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Letter from the Editor

Dear Readers,

With this issue, the *Journal of Transportation and Statistics* completes its first year of publication. The occasion provides a chance to reflect on the mission of the Journal and to clarify its editorial policy. It is also an opportunity to thank Dr. T.R. Lakshmanan, first Director of the Bureau of Transportation Statistics and founder of this journal, for his innovative leadership and intellectual inspiration.

The JTS is about transportation information for an information age. Its fundamental objectives remain unchanged:

- measuring transportation activity and the performance of transportation systems,
- measuring and analyzing the importance of transportation and its consequences,
- measuring and analyzing transportation trends, and
- advancing the science of acquiring, validating, managing, and disseminating transportation information.

As a journal of a federal statistical agency, the JTS will continue to focus on data, description, and analysis and will explicitly avoid policy studies.

Response to the Journal's calls for papers has been good, and I am pleased with the quality of the papers we have published. I thank the authors for their contributions and our editorial board and reviewers for their invaluable expert assistance.

As soon as possible, and most likely by the middle of 1999, it is our intention to begin publishing on a quarterly basis. At that time, we will add a new feature to the Journal: a comprehensive statistical series of transportation indicators. The series will build over a period of a year and will cover all modes and pertain to nearly every major aspect of transportation, from safety to mobility, economics, the human and natural environment, and national security. We hope that this new feature will increase the value of the JTS to its readers.

Your interests, ideas, and recommendations for improving the JTS are important to us. We invite you to communicate with us via e-mail at journal@bts.gov, by visiting our website at www.bts.gov/programs/jts/, or by writing to me at the address on page ii of the journal. Thank you for your interest and support.

DAVID L. GREENE

Editor-in-Chief

The External Damage Cost of Noise Emitted from Motor Vehicles

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ABSTRACT

With a detailed model of the cost of motor vehicle noise in the United States in 1990, we estimate that the external damage cost of this noise could range from as little as $100 million per year to as much as $40 billion per year, although we believe that the cost is not likely to exceed $5 billion (1991$). Our base-case estimate is $3 billion. The wide range is due primarily to uncertainty regarding the cost of noise per decibel above a threshold, the interest rate, the amount of noise attenuation due to ground cover and intervening structures, the threshold level below which damages are assumed to be zero, the density of housing alongside roads, average traffic speeds, and the cost of noise away from the home.

INTRODUCTION

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

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

Noise is a prominent enough problem that it measurably affects the value of homes. Econometric or "hedonic" price analyses measure this effect by estimating the sales price of a house as a function of a number of important characteristics, including the ambient noise level or distance from a major noise source (Nelson 1978; Hall and Welland 1987; O'Byrne et al. 1985). If such an analysis does not omit important determinants of sales price, it can tell us how much an additional decibel of noise (above a certain threshold) reduces the value of a home.[2] This dollar-per-decibel measure, multiplied by the average value of homes, the number of homes exposed to noise above a threshold, and the amount of motor vehicle noise above a threshold, will tell us the external "damage cost" of motor vehicle noise in and around the home. The cost of noise in and around the home then can be scaled by the ratio of time spent in all activities affected by motor vehicle noise to time spent in or around the home, to produce the total external damage cost of motor vehicle noise.

In this paper, we present such a model of the total external damage cost of noise emitted from motor vehicles in the United States. Because of considerable uncertainty in the value of several key parameters, we are able to estimate only the order of magnitude of the cost. Indeed, we find that the cost could range from as little as $100 million per year to approximately $40 billion per year, although we believe that the cost is not likely to exceed $5 billion (1990 data, 1991$). (This range does not include the external damage cost of noise from activities related to motor vehicle use, such as highway construction or the cost of controlling noise.) Our base-case estimate is $3 billion. In sensitivity analyses presented at the end of the paper, we show that this wide range is due primarily to uncertainty regarding the cost of noise per decibel (dBA) above a threshold, the interest rate, the amount of noise attenuation due to ground cover and intervening structures, the threshold level below which damages are assumed to be zero, the density of housing alongside roads, average traffic speeds, and the cost of noise away from the home.

THE NEED FOR THIS ANALYSIS

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

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

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

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

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

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

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

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

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

THE MODEL

General Noise Cost Model

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

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

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

where:

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

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

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

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

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

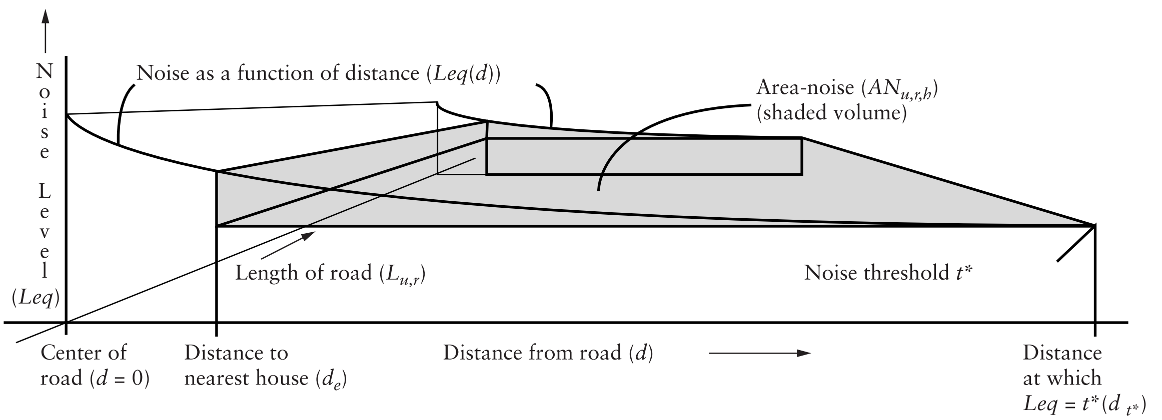
$ANB_{u,r,h}$ = the motor vehicle "area-noise" level below the noise-damage threshold t^* in area u along road type r with noise barrier of height-class h (dBA-ft);

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

---

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

FIGURE 1 Noise Fall Off with Distance from the Road



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

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

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

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

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

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

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

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

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

5,280 = feet/mile.

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

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

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

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

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

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

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

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

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

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

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

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

where:

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

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

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

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

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

50 = the reference distance (feet);

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

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

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

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

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

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

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

24 = hours in a day;

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

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

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

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

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

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

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

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

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

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

Simplifying Assumptions Underlying the Motor Vehicle Area-Noise Submodel

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

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

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

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

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

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

Limits of Integration of Noise Equation

Equation (3), the expression for area-noise level, is the product of $L_{u,r,h}$ 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 estimated the number and width of lanes, the width of dividers and shoulders, and the distance from the closest housing unit to the road edge, for each type of road. Table 1 shows our assumptions for the base case, low-cost case, and high-cost case, and the calculation of the equivalent distance to the closest residence in the base case. Generally, we assumed that housing units can be built up to the edge of the road right-of-way, but not in the right-of-way. On the presumption that barriers usually are built along roads that are relatively close to housing areas, we have assumed that houses typically are closer to roads that have barriers than to roads that do not.

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

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

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

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

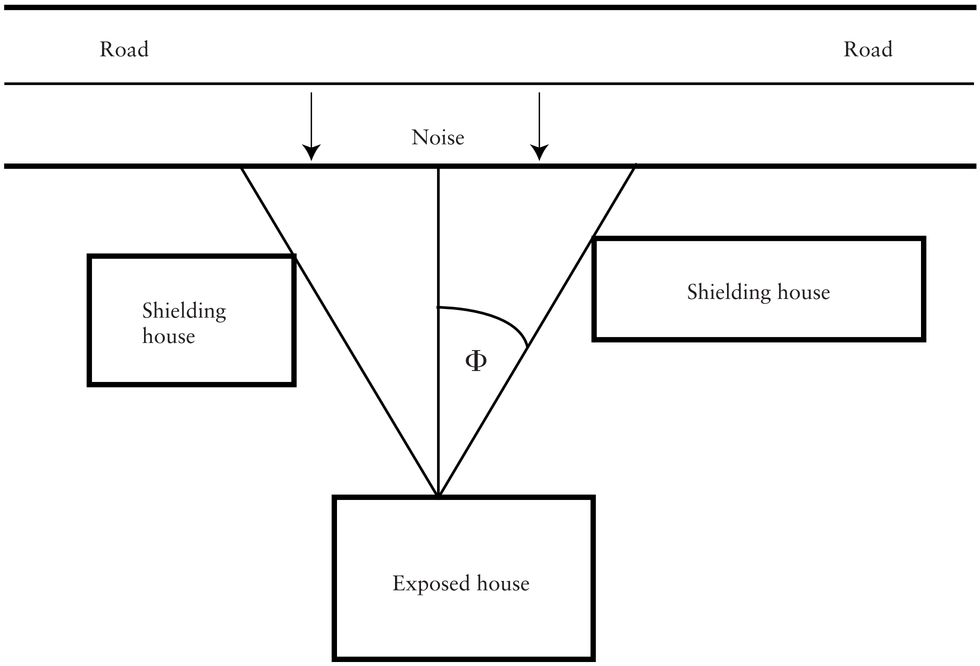
[2] FHWA (USDOT 1992) reports miles of roadway by width of lane and amount of vehicle traffic for Interstates, other freeways, major arterials, minor arterials, and collectors (but not local roads) in urban areas in 1991. With these data, we estimated a mileage-weighted average lane width for each of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

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

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

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

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



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

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

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

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

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

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

Ground-Cover Coefficient (α) (Noise Reflection)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[1] Calculated as:

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

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

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

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

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

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

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

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

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

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

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

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

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

$$M_u^* = H_u / A_u$$

where:

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

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

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

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

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

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

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

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

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

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

where:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Effect of Noise Barriers (B_h)

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

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

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

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

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

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

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

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

[2] Greater noise reduction results in a lower damage cost, and vice versa.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

TOTAL EXTERNAL DAMAGE COST OF NOISE EMITTED FROM MOTOR VEHICLES

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

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

Sensitivity Analyses

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

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

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

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

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

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

TABLE 6 Sensitivity Analyses

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Noise barrier reduction (dBA) (B_h). We also tested the sensitivity of our results to different assumptions regarding the attenuation provided by noise barriers. The variations are shown in table 3, and the results are shown in table 6. The affect in B_h affect 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 they are. Of course, if the costs of a particular project with and without noise barriers are analyzed, then the effectiveness of the barriers (B_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.

Comparison with Other Estimates

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

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

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

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

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

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

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

TABLE 7 The Marginal Cost of Noise from a 10% Increase in VMT, for Different Types of Vehicles on Different Types of Roads, in Urbanized Areas
(In 1991$/1,000 VMT)

A. Base case

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

B. Low-cost case

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

C. High-cost case

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

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

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

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

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

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

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

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

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

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

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

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

Cost of Motor Vehicle Noise Given Noise from Other Sources

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

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

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

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

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

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

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

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

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

CONCLUSION

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

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

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

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

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

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

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

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

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Analyzing the Travel Behavior of Home-Based Workers in the 1991 CALTRANS Statewide Travel Survey

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ABSTRACT

This study compares the travel patterns of three different groups of workers identified in the 1991 Caltrans Statewide Travel Survey: home-based business (HBB) workers, home-based telecommuters (HBT), and non-home-based (NHB) workers. HBB workers have the highest average daily trip rate of the three groups, while rates for HBTs and NHB workers are statistically equivalent. Differences in drive-alone trip rates and time spent traveling are similar to those of other studies, with HBTs making 0.6 (18%) fewer trips and traveling 46% less time than NHB workers. Although HBB workers have the highest work-related trip rate, the NHB group makes nearly twice as many work and work-related trips combined as the HBB group, and more than three times as many as HBTs. The temporal distribution of HBB trips is unimodal, in contrast to the traditional bi-modal distribution for NHB trips and a flat distribution (from 9 a.m. to 6 p.m.) for HBTs. The HBB group is quite heterogeneous, with distinct differences across industry in overall trip rates, freeway use, and rates by purpose.

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INTRODUCTION

Home-based work is a multifaceted phenomenon, encompassing full- and part-time home-based businesses as primary sources of income (whether on a fully self-employed or contract-work basis); moonlighting at a home-based business (HBB) as a secondary source of income; working overtime on evenings and weekends, whose practitioners are sometimes referred to as supplementers (Kraut 1988, 1989) or *work permeators* (Salomon 1990); and home-based telecommuting, in which a salaried employee works at home part or full time instead of commuting to a conventional workplace at the usual time (Mokhtarian 1991).

Definitions and measurement are problematic, but home-based work in all its forms appears to constitute a sizable and growing component of the labor market. Growth in home-based work is related to the increased use of contingent workers (Giuliano 1998), which in turn is driven by a variety of economic and demographic forces, and facilitated by advances in information and communications technologies. The same factors are driving and facilitating a rise in the number of mobile workers, whether home-based or non-home-based—that is, individuals with heavy work-related travel demands (Pratt 1997). Figure 1 illustrates a range of estimates of the number of home-based workers in the United States in recent years, taken from a variety of sources.

To date, most research in this area has focused on the first and last types of home-based work—primary home-based businesses and telecommuting—and this paper is no exception. A number of studies have examined characteristics of home-based workers (Pratt 1984, 1993a; Pratt and Davis 1985; Horvath 1986; Deming 1994; Gurstein et al. 1995), the adoption of home-based work (Bernardino et al. 1993; Mahmassani et al. 1993; Mokhtarian and Salomon 1996, 1997), and impacts of home-based work on the family (Bailyn 1989; Christensen 1988a, 1988b, 1989; Costello 1988; Gurstein 1991; Hall 1989; Mokhtarian et al. 1998; Olson 1988; Salomon and Salomon 1984; Shamir 1991; Shamir and Salomon 1985). Several other studies have analyzed the travel behavior specifically of telecommuters (Kitamura et al. 1990; Pendyala et al. 1991; Hamer et al. 1991; Hamer et al. 1992; Mokhtarian et al. 1995; Henderson et al. 1996; Koenig et al. 1996; Henderson and Mokhtarian 1996; RTA 1995), although these studies are all based on small, specialized, self-selected samples of fewer than 100 telecommuters.

Little or no study has been performed of the travel behavior of HBB workers, even though their behavior may differ from that of conventional, non-home-based (NHB) workers in important ways.[1] For example, HBB workers typically would not have a commute trip *per se*, but their work-related travel may exceed that of NHB workers on average. HBB work-related trips may tend to occur off-peak, but it is not known whether their temporal distribution differs significantly from that of NHB workers' work-related travel. It is not even known how simple indicators such as number of total trips and vehicle-miles traveled (VMT) differ among types of workers.

Typical urban travel demand forecasting practice (Harvey et al. 1993) is to model trip generation rates separately by purposes such as home-based work, home-based other, and non-home-based.[2] Home-based trip generation is modeled as a function of demographic characteristics such as household size and vehicle ownership, and non-home-based trip generation is often estimated simply by factoring home-based trips according to the relative proportions of these types in the calibration sample. Nowhere in the typical trip generation process are the work location (in-home or out-of-home) or employment type (self-employed or salaried) used as explanatory variables, which could be an important omission. For example, if home-based workers tend to replace conventional commute trips with shorter but more numerous work-related trips occurring predominantly off-peak, then a marked increase in the number of home-based businesses may appreciably alter the ratio of commute trips to other trips, as well as the spatial and temporal characteristics of travel for the population as a whole. Thus, in view of the

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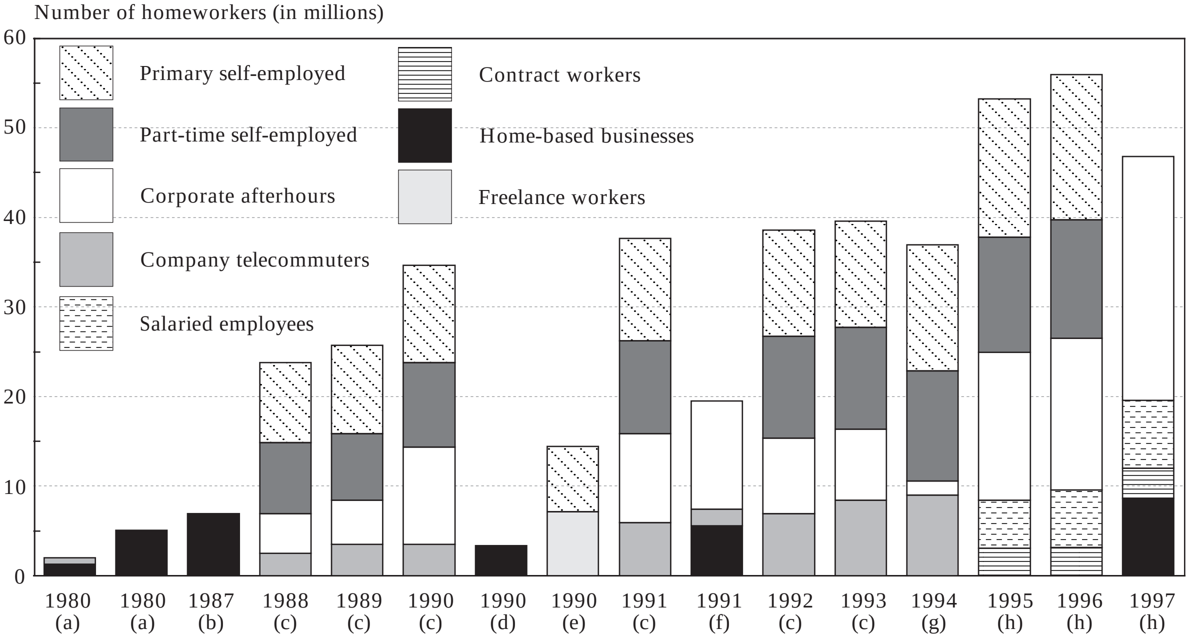
[1] Although this study focuses on the comparison of home-based and non-home-based workers, the same comment could be made for the overlapping groups of contingent and mobile workers.

[2] These descriptions refer to *trips* rather than *workers*, unlike the usage throughout the rest of this paper.

FIGURE 1 Estimates of the Number of U.S. Homeworkers



General note: Different terms are used from one source to the next. There may be overlap between terms taken from different sources, and the same term may mean different things for different sources. The top four categories in the figure legend are mutually exclusive with each other but not always with the bottom two categories, which were generally used in studies different from the first four (1997 being an exception). The fifth and sixth categories form a partition of the fourth category. To reduce the number of category labels used, in some cases the authors of this paper judgmentally classified workers into an existing category. The notes below attempt to use the sources' original language as much as possible.

(a) In the 1980 census, 2.1 million paid workers reported that they "usually got to work the previous week" by "working at home," as cited in Pratt and Davis (1995). Of these, 1.3 million were employees of their own company or self-employed but unincorporated. The remainder were salaried employees of public or private organizations. A 1980 taxpayer usage study of federal income tax returns, cited by the same source, estimated the number of nonfarm proprietors located at home to be 5.1 million. Many of these are likely to constitute moonlighting or hobby activities rather than primary jobs.

(b) The 1987 Characteristics of Business Owners survey cited in Pratt (1993b) found 7 million home-based businesses, "including the majority of women-owned businesses (54.6%) and nearly half of all non-minority male-owned businesses (49.8%)." Note that the number of home-based businesses will not equal the number of home-based business workers, because a single individual may work in more than one home-based business (Pratt and Davis 1985) and a single business may employ more than one worker in the home.

(c) The number of home-based workers of all kinds (including afterhours work) increased from nearly 25 million in 1988 to 39 million in 1993, according to the Annual Work at Home Survey conducted by Link Resources, cited in Braus (1993). Braus discusses the discrepancy between the Link Resources numbers and the CPS numbers (see note f).

(d) The 1990 census reported 3.4 million workers who "usually got to work the previous week" by "working at home," as cited in USDOT (1994).

(e) A 1990 proprietary survey cited in Pratt (1993b) found 7.4 million home business owners (including moonlighters), plus 7.2 million freelance workers.

(f) The May 1991 Current Population Survey (Deming 1994) found 20.0 million nonfarm employees (18.3% of the workforce) doing some work at home for the primary job: 12.2 million of these were work permeators doing overtime work at home for no extra pay, 1.9 million were telecommuters, and the remaining 5.6 million were home-based businesses. However, despite the fact that the work at home was to be associated with the primary job for all of these workers, only 3 million of the 5.6 million self-employed homeworkers worked eight hours a week or more, and only 976,000 of them worked 35 hours a week or more.

