
TSP = total suspended particulate matter
TIUS = *Truck Inventory and Use Survey* (U. S. Bureau of the Census)
USDOE = U. S. Department of Energy
USDOL = U. S. Department of Labor
USDOT = U. S. Department of Transportation
VMT = vehicle-miles of travel
VOC = volatile organic compound
WTP = willingness-to-pay

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14. THE EXTERNAL DAMAGE COST OF DIRECT NOISE FROM MOTOR VEHICLES

14.1 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 (Organization for Economic Cooperation and Development [OECD], 1988). And motor 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 $/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 report, we present such a model of the total external damage cost of direct motor-vehicle noise in the U. S.[3] We find that the external damage cost of direct motor-vehicle noise could range from as little as $100 million per year to approximately $40

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[1]The OECD (1988) states that "transport is by far the major source of noise, ahead of building or industry, with road traffic the chief offender" (p. 43-44). They estimate that in the early 1980s, 37% of the U. S. population was exposed to road traffic noise of 55 dBA or greater (outdoor level, 24-hour L_{eq}), 18.0% to 60 dBA or greeter, 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 U. S. 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).

[3]Note that we estimate *direct external damage costs*. We do not include the cost of "indirect" motor-vehicle noise, such as from highway construction, or the cost of controlling noise related to motor-vehicle use, or the loss of use of property that is unused because of motor-vehicle noise. Note too that our estimates assume that motor vehicles are the only source of noise. All of these points are discussed more later.

billion per year (1990 data, 1991$), although we believe that the cost is not likely to exceed $5 billion. In sensitivity analyses presented at the end of the report, we show that this 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 outside of the home.

14.2 THE NEED FOR THIS ANALYSIS

We perform this analysis because there is no detailed, comprehensive, up-to-date estimate of the cost of motor-vehicle noise. 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 U. S.: the 1983 study of Fuller et al., the results of which have been cited in virtually every review of the social costs of transportation in the U. S. Fuller et al. (1983) 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: the band of "moderate" exposure (55 to 65 dbA), the band of "significant" exposure (65 to 75 dBA), and the band of "severe" exposure (more than 75 dBA);

(2) "excess" dBA of noise, equal to the noise level at the midpoint of each distance/noise band minus the threshold noise level (assumed to be 55 dBA);

(3) the dollar reduction in property value per excess dBA (estimated to be $152/excess-dBA [1977$])

Fuller et al. (1983) used a 1970s-vintage noise-generation equation to delineate the distance/noise bands. They assumed that within each band the noise level was equal to the midpoint or average of the countour values -- for example, everywhere within the noise band defined by the 55 dBA and 65 dBA contours, the noise level was 60 dBA. 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 outside of the home.

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

1). We use latest noise-generation equation, in 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 accelerating vehicles (Anderson, 1995; Rilett, 1995; Jung and Blaney, 1988). The Fuller et al. (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 integrate the updated noise-generation equation over the entire area of land exposed to noise above a threshold. (In essence, we have an infinite number of distance/noise bands.)

3). We calculate noise costs in detail, for several different types of road and traffic conditions, in each of 377 urbanized areas[4] and one aggregated rural area of the U.S. We use urbanized-area-specific data on miles of roadway, traffic volume, housing density, and housing value, rather than nationally aggregated data.

4). We account for the noise reductions provided by noise barriers, as a function of the height and length of the barrier.

5). We use time-activity data to extend the analysis to include the cost of noise damages to activities in commercial, industrial and municipal areas.

6). We estimate marginal costs for light-duty automobiles (LDAs), medium-duty trucks (MDTs), heavy-duty trucks (HDTs), buses, and motorcycles, on six different types of roads.

7). We estimate a base case, a low-cost case and a high-cost case, and perform sensitivity analyses on several key variables.

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

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[4]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" (SMSA).

14.3 THE MODEL

14.3.1 The general noise-cost model

As outlined in the introduction, our general cost model is conceptually straightforward: the external damage cost of direct motor-vehicle noise 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 non-residential areas ((To+Ti)/Ti). We do this multiplication for each of six types of roads in each of 377 urbanized areas (plus one aggregated rural area). Formally:

$$Cn = \left(\left(\sum_u \left(\sum_r \left(\sum_h AN_{u,r,h} \right) \right) \right) \cdot M_u \cdot P_u \right) \cdot HV \cdot \frac{To + Ti}{Ti} \tag{0}$$

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

where:

Cn = the total direct external damage cost of motor-vehicle noise in the U.S. 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 14-1) 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])

4

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*

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

To = 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" from the roadway to the point at which traffic noise drops to the threshold level (ft) ("equivalent distance" is defined below)

d_e = the "equivalent distance" from the roadway to the closest residence (ft) ("equivalent distance" is defined below)

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

$Leq(d)_{u,r,h}$ = motor-vehicle noise (decibels) 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 14-1). The units of the integrated equation are dBA-ft.

5280 = feet/mile

Note that we calculate the cost of noise from motor-vehicle traffic on all roads in all 377 urbanized areas of the U.S.. We are able to do this because we have detailed data -- on housing value, housing density, road mileage, traffic volume, etc. -- for each of the 377 urbanized areas.

Unfortunately, we do not have detailed data for rural "areas". We may presume, though, that along most rural roads the cost of motor-vehicle noise is near zero, because traffic volume on most rural roads is relatively low, and houses in most rural areas are far from roads and few and far between. Hence, it is reasonable to assume a zero cost along *most* rural roads.

Still, in some towns the traffic volume and exposure will be high enough to produce non-trivial damages. But how to identify the rural areas where motor-vehicle noise is a problem? One indication is the presence of a noise barrier: presumably, if the Federal government has built a noise barrier along a road in a rural town, motor-vehicle noise is a problem in that town. In this study, we enumerate all of the noise barriers built outside of urbanized areas, and aggregate them into one generic rural area for which we calculate noise damages. That is, the
 "one aggregated rural area" that we refer to throughout this report is the aggregation of all rural towns that have at least one noise barrier. We assume that the cost of noise

from motor-vehicle traffic on all *other* rural roads -- that is, on all rural roads that are not located in a town that has a noise barrier somewhere -- is zero.

   To calculate noise costs in rural towns that have a noise barrier, we estimate the extent of the road network, the volume of traffic, and the density and value of houses exposed to motor-vehicle noise. This is discussed further later in this report.

   All of the parameters in the model are discussed next.

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

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

For $\alpha = 1.0$: $\Phi' = \dfrac{180}{\pi} \cdot 2\sin(\Phi)$

For $\alpha < 1.0$ and $\Phi < 90^{\circ}$:

if $\Phi = 0$ and $\alpha = 0$, $\Phi' = 0$; if $\Phi = 0$ and $\alpha \neq 0$, $\Phi' = 5.00$; otherwise :

$$\Phi' = 2 \cdot \Phi \cdot \left(1 - \frac{M}{|\Phi|} \cdot \left(\frac{|\Phi|}{90} \right)^{N} \right)$$

$$M = 90 \cdot \left(\frac{0.58 \cdot \alpha^{0.9}}{0.58 \cdot \alpha^{0.9} + 1} \right)$$

$$N = \frac{1}{0.134 \cdot \alpha + 0.225}$$

For $\alpha < 1.0$ and $\Phi = 90^{\circ}$:

$$\Phi' = \frac{180}{1 + 0.58 \cdot \alpha^{0.9}}$$

$$V_{u,r,h} = Dvmt_{u,r,h}/(24 \cdot L_{u,r,h})$$

$$K_{u,r} = Ka_{u,r} + Km_{u,r} + Kh_{u,r} + Kb_{u,r} + Kc_{u,r}$$

$$Ka_{u,r} = Fa_{u,r}/Sa_r \cdot (Sa_r^{4.174} \cdot 10^{0.115} + 10^{Ca_r})$$

$$Km_{u,r} = Fm_{u,r}/Sm_r \cdot (Sm_r^{3.392} \cdot 10^{2.059} + 10^{Cm\,r})$$

$$Kh_{u,r} = Fh_{u,r}/Sh_r \cdot (Sh_r^{3.588} \cdot 10^{2.102} + 10^{Ch_r})$$

$$Kb_{u,r} = Fb_{u,r}/Sb_r \cdot (Sb_r^{2.348} \cdot 10^{3.801} + 10^{Cb\,r})$$

$$Kc_{u,r} = Fc_{u,r}/Sc_r \cdot (Sc_r^{4.102} \cdot 10^{1.001} + 10^{Cc_r})$$

$$Fa_{u,r} = 1 - Fm_{u,r} - Fh_{u,r} - Fb_{u,r} - Fc_{u,r}$$

$$Ca_r = FCa_r \cdot 5.013 + (1 - FCa_r) \cdot 6.700$$

$$Cm_r = FCm_r \cdot 6.800 + (1 - FCm_r) \cdot 7.400$$

$$Ch_r = FCh_r \cdot 7.430 + (1 - FCh_r) \cdot 8.000$$

$$Cb_r = FCb_r \cdot 6.800 + (1 - FCb_r) \cdot 7.400$$

$$Cc_r = FCc_r \cdot 5.877 + (1 - FCc_r) \cdot 5.877$$

where:

$Leq(d)_{u,r,h}$ = the equivalent sound level (equation from Anderson, 1995)[5]

Φ' = the equivalent subtending angle, used to model the decrease in the noise level caused by intermediate obstructions (equation from 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 dn is the distance from the middle of the near lane to noise recipient, and df is the distance from the middle of the far lane to the noise recipient[6] (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: the angle between two lines emanating towards 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 (house, hill, etc.) 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 sound wall of height-class **h** (zero height and zero reduction if no noise barrier) (dBA)

$Dvmt_{u,r}$ = daily vehicle miles of travel in urban area **u** on road type **r**

$L_{u,r}$ = miles of roadway type **r** in urban area **u**

24 = hours in a day

$Kv_{u,r}$ = the noise-energy emissions from vehicle-type v in urban area **u** on road type **r** (equation and exponent values from the FHWA's Transportation Noise Model; Anderson, 1995)

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[5]Note that Fuller et al. (1983) used an older, simpler equation for Leq:

$$Leq(d) = 10 \cdot \log_{10} \left\{ \frac{V}{S \cdot d} + EL(S) - 2 - 5 \cdot \log_{10} \left\{ \frac{d}{50} \right\} \right\}$$

where the EL(S) function is similar to our K function.

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

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

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

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; Anderson, 1995)

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

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

Our approach is to integrate equation **(1)** 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 which has the units dBA-ft. When the evaluated integral of equation **(1)** 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 barrier of height-class **h** (zero height if no noise barrier), as the Area-Noise Level, $AN_{u,r,h}$ (see Figure 14-1).