(g) Source: Find/SVP Annual Work-at-Home Survey, personal communication with Joanne H. Pratt representing Find/SVP. The 1994 data for company telecommuters (defined by Find/SVP to include contract workers as well as salaried employees) is also cited in Russell (1996).

(h) Source: Undated (1997) press release on the Find/SVP web site at http://etrg.findsvp.com/prls/pr97/ telecom.html. At the time of this writing, this source was difficult to interpret: e.g., it states that 52.1 million Americans do some form of work at home, but the following subcategories "bring work home" (27.5 million), "telecommute" (11.1 million, earlier disaggregated into 7.7 million conventional salaried employees and 3.4 million contract workers, but the current version is confusing on this point) and "operate a home business" (8.7 million) only add to 47.3 million. Separately, 18.3 million Americans are projected to be self-employed and do some work at home, but this group partially overlaps the previous one.

growing popularity of both types of home-based work, it is important to increase our understanding of their travel characteristics.

This paper describes a first effort to analyze the travel behavior of HBB workers. It also offers the first representative-sample investigation of the telecommuting-day travel behavior of telecommuters. Due to limitations of the data it is not the definitive study, but the findings presented here constitute a useful foundation on which to pursue further research. This paper uses the 1991 California State Department of Transportation (Caltrans) Statewide Travel Survey data to compare key travel indicators across three groups: home-based business workers, home-based telecommuters (HBT), and non-home-based or conventional workers. The next section describes the data set and how the sample used in this study was defined. The following section presents the comparison of travel measures (trips and travel time in total and by purpose, mode, and time of day) across the three study groups, and the final section offers some conclusions and directions for further research.

DATA AND SAMPLE SELECTION

Overview of the Data Set

In 1991, Caltrans conducted a statewide travel survey (Ochoa and Jones 1993). Nearly 34,000 individuals provided travel information for a 24-hour period on a weekday. Respondents recorded trip data in a "memory jogger" format, later retrieved through telephone interviews. Each respondent was weighted appropriately to replicate the 1990 Census distributions in terms of household vehicle ownership, owner/renter status, and geographical location.

The data were collected for general transportation analysis purposes, and not specifically for the study of home-based work. This constitutes both a strength and a weakness for the current study. The strength lies in the fact that the sample is large and representative. Empirical telecommuting research to date has been based primarily on specific small-scale demonstration programs that usually have an explicit goal of reducing travel. Participants in these programs tend to be geographically localized and self-selected, and may be biased in favor of demonstrating positive transportation impacts of telecommuting. Such a bias is not likely to be present in the statewide data, which were not gathered in the context of a telecommuting program. Thus, it will be of interest to compare the telecommuting-day travel patterns found for telecommuters in this sample, and differences between telecommuters and conventional workers, with those of previously published specialized-sample studies. Any similarities of findings will provide greater confidence in the robustness of both previous and current results. Differences in findings may suggest avenues of further research.

Such a comparison will not be definitive, however, due to the weakness of the statewide data set. Because the data were not collected specifically with home-based workers in mind, identification of these workers is indirect and approximate, as discussed below. Another weakness of the data set that limits the insight that can be obtained into the travel patterns of HBB workers is the lack of information on the occupation of the tripmaker. HBB workers are quite heterogeneous—including, for example, farmers, live-in domestics, artists and craft workers, providers of services within the worker's home (e.g., beauty shops, child care, or electronics repair), providers of external but location-dependent services (e.g., plumbing, electrical, and painting), providers of products prepared in the home and delivered (catering), professional consultants (e.g., accounting/tax, legal, management, planning), and clerical workers (e.g., word processing, transcription, data entry). Travel characteristics will vary across these segments. Some information is available on the industry in which the tripmaker works (the five categories of retail trade, services, education, government, and other), but as occupations may vary widely within industry, this variable is of limited value. Finally, a major shortcoming of the database is that trip lengths were not directly collected, so it is not possible to analyze VMT, person-miles traveled, or emissions across the study groups. Travel times and proportion of trips using the freeway are analyzed as surrogates for distances.

Definition and Selection of Comparison Groups

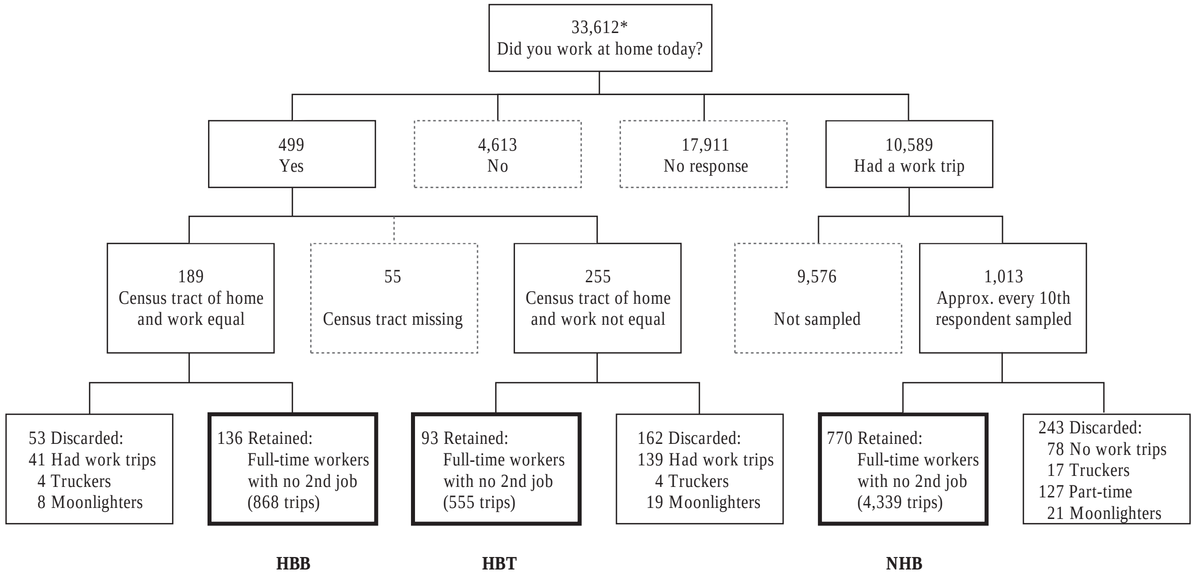
Although the statewide data were not collected specifically for a study of home-based work, the survey had one uncommon and critical feature. Telephone interviewers were instructed to ask respondents who were employed, but who did not report a work trip, whether they worked at home on the designated day. The response to that question formed the basis for identifying the comparison groups to be used in this study. Figure 2 illustrates the filtering process used to create the final sample. Three responses to the question were coded: yes, no, and had a work trip. It is assumed that those with no response coded are for the most part not employed. To reduce the group having a work trip to a manageable size, an initial 1-in-10 sample of this group was selected before applying any further screens.

To distinguish between home-based businesses and telecommuters, the census tracts of the home and workplace were compared. Those who indicated working at home were classified as HBB workers if the census tract of their home matched the census tract of their workplace, and were classified as telecommuters if the two census tracts did not match (see Handy and Mokhtarian 1995 for an earlier use of this criterion on the same data set). Obviously it is possible for a telecommuter's regular workplace to be close to home and so this rule may misclassify some HBTs as HBB workers, but such cases are expected to be relatively infrequent as telecommuters' commute distances tend to be longer than average (Mokhtarian et al. 1995) and as census tracts are not generally very large.

Another key decision was to discard from the analysis respondents who indicated that they had a second job (moonlighters). For moonlighters who worked at home, it was not possible to tell whether the home-based work was for their primary or secondary job. If the latter were the case, such workers could be mistakenly classified as telecommuters when in fact they were conventional employees. Further, preliminary exploration indicated that the tripmaking behavior of moonlighters was not typical, with higher average trip rates in every study group than the remainder of the group. To be consistent, moonlighters were eliminated from all three study groups.

Despite written instructions to ask the question "did you work at home today" only when a work trip had not been reported, measurement errors of some kind resulted in a number of respondents in the home-based work category in fact reporting a

FIGURE 2 Selection of Comparison Groups



* Unweighted number of respondents.

trip to work (not just work-related, which was coded differently). Since that cast some doubt on the validity of their classification as home-based workers, those respondents were removed from the analysis. Conversely, for several individuals who had been coded as having a work trip, no such trip was found for them. Those respondents were also discarded. Since neither group of home-based workers contained any part-time workers, part-timers were removed from the NHB group as well for consistency. Those who drove or rode in trucks other than pick-ups were also removed from all three groups.

Some of those classified as NHB workers may in fact be telecommuters who were not telecommuting on the designated data-collection day. If telecommuting occurs, say, 1.2 days a week or 24% of the time on average (as found by Handy and Mokhtarian 1995), then this one-day travel diary may have captured only about 24% of telecommuters in the sample on their telecommuting day. First, however, there is no way to identify and remove telecommuters from the NHB group. Second, the 76% of telecommuters who would be misclassified as NHB workers would still constitute a small proportion of the total NHB sample. Third, it may be expected that telecommuters' travel on an ordinary commuting day would not differ greatly from that of nontelecommuters with similar sociodemographic characteristics. Although previous studies (e.g., Henderson et al. 1996; Koenig et al. 1996) found that telecommuters' nontelecommuting-day travel differed from that of a nontelecommuting control group (with telecommuters traveling significantly longer distances), the difference appeared to be primarily due to telecommuters having a longer average commute length rather than to spillover effects of telecommuting onto nontelecommuting days. Fourth, there is little reason to believe that telecommuters who were misclassified in that way differ materially from those who *were* classified as HBT, and if that is true, the group classified as HBT constitutes a representative sample of telecommuters. As such, a representative picture of telecommuters' travel behavior is presented, and it is travel behavior rather than the precise size of the segment that is the focus of this paper.

The groups analyzed here, then, were of the following sizes (unweighted): HBB = 136 people, 868 trips; HBT = 93 people, 555 trips; NHB = 770 people, 4,339 trips. The weights described earlier were applied to each case, with the total weighted sample size normalized to equal the unweighted sample size of 999 to retain the validity of the statistical tests. As the same weight belonging to an individual was applied to all trips made by that individual, the weighted number of trips will not equal the unweighted number if trip rates are not independent of the case weight (e.g., if more heavily weighted respondents tend to make fewer trips). The weighted sample sizes are: HBB = 109 people, 668 trips; HBT = 79 people, 414 trips; NHB = 811 people, 4,323 trips. The differences between the unweighted and weighted sample sizes imply that home-based workers of both types were overrepresented in the raw sample. All subsequent analysis is conducted on the weighted version of the sample.

Socioeconomic Characteristics of the Sample

Table 1 summarizes key socioeconomic characteristics for each of the three study groups. Because individual comparisons are of interest, pairwise t-tests were conducted for the (quasi-) continuous variables age, number of people in the household, number of people 5 years old or older, and number of vehicles; whereas chi-square tests were conducted for the categorical variables gender, dwelling unit type, industry, and income.

Taking each variable in turn, it can be seen that telecommuters are marginally ($p = 0.18$ and 0.07) older (2½ years, on average) than members of the other two groups, whose average age is nearly 40. The gender distribution was not significantly different across groups ($p = 0.17$). The relatively low proportion of women (36.7%) in the telecommuter group is counter to the stereotype that telecommuting appeals more heavily to working mothers trying to balance family and career, and contrasts with at least one empirical study finding equal proportions of men and women telecommuting (Mokhtarian et al. 1998). It is, however, consistent with the most recent Find/SVP annual nationwide survey of home-based work in the United States, which reports that approximately one-third of telecommuters are female (Gordon

TABLE 1 Socioeconomic Characteristics of the Sample

		Group (weighted size)^1		
Variable	**Indicator**	**HBB (109)**	**HBT (79)**	**NHB (811)**
Age	Mean	39.7	42.2	39.7
Gender	% female	50.5	36.7	45.8
No. in household$^{BT, BN, TN}$	Mean	2.5	3.3	2.9
No. ≥ 5 yrs. old$^{BT, BN}$	Mean	2.4	2.8	2.7
No. of vehicles	Mean	2.1	2.4	2.3
Dwelling unit type	% single family house	77.1	77.2	74.3
Industry*	% retail trade	5.6	3.8	12.7
	% services	48.6	28.2	35.4
	% education	7.5	12.8	7.2
	% government	—	5.1	15.2
	% other	38.3	50.0	29.5
Annual household income	% < $20 K	9.0	8.1	8.8
	% $20–35 K	24.0	16.2	23.8
	% $35–50 K	22.0	31.1	24.9
	% $50–75 K	17.0	28.4	22.2
	% > $75 K	28.0	16.2	20.3

[1] Sizes are smaller for some variables due to missing data.

Key: BT: HBB and HBT are significantly different ($\alpha = 0.05$); BN: HBB and NHB are significantly different; TN: HBT and NHB are significantly different; *: group type and industry are not independent (χ^2 test, $\alpha = 0.05$).

1997). Other researchers (e.g., Olson and Primps 1984; Bailyn 1989; Holcomb 1991) have identified two tiers of home-based workers: the predominantly female tier of clerical workers and the more heavily male tier of professional workers. It is quite possible that among telecommuters the latter tier is larger than the former.

The proportion of females among the HBB workers is 50.5%. By comparison (Deming 1994), in the 1991 Current Population Survey (CPS), women constituted 48.1% of those who worked at home for pay at least eight hours a week,[3] and 59.1% of those working at home for pay at least 35 hours a week (9% of the total being telecommuters). The proportion of women (45.8%) in the NHB group is virtually identical to the proportion of women in the U.S. civilian labor force as a whole in 1991 (USDOC 1995, table 628).

On the other hand, in keeping with the stereotype, telecommuters do have significantly larger households on average than the other two groups, and more children under age 5. Perhaps surprisingly, though, home-based business workers have the lowest number of people and young children in their households. Similarly, telecommuters have the most vehicles in their households, and HBB workers have the least (the difference being marginally significant at p = 0.07). Both types of home-based workers are slightly more likely to live in single-family houses than members of the NHB group, which is consistent with their needs for work space at home, but the difference is not significant.

Turning to industry of employment, HBB workers are more likely to be found in services (48.6%) and "other" (38.3%) industries than the other two groups. By comparison, the 1991 CPS classified as service industry 54.0% of the group working at home for pay at least eight hours a week (HBBs and HBTs). The service industry encompasses businesses as diverse as plumbing and management consulting. There are no government workers in this group, which is as expected and therefore engenders some confidence in the criterion used to define the group.

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[3] This group comprises both telecommuters and self-employed workers as a separate breakdown by gender was not provided, but telecommuters are only 16% of the total.

Fully half of all telecommuters are found in the "other" category, which is obviously quite broad, with services being the next largest industry at 28.2%. A higher proportion of telecommuters are in education (12.8%) than are conventional workers (7.2%), which is plausible in view of the flexibility enjoyed by many workers in that industry. It is also natural that relatively few telecommuters are in the retail trade industry (3.8%, compared to 12.7% for NHB workers). It may be surprising that proportionately fewer telecommuters are in government, in view of the numerous public-sector telecommuting programs in California, but a high proportion of NHB workers in government are likely to hold location-dependent jobs such as those of police, firefighters, garbage collectors, meter readers, and building inspectors.

The distribution of NHB workers across industries is roughly consistent with that of the U.S. workforce as a whole. The 1991 CPS reports 16.5% and 35.1% of all workers in the retail trade and service industries, respectively, compared with 12.7% and 35.4% for the Caltrans sample taken the same year. Other industry categories were defined differently in the two studies, so that direct comparisons cannot be made.

Although all three groups share the same median annual household income category of $35,000 to $50,000, there are some interesting minor differences in distribution across the groups. Income is unimodally distributed for the HBT and NHB groups, but bi-modally distributed for the HBB workers. Almost half (46%) of the HBB group falls into the $20,000 to $50,000 range, but more than one-quarter of the group is in the single category of more than $75,000. Sixty percent of the HBT group falls into the $35,000 to $75,000 range, but another 16% lie in the highest category of more than $75,000. The NHB group has the most uniform distribution of the three.

COMPARISON OF TRAVEL INDICATORS

Table 2 presents selected mean trip rates (one-way, unlinked trips) for each of the three groups, and figures 3–5 illustrate trip shares by purpose, mode, and time of day for each group. Patterns are similar for rates and shares, but their contributions are complementary rather than redundant. Because the per-capita trip totals are not identical across groups, in any given category shares could be similar between two groups while rates are different, or conversely. Table 3 presents mean travel time by purpose and mode for each group.

TABLE 2 Daily Mean Trip Rates by Group

	Group		
Variable	**HBB 109 people 668 trips**	**HBT 79 people 414 trips**	**NHB 811 people 4,323 trips**
Total person-trips	6.1	5.2	5.3
% trips using freeway$^{BN, TN}$	21.2	23.7	39.1
Trips by purpose^{1}*			
Work	—	—	1.3
Work-related	0.9	0.5	0.4
Social/recreation/ shop	1.3	1.4	0.9
School	0.0	0.1	0.1
Serve passenger	0.3	0.4	0.3
Change mode	0.2	—	0.1
Other	1.5	1.1	0.7
Return home	1.9	1.8	1.6
Trips by mode*			
Drive alone	3.5	2.7	3.3
Carpool	1.6	2.2	1.5
Transit/other	0.2	0.0	0.2
Bicycle/walk	0.8	0.3	0.3
Trips by time of day*			
Midnight to 3 a.m.	0.0	0.0	0.0
3 to 6 a.m.	0.0	0.1	0.2
6 to 9 a.m.	1.0	0.5	1.1
9 a.m. to noon	1.7	1.3	0.8
Noon to 3 p.m.	1.3	1.4	0.9
3 to 6 p.m.	1.0	1.4	1.4
6 to 9 p.m.	1.0	0.5	0.8
9 p.m. to midnight	0.1	0.1	0.2

[1] For the χ^2 test, the work and work-related categories were combined, and the school, change mode, and "other" categories were combined, to avoid small cell sizes.

Key: — means absolutely zero trips, whereas 0.0 means zero rounded off (i.e., fewer than 0.05); BN: HBB and NHB are significantly different ($\alpha = 0.05$); TN: HBT and NHB are significantly different; *: group type and the row variable are not independent (χ^2 test, $\alpha = 0.05$).

Total Trips

Perhaps not surprisingly, HBB workers have the highest average number of daily person trips, at

6.1. Since the variance for this group is relatively higher than for the other two groups, however, the HBB-HBT difference is not significant, and the HBB-NHB difference is only significant at p = 0.09. It could be expected that HBB workers would make more work-related trips than the other two groups, and this is confirmed by table 2. However, the table and figure 3 illustrate that HBB workers also have higher trip rates and shares for other trip purposes as well, including social/recreation/shop, return home, and "other."