The integration of equation **(1)** and the expression for $AN_{u,r,h.}$ is as follows:

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

$$= \frac{L_{u,r,h}}{5280} \cdot \left(\left(\int_{d_e}^{d_{t*}} 10 \cdot \log_{10}\left\{ 0.0296 \cdot \frac{\Phi'}{180} \cdot V_{u,r,h} \cdot K_{u,r} \cdot \left(\frac{50}{d} \right)^{1+\alpha} \right\} - B_h \right) - ANB_{u,r,h} \right)$$

converting from log₁₀ to natural logₑ (for the integration):

$$= \frac{L_{u,r,h}}{5280} \cdot \left(\left(\int_{d_e}^{d_{t*}} 10 \cdot \frac{1}{\log_e 10} \log_e\left\{ 0.0296 \cdot \frac{\Phi'}{180} \cdot V_{u,r,h} \cdot K_{u,r} \cdot \left(\frac{50}{d} \right)^{1+\alpha} \right\} - B_h \right) - ANB_{u,r,h} \right)$$

simplifying and rearranging:

$$= \frac{Lu,r,h}{5280} \cdot \left(\left(\int_{d_e}^{d_{t*}} 4.34294 \cdot \log_e \left\{ 0.0001644 \cdot \Phi' \cdot 50^{1+\alpha} \cdot V_{u,r,h} \cdot K_{u,r} \cdot d^{-(1+\alpha)} \right\} - B_h \right) - ANB_{u,r,h} \right)$$

separating log of distance:

$$= \frac{Lu,r,h}{5280} \cdot$$

$$\left(\left(\int_{d_e}^{d_{t*}} 4.34294 \cdot \log_e \left\{ 0.0001644 \cdot \Phi' \cdot 50^{1+\alpha} \cdot V_{u,r,h} \cdot K_{u,r} \right\} - 4.34294 \cdot (1+\alpha) \cdot \log_e \{d\} - B_h \right) - ANB_{u,r,h} \right)$$

taking the integral:

$$= \frac{Lu,r,h}{5280} \cdot$$

$$\left(\left(\left| \begin{array}{l} {}^{d:Leq=t*} \\ \\ {}_{d=e} \end{array} \right. \begin{array}{l} 4.34294 \cdot \log_e \left\{ 0.0001644 \cdot \Phi' \cdot 50^{1+\alpha} \cdot V_{u,r,h} \cdot K_{u,r} \right\} d \\ \\ -4.34294 \cdot (1+\alpha) \cdot \left(d \cdot \log_e \{d\} - d \right) - B_h \cdot d \end{array} \right) - ANB_{u,r,h} \right)$$

$$= \frac{Lu,r,h}{5280} \cdot$$

$$\left(\left(\left| \begin{array}{l} {}^{d:Leq=t*} \\ \\ {}_{d=e} \end{array} \right. d \cdot \left(\begin{array}{l} 4.34294 \cdot \log_e \left\{ 0.0001644 \cdot \Phi' \cdot 50^{1+\alpha} \cdot V_{u,r,h} \cdot K_{u,r} \right\} \\ \\ -4.34294 \cdot (1+\alpha) \cdot \left(\log_e \{d\} - 1 \right) - B_h \end{array} \right) \right) - ANB_{u,r,h} \right)$$

finally, evaluating the integral, and substituting $t^* \cdot (d_t^* - d_e)$ for $ANB_{u,r,h}$:

$$AN_{u,r,h} = \frac{L_{u,r,h}}{5280} \cdot \Big[(d_t^* - d_e) \cdot \Big(4.34294 \log_e\{0.0001644 \cdot \Phi' \cdot 50^{1+\alpha} \cdot V_{u,r} \cdot K_{u,r}\} - B_h$$

$$- t^* \Big) - 4.34294 \, (1+\alpha) \cdot \Big(d_t^* \cdot (\log_e\{d_t^*\} - 1) - d_e \cdot (\log_e\{d_e\} - 1) \Big) \Big] \qquad \textbf{(2)}$$

Equation **(2),** 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^*)[7].

14.3.3 Simplifying assumptions underlying the motor-vehicle area-noise submodel

Although we account 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, the angle defined by intermediate obstructions, and the extent and height of noise barriers, we also omit or simplify several important factors. For example, we assume that all vehicles travel on smooth, level roads -- we do not estimate the effects of rough roads and potholes. We do 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 is crude.

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 have left these other parameters out of our model

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[7]As a check on the results of our integration, we also estimated $AN_{u,r,h}$ assuming that $Leq(d)_{u,r,h}$ is linear from d_e to d_t^*, and hence that the shaded volume of Figure 14-1 is a triangular wedge. The area of this triangular wedge is simply:

$$L_{u,r,h}/5280 \cdot \Big[(Leq(d_e) - t^*) \cdot (d_t^* - d_e) \, /2 \Big]$$

where:
$Leq(d_e)$ is $Leq(d)_{u,r,h}$ evaluated at $d = d_e$

Because the actual $Leq(d)_{u,r,h}$ is sublinear, as shown in Figure 14-1, the ratio of $AN_{u,r,h}$ estimated with the integrated $Leq(d)$ equation, to $AN_{u,r,h}$ estimated assuming a linear drop off from d_e to d_t^* (the triangular wedge) should be less than 1.00 but (according to our inspection of a plot of the Leq equation) generally greater than 0.50. This is indeed the case in every urbanized area.

because it is not possible 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.

14.4 BASE-CASE VALUES OF PARAMETERS IN THE MODEL, FOR URBANIZED AREAS

14.4.1 Limits of integration of noise equation

Equation **(2)**, the expression for area-noise level, is the product of $L_{u,r,h}$ 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 must estimate 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 14-1 shows are assumptions for the base base, low-cost case, and high-cost case, and the calculation of the equivalent distance to the closest residence in the base case. Generally, we assume that housing units can be built up to the edge of the road right-of-way, but not in the right-of-way[8]. 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 **(1)** for d at Leq = t*, for each value of 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 one aggregated rural area) **u** and for each height class **h**. Where d_{t^*} is less than e, we assume that there are no noise damages in that urbanized area along road type **r** at height class **h**.

Columns N1-N6 of the Appendix show the value of $AN_{u,r,h} \cdot M_u^* \cdot FVO_u^*/10^6$ for each of the six road types in all 377 urban areas and one aggregated rural area. (The parameters M_u^* and FVO_u^* are explained below.) Note that in the Appendix, the data

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[8]The loss of use of the land in the road right of way is not an external or unaccounted-for cost of highways if the price paid by the highway authority for the land in the right-of-way fully reflects the value of the land, which is the present value of the foregone stream of rents available were there no highway. Of course, if the highway authority pays less than the social value of the land, then there is an unaccounted-for cost of highway use; namely, the difference between the payment and the foregone value.

and calculations for different height classes of barriers are listed on separate lines immediately below the areas in which the noise barriers are built.

14.4.2 The subtending angle (Φ)

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 U.S. Instead, we adopt a much simpler approach, and use 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. To visualize this, imagine 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 degrees, or one-half of 180 degrees (Jung and Blaney, 1988).

The subtending angle really is meant to model the noise field at a single receptor, not the "average" noise field over a complex arrangement of structures. Nevertheless, we have no other way to account formally but simply for attenuation due to shielding. We assume 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 degrees, or 30 degrees on either side of the perpendicular, so that Φ=30.

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

14.4.3 The ground-cover coefficient (α)

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 assume in our base case that $\alpha = 0.375$. (Blaney [1995] reports a value of 0.66 for 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 urban areas the average must be some mix of hard and soft ground -- leaning, we believe slightly towards the "hard" side. We assume a value of 0.50 for our low-cost case, and 0.25 for our high-cost case.

14.4.4 The 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, 1986) emphasizes, the threshold is different for different people and in different places. Our literature review indicates that the threshold is around 55 dB.

According to a World Health Organization task group, daytime noise levels of less than 50 dBA L_{eq} outdoors cause little or no serious annoyance in the community (OECD, 1986). The task group considers daytime noise limits of 55 dBA L_{eq} as a general health goal for outdoor noise in residential areas. However, they stated that "at night, an outdoor level of about 45 dBA L_{eq} is required to meet sleep criteria" (OECD, 1986, p. 37). Linster (1990) and the OECD (1988) say that research in OECD countries indicates that outdoor level should not exceed 55 dBA L_{eq}. (For reference, a graph in Linster [1990] shows that a truck, motorcycle, or subway produce about 90 dBA, a busy intersection about 80, a nearby freeway about 70, a busy street through an open window about 60, and a quiet living room about 40.) One study of the social cost of traffic noise, in Germany, assumes a threshold value of 30 dBA, but Rothengatter (1990) thinks that this is "remarkably low" (p. 161). Finally, in his analysis of the effect of noise on the Helsinki housing market, Vainio (1995) tests "different partially linear noise specifications," and finds that "the cutoff level of 55 dBA L_{eq} is supported by the data" (p. 163).

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

14.4.5 Road mileage ($L_{u,r}$) and Vehicle miles of travel ($Dvmt_{u,r}$)

The FHWA provides data on miles of roadway ($L_{u,r}$) and vehicle miles of travel ($Dvmt_{u,r}$) on six classes of road **r** (freeway, other limited-access highways, principal arterial, minor arterial, collector street, local road), in each of 382 urbanized areas (FHWA, 1991a, 1991b). These data are shown in columns H1-H6 and J1-J6 of the Appendix to this report. Note that these data do not include the extent and height of noise barriers. Those data are contained in a separate publication, and are discussed below.

While the FHWA data pertain to 382 "urbanized areas" defined by FHWA, the Bureau of the Census data on housing (discussed below) pertain to 396 "urbanized areas" defined by the Census. Fortunately, the Census Bureau's urbanized areas are largely the same as FHWA's urbanized areas: 377 of the Census Bureau urbanized areas correspond with 377 of the FHWA's urbanized areas. Five FHWA urbanized areas did not match initially any Census urbanized areas, but when we consulted atlases and compared land area and populations, we found that two of the five should be considered to be parts of other FHWA urbanized areas. We therefore added the data from these two into the larger FHWA areas. The remaining three FHWA urbanized areas that could not be matched up with Census Bureau urbanized areas were small in population and in traffic volume, and so we ignored them..

14.4.6 Traffic speed by type of road (Sa_r, Sm_r, Sh_r, Sb_r, Sc_r)

We assume that the speed of traffic varies from road type to road type, but otherwise does not vary from urban area to urban area. The average speeds assumed in our analysis are listed in Table 14-2. 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. The overall average speeds by vehicle type are consistent with the average speeds assumed or estimated in Report #4 of this social-cost series.

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 assume that speeds are 85% of those in the base case.

14.4.7 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. The FHWA (1991c) reports the MDT and HDT fractions of traffic volume ($Fm_{u,r}$ and $Fh_{u,r}$), by state, but not by urbanized area. We assume that the state-level fractions apply to each urbanized area in the state (and to the aggregated rural area). The MDT and HDT fractions are shown in columns KB1-KB6 and LB1-LB6 of the Appendix.

The 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. The FHWA (*Highway Statistics 1991*, 1992) reports national VMT by 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, on the basis of 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.

14.4.8 The fraction of traffic that is 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 (see the equations above). In our model, we weight the "cruising" exponent value by the fraction of vehicles that, on average, at any given time, are cruising at steady speed on road type **r**. We assume that the remaining vehicles are accelerating, and so weight the "accelerating" exponent value by one-minus the cruising fraction.

Table 14-3 shows what fraction of each type of vehicle we assume is cruising on each type of road. 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 assume that the cruising fraction is related to the average speed. In the low-cost case, we assume lower cruising fractions.

Table 14-3 also shows the final calculated overall exponent, for each vehicle and road type, reflecting the fraction of cruising and accelerating vehicles for each road type.

14.4.9 The density of housing units in areas exposed to motor-vehicle noise above the threshold (M_u)

As shown in equation **(0)**, the calculated cost of motor-vehicle noise is directly proportional to the density of housing units in the areas exposed to motor-vehicle noise above the threshold t* (i.e., the areas near roads). Ideally, one would estimate this housing density as a function of proximity to and traffic volume on each type of road in each urbanized area. However, there are no data on housing density along specific types of roads. Rather, the data available are:

• the total land area of each urbanized area, and of central cities and
urban fringes within urbanized areas (Bureau of the Census, 1990a)
(column D of the separate Appendix to this report);

• the number of housing units (HUs) in each urbanized area, and in
central cities and urban fringes within urbanized areas (Bureau of the
Census, 1990a) (column E of the separate Appendix to this report);

• miles of roadway ($L_{u,r}$) and vehicle miles of travel ($Dvmt_{u,r}$) on six
classes of road **r** in urbanized areas (FHWA, 1991a, 1991b) (columns
H1-H6 and J1-J6 of the separate Appendix to this report).

Given this, the smallest possible unit of analysis is the urbanized area[9], and
consequently we will estimate a single uniform density for each urbanized area.
If one divides the total Census-reported number of HUs in an urbanized area by
the total Census-reported land area, the result is the average density of HUs throughout
the urbanized area (let us call this $M_u{}^*$), which 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). Nevertheless, we must start with what we know, $M_u{}^*$,
and estimate what we wish to know, M_u, with respect to this. Thus, we have:

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

$$M_u{}^* = H_u / A_u$$

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 overall all of area **u** (shown in column F of the
Appendix) (HUs/mi^2)
AD = the adjustment factor for HU density (discussed below)
H_u = the number of HUs in area **u** (column E of the Appendix)

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[9]Although the Bureau of the Census classifies its data by "central city" and "fringe," the FHWA does not
similarly classify its road mileage and traffic volume data, and hence in our analysis we cannot
distinguish between central cities and fringe areas. However, it is not clear that an analysis disaggregated
by central city versus fringe would yield significantly different results. For example, our assumption of
constant density and housing value throughout the urban area might understate housing-value density
($/mi^2) and hence noise damages in central cities, but overstate housing-value density (and hence noise
damages) in fringe areas. These differences might roughly balance, and yield a result similar to ours
estimated over the entire urbanized area.

A_u = the total land area of area **u** (mi^2) (column D of the Appendix)

Estimating the density adjustement factor AD. A priori, it is 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 is 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 multiply $M_u{}^*$ 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, matches 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* (Bureau of the Census, 1991). The adjustment factor AD is the same for all urbanized areas.

According to the *American Housing Survey for the United States in 1989* (Bureau of the Census, 1991), 2.3 million housing units in multi-unit structures (mainly apartments) in "urban" areas were within 300 feet of a "4+ lane highway, railroad, or airport" in 1989. Now, an "urban" area in the Census' *American Housing Survey for the United States in 1989* was defined as an "urbanized" area plus places of 2,500 or more inhabitants outside of urbanized areas, and therefore was larger than an urbanized area, although only slightly: in the 1990 Census (Bureau of the Census, 1990a), there were 64 million housing units in "urbanized" areas, and in the *American Housing Survey for the United States in 1989* (Bureau of the Census, 1991), there were 69 million housing units in urban areas. If we reduce the 2.3 million by 7% to account for the difference between an "urban" and an "urbanized" area, but then increase it by 2% to account for growth between 1989 and 1990 (the 2.3 million had increased to 2.5 million by 1993 [Bureau of the Census, 1995]), the result is 2.2 million units within 300 feet of a 4+ lane highway, railroad, or airport.

If 70% to 90% of these 2.2 million units were next to 4+ lane highways (rather than railroads or airports), and if the number of single-unit houses next to 4+ lane highways was 100% to 300% the number of apartments next to 4+ lane highways (in urban areas, the ratio of single-unit to multi-unit structures is about 2:1), then in 1989 some 3 to 8 million housing units in urban areas were within 300 feet of a 4+ lane highway. Our best estimate is 5 to 6 million.

Now, if as a starting point we assume that $M_u = M_u{}^*$, then our model calculates that: about 2 million housing units were within 300 feet of an interstate freeway or 4+ lane "other freeway;" 2 million units were within 300 feet of a 4+ lane "principal arterial;" and 1 million units were within 300 feet of a 4+ lane "minor arterial". This results in a total of 2 million to 5 million units within 300 feet of a 4+ lane highway,

depending on whether one counts arterials as "highways".[10] Our best estimate includes all principal arterials but only half of the minor arterials, and results in about 4 million units within 300 feet of a 4+ lane highway. Therefore, on the basis of this analysis, we assume:

$$AD = 1.40$$

We assume 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 consider density adjustment factors of 1.00 and 1.50 instead of 1.40.

14.4.10 The annualized value of housing units 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 **(0)**). Ideally, one would estimate annualized housing value just as one would estimate housing density: as a function of proximity to and traffic volume on each type of road in each urbanized area. However, there are no data on annualized housing value along specific types of roads. Rather, the data available to us are:

- the median value of owner-occupied housing units (HUs) or houses for sale in each urbanized area in 1990 (call this FVO_u*) (Bureau of the Census, 1990a; column G of the Appendix to this report)

- the median annual cost of all HUs in all urban areas (not each urban area) of the U.S. (call this AHCUS) (Bureau of the Census, 1991, 1995b)[11]

- the median annual cost of owner-occupied HUs in all urban areas (not each urban area) of the U.S. (call this AOCUS) (Bureau of the Census, 1991, 1995b)

We will work from these data towards an estimate of P_u, the annualized housing value in areas near roadways, in each urban area **u**, in 1991. (We use 1991 because we wish to have the results in 1991$).

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[10]It is not clear if a 4+ lane arterial, as defined by the FHWA, is a 4+ lane highway as defined by the Census. The instruction manual for Census surveyors gives little additional detail, merely telling the surveyors to count any "divided or undivided highway of four or more lanes" (Bureau of the Census, personal communication, 1995a). These instructions suggest that surveyors count 4+ lane principal arterials, and perhaps even 4+ lane minor arterials, as 4+ lane highways.

[11]The 1990 Census might report annual housing cost by urban area; we did not check.

First, we note that in general, the annualized value or cost of any HU is equal to the full value or cost multiplied by an annualization factor (AF). Thus:

$$P_u = AF \cdot FV_u$$

$$AF = \frac{i}{1 - (1+i)^{-t}}$$

where:

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

AF = the annualization factor

FV_u = the average full value of all HUs exposed to noise above a threshold, in area urban area **u**

i = the annual interest rate for investment in HUs

t = the term of the investment in HUs (years)

We do not know FV_u, the average full value of all HUs near roadways in each urban area, but as noted above we do know the median value of owner-occupied HUs or houses for sale in each urbanized area (Bureau of the Census, 1990a). We can use these data to estimate FV_u:

$$FV_u = FVO_u * \cdot \frac{AHCUS}{AOCUS} \cdot AV \cdot V_{91/90}$$

$$AV = \frac{FVO_u}{FVO_u *}$$

where:

FVO_u* = the median value of owner-occupied HUs or houses for sale in each urbanized area **u** in 1990 (Bureau of the Census, 1990a; column G of the Appendix to this report)

FVO_u = the median value of owner-occupied HUs or houses for sale, in areas exposed to motor-vehicle noise above a threshold, within each urbanized area **u** in 1990

AHCUS = the median annual cost of all occupied HUs in all urban areas of the U.S. in 1991 (Bureau of the Census, *American Housing Survey [AHS],* 1991, 1995b)

AOCUS = the median annual cost of owner-occupied HUs in all urban areas of the U. S. in 1991 (Bureau of the Census, *American Housing Survey [AHS],* 1991, 1995b)

$V_{91/90}$ = the ratio of housing value in 1991 to housing value in 1990

With this, we derive the following complete expression for P_u:

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

Thus, we estimate the annualized value of HUs near roads in each urban area by annualizing the full value of owner-occupied HUs in each urban area **u**, and then adjusting for the difference between the annualized cost of all HUs and the annualized cost of owner-occupied HUs, and for the difference between the value of HUs near roads and the value of HUs throughout the urban area.

Interest rate (i) and annualization period (t). As discussed in Report #2 of this social-cost series, the appropriate real annual interest rate for investment in housing appears to be 4% to 7% per year. The lifetime of the investment probably is on the order of 30 to 40 years[12]. 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 assume values half-way between the low and high: 5.5% and 35 years (AF = 0.0650).

The median annual cost of all occupied HUs in urban areas (AHCUS) and of owner-occupied HUs in urban areas (AOCUS). In 1989, AHCUS was $5,268 (Bureau of the Census, 1991); in 1993, it was $6,324 (Bureau of the Census, 1995b). We interpolate a value of $5796 in 1991 (we interpolate for 1991 because we wish to express the results in 1991 housing $). In 1989, AOCUS was $5,376 (Bureau of the Census, 1991); in 1993, it was $6,864 (Bureau of the Census, 1995b). We interpolate a value of $6120 in 1991. Consequently, AHCUS/AOCUS is equal to 0.95[13]

The ratio of the value of HUs near roads to the value of all HUs in urban areas (AV). We believe that, for a variety of reasons, including exposure to noise, housing

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[12]Note that in our analysis of the cost of residential garages, in Report #6 of this social-cost series, we assume a much longer life than we assume here for HUs. That is because there we estimate the life of *all* investments, including investments for remodeling and major repair, whereas here we estimate the life of the initial investment only. In the former case, for garages, the life of all investments corresponds to the physical life of the house (assuming zero salvage value). The effective life of the initial investment in a house will be less than the physical life. However, this difference in life does not matter much, because for interest rates less than 10%, the annualization factor is close to the interest rate if t is over 30 years.

[13]The Census' *AHS* shows the median housing cost for all HUs in all urban areas, and the median housing cost plus the maintenance cost for owner-occupied HUs in all urban areas. The median housing cost includes utilities, real estate taxes, condominium fees, and other charges, as well as mortgage or rent payments. We assume that our parameter AHCUS is equal to the *AHS* median housing cost for all HUs, and that AOCUS is equal to the *AHS* median for owner-occupied HUs, minus the cost of maintenance as reported by the *AHS*. Thus, even though the *AHS* data include costs (such as utilities) that we would like to exclude, they at least allow us to estimate AHCUS and AOCUS on the same basis.

value declines the closer that one gets to a major roadway. However, the parameter HV should be applied to the no-noise or pre-devaluation value, not with to the noise-devalued value. This means that, technically, what we want to know is not the actual noise-devalued value of houses in areas of excess motor-vehicle noise, but rather what the value of those houses would be were they exactly as they are *except* not devalued on account of the motor-vehicle noise. We expect 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 assume that, if there were no noise from roads, the value of HUs near roads would be 5% less than the average value in the urban area (AV = 0.95). In our low-cost case we assume that AV = 0.90, and in our high-cost case, we assume that AV = 1.00.

> ***The ratio of housing value in 1991 to housing value in 1990.*** Although we estimate noise costs on the basis of 1990 activity data, we express the results in 1991$, because all costs in this social-cost analysis are expressed in 1991$. Because costs are calculated as fraction of housing value, we will us 1991 rather than 1990 housing values in order to have the results in 1991$. Data from the AHS (Bureau of the Census, 1991, 1995b; discussed above in regards to parameters AHCUS/AOCUS) indicate that the value of housing increased by % year from 1989 to 1993. Hence, we assume that $V_{91/90}$ = 1.047.