Telecommuters have the lowest trip rate of the three groups, which is in keeping with conventional wisdom and which has been empirically demonstrated in the small-scale studies cited earlier (both when telecommuters have been compared with nontelecommuters and when their own travel has been compared on telecommuting and non-telecommuting days). However, it is noteworthy that the rate for conventional workers is just 0.1 trips per person per day higher than that for telecommuters, a difference that is not statistically significant (p = 0.78). Previous studies (Pendyala et al. 1991; Henderson et al. 1996) have found differences of 1.7–2.0 trips a day between telecommuters (on their telecommuting days) and nontelecommuters. One reason for this contrasting result may be that at least one previous study

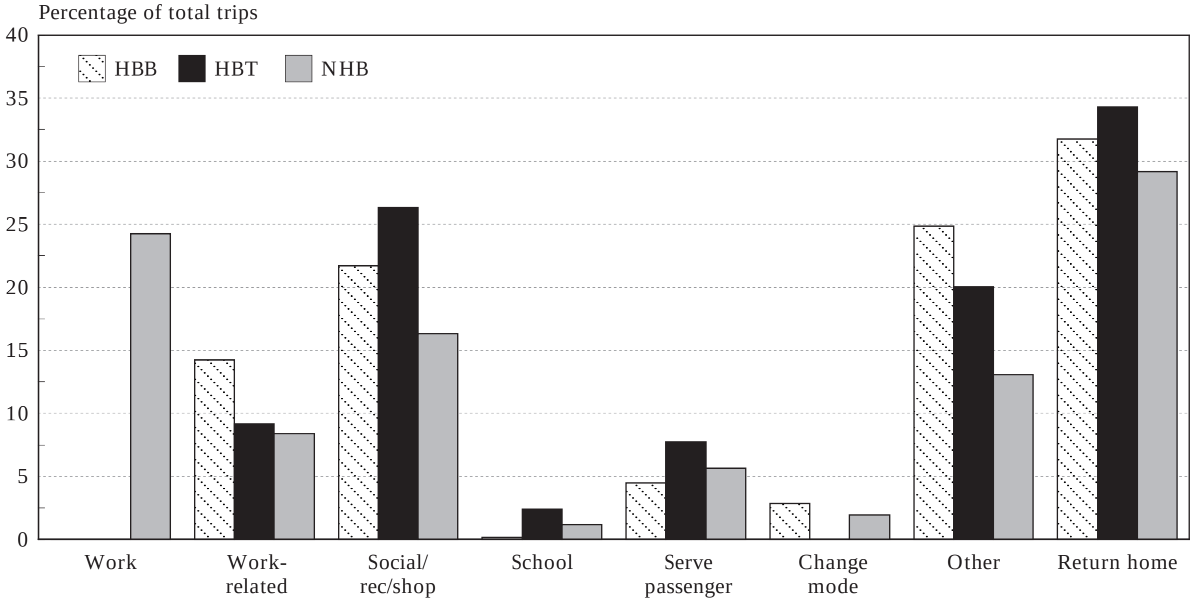
TABLE 3 Daily Mean Travel Time by Group

	Group		
Variable	**HBB** **109 people** **668 trips**	**HBT** **79 people** **414 trips**	**NHB** **811 people** **4,323 trips**
Total person travel time (hours)[BN]	1.43	1.50	1.77
Hours by purpose[1]*			
Work	—	—	0.46
Work-related	0.25	0.15	0.15
Social/recreation/shop	0.30	0.35	0.23
School	0.00	0.05	0.03
Serve passenger	0.04	0.11	0.08
Change mode	0.02	—	0.04
Other	0.39	0.28	0.21
Return home	0.43	0.56	0.56
Hours by mode*			
Drive alone	0.82	0.62	1.14
Carpool	0.41	0.77	0.47
Transit/other	0.03	0.01	0.09
Bicycle/walk	0.17	0.10	0.06

[1] For the χ^2 test, the work and work-related categories were combined, and the school, change mode, and "other" categories were combined, to avoid small cell sizes.

Key: — means absolutely zero travel time, whereas 0.00 means zero rounded off (i.e., fewer than 0.005 hours); BN: HBB and NHB are significantly different ($\alpha = 0.05$); *: group type and the row variable are not independent (χ^2 test, $\alpha = 0.05$).

FIGURE 3 Distribution of Trips by Purpose



(Koenig et al. 1996) found a small number of commute trips being made by telecommuters on telecommuting days, whereas in this study people making work trips were eliminated from the HBT sample to prevent the likely misclassification of a conventional worker as a telecommuter. However, the average number of 0.1 daily vehicle commute trips by telecommuters seen in that earlier study would compensate for at best a small part of the difference.

Differences in travel patterns may be indirectly inferred from the proportion of trips that involve freeway use. Nearly two-fifths of NHB trips used the freeway, compared with 21% to 24% for the other two groups. If freeway use can be taken as a proxy for distance, then this result suggests that NHB workers travel significantly farther than do the HBB workers and telecommuters on their telecommuting days, which again is in line with expectations and with findings of previous telecommuting studies.

Trips by Purpose

Examining the trip purpose distribution more closely, for the two home-based groups (by design), neither of them have any "work trips" (i.e., trips for which "work" was the stated purpose at the destination). The NHB group has 1.3 work trips per day, one of which is the commute trip and the remainder being trips back to the workplace in the middle of the day. Although HBB workers have the highest number of work-related trips (0.9), the NHB group makes nearly twice as many work and work-related trips combined as the HBB group, and more than three times as many as the HBTs. HBTs, however, make slightly more work-related trips (0.5) than the NHB workers (0.4).

Telecommuters have the highest social/recreation/shop trip rate of the three groups, potentially a reaction to the more isolated nature of their workday. This is consistent with Balepur et al. (1998), who found somewhat higher proportions of shopping and social/recreational trips by telecommuters on telecommuting days than on their nontelecommuting days and by nontelecommuters. It is also consistent with Gould et al. (1998), who found that home-based workers spent more time shopping and traveling to shopping than did office workers. HBB workers make the most "return home" trips, followed closely by the telecommuter group. This suggests that less trip chaining takes place for these two types of workers.

Trips by Mode

Turning to the distribution of trips by mode, table 2 and figure 4 show that home-based business workers and NHB workers have similar rates and shares of drive-alone, carpool, and transit/other trips, although trip rates are slightly higher in the HBB group for drive alone and carpool. Most of the difference in total daily trips between the HBB and NHB groups lies in the higher number of bicycle/walk trips by the home-based business workers. Cross-tabulation of mode and purpose (not shown) indicates that these nonvehicular trips by the HBB group are predominantly for social/recreation/shop (0.34), other (0.21), and return home (0.17) purposes.

Telecommuters have a different mode split from the other two groups. They make fewer drive-alone trips, more carpool trips, and a negligible number of transit/other trips. These results are likely derived from the larger household sizes for this group observed in table 1, with differences in share also deriving from the lack of a commute trip. Interestingly, the bicycle/walk trip rate for telecommuters is equivalent to that for NHB workers, not to the higher rate for HBB workers as

FIGURE 4 Distribution of Trips by Mode

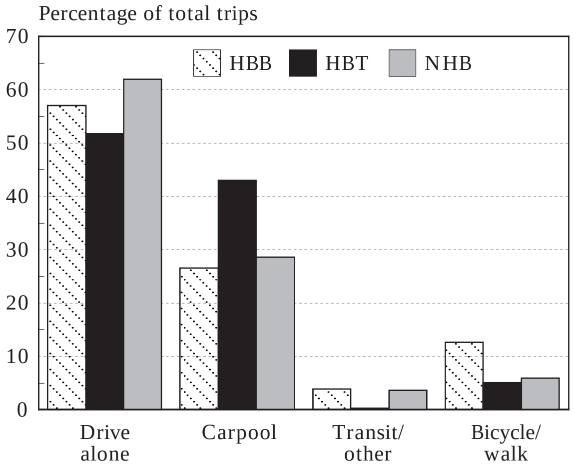
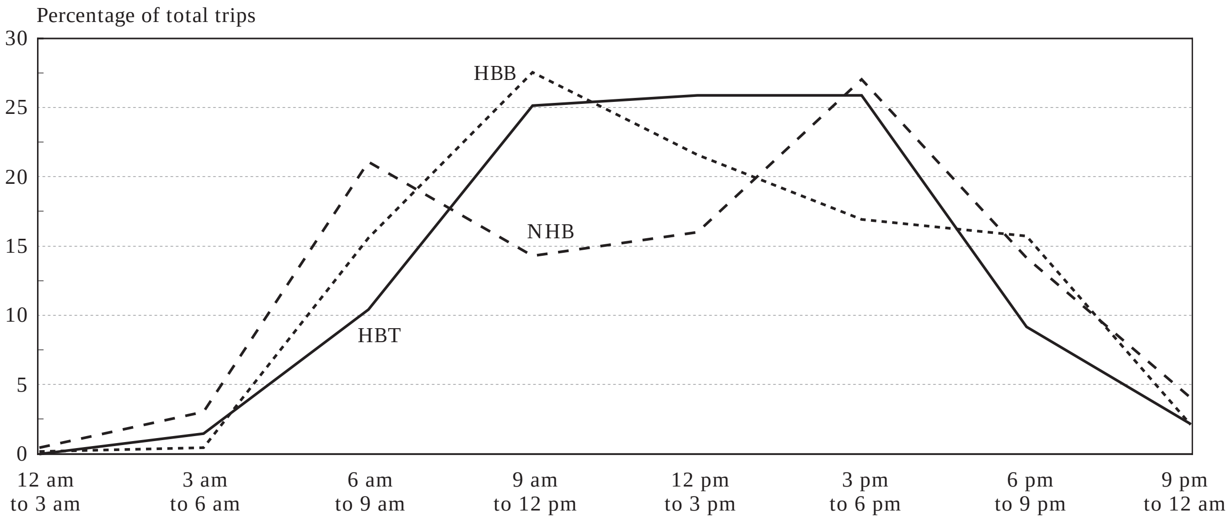


FIGURE 5 Distribution of Trip Start Times by Time of Day



might have been expected. Also, the small number of transit trips on telecommuting days is similar to the results of previous studies in the United States (particularly Mokhtarian et al. 1997) and the Netherlands (Hamer et al. 1992), but those studies have found higher rather than lower shares of drive alone trips by telecommuters on telecommuting days (e.g., Pendyala et al. 1991; Henderson et al. 1996; Mokhtarian et al. 1997).

Importantly, unlike the case for total trips, the difference in daily drive-alone trip rates between HBT (2.7) and NHB workers (3.3) is comparable to those found in other studies. Koenig et al. (1996) reported nearly identical rates of 2.73 drive-alone trips by telecommuters on telecommuting days and 3.29 drive-alone trips by nontelecommuters. The Roads and Traffic Authority (RTA 1995) of New South Wales reported daily averages of 2.37 car trips (including carpool) by telecommuters on telecommuting days and 3.14 car trips for the nontelecommuting control group. The results of Henderson et al. (1996) are not as close (2.58 and 4.33 drive-alone trips per day, respectively), but are still generally similar. It has been argued elsewhere (e.g. Koenig et al. 1996) that it is the reduction in drive-alone trips due to telecommuting that is most important, since those are the only trips that materially affect congestion and air quality.

Trips by Time of Day

Table 2 and figure 5 show the trip rates and shares, respectively, classified by the time of day the trip started. The temporal distributions are quite different for the three groups. The NHB group exhibits the traditional bi-modal distribution, with a morning peak and a larger afternoon peak. The HBB distribution is unimodal, with a peak in the 9 a.m. to noon interval and with sizable but successively declining shares later in the day. The relatively low trip rate in the 3 p.m. to 6 p.m. interval is particularly interesting, suggesting that this group is more successful at avoiding the afternoon peak (for whatever reasons) than the other two groups. The HBT distribution is almost exactly symmetric about the noon to 3 p.m. interval and is flat rather than peaked. That is, trips are uniformly distributed across the nine hours from 9 a.m. to 6 p.m., with 77% of the total for HBT falling in that range. By comparison, 66% of HBB trips and 57% of NHB trips fall within the same nine hours. The finding that telecommuters travel less during peak periods than nontelecommuters is consistent with Pendyala et al. (1991).

Travel Time

Table 3 shows that HBB workers have the lowest average daily travel time, although they have the highest trip rate of the three groups (see table 2). Because they also travel more in the offpeak, when average speeds are higher, this partially confounds any conclusion about distance traveled. However, the other surrogate indicator of distance, proportion of trips using the freeway, is also lowest for the HBB group, which suggests that they do in fact travel the shortest distance.

As expected, NHB workers travel the longest, an average of about 16 minutes (difference significant at p = 0.09) and 20 minutes (p = 0.02) longer than HBT and HBB workers, respectively. Their one-way commute trip is about half an hour, and probably because of the trip home from work, they spend the most time returning home of the three groups. NHB workers spend less time than the others in travel for social/recreation/shop and "other" activities. Consistent with the results for number of trips, telecommuters spend more time than the other workers in travel for social/recreation/shop purposes, and they also spend the most time on serve passenger trips (again related to their larger household sizes).

As for travel time by mode, the HBB and NHB workers have roughly comparable times and shares for the drive alone, carpool, and transit/other modes. Contrary to the case for trips but consistent with the comparison for overall travel time, NHB workers spend more time in each mode. As with number of trips, HBB workers spend the most time bicycling/walking of the three groups. Telecommuters have a different distribution from the other two groups, with the shortest drive-alone time and the longest carpool time. Although telecommuters and NHB workers make equal numbers of bicycle/walk trips, telecommuters spend a few minutes longer on such trips than the other group. This is a natural result in view of the time telecommuters save by not making the commute and the potential desire to compensate for a lower level of physical exercise during the workday itself, relative to the NHB group.

Telecommuters spend 46% less time driving alone than NHB workers. This compares consistently with previous studies that found that telecommuters on their telecommuting days had 42% (Henderson et al. 1996) and 67% (Koenig et al. 1996) fewer vehicle-miles traveled than a non-telecommuting control group, where only drive-alone trips were counted in the VMT totals.

HBB Worker Differences by Industry

Because so little is known about the travel behavior of HBB workers, it is useful to examine that group in more detail. In particular, because the group is so heterogeneous, it is instructive to analyze differences in trip rates and trip purpose distributions across industry. It should, however, be cautioned that sample sizes within industry groups are small (unweighted sizes of 15, 67, 7, and 42 for the four industry groups respectively; weighted sizes as shown in table 4), and hence this analysis can only be suggestive rather than conclusive.

Table 4 presents the comparison, which shows clear differences across industries. Overall trip rates are much higher for workers in the retail trade (7.5) and service industries (7.2) than for education (5.4) and "other" (4.9). There are substantial differences in freeway use among the groups. The retail trade group uses a freeway 36% of the time, four times as often as the education group. Despite having overall trip rates similar to the retail trade group, the services group uses the freeway for only 19% of its trips. The "other" group uses the freeway almost three times as much (25%) as the education group (9%; difference significant at p = 0.09), despite making fewer trips altogether.

The breakdown of trip rates by purpose sheds further light on the differences in overall trip rates. HBB workers in retail trade make more than twice as many work-related trips on average (2.6 per day) as those in the other three groups. Many of these may be deliveries or sales calls, which would be consistent with the high level of freeway use by this group. Workers in the "other" industry category, on the other hand, make very few work-related trips: on average, fewer than one in three of these workers makes such a trip on a given day. Although this group includes a wide variety of industries (financial/insurance/real estate, transportation/utilities/communications, manufacturing, wholesale trade, agriculture, forestry, fisheries, mining, and construction), it may be dominated by largely location-dependent work such as agriculture. It is notable that this group has the highest social/recreation/shop trip rate of the four, suggesting that there may be some tradeoff between mobility at work and mobility for leisure.

TABLE 4 Home-Based Business Workers' Travel by Industry

Variable	Retail trade 6 people 43 trips	Services 52 people 372 trips	Education 8 people 44 trips	Other 41 people 197 trips
Total person-trips^{SO}	7.5	7.2	5.4	4.9
% trips using freeway^{RE}	36.0	19.4	9.0	25.3
Trips by purpose[1]*				
Work	—	—	—	—
Work-related	2.6	1.1	1.2	0.3
Social/recreation/shop	1.2	1.3	0.5	1.6
School	0.1	0.0	0.0	—
Serve passenger	0.3	0.3	0.8	0.2
Change mode	—	—	—	0.5
Other	1.3	2.0	1.1	1.0
Return home	1.5	2.6	1.8	1.3

Industry

[1] For the χ^2 test, the work and work-related categories were combined, and the school, change mode, and "other" categories were combined, to avoid small cell sizes.

Key: — means absolutely zero trips, whereas 0.0 means zero rounded off (i.e., fewer than 0.05); SO: Services and Other are significantly different ($\alpha = 0.05$); RE: Retail trade and Education are significantly different; *: group type and purpose are not independent (χ^2 test, $\alpha = 0.05$).

The services group has much higher trip rates for "other" and return home purposes than the other three groups. The high return home trip rate suggests that this group engages in trip chaining to a lesser degree than the others. A final point of note in the table is the relatively high number of serve passenger trips for workers in the education industry (again, however, these are based on a small sample). These could be in-home childcare providers taking their charges on a field trip, or perhaps school bus drivers. In either case, those trips would more accurately have been classified as work-related, but the distinction is rather weak. Some of those trips could be teachers taking their own family members to various activities. This group has the lowest social/recreation/shop trip rate of all (rates for the other groups are two and a half to three times as high), again suggesting some kind of tradeoff among activities.

CONCLUSIONS

Current urban travel demand forecasting practice does not use work location (in-home or out-of-home) or employment type (self-employed or salaried) as explanatory variables. In view of the results found here, and the growing importance of home-based and mobile work to an information economy, current modeling practice could perhaps be improved with further attention to the association of these indicators with significant differences in travel behavior. The research presented here is the first known U.S. study of HBB travel, and the first representative-sample study of HBT travel on their telecommuting days. Some interesting findings emerge.

HBB workers have the highest average daily unlinked trip rate of the three groups, at 6.1 trips per day. However, much of the difference between HBB and NHB trip rates (5.3 per day) lies in a higher frequency of bicycle/walk trips in the former group. As expected, HBTs have the lowest total trip rate (5.2 per day), but in marked contrast to other studies, the rate is statistically equivalent to the rate for NHB workers. On the other hand, the difference in *drive-alone* trip rates between HBTs and NHB workers is comparable to previous results, with HBTs making an average of 0.6 (18%) fewer drive-alone trips per day. The lower drive-alone mode *share* for HBTs compared to NHB workers, however, poses another contrast to previous findings. Consistent with earlier studies, transit use by HBTs on telecommuting days is negligible.

Taking both freeway use and travel time as indicators of trip distance suggests that the NHB group travels farthest, which is as expected. It could be noted, however, that based on previous studies, telecommuters are likely to travel farther on their nontelecommuting days than the other two groups, due to having above-average commute lengths. There are substantial variations in freeway use across industry within the HBB group.

Although HBB workers have the highest work-related trip rate, the NHB group makes nearly twice as many work and work-related trips combined as does the HBB group, and more than three times as many as HBTs. The temporal distribution of HBB trips is unimodal, in contrast to the traditional bimodal distribution for NHB trips and a flat distribution (from 9 a.m. to 6 p.m.) for HBTs. HBB workers have the fewest trips in the afternoon interval of 3 p.m. to 6 p.m., whereas telecommuters have the fewest trips during the morning peak of 6 a.m. to 9 a.m. and between 6 p.m. and 9 p.m.

The HBB group is quite heterogeneous, with distinct differences across industry in overall trip rates and rates by purpose. The retail subgroup makes the most work-related trips, the services subgroup makes the most return home and "other" trips, the education subgroup makes the most serve passenger and fewest social/recreation/shop trips, and the "other industries" subgroup makes the most social/recreation/shop and fewest work-related trips. The sample sizes are small for these subgroups, however.

The approximate nature of the identification of the three groups in this study means that these results should be viewed with some caution. The representative-sample, general-purpose data set used in this study offers two key points of comparison with earlier studies of telecommuting based on self-selected, special-purpose samples: number of trips and travel distance. Here, it is found that telecommuters on their telecommuting days make essentially the same number of total trips as conventional workers, compared with telecommuting-day decreases of up to two full trips per day in previous studies. On the other hand, the lower drive-alone trip rates for telecommuters compared with conventional workers have been found to be similar to those in other studies. Further, to the extent that travel time approximates travel distance, the finding here that telecommuters drive alone for 46% less time than conventional workers is similar to previous findings for vehicle-miles traveled.

This initial study offers a useful foundation upon which to build, but a number of research questions remain. On the same data set, it would be of interest to explore differences by metropolitan and nonmetropolitan areas; however, sample sizes for the HBB and HBT groups will be dangerously small. It may be possible to combine the statewide database with supplemental data collected at the regional level to obtain larger sample sizes for those two groups in particular. Along the same lines, it would be valuable to explore differences by gender and household type (e.g., with and without children), although the same caveat about sample sizes applies. Also, this study focused on travel behavior at the individual level for maximum comparability with earlier telecommuting studies, but as regional travel demand forecasting is typically done with the household as the unit of analysis, it would be of interest to take the same perspective with this sample. In that case, however, it would be important to distinguish households having various mixtures of workers among the three study groups.

Future similar data-collection efforts would be far more valuable if information on occupation and trip lengths were obtained. The former measure is an important basis for segmenting travel patterns within each group, and the latter measure is essential to conducting a meaningful comparison of emissions across the three groups. Replicating and extending this study on the Nationwide Personal Transportation Survey (NPTS) data would be of particular interest; although the NPTS sample does not contain occupation data, it does report trip lengths.