14.4.11 The diminution in annualized housing value per excess decibel (HV)

Several studies (Nelson, 1978; Hall and Welland, 1987; O'Byrne, Nelson and Seneca, 1985; Vainio, 1995) have 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 WTP for residences at different hypothetical levels of airport noise has 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. (1996) 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. We, of course, wish to know the implicit valuation of all householders, because everybody is affected by noise. Can we assume that the parameter HV for all households (which is what we wish to know) is the same as HV estimated for home owners? Probably not: the sample of home buyers, whose purchase decisions are the basis of most of the hedonic-price-analysis estimates of HV, probably is not representative of the whole population to which we will apply HV. 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%-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 foregoing, we assume a range of 0.2% (low-cost case) to 1.5% (high-cost case) of housing value, per decibel of noise. In our base case, we assume a value half-way 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 re-estimate results at for different parameter values.

In the original econometric studies, the parameter HV is estimated with respect to the sales price or full value of a housing unit. However, if the full (or "initial") value of a housing unit changes by X%, then the annualized value also changes by X%, because the annualized value is equal to the full value multiplied by the constant annualization factor. Hence, we estimate the annualized cost of noise in residential areas simply by multiplying HV, the change in value per excess decibel, by P, the median annualized value of housing units, and by the number of excess decibels. We assume that HV is the same in every area **u**.

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 assume that the marginal cost of each decibel is the same -- i.e., that 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 50-55 dBA change is equal to the WTP for a 75-80 dBA change. Nevertheless, not only do most studies use a linear functional form[14], the few that have tried non-linear forms have found that they are not any better than linear forms. For example, Hall and Welland (1987) found that linear functions work about as well as non-linear ones, although they note that their analysis did not contain a sufficient sample to conduct a robust test of functional form, and caution against relying too heavily upon the linear form. Similarly, Feitelson et al. (1996) found that non-linear

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[14]At least one study (McMillan, et al., 1980) has used a logarithmic functional form.

specifications did not explain WTP for noise any better than did linear specifications[15]. Because of this, and because nonlinear functions generally are not available, we have assumed that the cost of noise is linearly related to the level, and hence that 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 are 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 does have these kinds of subtle effects, but we are unable to estimate their dollar value.

(iii). The parameter HV really 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 than did 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 adjust for it.

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[15]However, Feitelson et al. (1996) did find that the WTP function for noise is "kinked, whereby, above a certain disturbance level, households are not willing to consider the residence, and thus their WTP drops to zero" (p. 12).

14.4.12 The effect of noise barriers (B_h)

Many roads have noise barriers, which attenuate vehicle traffic noise and reduce total exposure to noise. In equation **(1)**, we represent the reduction in noise, B_h, provided by a noise barrier, as a function only of the height h 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 the thickness and construction of the noise barrier, 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). Relatively complex models of the effect of noise barriers are available (e.g., Jung and Blaney, 1988). However, to keep the integration of equation **(1)** and the size of the analysis manageable, we use a very simplified model of the effect of noise barriers: we place each noise barrier into one of three height categories, and assume that the attenuation provided by a barrier is a function only of the height of the barrier. (Later in this section we compare our simple assumptions with the results of a more sophisticated model.)

In a 1976 study that analyzed the cost-effectiveness of various measures to reduce traffic noise damages, the National Cooperative Highway Research Program (NCHRP) presented the dBA reduction in noise provided by barriers of three different heights: 10, 15, and 20 feet (Table 14-4). As shown in Table 14-4, we have assumed simply that the reduction estimated by NCHRP (1976) for a 10-foot barrier applies to any barrier less than 12.5 feet in height, that the reduction estimated for a 15-foot barrier applies to any barrier between 12.5 and 17.5 feet, and that the reduction estimated by NCHRP (1976) for a 20-foot barrier applies to any barrier over 17.5 feet. In sensitivity analyses, we examine different values for B_h.

Using FHWA data on all noise barriers in the U.S. constructed with the assistance of federal funding as of December 31, 1989, we classified the barriers into the three height groups of Table 14-4. We assume that the dBA reductions of Table 14-4 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_h) in equation **(1)** for stretches of road upon which noise barriers were erected.

Comparison of our assumption with the results of a more sophisticated model. We emphasize that ours is a very simple model of the effect of noise barriers, and undoubtedly inaccurate in many instances. The attenuation achieved by noise barriers is, in specific circumstances, understood at a considerably more complex level. Nevertheless, a comparison of our assumptions with the results of a more sophisticated analysis indicates that our assumptions are reasonable over a wide range, and not likely to be so much in error as to significantly effect the overall results of our analysis.

Jung and Blaney (1988) present an equation that estimates the reduction in noise as a function of the height of the barrier, the height of the noise source, the height of the noise recipient, and the distance from the source to the barrier and the barrier to the

recipient. The equation is a fit to values tabulated from the FHWA's old noise-prediction model, STAMINA:

$$B_{h,d} = 5 + 14.4 \cdot e^{-0.175 \cdot (2 - \log No)^{2.5}}$$

$$No = 3.207 \cdot \left(\sqrt{(h_t - h_s)^2 + d_s^2} + \sqrt{(h_t - h_r)^2 + d_r^2} - \sqrt{(h_s - h_r)^2 + (d_s + d_r)^2} \right)$$

where:

$B_{h,d}$ = the reduction in noise provided by the noise barrier, as a function of the height of the barrier h_t and the distance from the barrier d (dBA)

h_t = the height of the noise barrier (we test 3.048 meters [10 feet], 4.572 meters [15 feet], and 6.096 meters [20 feet])

h_s = the height of the noise source (Jung and Blaney [1988] recommend 0.0 meters for LDAs, 0.7 meters for MDTs, and 2.44 meters for HDTs. [They do not give separate values for buses or motorcycles.] assuming these values, and that MDTs account for 3.5% of traffic volume, and HDTs 4.4%, and that the average speeds for LDAs, MDTs, and HDTs, are 80.45, 74.82, and 72.41 km/h, we estimate a noise-weighted average source height of 1.3 meters)

d_s = the distance from the source to the barrier (meters; column headings of the table)

h_r = the height of the noise receptor (we assume that 85% of the exposure is at ground level at 1.5 meters, and that the remaining 15% is at 4.5 meters, giving a weighted average height of 2.0 meters)

d_r = the distance from the barrier to the noise receptor (meters; row headings in the table)

In principle, we could substitute this expression for the B_h term in our equation **(1)**, and then estimate the distance-integrated noise reduction provided by every individual barrier in the U.S. This, however, would greatly complicate the derivation of equation **(2)** (because the Jung and Blaney [1988] expression, shown in Table 14-5, is a fairly complicated function of distance), and also would add a separate line of analysis for each barrier.

Instead, we use Jung and Blaney's (1988) equation to test the reasonableness of our assumption that noise is a function only of the height of the barrier. We do this in Table 14-5, which compares the noise-attenuation predictions of the Jung and Blaney (1988) model, for each of the three noise-barrier heights considered by the NCHRP (1976), with the NCHRP's (1976) point estimates of the noise attenuation provided by each of the three heights of barrier. The shaded cells of the table contain Jung-and-

Blaney calculated values that are within 1.0 dBA of the NCHRP's (1976) point estimate, for each barrier height.

The analysis presented in Table 14-5 reveals two important and related points. First, the noise reduction provided by the barrier is nearly constant beyond 15 meters or so from the barrier. This means that assuming a single value for the reduction over the entire distance from the roadway, as we do here, is not necessarily a terrible approximation. Thus, in some cases at least little would be gained by actually integrating the reduction over the entire distance away from the barrier.

Second, the NCHRP (1976) estimates that we use here fall within the relatively narrow range of values estimated by the Jung and Blaney (1988) model, and are within 1.0 dBA of most of the pertinent values. The NCHRP (1976) estimate that a 10-foot barrier provides an 8.4-dBA reduction is within 1.0 dBA of more than half of the values estimated over a wide range of distances by the Jung and Blaney (1988) model. The NCHRP (1976) estimates of the reductions provided by higher barriers are within the range of values estimated by the Jung and Blaney (1988) model for barriers along relatively wide roads (relatively large distance d_S from average source to barrier; e.g., freeways), which is where one would expect to find the relatively high barriers. (Wider roads typically carrier more traffic, which generates more noise, and warrants a higher noise barrier.)

Of course, even the Jung and Blaney (1988) model, and the STAMINA tabulations from which it was estimated, is a simplification of reality. There are even more sophisticated models of noise barriers. Nevertheless, it seems likely to us that:

1) the point estimates of the NCHRP (1976), which we use here as the basis of our three height classes, are valid over a relatively wide range of conditions and distances; and

2) given further 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 to the total estimates damage cost of motor-vehicle noise.

14.4.13 Road mileage by height of noise barrier ($L_{u,r,h}$)

In this section we explain how we determine the extent of roadway mileage, by type of road and area, in each of four barrier-height classes, including zero height.

The FHWA reports the length, height, location, and name of road of each noise barrier built with Federal funding, as of December 31, 1989 (FHWA, 1990). We used this information to classify the noise barriers in one of the 377 urbanized areas and one of the six classes of roads of this analysis. If a noise barrier's reported location was the name of one of the 377 urbanized areas, then of course we assigned the barrier to that urbanized area. Otherwise, we consulted an atlas to find the location of the barrier; if the location actually was in or near one of the 377 urbanized areas, then again we assigned the barrier to the area. If the barrier was not in or near an urbanized area, we placed it in a generic "non-urban" category. We discuss non-urban noise barriers below.

Next, we assigned the barriers to one of the six types of road (interstate freeway, other freeway, principal arterial, minor arterial, collector, local road). The FHWA report gives the actual *name* (e.g., "I-80," or "Sepulveda Blvd.", or "Seward Highway"), but not the type (e.g., freeway, arterial), of each road that has a noise barrier. We inferred the type of road from its name. We assumed that all roads prefixed by an "I" (e.g., "I-80," where the "I" stands for "Interstate"), are *interstate freeways* in the FHWA classification. We assumed that all roads prefixed by "US" (e.g., US 50), or named "Toll road" "Parkway," or "Loop" are *other freeways*. "Boulevards," "Routes," and "Roads" were presumed to be *principal arterials*. We assumed that no noise barriers were built along minor arterials, collector streets, or local roads. Finally, as mentioned above, we grouped each noise barrier according to height. Thus, each noise barrier was grouped according to height, type of road, and area in which it was built.

Note that the FHWA report includes only noise barriers built with at least some federal funding. Presumably most but not all noise barriers are built with some federal funding. We assume that the length of noise barriers built exclusively with state or local funds is 25% of the length of federally funded noise barriers, in every height class, road type, and area[16]. We examine the effect of this assumption in sensitivity analyses.