Further, collecting data across a multi-day period would permit a direct comparison of travel on home-based work days versus other days (both within the two home-based groups and across all three groups), possibly with an analysis of the transference of travel between the two types of days. Any such data-collection effort should obtain information on the frequency of occurrence of home-based versus non-home-based work days, to be able to properly assess the aggregate effects of home-based work. In a study of center-based telecommuting, for example (Balepur et al. 1998), it was found that although telecommuters traveled 65% fewer vehicle-miles on a telecommuting day than on a conventional commuting day, when travel on each day type was weighted by the frequency of occurrence of each type of day, the overall reduction in weekday vehicle travel for telecommuters was only 17% of their non-telecommuting baseline. It is important to be able to put the former number in the context of the latter, to avoid overstating the potential of home-based work to reduce travel.

Finally, it is important to realize that inferences about causality are not justified with the data used here. We are able to identify differences among groups, but not to assert with confidence whether status as a home-based or conventional worker was a cause or consequence of these differences. There is, of course, some value in identifying patterns of association. However, causal inferences could be made more confidently with panel data (or, at the simplest, before-and-after data such as that often collected for the telecommuting studies done previously) that tracks individuals through changes in work location status over time. Changes in travel patterns observed subsequent to changes in work status are more likely to be effects rather than causes, although even there, third-party correlation and other effects cannot technically be ruled out. It would be of particular interest to identify, classify, monitor trends in, and study the travel patterns of mobile workers, whether home-based or non-home-based.

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Home-to-Work Trips During the Transportation Strikes in Ile-de-France at the End of 1995

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ABSTRACT

In November–December 1995, the region of Ile-de-France experienced strikes resulting in a virtually complete interruption of public transport. During this period, a majority of economic activity continued. The Direction Régionale de l'Équipement (Department of Transportation Local Service) carried out a survey of this time period from which several lessons can be learned. Considerable congestion on the roads increased the journey-to-work by 70%. Ninety percent of the workforce advanced their hour of departure from their residence by 90 minutes on average, and 80% left work more than 90 minutes early. The peak schedule of demand was advanced by up to 2 hours in the morning and 2½ hours in the evening. The peaks were broader and flatter, particularly in the morning. Almost 50% of those normally using public transport switched to private car, most often a carpool. The stopgap measures taken in the absence of public transport worked to some degree. Since the end of the strike, however, commuters returned to their earlier modes of transport.

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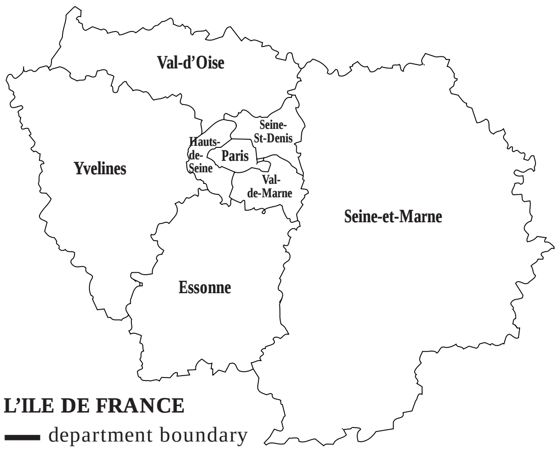
INTRODUCTION

For three weeks, from November 24 to December 17, 1995, the region of Ile-de-France (see box 1) experienced a situation hitherto unknown—a virtually complete public transport system strike. The RATP and the SNCF,[1] which normally provide close to 95% of passenger transportation, were paralyzed; only private services (the APTR and the ADATRIF provided 5%) remained. After December 8, the managing authority of public transport (the Syndicat des Transports Parisiens or the Syndicate of Parisian Transports) offered alternative modes of transportation, chartering buses between Paris and its suburbs, and running boats on the Seine. This substitute supply was always very marginal.

FIGURE 1 The Ile-de-France



Sources: IGN-BD Carto

Although there was a prolonged lack of public transport, the other sectors of the economy suffered very little from the effects of the strikes. Employed individuals were able to reorganize their trips, particularly to work, in an atmosphere that was unexpectedly user-friendly.

The characterization of this "crisis," and the lessons drawn from it regarding the possibilities for the evolution of a balance between the different modes of transport in an urban setting, is the subject of this paper. The agencies responsible for the *Enquête Globale de Transport* (General Survey on Transports) carried out a survey during the course of the first trimester of 1996 concerning the trips of the Franciliens (inhabitants of the Ile-de-France region) during the strikes (see boxes 2 and 3 about the General Survey on Transports). The survey relied on the ability of individuals to remember trips made the day before. In this paper, we focus on the most common trips, that is, the trips from home to work or school, and back. In addition, information was gathered regarding trips for other purposes, which will not be presented here.

The following sections analyze absenteeism, effects on the duration of trips, adaptation of schedules, the effects on the choice of transport mode, and the longevity of the mode changes.

BOX 1 Some Facts About Ile-de-France

The region of Ile-de-France is comprised of 12,000 square kilometers, or 2.2% of the territory of France, 19% of the population, and close to 23% of the actively employed population.

Ile-de-France has 1,300 districts, divided into eight departments (see figure 1):

- the Seine, with the same perimeter as the city of Paris, has 2,157,000 inhabitants over an area of 105 square kilometers;
- the Hauts-de-Seine, the Seine-St-Denis, and the Val-de-Marne consist of the inner suburbs, at the border of Paris, with 4,066,000 inhabitants over an area of 656 square kilometers;
- the Seine-et-Marne, the Yvelines, the Essonne, and the Val-d'Oise form the outer suburbs, at the periphery, with 4,746,000 inhabitants over an area of 11,251 square kilometers.

The residents of Ile-de-France complete 33 million trips daily, of which 34% are made on foot, 20% are made using public transportation, 2% are made by bicycle, and 43% are made by car. Parisians constitute 21% of this total, the residents of the inner suburbs make up 36%, and 42% are from the outer suburbs.

The Syndicat des Transports Parisiens (Syndicate of Parisian Transports) manages the public transportation for this region.

ABSENTEEISM[2]

Among the 3.370 million individuals likely to have made home-to-work trips (see table 1), 360,000, approximately 11%, claim to have given up, at

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[1] RATP: "Régie Autonome des Transports Parisiens" and SNCF: "Société Nationale des Chemins de Fer:" the two major public transport operators in the Ile-de-France Region.

[2] Employed people working outside the home, who were in Ile-de-France during the strike period.

least once, the attempt to go to work. Whatever the reasons behind this decision, the data confirm the general opinion that “everybody went to work.” In addition, 40,000 individuals reported that they worked at home during the strike.

The rate of absenteeism varied with proximity to the workplace, or, more precisely, the relative geographic positions of residence and workplace. The long-distance radial links (Paris to the outer suburbs) were the most affected, with 20% of the individuals experiencing some absenteeism; whereas commuters traveling within the outer suburbs experienced absences of only 5%.

The lack of public transportation obviously penalized, to a much greater extent, the populations who were the heaviest users, and who found themselves confronted with a substitute transport (essentially the car) whose efficacy was greatly decreased by congestion. Furthermore, the highest rate of absenteeism was for those individuals commuting to Paris.

BOX 2 Survey on Trips Before, During, and After the Strikes at the End of 1995

The survey on the trips before, during, and after the strikes at the end of 1995, was carried out by telephone during the first quarter of 1996, with 4,056 individuals at least 15 years of age, chosen by the method of quotas (using the results of the 1990 population census and the employment surveys of 1994, by sex, residence zone, and socioeconomic status). The survey’s objective was to collect the maximum amount of information on the trips of the Franciliens during the strikes and the modes used in the absence of public transportation. The survey especially focused on which modes were used most for work or study trips before, during, and after the strikes, the changes in modes used during the strikes, and their eventual longevity. It also addressed certain factors of economic importance, such as absenteeism or the reduction of the work day.

TABLE 1 “During the Strikes, Did You Regularly Go to Work?” (Population: employed individuals working outside the home)

Type of link home–work	Yes	No	Total number
Paris–Paris	87%	13%	415,000
Paris–inner suburbs	86%	14%	650,000
Paris–outer suburbs	79%	21%	331,000
Inner suburbs–inner suburbs	90%	10%	657,000
Inner suburbs–outer suburbs	92%	8%	480,000
Outer suburbs–outer suburbs	95%	50%	837,000
Whole of the Ile-de-France	89%	11%	100%
Total number	3,009,000	361,000	3,370,000

BOX 3 The General Survey on Transports

The Direction Régionale de l’Équipement d’Ile-de-France (Regional Service of the Administration in Ile-de-France) regularly carries out a survey on the trips of individuals, Enquête Globale de Transports (General Survey on Transports). Its objective is to compile a complete description of the trips of Franciliens within the region, on an average day of the week. It was carried out in 1976, 1983, and 1991, the years following the Recensement Général de la Population (General Census of the Population). The latest edition was associated with the Minister of Transports (Direction des Routes et Direction des Transports Terrestres (Direction of Roads and Direction of Land Transports)), the Conseil Régional d’Ile-de-France (Regional Council of Ile-de-France), the City of Paris, the Syndicat des Transports Parisiens (Syndicate of Parisian Transports), the RATP, the SNCF, and the Direction Regionale de l’INSEE (Regional Direction of the INSEE (National Institute of Statistics and Economic Studies)).

In 1991, the questionnaire, administered at the residences of 16,000 households, covered income, number of individuals, number of employed individuals, vehicle ownership, the characteristics of the individuals over six years old (age, sex, profession, location of work, etc.), as well as the trips of these individuals. Each respondent described the day before, detailing the hours of departure, arrival, the trip purpose, the mode of transport, the itinerary followed, and the destinations. The distances were calculated from a 300 meter grid. Durations were calculated from the hours of departure and arrival.

The principal survey was complemented by additional data-collection efforts:

- a survey on the trips at the end of the week;
- a qualitative survey, aimed at identifying the opinions and desires on the subject of transportation;
- a “handicap situation” survey, designed to evalutate the effect of limitations and incapacities on trips; and
- two surveys counting vehicles: one at the gates of Paris, the other at the boundaries of the region.

A strong presence at work was encouraged by employers who, most frequently, authorized adjustments of schedule. Most employees (87%) were not required to maintain their normal work hours. The 13% required to keep these hours usually did so the same day, for example, those arriving late stayed later in the evening.

Finally, approximately 180,000 individuals (3% of employed persons and students) found a temporary residence during the strikes that was closer to their workplace or place of study in order to minimize commuting time.

DURATION OF TRIP

In the special strike survey, trip time data were recorded as declared by respondents, and not calculated, in contrast to the normal practice of the Enquête Globale de Transports. Direct comparison of the data of the two systems is therefore impossible. As an example, the average travel time for home to work in the strike survey was 31 minutes, compared with 35 minutes in the Enqûete Globale de Transports.

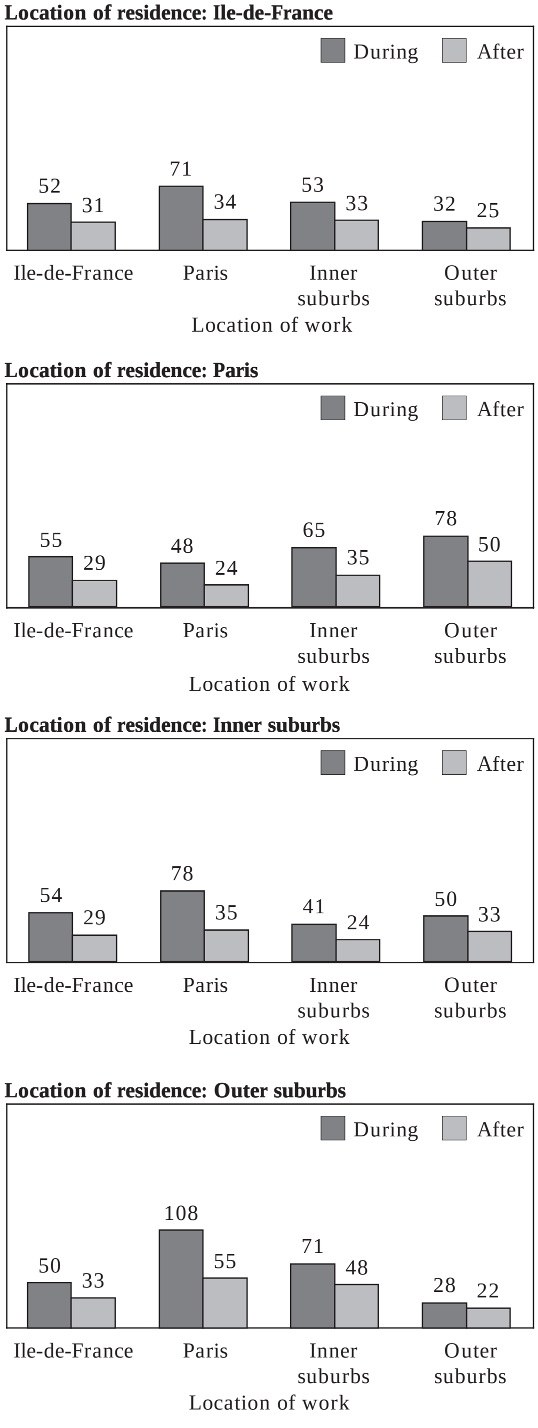
The survey on trips during the strike provides information about minimum and maximum trip duration, average trip duration (defined as the trip time at the end of the strike period), as well as trip times after the situation returned to normal. This latter time constitutes a useful reference to evaluate the effect of the strikes.

Average Trip Times During the Strikes

Figure 2 compares the average trip times during the strikes with trip times after the strikes. Figure 3 shows the maximum, average, and minimum trip duration at the end of the strikes, proving that after a certain number of experiments, the Franciliens were able to optimize their travel practices. For all Franciliens, travel time to work increased by 70% (from 31 to 52 minutes).

The residents of Paris and the inner suburbs experienced the most augmentations in trip duration (about 90%) corresponding to a loss of time averaging 26 minutes. Those in the outer suburbs suffered a lengthening of 50%, for a loss of 17 minutes. The Parisians suffered a relatively constant loss of time (from 24 to 29 minutes), regardless of the locality of their workplace.

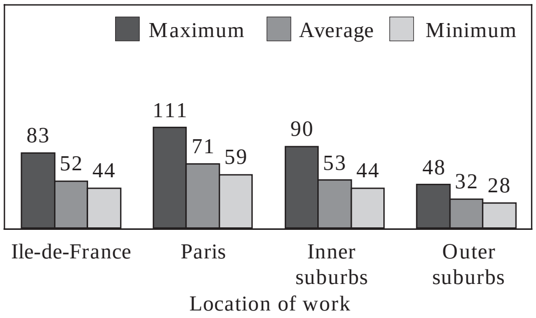
FIGURE 2 Average Trip Time During and After the Strikes (In minutes)



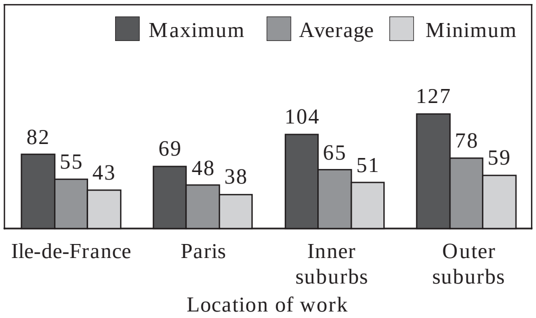
Residents of the inner suburbs working in Paris were especially penalized, with an increase in duration of 43 minutes. The increase in time was much less (17 minutes) for those in the opposite situation. Residents of the outer suburbs who worked in the outer suburbs were barely affected (6 minutes), but were moderately affected if they had to

FIGURE 3 **Minimum, Average, and Maximum Trip Duration at the End of the Strikes**
(In minutes)

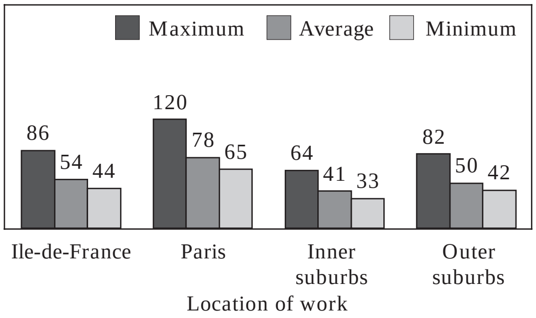
Location of residence: Ile-de-France



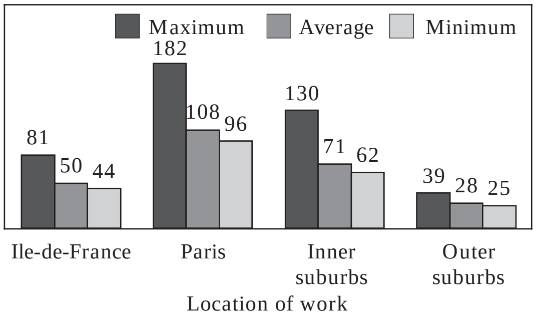
Location of residence: Paris



Location of residence: Inner suburbs



Location of residence: Outer suburbs



travel to the inner suburbs (24 minutes), and greatly affected if they worked in Paris (53 minutes).

For the overall population of Franciliens, the location of the workplace determined the duration of the commute: a job in the outer suburbs resulted in a loss of 8 minutes, but increased to 21 minutes for the inner suburbs, and to 43 minutes for a job in Paris or more than double the usual time (+ 120%).

Variability of Trip Times

Even if we assume that the average time stated at the end of the strike period constitutes in a certain sense an optimized trip, the relationship between the maximum times (corresponding, no doubt, to unsuccessful or difficult attempts) and minimum times (corresponding, in contrast, to strokes of "luck") indicates the deterioration of the reliability of the duration of home-to-work trips. This relation is, on average, 1.9, and varies from 1.6 (internal migrations within the outer suburbs) to 2.2 (migrations between Paris and the outer suburbs). This uncertainty is independent of the location of residence (1.9), but depends instead on the location of the workplace: 1.9 in Paris, 2.0 in the inner suburbs, 1.7 in the outer suburbs.

Ability To Optimize Travel Time

If we consider that the ratio of the average stated travel time at the end of the strike period and the minimum time during the strike period gives some idea of the optimization of the organization of trips, a distinction emerges between the outer suburbs and the rest of the region. Location within the outer suburbs, either of work or of residence, is associated with an average time close to the minimum (+ 14%), for those in the rest of the region, average times are 20% to 25% greater than minimum travel times.

ADAPTATION OF DEPARTURE SCHEDULES

To cope with a considerable increase in the duration of their work trips, Franciliens noticeably advanced their departure times, whether in heading to work or in returning to their residences. The measurement considered here is the cumulative number of departures after the normal work hours, on one hand, in the period near the end of the strikes, and on the other, after the strikes.

Departures for Work

For all Franciliens, the time of departure advanced, beginning very early (from 4 a.m.), and increasing until the period between 6 a.m. and 7 a.m.; by 7 a.m., 33% of employed individuals had already departed compared with only 19% under ordinary circumstances (see figure 4). Furthermore, by 9 a.m., 90% of the workforce had departed, as usual. Globally, ignoring the compensating effect of strategies of leaving earlier or later, we can conclude that only 10% of the employed did not modify their hour of departure. On average, the hour of departure was advanced between 30 minutes and an hour during the worst of the strike (see figure 4).

The employed Franciliens made use of this strategy in varying degrees, except for those making trips within the greater suburbs, as their travel time penalties were very small.

Another way of looking at the strategy of travel time adjustment is to consider the maximum number of individuals who advanced their departure, and the significance of the given advancement. For those traveling between the outer suburbs and either Paris or the inner suburbs, the largest proportion advanced their departure time to between 6 a.m. and 6:30 a.m. Almost half of those who travel between the outer suburbs and Paris, and one-quarter of those going between the inner and outer suburbs advanced their departure times. The maximum rate of early departures occurred around 7:30 a.m. for internal links within the inner or outer suburbs as well as for those trips made between the inner suburbs and Paris. One-quarter of the departures between the inner suburbs and Paris were around 7:30 a.m., but were only 13% within the inner suburbs, and 6% within the outer suburbs. Finally, the peak of early departures for journeys within Paris was reached at 8:00 a.m. (15%).

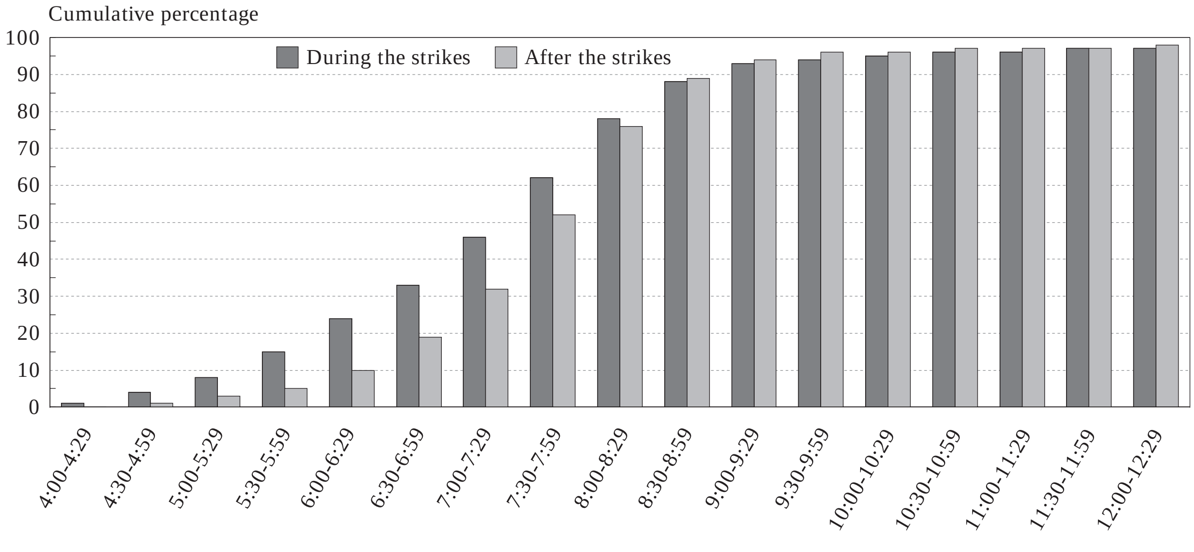
In most cases, a return to normal levels of departures occurs around 9 a.m., with about 90% of departures having taken place. However, the situation appears to be more complicated for the links between the outer suburbs and Paris, where the strategy of early departure is complemented by that of delayed departure: it is only by the end of the morning that the normal situation is reestablished.

The degree of advanced departures, calculated on average per half hour, varied according to the type of link. The maximum was about 30 minutes within the inner and outer suburbs, 30 to 60 minutes within Paris, 60 minutes between the inner suburbs and Paris or the outer suburbs, and 90 minutes between the outer suburbs and Paris.

The Morning Peak

The peak is defined here as the hour-long period recording the maximum number of departures. For the whole of Ile-de-France, the peak hour is between 7:30 and 8:30 a.m. for links outside of Paris. Within Paris, the peak is between 8 and 9

FIGURE 4 Cumulative Departures for Work or School: Whole of Ile-de-France



a.m. A forward shift occurs for commutes from Paris to the suburbs: 7 to 8 a.m. instead of 8 to 9 a.m. for the inner suburbs, and 5 to 6 a.m. instead of 7 to 8 a.m. for the outer suburbs.

The intensity of the peak was clearly dampened during the strikes. It fell from 43% to 32% of departures for the whole of Ile-de-France. Within Paris, the number of departures occurring during the peak hour dropped from 51% to 36%. In the outer suburbs peak departures declined from 48% to 44%.

Returning Home

In the evening, we found the same anticipatory strategy for departures at the end of work (see figure 5). This strategy starts in the early afternoon and reaches its peak around 5 p.m. with a return to normal around 7 p.m., at which time approximately 80% of the departures have occurred. It therefore appears that 20% of the employed individuals did not leave work earlier than usual. Those returning to their residences early advanced the time by 1 to 1½ hours.

Zone by zone, the shift forward is parallel to that of the morning, with increased values in general. In the evening, on average, the individuals traveling within the outer suburbs do not change their hours at all.

The Evening Peak

The evening peak (with the same definition as the morning) advanced by 30 minutes. This advancement varies considerably according to the type of trip, reaching 1½ hours within Paris, and up to 2½ hours for individuals traveling between Paris and the outer suburbs.

The evening peak, traditionally less intense than that of the morning, saw a somewhat reduced number of departures for home, from 32% to 26%.

EFFECT ON THE CHOICE OF TRANSPORTATION MODE

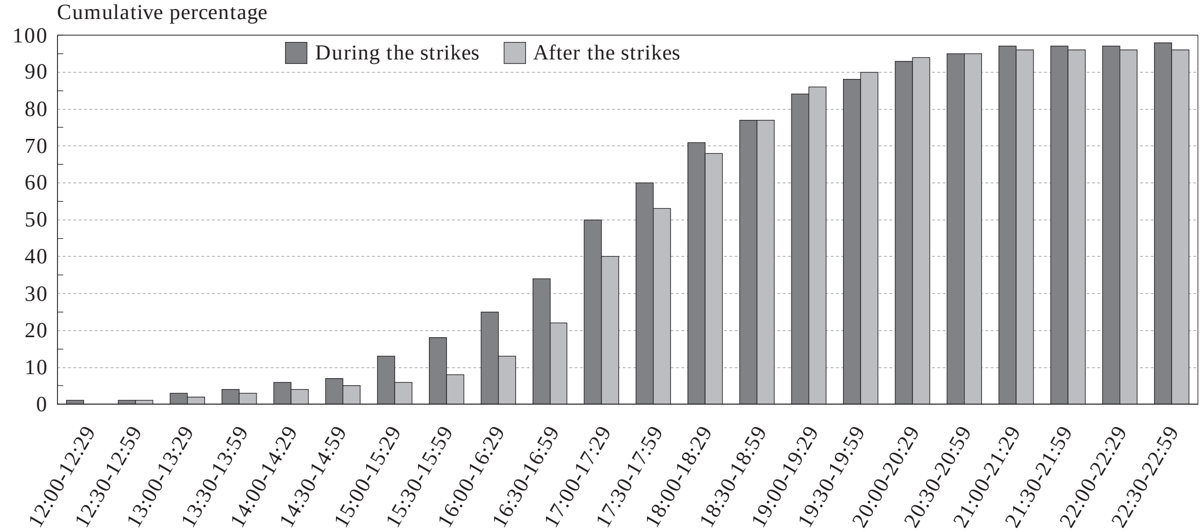
The population observed here is that of employed individuals and students traveling to a location more than one-quarter hour by foot from their residence. Only those who did not temporarily change their residence, and who made trips before, during, and after the strikes are included in the statistics presented in this section.

Modes of Transport During the Strikes

Given the almost total absence of supply, one is not surprised to see the near disappearance of the use of public transport (2% of the trips). As a result, 39% of the global demand turned to other modes as follows:

- Car passenger, 3%
- Carpool passenger, 5%

FIGURE 5 Cumulative Returns to Home from Work or School: Whole of Ile-de-France



- Car driver, 11%
- Walking, 11%
- Bicycle, 5%
- Other, 5%

Half the travelers turned to the car. Most drove (11%) but 8% traveled as a passenger. The percentage of work trips taken as a driver of a car increased from 51% to 62%, which is easily enough to create considerable congestion, in spite of the adaptions in schedules.

The second substitute mode of choice was walking (for trips of more than one-quarter hour), replacing public transport for 11% of commuters. The bicycle served as an alternative for 5% of commuters, conversely; the motorcycle does not seem to have played a significant role. Naturally, the availability of a bicycle is much more common that that of a motorcycle, and, moreover, the acquisition of bicycles increased considerably during the strike.

The Franciliens, with great imagination, used "other" modes of transport 5% of the time. Included in this percentage are the many novice roller skaters, occasionally "accepting a tow" from a motor vehicle!

The Return to Normal

Figure 6 shows evidence that one or two months after the end of the strikes, the mode of transport returned to the normal pre-strike configuration. None of the alternative modes used in a significant manner saw its market share permanently influenced.

The sample size of the survey does not permit a close analysis of changes occurring in the utilization of the modes. It does, however, provide information about why those choosing two of the alternatives to public transport and car driver, namely the bicycle and carpooling, ultimately returned to public transport.[3]

Individuals who temporarily used the bicycle as a replacement for public transport, listed the following as reasons for having abandoned it as a mode of transport:

- safety hazard,
- exposure to pollution, and
- convenience of public transport.

The regular users of public transport who found a replacement in carpooling listed the following as reasons for having abandoned it as a mode of transport:

- punctuality of public transport,
- difficulty of organizing carpools,
- speed of public transport, and
- absence of a carpooling supply under normal circumstances.

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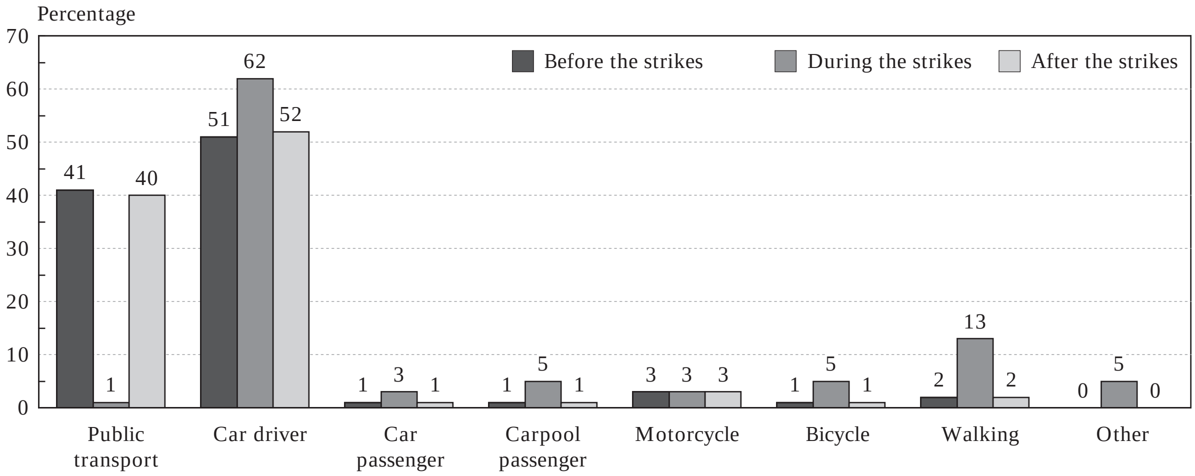
[3] Further analysis has only limited applications because of the small sample size.

FIGURE 6 Home-to-Work or Home-to-School Mode of Transport



CONCLUSION

This exceptional period is rich in information regarding the behavior of Franciliens and the organization of trips in Ile-de-France. It is clear that the difficulties created by the lack of public transport throughout the region were worst in those regions where public transport traditionally plays a major role, that is, on the radial links and within the downtown area. The automobile was the primary alternative mode, causing congestion, and, as a consequence, considerable delay for the majority of those traveling. Nevertheless, after a short adaption period, the local economy continued to function nearly normally.

The observed increase in travel times provides an indicator for the evaluation of the role of public transport in mitigating highway congestion. The increased duration of trips by 70% corresponds roughly to a daily loss of 3 million hours for commuting trips alone. Valued conservatively at 50 francs per hour, the corresponding annual loss would be 30 billion francs, or the equivalent of the running budget of public transport.

Although the strikes lasted three weeks, the situation was not a stable one. The strikes were accepted as temporary, and the generous support of the strike by the population was, no doubt, linked more to the social consequences anticipated by the strike than to any conviction of the pertinence of the demands of the strikers. Furthermore, the tolerance shown by the majority of employers in accepting altered schedules and, above all, the reduction in hours worked would certainly not have continued indefinitely. That the strikes were understood to be temporary limits the conclusions one can draw from the changes in travel behavior observed.

The leveling off of the demand peak is a matter worthy of further analysis. Certainly, what was observed during this period was largely a result of constraints imposed by the capacity of the road network.

Nevertheless, the widespread practice of advancing departure times suggests that this behavior may play a significant role under normal conditions, a fact that remains to be fully evaluated in the area of road capacity management.

The last significant observation is the instantaneous reestablishment of the prior distribution in the modes of transport following the end of the strike. Although we know that travelers, and those using public transport in particular, are inclined to mass behavior, everything occurred as if the employed individuals were behaving economically rationally, and used the mode that, objectively, performed the best for them.

The possibilities offered by the presently marginal practices of carpooling and cycling remain unrealized. Since December 1995, and in the months that followed, some have declared that they see these modes as solutions to be encouraged. In fact, the survey shows very clearly that carpooling disappeared quickly, and many believe that carpooling will only develop in Ile-de-France if there are incentives. Similarly, policies implemented, especially in Paris, to make the road system more bicycle friendly, so far have not produced a spectacular return, and it is too early to determine whether in the future bicyclists will return to the large Parisian avenues.

Weighting or Imputations? The Example of Nonresponses for Daily Trips in the French NPTS

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ABSTRACT

This paper reports on methods used to correct nonresponse for daily mobility in the French National Personal Transportation Surveys. A two-stage technique was used for *unit* nonresponse: 1) post-stratification according to the households' characteristics related to response behavior; and 2) correction for sampling error by calibration on margins. Imputation procedures (e.g., deductive, regression-based, hot-deck) were also used to correct *item* nonresponse. These methods maintained the consistent relationships among the main variables describing trips. The paper also addresses how the specific circumstances of this case (e.g., sample drawn from the census, no computer assistance during the interviews) led to the choice of methods.

INTRODUCTION

All sample surveys contain incomplete data, even if great care is taken before and during data collection. Two fundamental types of nonresponse may occur:

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1. *unit* nonresponse, when no information is collected for a household or an individual (e.g., not at home, unable to answer);
2. *item* nonresponse, when most of the questions for a unit are answered, but for some respondents, either no answer is given or the answer is clearly wrong and must be deleted.

Missing data for items can occur when an interviewer fails to ask a question, the respondent is not able or refuses to provide an answer, or the interviewer fails to record correctly the answer provided.

There is no a priori justification for assuming that people who respond have the same characteristics as those who do not. Thus, in computing estimates from the available data collected, we may face biases whose size and direction of error are unknown. In this paper, we show how nonresponse problems were addressed for daily trips in the French National Personal Transportation Survey (Madre and Maffre 1994).

There are two main strategies for handling nonresponse: 1) re-weighting by increasing certain expansion factors, which is commonly used for unit nonresponse; and 2) imputation, replacing the missing item by a value consistent with the respondent sample, which is generally used for item nonresponse. There are also intermediate cases, for instance, weighting for omitted trips. We will discuss advantages and disadvantages of each method.

THE SAMPLE DESIGN AND DATA COLLECTION

From a sample of 20,002 dwellings drawn from the census of 1990 and from the list of new residences built since that date, 20,053 address cards were prepared. The increase in households is due to “burst” lodging (dwellings that have been divided into two or more separate residences since the last census). The sample was spread over eight waves from May 1993 to April 1994 in order to neutralize the seasonal effects, which are important for personal trips. One individual was chosen (the probability of being chosen was equal for everyone in the household) among the eligible individuals (individuals six years and older,[1] present at the time of the survey, and able to answer) of each household. The chosen individual was interviewed face-to-face and asked to describe all trips he or she made the day before and the previous weekend. All motorized households had to complete a car diary, in which they reported all trips made by one of their vehicles, chosen at random, during the span of one week. Generally, the car diary was completed after the interview on daily mobility, which did not allow immediate cross-checking of individual car trips, but only the computation of global statistics from both data sources on the same sample of households. Information collected with those survey instruments is described in a later section.

During each of the eight waves, the surveyor interviewed a given set of households living in the same area. The interviews were spread over the six-week period of the wave, but the day of interview was not assigned a priori. As a result, it was necessary to correct for temporal representativeness (especially for the days of the week) in the weighting procedure.

Although the majority of residences in our first sample were the main residence of a household, this was not always the case: among the 20,053 dwellings visited, 2,666 (13.3%) were out of scope (vacant housing, or second or occasional homes). Among the 17,387 selected households in scope, 3,174 (18.3%) of them refused to respond to the survey.

CORRECTION FOR UNIT NONRESPONSE

For each residence drawn from the 1990 census, there is useful information concerning the probability that a household will respond to the survey. The relationship between the household characteristics and the probability of response is called the response mechanism. We estimated a logit model to describe the response mechanism. Although the household living in a selected dwelling could be different from the one that lived there in 1990, we assumed they were the same, since the survey was conducted only three years after the census.

Nonresponse Correction: Post-Stratification

The main factors explaining unit nonresponse are listed below, from the most important to least important ones.

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[1] Unlike the previous survey (1981 to 1982), children under six years old did not describe their mobility.

1. People living in rural areas or in small towns (<20,000 inhabitants) had a lower rate of nonresponse than those living in the conurbation of Paris. We distinguish three classes: 1) rural + small urban areas (<20,000 inhabitants) with a response rate of 86%; 2) medium-size + large urban areas (20,000 to 2 million inhabitants), with a response rate of 81%; and 3) the Paris urban area (10 million inhabitants), with a response rate of 74%.
2. Single persons were less likely to respond than households with many persons. We identified three categories: 1) households of one person, with a response rate of 72%; 2) households composed of two persons, with a response rate of 81%; and 3) households composed of more than two persons, with a response rate of 87%.
3. Motorized households had a higher response rate than those with no car. We identified 3 classes: 1) nonmotorized households, with a response rate of 72%; 2) households with one car, with a response rate of 82%; and 3) multivehicle households, with a response rate of 87%).
4. Households whose head was over 60 years old had a 78% response rate; those with a younger head had an 84% response rate. We chose only two age groups, because under 60 the response rates seem almost constant across age groups.

By cross-classifying these variables, we obtained 54 classes, which form the framework for post-stratification. The response rates ranged from 55% for an individual who is single, living in the Paris conurbation, with no car, and who is over 60 years old (230 people in this class), to 90% for three or more persons living together in rural areas or small towns, with two or more cars, and whose household's head is under 60 years old (2,358 people in this class). We implemented the post-stratification by multiplying the reciprocal of the household's selection probability with the reciprocal of the individual's selection probability and with the reciprocal of the response rate of the individual class:

$$\text{Postratification weight} = \frac{1}{\text{Household's selection probability}} \times \frac{1}{\text{Individual's selection probability}} \times \frac{1}{\text{Response rate of the individual class}}$$

Sampling Error Correction: Calibration on Margins

After reducing the error due to nonresponse by the post-stratification, we found that the margins in the sample differed from those of the largest household survey conducted by INSEE (the French National Institute of Statistics and Economic Studies), an employment survey in which 80,000 households were interviewed in 1993–94. That survey is considered to be a mini-census.[2] We corrected these differences by a calibration on margins. This stage is essential to ensure a representative sample allowing comparison with other data sources (e.g., other INSEE surveys). Calibration on margins is done by iterative proportional fitting, a methodology developed by Deming and Stephan in the early 1940s. We used INSEE-developed software called CALMAR for calibration on margins (Sautory 1993).

Calibration on margins must be based on variables that explain (or are correlated with) transport behavior, and for which the total is accurately known. We took advantage of this stage to compute two temporal variables—"the day of the week" and "the period of the year"—in order to neutralize the temporal effects. Therefore, the variables used to calibrate on margins for the person describing daily trips are the following (see table 1):

- the social category of the individual;
- age and gender;
- the size of the household;
- the zone of residence: three concentric zones (city center, and inner and outer suburbs) for four different urban area sizes;
- the day of the week (one day before the visit of the interviewer) for which daily trips are described (so each day of the week is equally represented); and
- the period of the survey (the year was divided into eight waves).

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[2] Obviously, the employment survey is subject to sampling error, but it is also more accurate than the NPTS's sample (with only 14,000 households). The survey methodology was exactly the same in both cases (face-to-face interview), which leads us to conclude that the only source of difference is sampling error.