The lengths of all noise barriers of the same height-class, type of road and area were then summed:

$$L_{u,r,h^*} = NF \cdot \sum BL_{u,r,h^*}$$

where:

L_{u,r,h^*} = total length of federal, state, and local noise barriers that are of height-class **h***, built along road of type **r,** and located in area **u.**

BL_{u,r,h^*} = the length of an individual, federally funded noise barrier of height-class **h*** located on a road of type **r** (interstate, other freeway, principal arterial) in area **u**

NF = the ratio of total miles of noise barriers (including non-federally funded noise barriers) to miles of federally funded noise barriers, in every height class, road type, and area (assumed to be 1.25; we consider 2.0 in a scenario analysis)

h^* = noise barrier height class (high, medium, low); the difference between h and h* is that h includes height-class zero (i.e., no noise barrier), and h* does not

The length of roads without noise barriers (in our model, noise barriers of zero height) was calculated as the difference between total miles of road and total miles of road with noise barriers:

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[16]Also, we assume that this 25% scale-up factor accounts for roads, such as those sunk between two steep embankments, situated in such a way as to create an effective noise barrier.

$$L_{u,r,none} = L_{u,r} - L_{u,r,high} - L_{u,r,medium} - L_{u,r,low}$$

where $L_{u,r}$ is the total length of road type **r** in area **u**, and $L_{u,r,h*}$ (where h* is high, medium, or low) is calculated as above.

Miles of roadway by barrier height class are shown in the Appendix, columns H1 to H6.

14.4.14 Time spent in one's home, and outside of one's home (Ti, To)

Traffic noise causes damages at places other than one's home or residential property. We account for these costs by extrapolating residential costs in proportion to the amount of time spent outside (To) versus in or around (Ti) one's home.

Recall that we estimate 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 consider the effect of noise on the value of the home-owner's home only; they do not capture the effect of noise on activities done outside of one's home.[17] Because these studies account only for the cost of noise in and around one's home, and because we have not found any studies of the cost of noise outside of the home, we must scale the results for residential areas, to account for the cost of motor-vehicle noise outside of one's home.

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) outside of the home -- say, at the office. For example, the value of quiet in an office or in school may well exceed the 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 do not have data for this ideal estimation. So, instead, we use a simple binary classification: in every away-from-home location, the exposure to and cost of motor-vehicle noise either is zero, or else is the

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[17]This is because, presumably, when people assess noise when they look for a home, they assess the differences in exposure to noise that will result from choosing one home over another. For example, they certainly will compare noise in and around the homes, because local exposure to noise will depend on which home they buy. But buyers will not consider noise exposure at places that they will go and during activities that they will do *regardless* of which home they buy. 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. Because noise is very localized, one can assume that the value of noise implicit in the price of a home is based on exposure to noise only in and around the home.

same as the exposure to and cost of motor-vehicle noise in one's home, per minute on average. The basis of this classification, which is shown in Table 14-6, 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 that are impacted by noise, we assume that the cost of the noise is proportional to the amount of time spent in that location divided by the amount of time spent in one's home.

Table 14-6 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 (Ti), and 250.6 minutes at non-home places (To) where in our judgment motor-vehicle noise might be a problem (Table 14-6). In the high-cost case, we assume that motor-vehicle noise also disturbs the time spent in transit (111.4 minutes; see discussion next) and an additional 62.7 minutes of activities in various indoor and outdoor activities, so that the parameter To = 424.7 minutes (Table 14-6).

Noise costs while in transit. The case of noise experienced while in transit -- in vehicles -- is especially problematic, because people spend, on average, 111.4 minutes per day in transit (Table 14-6), and while in transit are right at the source of the motor-vehicle noise. There are at least three ways to approach this:

1). One can assume that the noise exposure in a vehicle is the same as that in a house located, say, five feet from the edge of the road, and that noise cost per excess decibel per minute in transit is the same as in a home. With these assumptions, one then can evaluate the noise model at distance d = 5 feet (rather than integrated and evaluated from d_e to d_{t^*}), and with the scaling factor (To + Ti)/(Ti) equal to 111.4/921.1 (time in transit/time in one's home). This results in damages of the same order of magnitude as damages in one's 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, because one doesn't do much in transit anyway. Also, the first assumption might overstate exposure.

2). One can ignore noise costs while in transit, on the admittedly weak grounds that it is not so noisy inside of vehicles as to disturb the few things that one can do inside of a vehicle anyway. Noise disturbs sleeping, reading, and conversation, none of which occur often in vehicles[18]. We adopt this approach in our base case.

3). One can include the 111.4 minutes in transit in the "To" of the (To+Ti)/Ti scaling factor, treating it just 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 to the first approach, because the effective average distance

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[18]We do not suggest that people do not care at all about noise in vehicles. Obviously, they do. For example, Turrentine et al.'s (1991) study of driver reaction to alternative-fuel vehicles found that drivers noticed and liked the fact that electric vehicles are completely quiet when the are stopped. We mean only that noise in vehicles probably is less bothersome than noise in homes.

from the road is much more than the 5 feet assumed in the first approach. We adopt this approach in the high-cost case[19].

14.5 NOISE COSTS IN TOWNS IN NON-URBANIZED AREAS

As mentioned above, in this study, we enumerate all of the noise barriers built outside of urbanized areas, and aggregate them into one generic rural area for which we calculate noise damages. The FHWA (1990) lists over 400 barriers in 92 towns not in an urbanized area. We treat these 92 towns as one aggregated rural area, and use the noise model discussed above to estimate noise costs.

To calculate noise costs in rural areas, we must re-specify some of the parameters of the model. Unfortunately, we are given only the length and height of the noise barriers in these towns; the other parameter values we must estimate. Our estimates and assumptions are as follows:

- $L_{u,r,h}$, *miles of interstate, other freeway, and principal arterial, without noise barriers.* The FHWA (1990) reports the height and length of noise barriers along interstates, other freeways, and principal arterials in non-urbanized areas. However, there are no data on the extent of roads, in these areas, without noise barriers. We assume that in the aggregated rural area, the ratio of miles of road (interstate, other freeway, or principal arterial) without noise barriers to miles of road with noise barriers is one-fifth of the same ratio for all urbanized areas. Thus, given that we calculate that in urbanized areas there are 18.5 miles of interstate without noise barriers for every mile of interstate with noise barriers, we assume that in the aggregated rural area there are 3.7 miles of interstate without noise barriers for every mile of interstate with noise barriers. Similarly, we assume that there are 6.46 miles of "other freeways" without noise barriers for every mile of "other freeway" with noise barriers, and 187.5 miles of principal arterials without noise barriers for every mile of principal arterial with noise barriers.

- $L_{u,r,h}$, *miles of minor arterial, collector street, and local road without noise barriers.* There are no noise barriers along these types of roads, and hence the method used above to estimate the extent of the roadway cannot be used. We assume instead that in the aggregated rural area,

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

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the ratio of miles of road (minor arterial, collector, or local road) to miles of interstate + miles of other freeway + miles of principal arterial is equal to the same ratio for all urbanized areas.

- M_u, *the density of housing units exposed to motor-vehicle noise above the threshold t^*(units/mi^2).* On the basis of data in the *American Housing Survey* (AHS, Bureau of the Census, 1991), we assume that density of housing units exposed to motor-vehicle noise in rural areas is one-fifth the density of homes exposed to motor-vehicle noise in urbanized areas. The *AHS* reports the median lot size for single-unit residential structures (0.24 acres in urban areas, and 2.26 acres in rural areas), and the number of apartments units in multi-unit buildings of each five size classes (2-4 units, 5-9 units, 10-19 units, 20-49 units, and 50 or more units), in urban and rural areas in 1989. In order to calculate the overall housing-unit density, we must make some assumptions about the number of units in and land area occupied by each of the five size-classes of multi-unit buildings:

	2 to 4 units	5 to 9 units	10 to 19 units	20 to 49 units	50 or more units
units/building	3	7	15	35	75
acres/building, urban	0.5	1.0	1.75	3.0	4.0
acres/building, rural	0.75	1.5	2.5	5.0	10.0

With these data and assumptions, we estimate about 5 housing units per acre in urban areas, and 0.5 housing units per acre in rural areas. This suggests that the housing density in rural areas is one-tenth that in urbanized areas. We suspect, though, that in rural towns that have a noise barrier, the housing-unit density is higher than the rural average, because the presence of a barrier implies that a relatively large number of persons are bothered by the noise. Therefore, we assume that the density of housing units exposed to motor-vehicle noise in rural areas is one-fifth the average density of housing units exposed to motor-vehicle noise in all urbanized areas.

- P_u, *the median price of a housing unit ($/unit).* The median house value and median monthly housing cost is much lower outside of MSAs than in suburbs or central cities (Bureau of the Census, *American Housing Survey for the United States in 1993*, 1995b). However, it appears to us that the rural towns that have noise barriers are bedroom communities

that are more like suburbs (which have the highest median housing values) than they are typical rural towns. Therefore, we assume that the median price of a housing unit in rural towns that have a noise barrier is the same as the average of the median prices in all urbanized areas (FV_u).

- *Sx_r, vehicle speed by type of road.* Vehicles travel faster on roads in rural areas than on roads in urban areas. According to the FHWA's *Highway Statistics 1991* (1992), the average speed on rural interstates was 2% higher than the average speed on urban intertates, and the average speed on rural arterials was 4% higher. On that basis, we assume the following rural/urban speed ratios:

Interstate	Other freeways	Principal arterials	Minor arterials	Collectors	Local roads
1.02	1.04	1.04	1.04	1.02	1.00

- *$V_{u,r,h}$, traffic volume (vehicles/hour) in road type **r** with noise barrier of height class **h**.* Nationally, the traffic volume on rural roads is about one-third the volume on urban roads (FHWA, 1991a). However, the volume presumably is higher than average in the rural towns that have a noise barrier. We assume that in the aggregated rural area, the traffic volume on every type of road is half the average volume in all urbanized areas[20].

- *$Fm_{u,r}$, $Fh_{u,r}$, $Fb_{u,r}$, $Fc_{u,r}$, truck, bus, and motorcycle VMT fractions in rural areas.* Heavy trucks account for a much larger share of VMT on rural roads than on urban roads. We assume the following national-average VMT shares, for rural roads:

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[20]Interestingly, although the traffic volume, road network, and housing density are different in rural than in urban areas, daily VMT per household is about the same, as can be seen from the following data from the 1991 Household Vehicles Energy Consumption Survey (Energy Information Administration [EIA], 1993):

	Miles/HH	Vehicles/HH	Miles/vehicle
Urban	18.8	1.8	10.7
Central city	15.9	1.6	10.0
Suburban	20.4	1.9	11.0
Rural	19.5	1.9	10.4

HH = household

	Interstate	Other freeways	Principal arterials	Minor arterials	Collectors	Local roads
MDTs	0.040	0.040	0.045	0.043	0.044	0.038
HDTs	0.177	0.084	0.050	0.035	0.017	0.013
Buses	0.0028	0.0020	0.0074	0.0045	0.0069	0.0018
Motorcycles	0.0058	0.0025	0.0070	0.0041	0.0088	0.0046

The values for HDTs and MDTs are national averages, from FHWA (1991c). The values for buses and motorcycles are our estimates, from data in the FHWA's *Highway Statistics 1991* (1992).

- α, *the site parameter, or ground-cover coefficient (unitless).* We assume that the average rural town has more grass and vegetation and less than pavement than has the average urban area, and so has softer and more absorptive ground. This corresponds to a higher value of α. We assume 0.50.

- *Φ, the subtending angle.* If the housing density in rural towns is less than the density in urban towns, then the subtending angle, which depends in part on the spacing of houses, will be wider. We assume 40º (30º to 60º, low-cost and high-cost cases).