TABLE 1 Margins in the Sample and in the Population for Persons Interviewed on Daily Mobility

Variable	Margins in the sample after post-stratification (%)	Margins in the population (%)
Social category of the person		
Farmer	1.8	1.6
Craftsman/tradesman	3.5	3.3
Senior executive	6.3	5.6
Intermediary	9.9	9.3
Employees	14.3	13.6
Blue collars	12.9	12.9
Retired/students	17.8	18.1
Unemployed	20.4	22.5
Children (6 to 15 years old)	13.1	13.1
Gender and age		
Males:		
from 6 to 24 years old	13.8	14.6
from 25 to 34 years old	7.7	8.1
from 35 to 49 years old	11.6	11.6
from 50 to 64 years old	8.0	7.9
over 65 years old	6.3	6.4
Females:		
from 6 to 24 years old	13.5	13.9
from 25 to 34 years old	8.8	8.1
from 35 to 49 years old	12.6	11.6
from 50 to 64 years old	8.7	8.2
over 65 years old	9.0	9.6
Number of persons in the household		
1 person	11.9	12.0
2 persons	27.0	26.9
3 persons	19.9	19.7
4 persons	22.2	23.0
5 persons or more	19.0	18.4
Zone of residence		
Rural area living on farm	3.8	3.4
Small urban areas (<50,000 inhabitants)		
Central city	4.6	5.4
Inner suburbs	1.6	1.7
Outer suburbs	6.6	7.2
Medium-size urban areas (50,000 to 300,000 inhabitants)		
Central city	10.1	9.4
Inner suburbs	6.4	6.3
Outer suburbs	16.5	14.3
Large urban areas (> 300,000 inhabitants)		
Central city	10.1	10.2
Inner suburbs	11.9	12.4
Outer suburbs	9.4	10.4
Paris urban area		
City of Paris	3.7	3.9
Inner suburbs	12.2	12.7
Outer suburbs	3.1	2.7
Day		
Monday	20.4	20.0
Tuesday	19.5	20.0
Wednesday	18.0	20.0
Thursday	15.5	20.0
Friday	26.6	20.0
Wave		
1st (from 3 May to 14 June 1993)	12.4	11.6
2nd (from 14 June to 9 Aug. 1993)	12.0	15.4
3rd (from 9 Aug. to 11 Oct. 1993)	12.9	17.3
4th (from 11 Oct. to 15 Nov. 1993)	12.4	9.6
5th (from 15 Nov. 1993 to 3 Jan. 1994)	12.2	13.5
6th (from 3 Jan. to 14 Feb. 1994)	10.4	11.5
7th (from 14 Feb. to 21 March 1994)	10.4	9.6
8th (from 21 March to 30 April 1994)	13.4	11.5

Sources: INSEE-INRETS French NPTS 1993–94 and French Employ Survey 1993–94.

Discussion

Australian data has shown that within small homogeneous population groups the travel behavior of nonrespondents does not differ significantly from the behavior of respondents (Ampt and Polak 1996). Thus, post-stratification according to crossed categories with homogeneous response rates is essential. Unfortunately, the information used for calibrating on margins is slightly different from the sample base. There is no information on newly built dwellings in the census, and no information on car ownership in the employment survey used for calibration. Thus, the second stage changes the margins obtained after post-stratification, and is not satisfactory. Following the methods implemented in Austria (Sammer and Fallast 1996), we are now investigating a single-stage procedure.

For reasons of comparability and efficiency, our daily trips questionnaire was presented in a manner similar to urban survey questionnaires. On the other hand, some of the methods described here might be applied to other types of surveys. This is surely the case for calibration on margins. The size of the conurbation is the best explanatory factor of unit nonresponse, but geographic post-stratification is not sufficient to get a good fit to the sample and an expansion consistent with other data sources. For instance, calibration of age groups could be useful for demographic modeling (Armoogum et al. 1994, 1995). However, as contradictions could appear between the two steps of the procedure we have used, INSEE is now studying a single-step procedure that calibrates on margins according to variables explaining both the nonresponse mechanism and travel behavior.

CORRECTION OF ITEM NONRESPONSE

Correcting for item nonresponse has two objectives:

1. obtaining not only unbiased estimates of averages, but also keeping the distribution of each variable as "natural" as possible; and
2. checking and maintaining the consistency of relationships between the different variables that describe a trip (e.g., origin, destination, distance, time, mean of transport).

Standard Imputation Methods

The main imputation methods for item nonresponse are the following:

1. *Deductive imputation* refers to those cases where a missing value can be obtained through a logical conclusion. The deduction is based on responses given to other items on the questionnaire. A common example in travel diaries is travel distance, which can be checked and calculated from the location of the origin and destination of a trip.
2. *Overall mean imputation* consists of the replacement of all missing values for a given item by the respondent mean for that item. Unless the number of nonresponses is negligible, this procedure may lead to severely understated variance estimates and to invalid confidence intervals.
3. *Class mean imputation* partitions the unit response set into imputation classes such that elements in the same class are considered similar. This classification uses auxiliary variables. There will be some distortion of the "natural" distribution of values, but the bias is less severe than with overall mean imputation.
4. *Hot-deck and cold-deck imputations* replace missing responses with values selected from other respondents in the current survey in the hot-deck method; cold-deck procedures use sources other than the current survey. A number of hot-deck procedures have been proposed, including random overall imputation, random imputation within classes, sequential hot-deck imputation, and hierarchical hot-deck imputation.
5. *Regression imputation* uses respondent data to estimate a regression equation where the variable for which one or more imputations is needed is the dependent variable and other available variables serve as explanatory variables.

Validation and Correction of Daily Trip Data

Trips were described in a weekly stage diary in a previous 1981–82 survey, by interviews on the previous day and the last weekend in 1993–94, and in a weekly car diary for both surveys. The main characteristics of the trips are:

1. *origin and destination*, coded by French municipality and by NUTS3 (regions with about 500,000 inhabitants) for neighboring countries in the last survey;
2. *length*, as estimated by interviewed persons, calculated as the difference on the odometer at the origin and destination in car diaries;
3. *duration*, computed as the difference between arrival and departure times;
4. *transport mode* (up to four different modes in the case of a multimodal trip); and
5. *trip purpose*.

There are obvious relationships among these variables. Some locations are described in the general part of the questionnaire (e.g., the residence and the regular work place). Trip length must be consistent with the distance between the origin and destination (trip length must be greater than crow-flight[3] distance with a margin of 5 km, unless the origin and destination are located in two neighboring municipalities). Door-to-door mean speed (calculated as the ratio of trip length to trip duration) must stay within reasonable limits (see table 2). For car trips, for instance, door-to-door mean speed must fall between 2 km/h and the maximum authorized speed on motorways, which is 130 km/h in France.

Interview on Daily Mobility: 1993–94

Like most surveys, there were almost no item nonresponses on origin and destination locations. Only 10 out of 100,000 trips could not be coded. Thus, we have used crow-flight distances to fill item nonresponses on trip length (1,300 cases) or to replace responses leading to an unreasonable mean speed (400 cases). Generally, the crow-flight distance is multiplied by a circuity coefficient specific to each mode (e.g., 1.3 for private car).

In order to estimate missing or questionable values for duration, we used a regression technique, calibrating the relationship between mean speed and trip distance. For motorcycles and cars, this equation is:

$$\text{SPEED} = 1.4 + 14.6 \log(\text{DIST}+1)$$

For the 1993–94 car diary, where additional information about destinations in "city-centers" was available, four different estimates of this equation were made on correctly described trips:

- if origin and destination were in a city center:

$$\text{SPEED} = \underset{(9.3)}{1.54} + \underset{(185.7)}{15.25} \log(\text{DIST}+1.3) \quad R^2 = 0.474$$

- if origin or destination were in a city center:

$$\text{SPEED} = \underset{(14.9)}{2.46} + \underset{(219.5)}{15.72} \log(\text{DIST}+1.3) \quad R^2 = 0.467$$

- if origin and destination were not in a city center:

$$\text{SPEED} = \underset{(31.0)}{4.39} + \underset{(246.6)}{15.64} \log(\text{DIST}+1.3) \quad R^2 = 0.445$$

- if information was missing for origin or destination:

$$\text{SPEED} = \underset{(4.7)}{1.74} + \underset{(102.0).}{15.90} \log(\text{DIST}+1.3) \quad R^2 = 0.511$$

Because of congestion, the average speed is lower in denser areas, and increases significantly less with trip distance when origin and destination are both situated in city centers. In 1981–82, the previous form of this question concerned the use of a motorway during the trip. This information did not provide significantly different equations of speed as a function of trip distance.

Because walking trips usually have their origin and destination in the same municipality, crow-flight distance between municipalities cannot be used to compute trip distance. For this mode, we have assumed that the mean speed is 3 km/h, either to estimate trip length (500 cases) or to fill the few missing data on duration.

Using these techniques, we succeeded in getting totally consistent data on locations, distance, duration, mean speed, and mode. There are very few missing values left : 2 on trip distance, 6 on trip duration, plus 11 cases where trip duration was given, but arrival and departure times remain unknown (see table 3).

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[3] Defined as: crow-flight distance = $[(X_o - X_d)^2 + (Y_o - Y_d)^2]^{0.5}$; where (X_o, Y_o) are the origin's coordinates and (X_d, Y_d) are the destination's coordinates.

TABLE 2 Controlling Data by Mode

Mode	Speed (in km/h) Minimum	Speed (in km/h) Medium	Speed (in km/h) Maximum	Trip/crow-flight distance[1]
Walking	1	3	10	0.3
Bicycle	1	8	30	1.0
Motorcycles	2	15	[2]130	1.2
Car, truck, taxi	2	24	[3]130	1.3
Bus	2	12	110	1.4
Rail urban transport	3	12	75	1.1
Train	10	54	[4]150	1.2
Aircraft	100	400	1,000	1.1
Seacraft	1	10	75	1.1

[1] Crow-flight distance is between different municipalities. Thus, this coefficient is low for short-distance modes (especially for walking, bicycle, and urban transport), since some of those trips only cross the boundary between two neighboring municipalities. This coefficient is smaller for long trips (e.g., by air) than for medium-distance trips.

[2] Only 70 km/h for mopeds.

[3] We have admitted a few verified exceptions up to 140 km/h door-to-door.

[4] Up to 250 km/h for the TGV (high-speed train).

Sources: INSEE-INRETS 1981–82 and 1993–94 NPTS.

TABLE 3 Validation and Correction of Daily Trip Data

	1993–94 survey[1]		1981–82 weekly diary[2]		
				After correction	
Mode	Original file	After correction	Original file	Stages	Trips
Unknown origin	12	10	1,052	53	47
	0.0%	0.0%	1.5%	0.1%	0.1%
Unknown destination	10	7	914	50	44
	0.0%	0.0%	1.3%	0.1%	0.1%
Distance unknown	1,812	2	2,732	96	81
	1.9%	0.0%	3.8%	0.1%	0.1%
Distance over 5 km less than crow-flight distance	299	0	1,327	0	0
	0.3%	0.0%	1.8%	0.0%	0.0%
Unknown duration	59	6	769	168	162
	0.1%	0.0%	1.1%	0.2%	0.2%
Speed too fast	194	0	108	0	0
	0.2%	0.0%	0.1%	0.0%	0.0%
Speed too slow	292	0	1,469	0	0
	0.3%	0.0%	2.0%	0.0%	0.0%
Unknown transport mode	74	73	203	59	48
	0.1%	0.1%	0.3%	0.1%	0.1%

[1] Previous day and last weekend trips in 1993–94.

[2] Week-long stage diary in 1981–82 was converted into a trip diary for comparison with the 1993–94 survey (see the two columns at the right side).

Sources: INSEE-INRETS National Transportation Surveys.

The Trips Diary: 1981–82

For daily trips in the 1993–94 NPTS, hot-deck imputation was not appropriate, because trips were described for typical days (Saturday, Sunday, and a weekday). In 1981–82, similar trips were more frequent, as they were reported in a weekly diary. Thus, hot-deck inside a diary could be used in order to fill nonresponses or to make data consistent.

After matching origin-destination and trip distance, hot-decks were run to fill nonresponses, first on transport mode and then on trip duration. The criteria used to find a correctly described trip similar to one with inconsistent or missing information are: 1) geography (origin and destination in the same municipalities), and 2) trip purpose to provide mode or trip distance to provide duration. The results were not as satisfactory as those of the 1993–94 survey: out of 66,000 trips, 81 missing values were left on trip length and 162 on trip duration.

Car Diaries

In 1981–82, as in 1993–94, the driver had to copy the odometer at the beginning and the end of each trip. This information is highly structured (mileage must increase throughout the diary giving an objective measurement of trip distance), but there are occasional missing odometer readings for trip ends. In order to fill them, we first tried a hot-deck method structured by origin-destination and duration. If this was not successful, we computed mileage proportional to trip duration or to crow-flight distance, while ensuring that the mean speed stayed within reasonable limits. Finally, we filled nonresponses on trip duration with a hot-deck run on geographical and distance criteria. At the end, there were no missing values left for mileage or trip duration, but departure and arrival times were still missing for 105 trips out of 58,000 in 1981–82, and for 2,485 out of 200,000 in 1993–94. This satisfactory result for distance and duration is partly due to the fact that we skipped not only the diaries where the interviewer mentioned underreporting (about 5% of them), but also those where the information necessary for imputations was missing on at least one trip (less than 1% of diaries).

Reweighting for Underreporting of Short Trips or Underestimation of Short Distances

In the last NPTS, a selected person in the household had to describe the trips he or she made during the day before the interview and during the last weekend. As the last Saturday could be as much as one week earlier, we suspect that imperfect memory could affect the responses. The car diary collected in the same survey gives a more homogeneous image through the course of the week. Table 4 compares the results from these two survey instruments.

For weekdays, the two survey instruments give similar data for car trips. Because car diaries cannot be completed by persons absent too long from home, information on additional long-distance trips was obtained by interview (e.g., the return trip from holidays). If we limit the scope to trips within an 80 km crow-flight distance from the residence of the household, however, total travel (in vehicles-kilometers) is almost the same. There are 2% fewer trips collected in the car diary, but their average length is a little higher (9.9 km in the car diary vs. 9.7 km for car drivers in daily trips). Because of large sample sizes, this small difference is significant at a level of .05 and denotes a slightly different understanding of the notion of trip when the driver completes the diary alone, without the assistance of the interviewer (short stops may be omitted).

The previous weekend was too far in the past to ensure accurate memory of trips taken. Underestimation occurred about 30% of the time for very short trips (under 2 km). For longer trips, those on Sunday were a little less underreported than Saturday trips, probably because they were more recent. Thus, we used the figures in the two right columns of table 4 as correction coefficients for all motorized weekend trips. The figures offset the bias on average, but we are not sure that they

TABLE 4 Total Number of Car Driver Trips: Comparison Car Diary and Daily Trips

Trip distance	Weekday	Saturday	Sunday
<2 km	1.01	1.29	1.32
2–11 km	0.97	1.21	1.16
12–44 km	0.98	1.19	1.12
>44 km	0.91	1.06	1.00

Source: INSEE-INRETS 1993–94 NPTS.

correctly show the distributions, since they add the omitted trips to respondents who have described some and not to those who have declared none. In fact, if we compare the distribution of weekend trips for the persons interviewed on Monday with those obtained from later interviews, the proportion of zero trips explains less than 10% of the difference in average mobility (up to one-third for trips under 2 km). Thus, this reweighting method, which compensates, on average, for the underreporting of short weekend trips, does not seem to introduce a large bias in trip distributions (see tables 5 and 6). Moreover, this comparison shows almost the same rates of underreporting according to trip length as those obtained from the comparison with the car diary.

Comparison of the trip interviews and car diaries also allowed us to investigate drivers' perception's of distances. Controlled by the odometer, the car diaries estimated trip distance well. If we compare trips by class of crow-flight distance between origin and destination, we notice that long-distance trip lengths are a little overestimated. Moreover, there is a substantial underestimation of distance for trips whose origin and destination are in the same municipality; this underestimation is also observed for travel time, but it is less significant (see table 7). The underestimation of trip distance for car driver trips cannot be generalized to all modes. If we use the same coefficient of correction, many walking and cycling trips become too fast. Thus, in order to maintain consistency between time and distance variables, we could not implement a uniform correction for the underestimation of local trip distances.

TABLE 5 Frequency of Trips According to the Day of Interview (in percent)

Day	0 trip	1–2 trips	3–4 trips	>4 trips	Total
Total	23.9	25.2	22.1	28.8	100.0
Mon.	21.6	23.3	23.1	32.0	100.0
Tues.–Wed.	22.9	25.1	21.8	30.2	100.0
Thu.–Sat.	25.5	25.8	22.1	26.6	100.0

TABLE 6 Frequency of Short Trips by Day of Interview (in percent)

Day	0 trip	1–2 trips	>2 trips	Total
Total	84.7	11.0	4.3	100.0
Mon.	81.6	12.3	6.1	100.0
Tues.–Wed.	84.8	11.0	4.2	100.0
Thu.–Sat.	85.6	10.5	3.9	100.0

Note: Short trips are under 2 km.

In filling item nonresponses and verifying the consistency of data, geographical information plays a key role. That is why we have systematically used origin and destination in hot-decks. This information is accurately recalled by interviewed persons, but has to be geographically encoded during data processing. Manual coding is done only for difficult cases, since most municipality names in Europe can be automatically identified and coded (Flavigny and Madre 1994). Coding at a more detailed level is still a problem, except in some large urban areas (e.g., Montreal or Paris (Chapleau 1997)). In the case of car diaries, data are also strongly structured by the odometer. The comparison between different kinds of survey instruments allows us to assess memory effects and to detect substantial biases in the perception of short distances in travel diaries. Reweighting procedures are not always successful in correcting these biases, however. Thus, in the future, the need to collect data on trip distance will probably decrease, since this essential parameter of transport behavior can be calculated by traffic assignment algorithms, if the knowledge of locations (origin and destination) is sufficiently precise.

CONCLUSIONS

To some extent, the methods presented in this paper are specific to the context and characteristics of the NPTS. The analysis of the nonresponse mechanism for post-stratification relies on the availability of an exhaustive and up-to-date sampling base. Working with the National Institute of Statistics and Economics Studies, we had the opportunity, in 1993–94, to draw the sample from the relatively recent 1990 census. In some countries, this is not possible because of privacy and confidentiality concerns.

Some amount of household information is needed to compute imputations; implementation weighting procedures do not have this requirement. Therefore, weighting is the appropriate

TABLE 7 Car Driver Local Trips[1] Seen Through Different Survey Instruments

				Origin and destination (O-D) in distant municipalities								
	In the same			<15 km			>15 km			Total		
	DT	CD	DT/CD	DT	CD	DT/CD	DT	CD	DT/CD	DT	CD	CD/DT
Travel diary and car diary in 1981–82[2]												
Number of trips (millions)	79.0	172.0	1.04	164.0	155.0	1.06	29.0	29.0	100.00	372.0	356.0	1.04
Trip length (km)	2.8	3.7	0.76	8.3	9.1	0.90	37.6	39.1	0.96	7.9	8.9	0.88
Crow-flight distance (km)	0.0	0.0	—	5.9	6.0	0.99	28.5	28.2	1.01	4.8	4.9	0.99
Trip duration (mn)	9.7	10.1	0.96	17.0	17.0	1.00	42.8	44.1	0.97	15.5	15.8	0.98
Mean speed (km/h)	17.2	22.0	0.78	29.1	32.2	0.90	52.7	53.2	0.99	30.5	33.8	0.90
Daily trips and diary in 1993–94[3]												
Number of trips (millions)	193.0	199.0	0.97	230.0	216.0	1.06	56.0	55.0	1.02	479.0	470.0	1.02
Trip length (km)	2.6	3.4	0.77	8.8	9.3	0.95	37.4	36.2	1.03	9.7	9.9	0.97
Crow-flight distance (km)	0.0	0.0	—	6.3	6.4	1.00	28.5	28.8	0.99	6.4	6.3	1.01
Trip duration (mn)	8.8	9.6	0.92	16.4	16.7	0.98	41.4	40.2	1.03	16.2	16.4	0.99
Mean speed (km/h)	17.8	21.2	0.84	32.4	33.6	0.96	54.3	54.0	1.01	35.7	36.3	0.98

[1] As more long-distance trips were collected by interview than in a travel diary, we considered only local trips whose origin and destination were within 80 km from the residence, using a household car.

[2] DT collected in a weekly stage diary; CD refers to a weekly car diary.

[3] DT collected by interview on the previous day and on the last weekend (only single-mode trips; for multimodal trips, distance made by car and precise O-D are unknown). CD here refers to the same kind of weekly car diary; excluding trip purpose "to the station" (for comparison with single-mode trips).

Key: DT = daily trips; CD = car diary.

Sources: INSEE-INRETS 1981–82 and 1993–94 NPTS.

method for coping with unit nonresponse, while imputation is used to correct item nonresponse (Zmud and Arce 1997; Armoogum and Madre 1997). Of course, there are always intermediate cases, as illustrated by the example of omitted trips, in which the choice of method is not as clear.