- *all other parameters.* Same value as for urbanized areas.

14.6 TOTAL EXTERNAL DAMAGE COST OF DIRECT NOISE FROM MOTOR VEHICLES

14.6.1 Base case, low-cost case, and high-cost case.
Table 14-7 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 us a reasonable figure. However, there is considerable uncertainty in many of the parameter values, and this uncertainty compounds into a huge span between our low-cost and high-cost cases: less than $100 million to more than $40 billion -- a factor of about 400! 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 the high may not misrepresent the

uncertainty in the analysis. Nevertheless, we believe that noise damages do not exceed $5 or $10 billion annually.

14.6.2 Sensitivity analyses

In Table 14-8 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 14-7, given a change in each parameter value from its base-case value to its low 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 Ti), or for most of the parameters for rural areas, because damages in rural areas are so much smaller than damages in urban 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 **(0)**), total external noise costs Cn 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.

As discussed above, there is considerable uncertainty in the parameter HV, the change in the value of a housing unit per decibel of noise above the threshold. The order-of-magnitude uncertainty regarding this parameter results directly in order-of-magnitude uncertainty in the total costs.

In our view there is less uncertainty in the parameter AD, which adjusts the average housing density throughout the entire urban area (M_u*) to the density of houses in areas exposed to motor-vehicle noise (M_u), and still less uncertainty in the parameter AV, which adjusts the average housing value throughout the entire urban area to the value in areas exposed to motor-vehicle noise.

Time spent away from home in places impacted by noise (min) (To). As discussed above, we do not know for sure which activities and places outside of one's home are disturbed by traffic noise. In this scenario analysis, we assume that motor-vehicle noise also disturbs the time spent in transit (111.4 minutes; Tables 14-6, 14-8) and an additional 62.7 minutes of activities in various indoor and outdoor activities, bringing the parameter "To" to 424.7 minutes.

As one can see from the structure of the general model (equation **(0)**), away-from-home damages are simply proportional to the amount of time in away-from-home activities susceptible to noise. As shown in Table 14-8, the total costs increase by about 15% in this scenario.

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. Although the total external noise cost is a linear function of AF, AF itself is a nonlinear function of i and t, and hence total external noise costs Cn are not simply proportional to i and t. As shown in Table 14-8, 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 14-8, if t* is only 50 dBA rather than 55 dBA, the estimated cost of noise more than triples.

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 in which damages rapidly approach zero below 55 dBA. Unfortunately, the data to estimate such a nonlinear damage function are not available.

Scaling factor for accounting for state and local barriers (NF). In the base case, we assume that the ratio of total miles of noise barriers to miles of Federally financed noise barriers (as reported by FHWA) is 1.25. In this scenario, we assume that this ratio is 2.0 (i.e., that the FHWA data represent only half of all noise barriers). As shown in Table 14-8, this increase in the extent of noise barriers decreases total damages by a negligible amount, because there are so few noise barriers to begin with.

Ground-cover coefficient (α) and subtending angle (φ) in urban areas. The subtending angle and the ground-cover coefficient are relatively simple representations of very complex phenomena. Because noise attenuation is such a complex function of the characteristics of each site, there really is no way to estimate national average values. Our base-case values for Φ and α are merely plausible starting points, not elaborate calculations. 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.

The sensitivity analysis of Table 14-8 shows that this uncertainty has a significant effect on the results. For example, it turns out that 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 noise cost of motor-vehicle noise nationally.

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Ground-cover coefficient (α) and subtending angle (φ) in rural areas. Noise costs in rural areas are sensitive to the values of these parameters, but because rural noise costs are negligible compared to urban costs, total costs are not sensitive to changes in these or any other parameters for rural areas.

Equivalent distance to road (ft) (d_e) . The narrower the assumed right-of-way, the closer the houses to the road, and the greater the noise damages to residences. However, as shown in Table 14-8, modest variation in this parameter (see Table 14-1) changes the base-case costs by less than 10%.

Vehicle speeds (mph) (S). In our base case, we assume FHWA-reported average speeds for interstates and other freeways, and use our own estimates for the other four types of roads. However, in their analysis of noise costs, Fuller et al. (1983) assumed considerably lower average speeds than we do here. In our low-speed scenario (Table 14-2), costs drop by over 30%. Average vehicle speed, then, is an important parameter in the calculation of the external damage cost of noise.

In separate scenarios, not presented in Table 14-8, we varied the speed of medium and heavy trucks relative to the base-case LDA speeds. When we assumed that trucks travel at the same average speeds 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, noise costs decreased by less than 10%. Thus, the results are not quite so sensitive to our assumptions regarding the speed of trucks relative to the speed of cars.

Fraction of vehicles cruising (FC). Accelerating vehicles are noisier than cruising vehicles. 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 14-8, the lower assumed cruising fractions (Table 14-2) increase the total cost of noise by less than 5%.

Noise barrier reduction (dBA) (Bh). We also test the sensitivity of our results to different assumptions regarding the attenuation provided by noise barriers. The variations are shown in Tables 14-4, and the results are shown in Table 14-8. The changes in B_h change the results by 1% or less. Thus, uncertainty in the parameter B_h is unimportant.

B_h is unimportant in the aggregate because so few roads have noise barriers that it does not matter, nationally, how effective the noise barriers are. Of course, if one is analyzing the costs of a particular project with and without noise barriers, then the effectiveness of the barriers (B_h) 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.

14.6.3 Comparison with other estimates

Verhoef (1994) and Rothengatter (1990) review 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 reductions, 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 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 14-7 results divided by 1990 GNP of about 5.5 trillion dollars).

In the analysis of Fuller et al. (1983), the bulk of damage occurred along arterials. In our study, the bulk of the damages occur along interstates and other freeways (Table 14-7). Fuller, et. al (1983) found that damages on local roads were very small but not zero; we found them to be zero.

14.6.4 The marginal cost of noise from different types of vehicles on different types of roads, in urbanized areas

The cost of noise from an additional mile of vehicle travel depends on the type of vehicle and the type of driving added. All else 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 do 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 14-9, we show the marginal cost of noise per 1000 vehicle-miles of travel (VMT), 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 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 equal, roads with high-speed traffic generate more noise than do roads with low-speed traffic, and roads close to houses cause more disturbance than do 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 14-9, damages do *not* decline uniformly as goes from interstates down to local roads, because the effect of lower speed is being at least partially offset by the effect of 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 that the other freeways are closer to houses. 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.

14.6.5 Other components of the social-cost of noise related to motor-vehicle use.

Note that ours is an estimate of external damage cost of direct noise 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, because the total social cost of noise related to motor-vehicle use is equal to the external damage cost of noise 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 (such as highway construction), *plus* the cost of controlling noise related to motor-vehicle use. Moreover, as implied above, we have not counted every direct external cost of motor-vehicle noise: for example, we have not estimated all damages to property unused because of motor-vehicle noise. We now will consider these other components in turn.

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). This indirect noise can be attributed to motor-vehicle use, because its magnitude depends, indirectly, on the use of motor vehicles. For want of data, we do 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 these indirect sources of noise either are scattered and intermittent (e.g., highway construction), or else relatively remote (e.g., petroleum refineries), and as a consequence probably are much less damaging, in the aggregate, than is direct noise from motor vehicles.

Cost 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. In our larger analysis of the social-cost of motor-vehicle use, the cost of noise barriers is included in our estimates of the cost of the highway infrastructure. The cost of avoiding noise probably is reflected in differences in housing prices, and hence included (although not separately estimated) in our estimates of external damage costs. Considering each of the four in a bit more detail:

(i). The cost of insulating vehicles against their *own* noise is not an external cost of motor-vehicle use. In our larger analysis of the social-cost of motor-vehicle use, it is counted as a cost of owning and operating vehicles. However, the cost of insulating against noise from other vehicles, if such insulation is additional, arguably is a defensive expenditure and hence 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). The cost of noise barriers along highways is included in FHWA estimates of capital expenditures related to highways (*Highway Statistics*, annual; Report #7 in this social-cost series). The cost is relatively small, less than $100 million per year[21]. To the extent that highway user fees cover the cost of highways, then the cost of noise barriers is not an external cost of motor-vehicle use. We do not include this cost 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. (One will pay less for a house in a noisy area whether one expects to bear the noise or to spend something to mitigate it.) However, the matter of mitigation measures already in place when a house goes on the market is more complicated. If the hedonic price analysis relates the actual, post-mitigation noise levels to the market value, then the relationship between price and noise will be correct. But if the 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. Although we are unable to determine the extent to which hedonic price analyses underestimate the cost of noise by failing to account for the effect of investment in noise mitigation by home owners, we suspect that the problem is minor.

(iv). The personal cost of having to avoid noise (e.g., leave a noisy room or noisy 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[22]. If this is so, then avoidance

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[21]By 1990, all federally funded noise barriers had cost a total of $620,507,870 in 1989 dollars (FHWA, *Summary of Noise Barriers Constructed By December 31, 1989*, 1990). Multiplying by 1.25, to account for state and local noise barriers, and annualizing over 50 years at 4% to 9%, results in $34,717,267 to $64,916,272 per year, for noise barriers. Note, though, that this amount should be included already in FHWA's estimates of government expenditures on the roads (*Highway Statistics*, annual), and in the analysis of the social-cost of motor-vehicle use in Report #7 of the social-cost series. Generally, a noise barrier is built as part of a highway project, and all expenditures on highways are supposed to be included in the FWHA statistics. Most noise barriers probably are built with Federal aid money, and expenditures of federal money on noise barriers definitely are included in the FHWA expenditure statistics (FHWA, *Highway Statistics*, annual). If a noise barrier is built after a road is built, as a separate project, without aid money, and if the state department of transportation does not classify the expenditure as highway-related, then the expenditure probably will not show up in the FWHA statistics. We expect that this does not happen very often, because noise barriers probably are routinely considered to be part of highway projects are improvements.

[22]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.

costs are included in HV and hence in our estimates of the external cost of noise from motor vehicles.

   The cost to unused property. We estimate the cost of motor-vehicle noise in and around the home, and the cost of noise in places outside the home that are impacted by motor-vehicle noise. In our extension of noise costs from homes to places outside of the home, we consider outside places that people *use*; but we do not consider places that people don't use *because* of motor-vehicle noise. (The basis of our extension of noise damages from residential to non-residential areas is the amount of time that people spend in various places and pursuits, as shown in Table 14-6.) Thus, our approach probably does not capture the effect of noise on the value of property that remains unused because of motor-vehicle noise. The omission, however, likely is minor.

   Note that we omit noise costs only in places that remain *unused* because of motor-vehicle noise; we do not necessarily omit costs in places that remain *undeveloped* because of motor-vehicle noise. Imagine two places next to a freeway: an undeveloped but used greenbelt, and an undeveloped and unused parcel of land. Suppose further that, were there no motor-vehicle noise, both places would be developed into higher-value uses. The cost of motor-vehicle noise is the difference in the stream of "rents" to the land with motor-vehicle noise and without motor-vehicle noise, where "rents" in the case of the greenbelt include the value of use as a greenbelt *net* of the disutility of the noise. The disutility of noise in the greenbelt (which we in principle include in our scenario analysis) may be taken as an approximation of the difference between the stream of rents with motor-vehicle noise and the stream of rents without. Now, as can be seen in Table 14-6, we count noise costs in "Playgrounds and parks," and, in a scenario analysis, in "Other outdoor" places. Thus, our method in principle accounts for the noise cost in the greenbelt, albeit crudely. It does not, however, account for the loss of value to the undeveloped and *unused* land. We expect, though, that this loss is relatively small.

14.6.6 The 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, not only because it is not possible to identify and quantify all of the other noise sources, but because the incremental effect of motor-vehicle noise depends on the location and wave characteristics of all of the noise sources. Not only does noise from one source not "add" in a straightforward manner to noise from another source, noise sources might to some extent cancel one another.

   We can, however, offer this generalization: it is possible that noise levels will add in such a way that a reduction in motor-vehicle noise, when there are several sources of noise, will eliminate more decibels *above* the threshold than will a reduction in motor-vehicle noise when motor vehicles are the only noise source. To see this, imagine that

there are two sources of noise, motor-vehicles and construction equipment, which by themselves emit, respectively, 50 dBA and 70 dBA at the nearest house. In our analysis, which assumes a threshold of 55 dBA, the noise cost of motor vehicles by themselves will be zero, because their 50 dBA contribution is below the 55 dBA threshold. However, if in reality there also is construction noise, which by itself creates 70 dBA, but together with motor vehicles creates 70+X dBA, then the elimination of motor-vehicle noise will reduce exposure by the X dBA -- all of which are above the threshold -- and so reduce estimated noise costs.

To the extent that noise from other sources interacts with motor-vehicle noise as in the preceding example with construction equipment, we will have underestimated the cost of motor-vehicle noise, because we will have failed to count some motor-vehicle noise above the threshold. This underestimation might not be trivial. Because we assume a constant $/dBA damage, the dollar value of the overlooked X dBA, given a threshold of 55 dBA, is precisely the value of the difference between a threshold of 55 dBA and a threshold of 55 minus X dBA. Now, in one of the sensitivity analyses above, we report that the total cost of noise is about three times higher with a 50 rather than a 55 dBA threshold. *Hence, if in the example above, X = 5 dBA, then damages roughly triple.* This is a significant effect, and suggests that the true incremental noise cost of motor-vehicle use might depend significantly on the characteristics of other noise sources[23]. Against this, though, we note that, as mentioned in the introduction, it does appear that traffic is the main source of noise in most people's lives.

14.7 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 to $10 billion annually.

The considerable uncertainty in our analysis is due mainly to the uncertainty 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 outside of the home (To); and the housing density in areas exposed to motor-vehicle noise (determined by the adjustment factor AD). Assumptions about noise barriers and noise in rural areas are unimportant at the national scale.

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[23]This of course still is true if one uses a nonlinear damage function with no threshold rather than a linear function with a threshold. If the damage function is nonlinear, then the value of any given change in noise depends on where on the damage curve the change occurs, which in turn depends on the characteristics of all noise sources.

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 sensible policy recommendation can be to narrow the uncertainty. To reduce this uncertainty, researchers should:

- 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 (M_u), and housing value (P_u), by type of road, in each urban area

- use different parameters and a different model structure to account for the noise attenuation (parameters Φ and α)

- 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 jointly model motor-vehicle noise and other sources of noise. 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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TABLE 14-1. CALCULATION OF THE "EQUIVALENT DISTANCE" FROM THE NOISE SOURCE TO THE NOISE RECIPIENT (FEET, EXCEPT AS NOTED)

	Interstate	Other freeway	Principal arterial	Minor arterial	Collector	Local road[a]
Distance, pavement edge to first house, roads without barriers[a]	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[a]	50	40	30	25	20	20
Width of right shoulder of road[a]	10.0	10.0	5.0	4.0	4.0	4.0
Width of a lane[b]	12.0	12.0	11.5	11.3	11.1	10.9
Number of lanes[c]	5.4	4.5	3.4	2.5	2.1	1.8
Width of dividers plus left shoulders[d]	20.0	10.0	5.0	2.0	0.0	0.0
Equivalent distance, roads without barriers (base case)[e]	*111.6*	*88.2*	*59.9*	*43.1*	*35.1*	*33.5*
Equivalent distance, roads with barriers[e]	*95.7*	*77.8*	*54.7*	*43.1*	*35.1*	*33.5*

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

[b]The FHWA (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.

[c]The FHWA (1992) reports 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 can back-calculate the number of lanes of each type of road.

 The FHWA does estimate lane-miles of local roads, but its estimate is derived not from actual data on the number of lanes of local roads, but rather from the assumption that all local roads average two lanes. We feel that this is too high, and instead have assumed that local roads average 1.8 lanes.

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

[e]Equal to: $\sqrt{dn \cdot df}$, where dn is the distance from the middle of the near lane to 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.

TABLE 14-2. AVERAGE SPEEDS IN URBANIZED AREAS (MPH)

	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[a]	58.6	57.6	36.4	29.6	24.6	19.9	n.e.

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

Methods:

Interstates and other freeways: The FHWA *Highway Statistics 1990* (1991a) reports the average speed of all vehicles on highways with a 55 mph speed limit, 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 58.6 on interstates, and 57.6 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 on the basis of our judgment, and such 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 Report #4 of the social-cost series).

[a]Calculated as:

$$S_r = \frac{VMT_r}{\displaystyle\sum_v \frac{VMT_{v,r}}{S_{v,r}}}$$

where:

S_r = the average speed on road type r

VMT_r = total VMT on road type r (FHWA, 1991c)

$VMT_{v,r}$ = VMT by vehicle type v on road type r (FHWA, 1991c, and our estimates)

$S_{v,r}$ = average speed of vehicle type v on road type r (this table)

TABLE 14-3. FRACTION OF VEHICLES CRUISING (AS OPPOSED TO ACCELERATING), BY VEHICLE TYPE AND ROAD TYPE

	Interstate	Other freeway	Principal arterial	Minor arterial	Collector	Local road
Fraction cruising[a]						
LDAs	0.95	0.95	0.80	0.75	0.70	0.65
MDTs	0.95	0.95	0.80	0.75	0.70	0.65
HDTs	0.95	0.95	0.80	0.75	0.70	0.65
Buses	0.95	0.95	0.80	0.75	0.70	0.65
Motorcycles	0.95	0.95	0.80	0.75	0.70	0.65
Calculated "C" exponent[b]						
LDAs	5.10	5.10	5.35	5.43	5.52	5.60
MDTs	6.83	6.83	6.92	6.95	6.98	7.01
HDTs	7.46	7.46	7.54	7.57	7.60	7.63
Buses	6.83	6.83	6.92	6.95	6.98	7.01
Motorcycles	5.88	5.88	5.88	5.88	5.88	5.88

LDA = light-duty automobile, MDT = medium-duty truck, HDT = heavy-duty truck.

[a]As explained in the text, we assume that the lower the average speed, the greater the number of stops and starts, and hence the lower the fraction of vehicles cruising at any one time. In a scenario analysis, we examine the effect of assuming lower cruising fractions for all vehicles:

Interstate	Other freeway	Principal arterial	Minor arterial	Collector	Local road
0.90	0.90	0.70	0.65	0.60	0.50

[b]The exponents Ca_r, Cm_r, Ch_r, Cb_r, and Cc_r in our noise model.

TABLE 14-4. ASSUMED REDUCTIONS IN MOTOR-VEHICLE NOISE (dBA), BY BARRIER HEIGHT (FEET)

Height of noise barrier (feet)	Reduction in noise provided by barrier (parameter B_h, in dBA)		
	base case[a]	*low-cost scenario*[b]	*high-cost scenario*[b]
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

[a]These are the NCHRP's (1976) estimates of the reduction provided by a 10-foot, 15-foot, and 20-foot noise barrier.

[b]A greater noise reduction results in a lower damage cost, and vice-versa.

TABLE 14-5. COMPARISON OF OUR ASSUMPTIONS REGARDING THE NOISE REDUCTION PROVIDED BY NOISE BARRIERS WITH THE PREDICTIONS OF A MORE SOPHISTICATED MODEL (REDUCTIONS IN DBA)

$d_r \neg$ / d_s -->	10-foot noise barrier			
	6	11	15	21
15	10.0	8.8	8.2	7.7
23	9.9	8.6	8.0	7.4
46	9.8	8.5	7.8	7.2
76	9.7	8.4	7.7	7.1
152	9.7	8.4	7.6	7.0
$d_r \neg$ / d_s -->	15-foot noise barrier			
	6	11	15	21
15	14.0	12.8	12.1	11.6
23	13.8	12.5	11.7	11.0
46	13.6	12.1	11.2	10.4
76	13.5	12.0	11.0	10.2
152	13.4	11.8	10.8	9.9
$d_r \neg$ / d_s -->	20-foot noise barrier			
	6	11	15	21
15	16.2	15.3	14.7	14.2
23	16.0	14.9	14.2	13.6
46	15.7	14.5	13.7	12.9
76	15.6	14.3	13.4	12.5
152	15.5	14.2	13.2	12.3

The values shown in the cells are the reduction in noise, in dBA, provided by a 10-foot, 15-foot, or 20-foot-high noise barrier, as a function of the distance in meters from the source of the noise to the noise barrier (d_s), and the distance in meters from the noise barrier to the recipient of the noise (d_r). The reduction is calculated using the equation from Jung and Blaney (1988), shown in the text.

The purpose of this table is to compare the results of a relatively sophisticated calculation of the attenuation provided by noise barriers with our very simple assumptions based on the NCHRP (1976). As mentioned in the text, the NCHRP (1976) estimates that a 10-foot barrier provides an 8.4-dBA reduction, a 15-foot barrier provides a 10.8-dBA reduction, and a 20-foot barrier a 13.0-dBA reduction. The shaded cells in this table contain calculated values that are within 1.0 dBA of these NCHRP (1976) estimates.

TABLE 14-6. TIME SPENT IN VARIOUS LOCATIONS, AND THE IMPACT OF NOISE

Place	Affected by noise?[a] (scenario assumptions in parentheses)	Time Spent (minutes)[b]
Home (parameter "Ti")	Yes	921.1
Office	Yes[c]	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 "To"[d]	*n/a*	*250.6 (424.7)*

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

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

^cIn a survey of businesses and residences in England, 37-59% of business respondents, and 25-48% 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.

^dThe sum of minutes in all places outside of 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.

TABLE 14-7A. THE COST OF MOTOR-VEHICLE NOISE: RESULTS OF THE BASE-CASE ANALYSIS (MILLIONS OF 1991$)

	Urbanized areas	Rural areas[a]	All areas
In and around the home			
Interstates	944.1	3.7	947.8
Other freeways	551.6	0.7	552.3
Principal arterials	310.8	0.7	311.5
Minor arterials	144.4	0.2	144.6
Collectors	2.5	0.0	2.5
Local roads	0.0	0.0	0.0
Total in and around home[b]	1,953.4	5.3	1,958.7
Total away from home[c]	531.4	1.4	532.9
Total everywhere[d]	2,485	6.7	2,491.5

[a]As explained in the text, we calculate costs in rural areas in which a noise barrier has been built.

[b]The sum of costs in and around the home along each of the six types of roads above.

[c]As explained in the text, we assume that the cost of noise away from one's home is proportional to the amount of time spent away from one's home.

[d]Total costs in and around the home plus total costs away from home.