We have also modified trip weights to correct for memory effects. This compensates for the trip length bias by increasing average mobility, but could distort trip distributions by adding travel distances when respondents declare trips. Imputation could be another solution to this problem (Polak and Han 1997), but we lacked information to implement it. Indeed, in order to be cautious, all our imputations have used either external information (e.g., deriving trip distance from crow-flight distance) or information concerning the same person or the same diary. In any case, there was some interaction between weighting and imputing for car diaries, since we skipped all diaries where the information needed for imputation was missing for at least one trip. Thus, they were considered as missing units and were corrected by weighting.

In the future, travel surveys will make greater use of computer-assisted survey methods. Automatic checking of the data as soon as they are collected, either face-to-face (CAPI) or by phone (CATI), will allow the immediate correction of many errors by asking more details of the respondent. Nonetheless, corrections a posteriori will still be necessary for self-completed questionnaires. New approaches, such as artificial intelligence and neural networks, are now being tested for a new European Program on survey methods (MEST 1996 and TEST 1997).

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Productivity and Accessibility: Bridging Project-Specific and Macroeconomic Analyses of Transportation Investments

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ABSTRACT

Many studies of the local economic impacts of individual highway projects rely on overly narrow measures of economic benefits. Another type of research, focusing on economic productivity, defines benefits more broadly but is also limited by geographic and functional aggregation constraints. This paper attempts to bridge these two perspectives, describing how project-specific analysis methods can shed light on the overall macroeconomic effects of transportation infrastructure spending. It first identifies—at a micro level—the different functional elements of economic development benefits and business productivity. It then critically assesses the state of current methods and data for both aggregate-level analysis of capital investment benefits and local-level analysis of specific highway project impacts. Results of recent research are then used to illustrate how the analysis of local impacts of specific highway projects can be more fully measured in a context consistent with overall productivity and other economic concepts.

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MEASURING ECONOMIC DEVELOPMENT BENEFITS

Investments in highways and other types of transportation system improvements are widely recognized as an important means for achieving economic growth and development at the local, state, and national levels. Expansion and improvement of transportation facilities serve to reduce business costs and expand economic opportunities, ultimately helping to raise incomes and standards of living.

Current research on this topic is incomplete and tends to focus on partial economic effects in a given locality or on national economic effects of aggregate highway spending. On the one hand, there are national studies on the relationships between overall levels of highway capital investment and rates of change in business cost, productivity, and output at the state and federal levels. That "top-down" line of research is important for justifying overall spending and investment levels, but by itself yields little guidance on how targeting specific types of projects or settings can optimize the value of economic development benefits. On the other hand, there are regional (local and state) studies of the economic development benefits of improving highway speeds and throughput for specific corridors and facilities. This "bottom-up" line of research often focuses more on localized job creation and business attraction costs, rather than emphasizing total macroeconomic changes in employment, productivity, and income measures.

The challenge is to capture total economic productivity measurements when conducting local or state studies of specific project and program impacts. An approach that unifies disaggregate analysis with an evaluation of overall economic benefits will enable us to: 1) develop a more sophisticated understanding of economic development benefits at the project level, and 2) better guide decision-making in the area of state and federal budget planning. The need for a unified approach is based on our review of the existing literature, with empirical examples based on our recent research. The need to evaluate transportation investment at a geographically specific (micro) level is discussed in terms of travel cost effects, logistics cost effects, and "accessibility/agglomeration" effects. The accessibility/agglomeration effects are illustrated using a model of product differentiation, scale economies, and transportation costs for counties in Michigan. Total economic changes are described in terms of national and subnational macroeconomic structures, and illustrated for an application using the REMI regional economic model.

BRIDGING LOCAL AND GLOBAL PERSPECTIVES

It is important to establish a common understanding of how highway investment relates to jobs and economic benefits. Ultimately, the goal of economic development is to improve people's standard of living and quality of life; a major means for achieving this is by raising net income—resulting from wage increases and/or the creation of additional jobs. It is for this latter reason that studies of regional economic impacts tend to focus on jobs and associated income as a central measure of benefits.

Viewed from a regional perspective, the attraction of new income generated by additional jobs may be seen as a benefit regardless of whether the jobs are created by regional business expansion or by businesses moving into the area. From a national or global perspective, however, productivity is the driver that ultimately leads to additional income and business growth. Internal relocations of business are then seen as a benefit only to the extent that there is some element of productivity-induced growth associated with them. It is for this reason that studies of the national implications of transportation investment tend to focus on productivity gains.

There are several aspects of productivity that can be affected by transportation investment. Overall, productivity is defined as the ratio of output per unit of total factor inputs (which include labor, capital, and fuel). Productivity can be affected by many factors, including most notably the level of technology and the quality and capacity of supporting infrastructure, including: 1) education networks, 2) financial networks, and 3) transportation networks. Public spending on infrastructure, insofar as it improves one or more of these factors, can increase productivity and thus also increase wage income.

In addition to providing direct income benefits, greater productivity can also increase a region's competitive advantage. Increased business activity resulting from this regional advantage can therefore also lead to further income growth as jobs are attracted to the region. In the case of productivity improvements that occur equally across the United States, long-term employment growth may not occur unless there is idle labor—either preexisting unemployment or opportunity for expansion in labor force participation. Productivity increases in all regions, however, can still serve to increase national per capita income and wages. Thus, the analysis of productivity impacts can benefit from an integrated approach that considers regional-level competitive effects as well the aggregate national (or global) effects. In this respect, regional and national-level productivity research can improve our understanding of the true magnitude of net real benefits of transportation investments to the economy of an area.

LOCAL AND REGIONAL ECONOMIC EFFECTS OF HIGHWAYS

In order to understand the relevance of productivity measurements, it is first important to understand the ways in which individual highway investments can improve productivity and lead to economic growth at a micro (local business) level. In general, highway system improvements can reduce business costs of *current operations*, or provide new opportunities for production economies associated with *expanded operations*. Either way, greater income and higher levels of business activity can result. These cost impacts can be classified into three broad categories:

1. reduced *travel costs* for serving existing trips;
2. reduced *inventory/logistic costs*; and
3. greater operating *scale and accessibility* economies.

All of these components of business costs contribute to aggregate measures of overall economic productivity. However, each of these components can vary (and be examined separately) when analyzing how specific highway projects affect specific location areas and classes of trips. Thus, analysis of productivity changes caused by these accessibility factors needs to be conducted on a geographically detailed level. The ways in which each of these elements occur and can be measured are discussed below.

Travel Cost Effects

Nearly all major highway projects are justified by some calculation of user cost savings and its economic value. Typically, state and regional highway network models are used to estimate the level of time and cost savings for users—both on a per vehicle basis and for all vehicles anticipated to use the facilities. By applying generally accepted unit values of time savings, it is straightforward to translate those savings into dollar amounts and compare them with the project cost.

It is important to note that some elements of user benefits—for example, reduced travel times for truck shipments and "on-the-clock" business travel—lead directly to cost savings and hence productivity benefits for businesses. Other elements of user benefits (e.g., time savings for personal automobile trips) are important to society and improve "quality of life," although they do not create any additional business productivity. Therefore, any measurement of economic benefits of highway spending that consider productivity benefits without valuing *personal* (*nonbusiness*) *benefits* will underestimate the full social value of highway investment (although correctly value effects on money flow).

Reviews of the wide range of project-level impact studies generally find that the business element of highway project cost savings varies depending on the composition of the local and regional economy, the nature of the highway improvements, and the specific corridor direction (Lewis 1994). For instance, a study of truck shipping patterns in Indiana showed that travel was: 1) predominantly north-south for wood, furniture, and paper products, but 2) predominantly east-west for fabricated metal and machinery products (Black and Palmer 1993). Given that all industry groups had access to the exact same highway network in Indiana, it is reasonable to attribute the differences in shipment directions to the locations of input suppliers and/or product buyers among the relevant industries. The result of these differences in shipment patterns, then, was the finding that a new north-south highway would significantly reduce costs for the first set of industries but yield minimal cost savings for the second set of industries. A parallel type of finding emerged from the study of east-west highway improvement in Wisconsin (Weisbrod and Beckwith 1992).

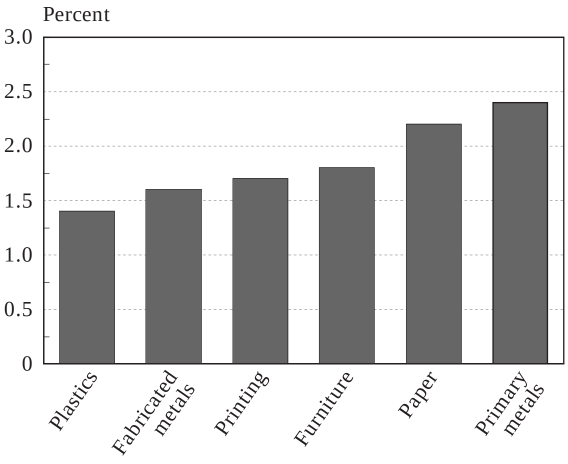
Since benefits for particular industries can differ depending on the highway corridor direction, it follows that estimates of the total value of highway benefits can differ if industry-specific effects are considered in the benefit valuation, in contrast to the traditional approach of benefit valuation (which does not separately consider such effects). To include industry-specific effects, the total value of manufacturing productivity benefits from travel cost savings needs to be defined as the outcome of multiplying four different factors:

1. the extent to which the planned project(s) will reduce shipping or other travel costs for users of the proposed (or improved) highway;
2. the extent to which each different industry has (or will have) patterns of shipping that will make use of that highway;
3. the portion of total business operating cost in each different industry that is affected by road vehicle travel costs; and
4. the size of each different industry in the study area (state, regional, or national economy).

Figure 1 shows the portion of total business costs that are sensitive to highway travel times (factor 3, above). The cost sensitivity is defined as the element of cost associated with the purchase of trucking services and use of in-house motor vehicles (including associated costs of drivers, mechanics, and repair services). The figure shows that these costs vary across industries. The actual pattern of business benefit may be very different, however. If, for instance, we were contemplating a program of improving north-south highway travel in Indiana, then the savings in business costs for fabricated metal manufacturing would be significantly less than if an alternative corridor direction were being considered.

There are three factors affecting the applicability of traditionally measured user travel costs for total benefit valuation, and their relationship to productivity:

FIGURE 1 Highway Transportation as a Percentage of Total Business Costs



Notes: Highway portion of total business costs represents the sum of business costs associated with purchases from the trucking industry, purchases of in-house vehicle fleets, and costs of drivers and mechanics.

Subsequent to this study, the Bureau of Transportation Statistics produced Transportation Satellite Accounts to address this topic (Fang et al. 1998).

Sources: U.S. Department of Commerce, input-output technological tables and industry-occupation matrices.

1. *Difference in business and nonbusiness effects.* Only a portion of user travel costs—that associated with business-related travel—directly affects business productivity.
2. *Difference in short-term user and long-term business effects.* The values of time and cost used in traditional travel demand models are derived from measures of direct effects on driver and passenger travel decisions, which are not necessarily the same as the long-term implications of transportation system speed or reliability changes on business inventories, logistics, scale economies, or manufacturing processes. (The derivation of value of time is reviewed in USDOT OST 1997).
3. *Differences in business responses.* Even if a highway project or policy had the exact same user cost savings impact on every type of business in the affected area, there would still be very different effects on business growth and income generation among the various industries. This occurs because there are differences among industries in their ability to relocate, their ability to expand into broader markets, the nature of market response to lower prices, and

the attractiveness of reinvesting cost savings in local expansion vs. distributing or reinvesting the profits elsewhere.

Logistic Cost Effects

Industrial location is a central strategic decision for manufacturing firms, and location relative to highway connections can represent an important basis for the long-term competitiveness of the production that takes place at a given establishment. For most industries, the cost of highway transportation is small in comparison to labor, capital, and other input costs. The operation of manufacturing in high-wage, high-rent but low-transportation cost locations therefore seems inconsistent with the overall magnitude of transportation costs in production. Only by consideration of total logistics costs, including inventory holding costs, can we fully capture the importance of highway transportation to industrial production.

Total logistics costs include ordering, inventory, and absolute transportation costs (McCann 1996). These costs are borne both for the use of inputs and the supply of final output. Models that evaluate only absolute transportation costs generally conclude that firms using heavy and bulky goods will be located close to the supplier or market. Total logistics cost considerations, however, would lead us to conclude that the value of goods shipped plays a significant role. Since inventory holding costs are a significant part of total production costs, the value of inputs and outputs determine the location of the producer and the wage and rent that the producer is willing to pay at any given location.

Logistics cost considerations are central to freight modal choice. Transportation options such as truck, rail, and ship offer a tradeoff between costs per unit and frequency of trips. While a large shipment of goods from one site to another may provide relatively lower average costs than would occur with smaller amounts, the reduced frequency of shipments may be an overall disadvantage for the firm. Since inventory costs are significant, the production location, transportation mode, and shipment frequency are interconnected decisions faced by manufacturers.

Another area of research on “time-based competition” examines how speed and reliability of product delivery have become increasingly important factors in business growth (Blackburn 1991). The cost savings associated with “just-in-time” processing is one example of the broader set of logistics cost considerations. More generally, producers solve the “logistics cost location production problem” in order to determine the optimal shipment frequency and modal choice (McCann 1993). The cost of acquiring and transporting goods must be balanced with the cost of holding inventory. In the long term, the profit maximizing location of production (and hence also the measure of economic benefit) may differ if logistics costs are added to direct user travel costs.

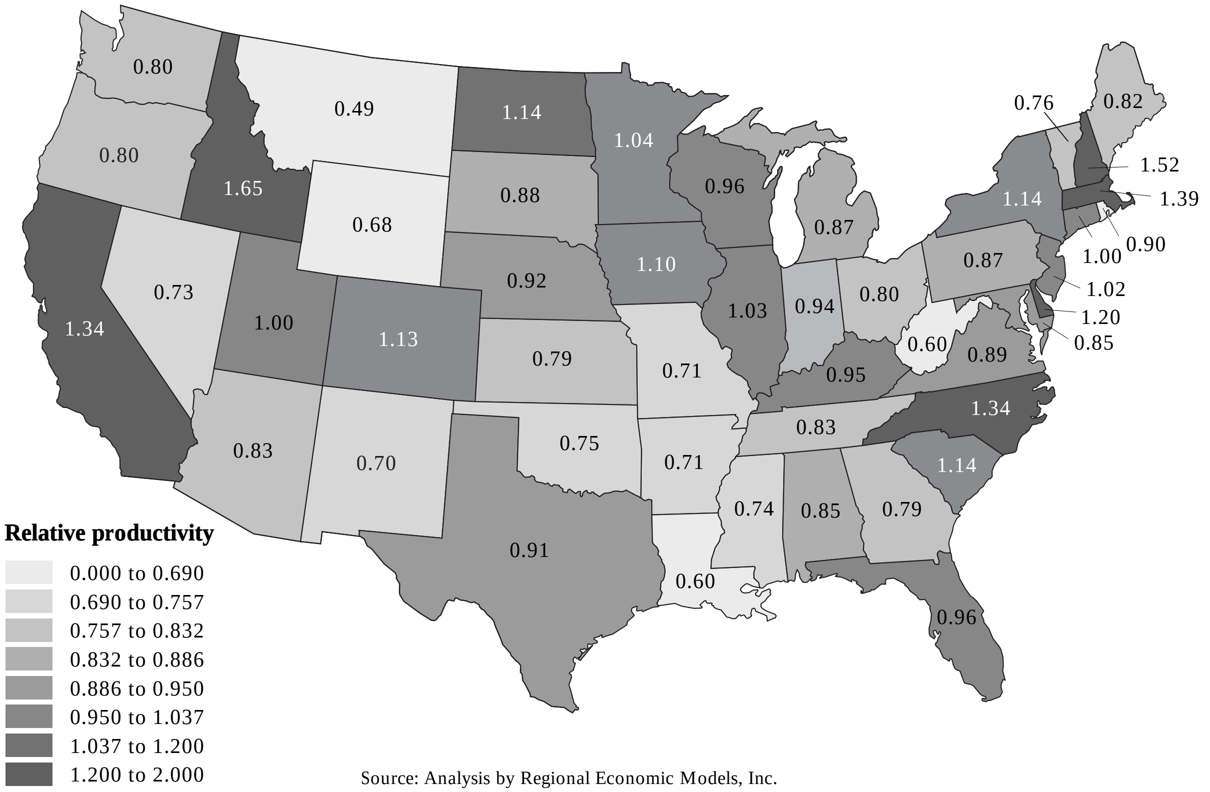
Accessibility and Scale Economy Effects

Highway projects have an important spatial location characteristic, beyond travel cost and logistics cost effects. They can serve to expand the market reach of businesses, allowing businesses an opportunity to realize “economies of scale” by serving broader markets more economically. In addition, highway system improvements can provide businesses with access to a greater variety of specialized labor skills and specialized input products, helping them to become more productive. (While the market expansion and scale economies of some firms may be partially offset by market loss and diseconomies for other firms, normally the net productivity effect of greater system accessibility would still be positive.)

The importance of accessibility and market size as it affects business productivity becomes apparent when we look at the major differences in productivity among U.S. locations, as well as among U.S. industries. Widely examined productivity differences between “core” and “periphery” regions persist, despite long-term trends toward convergence. Of particular interest are regional differences in productivity of industries, which vary both by state and by sector.

Figure 2 illustrates the relative total factor productivity differences by state in the Machinery and Computer industry (SIC 35). The most productive states are those with high-technology centers, such

FIGURE 2 Relative Productivity in Machinery and Computers (SIC 35): 1994



Source: Analysis by Regional Economic Models, Inc.

as the Silicon Valley in California, the region centered on Route 128 in Massachusetts (including Southern New Hampshire), and Research Triangle in North Carolina. Other high-productivity states with major computer industry facilities include Idaho and New York.

On an aggregate basis, disparities in productivity are large. In 1988, output per worker ranged from $44,488 in New Jersey to $26,196 in South Dakota, reflecting factors such as differences in workforce skills, technology investment, transportation access, and the nature of activity within those industries. The agglomeration of economic activities clearly appears to be important, however. Recent studies show that these productivity differences are directly related to the density of employment (Ciccone and Hall 1996). Highly productive states such as California, Illinois, and New York rank in the top 10 for employment density, while states with lower productivity indices such as Maine, Mississippi, and Montana are among the most sparsely populated states.

Density of employment and population is a major determinant of a business' accessibility to specialized inputs, and is also related to high levels of productivity in locations with concentrations of economic activity. Industrial and urban agglomerations provide high levels of productivity, because of the availability of a wider variety of labor skills and product inputs.

The importance of accessibility can be demonstrated by looking at how industrial and urban agglomerations function. These concentrations of economic activity, while highly productive, often involve significant congestion and other costs. Improvements in the transportation system can increase producers' access to specialized inputs and labor. In this way, the productivity benefits would mitigate the negative effects of urbanization. Empirical studies (e.g., McConnell and Schwab 1990) confirm the value of agglomeration economies and accessibility factors through business location preferences.

While highway investments may not greatly change the density of cities, they can help relieve urban congestion, which limits the productivity gains that can be achieved through agglomeration. Highway investments can also affect the pattern of interregional linkages, which can provide accessibility benefits similar to those of agglomeration economies. Recent research on interregional trade within the United States has in fact demonstrated how it is possible to model trade flows within counties and states, and estimate the benefits of accessibility to specialized labor and input products. One example is a recent modeling approach that utilizes estimates of transportation costs and accessibility to differentiated inputs as a basis for explaining wide differences in regional productivity (Treyz and Bumgardner 1996). This approach also provides a means for estimating interregional trade flows and benefits to improved locational accessibility.

MODELING ACCESSIBILITY THROUGH TRADE FLOWS

Much interregional trade and economic geography modeling utilizes estimates of transportation costs and accessibility to differentiated inputs as a basis for explaining wide differences in regional productivity (Krugman 1979, 1995). This type of modeling approach also provides a means for estimating travel flows and benefits associated with differences in locational accessibility. It does this by recognizing that when firms operate under a market structure of monopolistic competition, each produces a slightly differentiated product representing a specific market niche. Scale economies are incorporated in a production function in which output is produced using a fixed labor (overhead) requirement for each firm, a marginal labor requirement for each unit of output that is produced, and transportation costs proportional to output and distance. The demand for specialized consumption and inputs is represented under conditions where each firm faces a downward-sloping demand curve and therefore will set prices at a fixed markup over marginal costs. Similar approaches based on transportation networks and differentiated labor and intermediate inputs are widespread in the regional and urban literature (Ciccone and Hall 1996; Fujita 1989; Krugman 1995).