TABLE 14-7B. THE COST OF MOTOR-VEHICLE NOISE: RESULTS OF THE LOW-COST ANALYSIS (MILLIONS OF 1991$)

	Urbanized areas	Rural areas[a]	All areas
In and around the home			
Interstates	32.2	0.1	32.3
Other freeways	19.9	0.0	19.9
Principal arterials	8.4	0.0	8.4
Minor arterials	4.5	0.0	4.5
Collectors	0.0	0.0	0.0
Local roads	0.0	0.0	0.0
Total in and around home[b]	64.9	0.1	65.0
Total away from home[c]	17.7	0.0	17.7
Total everywhere[d]	83	0.2	82.7

[a]As explained in the text, we calculate costs in rural areas in which a noise barrier has been built.

[b]The sum of costs in and around the home along each of the six types of roads above.

[c]As explained in the text, we assume that the cost of noise away from one's home is proportional to the amount of time spent away from one's home.

[d]Total costs in and around the home plus total costs away from home.

TABLE 14-7C. THE COST OF MOTOR-VEHICLE NOISE: RESULTS OF THE HIGH-COST ANALYSIS (MILLIONS OF 1991$)

	Urbanized areas	Rural areas[a]	All areas
In and around the home			
Interstates	12,121.2	52.7	12,173.9
Other freeways	6,942.0	9.7	6,951.8
Principal arterials	5,381.0	15.9	5,396.9
Minor arterials	2,977.3	7.0	2,984.3
Collectors	466.7	1.4	468.0
Local roads	14.6	0.0	14.6
Total in and around home[b]	27,902.7	86.7	27,989.5
Total away from home[c]	12,865.4	40.0	12,905.4
Total everywhere[d]	40,768	126.7	40,894.9

[a]As explained in the text, we calculate costs in rural areas in which a noise barrier has been built.

[b]The sum of costs in and around the home along each of the six types of roads above.

[c]As explained in the text, we assume that the cost of noise away from one's home is proportional to the amount of time spent away from one's home.

[d]Total costs in and around the home plus total costs away from home.

TABLE 14-8. SENSITIVITY ANALYSES

Parameter (units) (symbol)[a]	Parameter input values[b]			Sensitivity[c]	
	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) (Ti)	921.1	921.1	921.1	0.0%	0.0%
Time spent away from home in places impacted by noise (min) (To)	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) (ϕ)	40	30	50	-0.1%	0.1%
Ground-cover coefficient, rural areas (α)	0.50	0.60	0.30	-0.0%	0.1%
Scaling factor for housing density, rural versus urban	0.20	0.20	0.20	0.0%	0.0%
Scaling factor for hourly vehicle volume, rural versus urban	0.50	0.50	0.50	0.0%	0.0%
Scaling factor for median value, rural versus urban	1.00	1.00	1.00	0.0%	0.0%
Factor for rural noise barriers[d]	0.20	0.20	0.20	0.0%	0.0%
Threshold noise level (dBA) (t*)	55	55	50	0.0%	219.3%
Scaling factor for accounting for state and local barriers (NF)	1.25	2.00	1.25	-5.0%	0.0%
Subtending angle, urban areas (deg) (ϕ)	30	20	40	-36.2%	34.2%
Ground-cover coefficient, urban areas (α)	0.375	0.50	0.25	-21.6%	32.5%
Equivalent distance to road (ft) (d_e)	see Table 14-1			-8.1%	4.5%
Vehicle speeds (mph) (S)	see Table 14-2			-33.3%	0.0%
Fraction of vehicles cruising (FC)	see Table 14-3			2.6%	0.0%
Noise barrier reduction (dBA) (Bh)	see Table 14-4			-0.5%	0.6%

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

[b]**Because damages in rural areas are so small, we did not bother to specify low-cost or high-cost values for or perform sensitivity analyses on most of the parameters for rural areas.**

cFor each parameter P, the percentage that represents the sensitivity is equal to:

$\left(\dfrac{Cn_P}{Cn_B} - 1\right) \cdot 100$, 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 (Table 14-7).

dThis is the ratio $\dfrac{Rnb}{Rb} : \dfrac{Unb}{Ub}$, where Rnb is rural non-barrier miles, Rb is rural-barrier-miles, Unb is urban non-barrier miles, and Ub is urban-barrier-miles.

TABLE 14-9. THE MARGINAL COST OF NOISE FROM A 10% INCREASE IN VMT, FOR DIFFERENT TYPES OF VEHICLES ON DIFFERENT TYPES OF ROADS, IN URBANIZED AREAS (1991$/1000-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

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

$/1000-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.

FIGURE 14-1. NOISE FALL OFF WITH DISTANCE FROM THE ROAD

noise as a function of distance (Leq(d))

area-noise (ANu,r,h)
(shaded volume)

n
o
i
s
e

l
e
v
e
l

(Leq)

length of road (Lu,r)

noise threshold t*

center of
road (d = 0)

distance to
nearest
house (d)

distance from road (d)

distance at
which Leq
= t* (d t*)
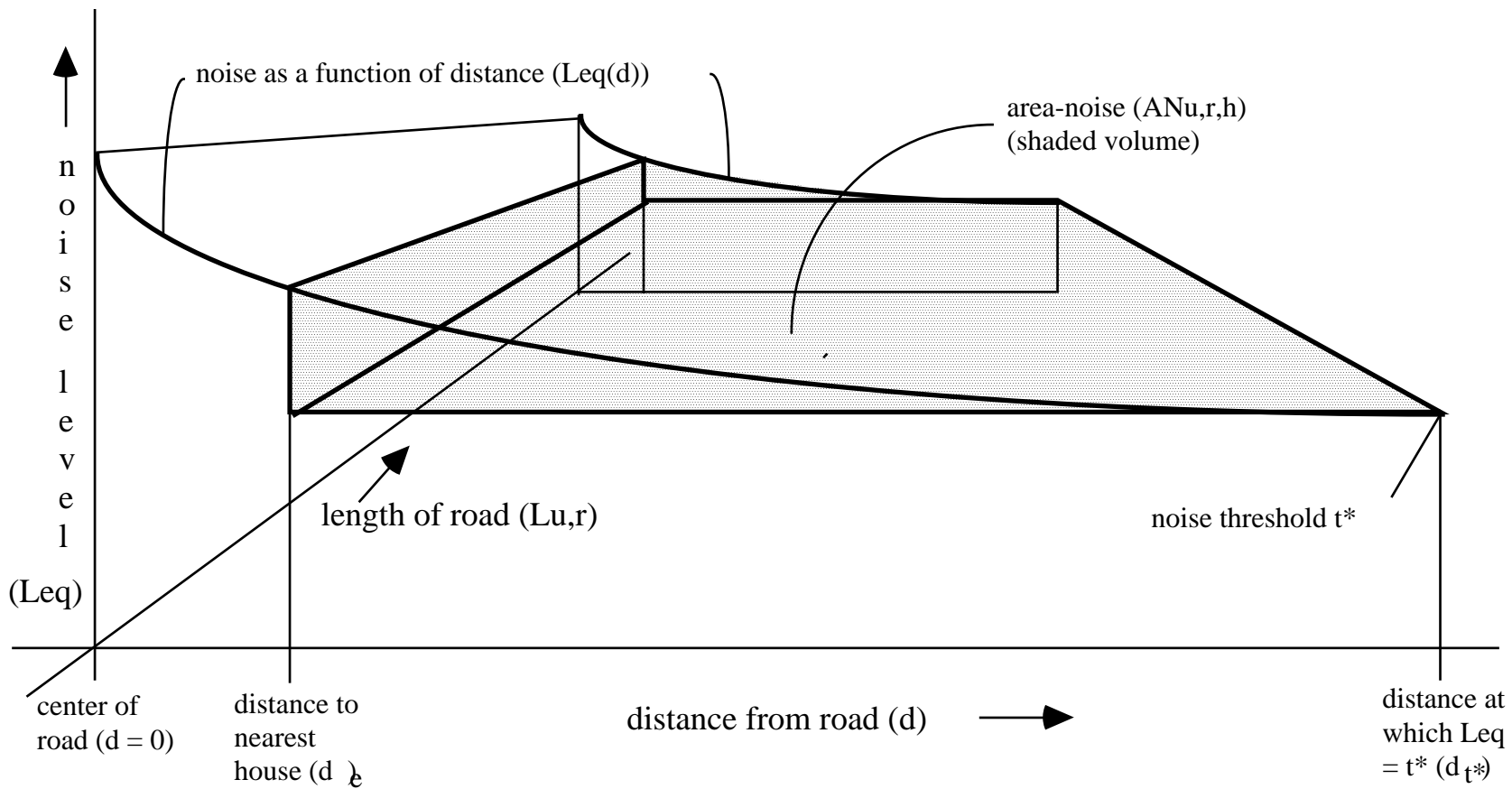
THE EXTERNAL DAMAGE COST OF DIRECT NOISE FROM MOTOR VEHICLES: DETAILS BY URBANIZED AREA

An Appendix to Report #14 in the series: *The Annualized Social Cost of Motor-Vehicle Use in the United States, based on 1990-1991 Data*

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APPENDIX TO REPORT #14: DETAILS BY URBANIZED AREA

This appendix shows the input parameter values and calculated dollar damages for each of the 377 urbanized areas and the aggregated rural area. The urban areas are the rows of the spreadsheet, and the parameter values and calculated results are the columns. The symbols used in the equations in Report #14 are shown in brackets in the column headings of the spreadsheet. (The subscripts are omitted.)
For each area we print out the following seven sets of data:

- population, land area, housing units, housing density, median value (columns C-G)
- miles of roadway, for six types of roads (columns H1-H6)
- daily vehicle miles of travel on six types of roads (columns J1-J6)
- fraction of medium-duty trucks on six types of roads (columns K1-K6)
- fraction of heavy-duty trucks on six types of roads (columns L1-L6)
- hourly traffic volume on six types of roads (columns M1-M6)
- noise impact on homes, for six types of roads (columns N1-N6) (discussed below)

We have printed the results by data set (e.g., miles of roadway, columns H1-H6), where each set shows the data for all of the 377 urbanized areas and the aggregated rural area. Each set of data, for all areas, is 14 pages. On all sheets, the urbanized area is column A, and the state is column B.
For each urbanized area or the aggregated rural area, the first row of values and results pertains to roads without noise barriers; a second row pertains to any roads with a low barrier, a third row to any roads with a medium barrier, and a fourth row to any roads with a high barrier.
The noise impact on homes, in columns N1-N6, is the product of the area-noise measure ($AN_{u,r,h}$), the unadjusted housing density (M_u^*), and the unadjusted median housing value in 1990 (FVO_u^*), divided by one million (see Report #14). To obtain damages in and around the home in urban area **u**, in millions of dollars (DH_u), this product must be further multiplied by an annualization factor (AF), a factor representing housing value lost per excess decibel (HV), a density adjustment factor (AD), housing-value adjustment factors (AHCUS/AOCUS, and AV), and a factor to scale to 1991 dollars ($V_{91/90}$). These parameters are explained in Report #14. Thus, if N_u is the column N result for area **u**, then:

$$DH_u \ (10^6 \ \$) = N_u \cdot AF \cdot HV \cdot AD \cdot AV \cdot V_{91/90} \cdot (AHCUS/AOCUS)$$