Relationship of Accessibility to Productivity

While the monopolistic competition model may be a simplification of reality, it does explain not only the trade in differentiated goods and services, but also the productivity benefits of access to these goods and services. Complete specifications of this model may take different forms and have been developed elsewhere. The following equations, however, serve to illustrate the relationship between transportation and productivity that is a common feature of these models.

Let the production of a manufactured good (x) use inputs of capital (k), labor (l), and differentiated services (v). This is specified in the Cobb-Douglas form:

$$x_j = k_j^{\alpha_1} l_j^{\alpha_2} v_j^{1 - \alpha_1 - \alpha_2} \tag{1}$$

with $0<\alpha_1,\alpha_2<1$. Furthermore, let the service input be defined by following the constant elasticity of substitution (CES) sub-production function:

$$v_j = [\textstyle\sum_h z_{hj}^{(\sigma - 1)/\sigma}]^{\sigma/(\sigma - 1)} . \tag{2}$$

The service input is a composite of slightly differentiated services (z), where the subscript h represents each variety of service. The elasticity of substitution between varieties is given by σ, with $1 < \sigma < \infty$. While high values (of σ) indicate that different services can be easily substituted for each other, values (of σ) near 1 means that services are not substitutable. In evaluating transportation policy, an inability to substitute between services implies that access to a large number of specialized services is an important productivity determinant.

The total costs of each manufacturer (TC_j) depend on input prices and the use of inputs, given by

$$TC_j = c_j k_j + w_j l_j + \textstyle\sum_{hj} p_{hj} z_{hj} \tag{3}$$

where c is the cost of capital, w is the wage rate, and p_{hj} is the price of each service in j, including transportation costs. If reduced transportation costs result in a lower price for services in location j, then manufacturers can produce the same level of output at a lower cost. Since manufacturers seek to maximize profits, a reduction in transportation costs for services would result in an increase in the productivity of labor and capital.

The demand for services can be derived by assuming profit-maximizing behavior for manufacturers. The demand function for services determines service trade, shown as:

$$z_{ij} = \frac{(1 - \alpha_1 - \alpha_2)\lambda_i X_j}{p_{ij}^{\sigma} \sum_i \lambda_i \, p_{ij}^{1 - \sigma}} \tag{4}$$

where z_{ij} is exports of all services h in location i to location j, $(1 - \alpha_1 - \alpha_2)$ is the total use of the service composite, λ_i is the proportion of all services in the economy that are produced in location i, X_j is the total production of manufacturers in location j, and p_{ij} is the price in location j of a service that is produced in location i, including transportation costs. Locations with a large variety of services, such as cities, have correspondingly high values of λ and therefore export more services. The price competition of each location i with other locations is incorporated in the denominator. If transportation costs decline between locations i and j, this would result in a reduced price p_{ij}, and an increase in exports from i to j, z_{ij}. Thus, reducing transportation costs results in both more trade and higher productivity.

Application of Accessibility Modeling

The above type of model can be solved for manufacturing or nonmanufacturing industries. The specific method shown in this paper is appropriate for service industries, where reliable, comprehensive transportation data is unavailable. (The U.S. Census of Transportation covers only shipments of manufacturing and natural resource products.) An approach for estimating trade flows in service industries is vital, since this type of industry accounts for a majority of U.S. employment.

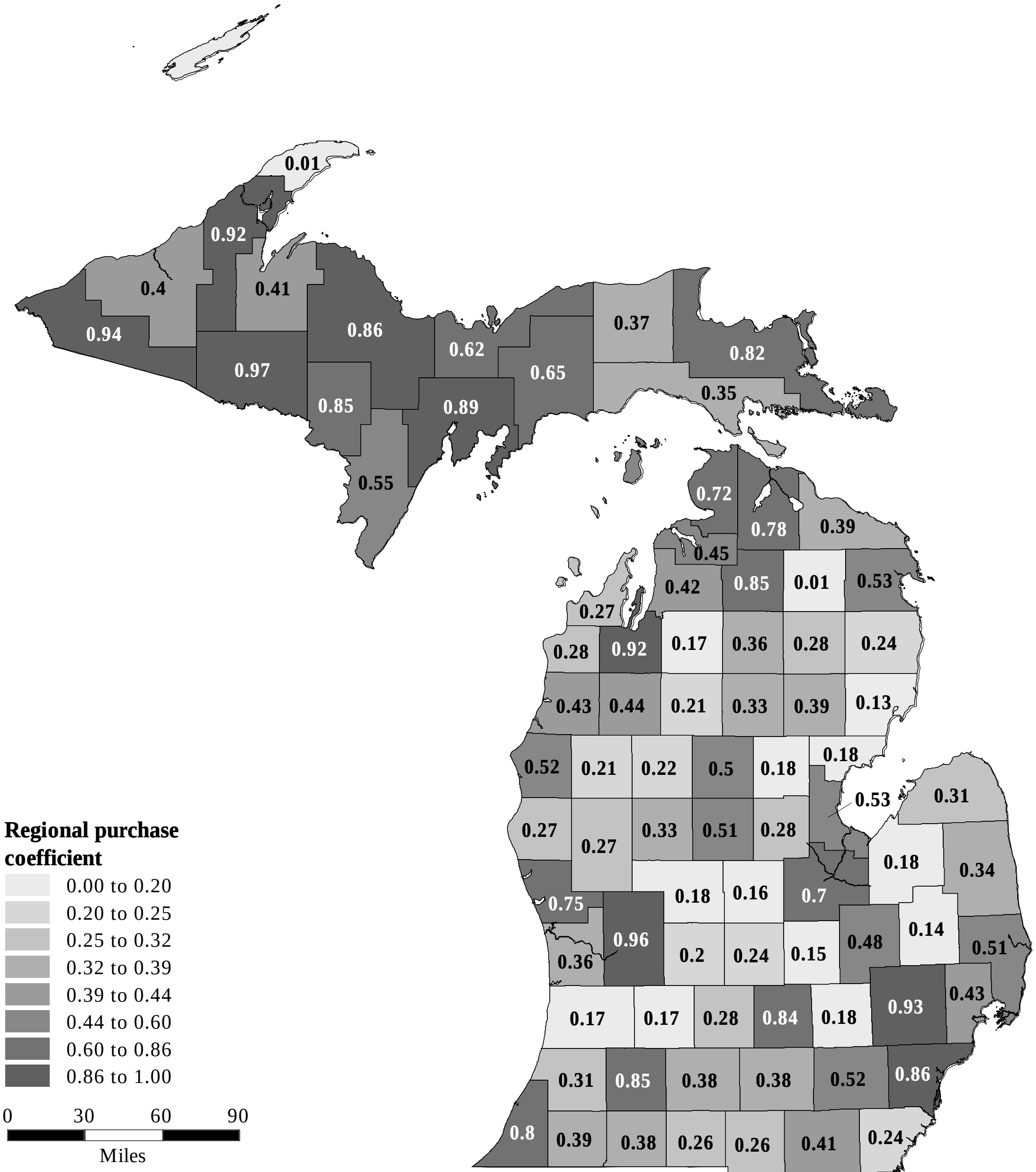
The basic inputs into the model are demand and supply by county, factor costs (e.g., the wage rate), and distances between counties. The elasticity of demand is calculated based on an econometrically estimated production function using U.S. Census of Services data. A calibration technique is used to estimate the transaction cost of distance, such that excess profits/losses (i.e., prices different from unity) are minimized.

"Regional purchase coefficient" (RPC) estimates from the model calibration for legal services in Michigan are shown in figure 3. The RPC is the proportion of local demand supplied locally, a summary statistic calculated from the complete 83-county by 83-county trade flow matrix. This proportion is relatively high in large, urban counties, such as the central counties in the Detroit area. In dense locations, consumers and producers are able to satisfy their needs for specialized legal services within the county. Other areas that supply a high proportion of their own demand include counties in the upper peninsula, in which distances are large and transportation costs prohibitive. RPCs are lowest in rural counties that have relatively easy access to large cities. Less than 25% of local demand is supplied locally in many of the counties surrounding Grand Rapids, Lansing, and Detroit. The model, therefore, shows a type of urban hierarchy, in which large cities provide specialized services that supply smaller cities, towns, and suburbs.

To illustrate the trade flows that occur among counties, the demand and supply interactions between Ingham county and the rest of Michigan are shown in figures 4 and 5. Ingham county is located in south central Michigan, and covers most of the urbanized area of the state capitol, Lansing. Figure 4 shows the location of legal service production that is purchased in Ingham county. The majority of legal services are supplied from the county itself (as shown in the RPC calculation above). Oakland and Wayne (Detroit Region) counties supply well over 5% of Ingham county's demand, since more specialized legal services are available from these locations. Thus, they are able to sell more legal services to Ingham county than are supplied by adjacent suburban counties.

Figure 5 shows the distribution of sales of legal services produced by Ingham county. Most of these services are sold within the county, yet about 15% of the output goes to adjacent and nearby suburban counties. Despite high levels of demand in Oakland and Wayne counties, they purchase less than 1% of Ingham county's output of legal services. The basis of this trade relationship is that Detroit region counties are able to obtain a variety of legal services from within their metropolitan area. This example illustrates how it is possible to model flows of goods and services within states based on accessibility measures. This approach also provides a basis for identifying and measuring the value of accessibility improvements to industries. Of course, the value of this approach (and need to apply it) for transportation investment

FIGURE 3 Michigan Counties: Regional Purchase Coefficient for Legal Services



Source: Analysis by Regional Economic Models, Inc.

decisionmaking will depend on the extent to which proposed system improvements are expected to significantly affect intercity (or intercounty) linkages in the network.

TOTAL PRODUCTIVITY BENEFITS OF HIGHWAY INVESTMENT

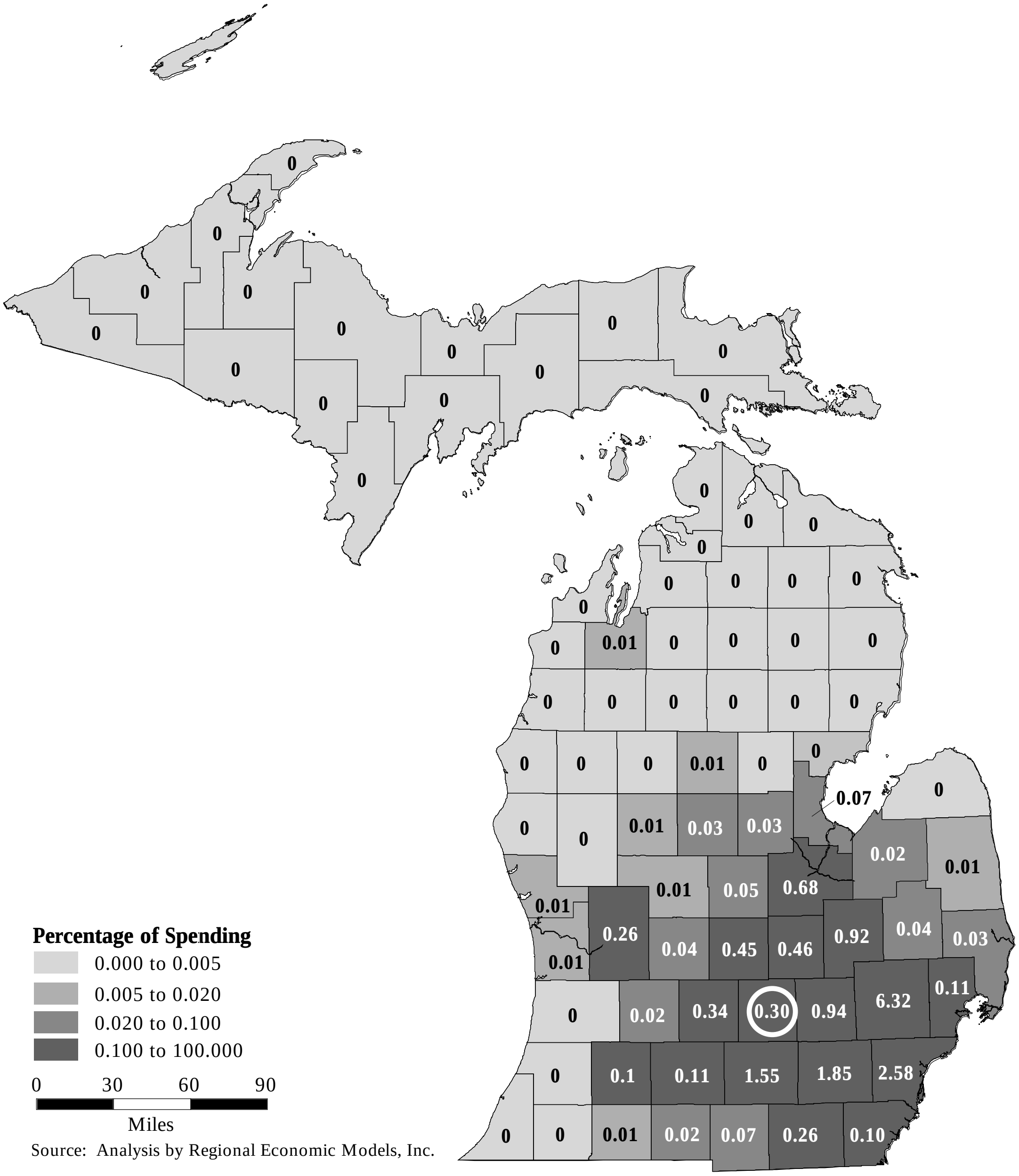
Overview of Productivity Research

The macroeconomic approach for assessing the productivity impacts of transportation investments is to estimate production (or cost) functions, which represent the causal relationship of public infrastructure ("capital stock") to changes in business output (or costs). The general form of the statistical models for production functions is as follows:

Output = function of the quantity and productivity of the various input factors (which include employment, private capital investment, and public infrastructure investment).

A number of reports have documented the relationship between rising business output levels over time and infrastructure spending levels (predomi-

FIGURE 4 Ingham County: Percentage of Legal Services Spending Flowing to Suppliers Located Elsewhere in Michigan

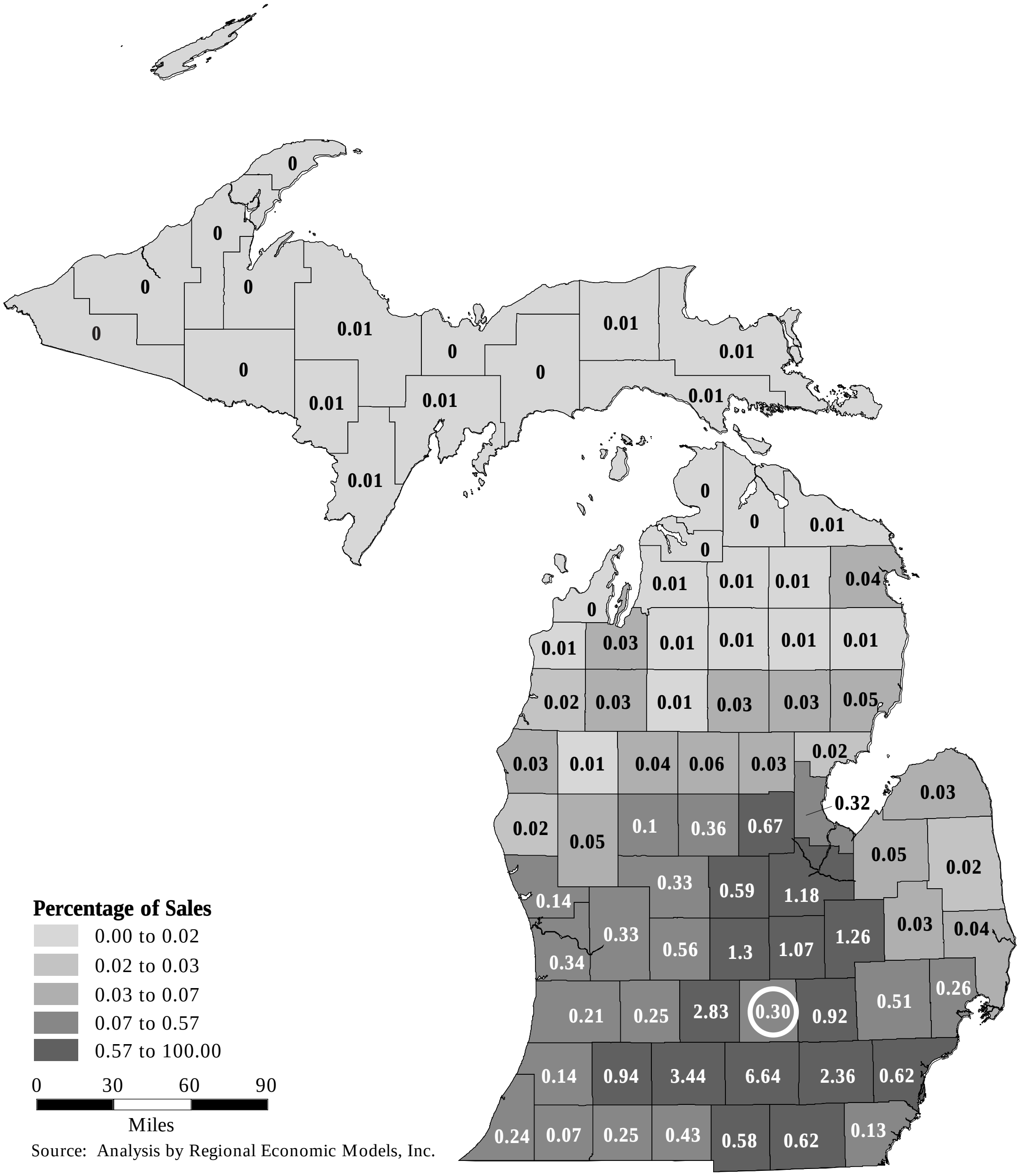


Source: Analysis by Regional Economic Models, Inc.

nantly highway capital stocks) over that same period of time (USDOT BTS 1995; Madrick 1996; Sturm et al. 1997). These studies were conducted at national, state, and metropolitan area geographic levels. Some addressed overall public infrastructure spending, while others focused on transportation investment, or just highway investment.

In general, the consensus findings to date are that there is a positive relationship of increasing business output levels to capital spending on infrastructure, although the impacts span a range above, at, and below the private return on capital. The relationship of [% Δ output / % Δ public capital] is most often found to be in the range of 0.2–0.4 at the national level, around 0.15 at the regional or state levels, and as low as 0.04 at the metropolitan levels (Aschauer 1989; Munnel 1990; Duffy-Deno and Eberts 1991; Toen-Gout and Van Sinderen 1994; Nadiri and Mamuneas 1996). The economic effect of transportation infrastructure

FIGURE 5 Ingham County: Percentage of Legal Services Sales from Purchasers Located Elsewhere in Michigan



Source: Analysis by Regional Economic Models, Inc.

spending appears to be lower for smaller geographic areas, because many of the broad network interconnection benefits to businesses are outside of these areas. The net sum of these effects is, however, reflected in the national measures of productivity.

Uses and Limitations of Productivity Research

By definition, the measurement of aggregate productivity effects reflects net overall changes in business costs and output levels. Additionally, it shows the net result of all positive and negative factors affecting productivity, including existing trip costs, inventory costs, scale economies, and accessibility cost factors. This type of research may be of significant potential use as an indicator of the value of public spending on transportation infrastructure (capital stock), and as a tool for identifying the optimum level of public spending on infrastructure given the magnitude of the current economy.

Of course, different kinds of transportation system improvements will have a range of impacts on the overall cost of business output in each industry. Transportation infrastructure investments can also lead to different marginal benefits for industries and geographic areas. The situation is even more complicated: highway infrastructure investments directly affect business costs and scale efficiencies, and can indirectly affect population inflow/outflow patterns, labor markets, and wage levels, all of which also affect demand for products and thus business output levels, jobs, and income generated.

There are also three significant limitations associated with this research, when used in isolation:

1. *Aggregate level of analyses.* There is currently only a limited base of information on how productivity effects of transportation investment can differ by specific combinations of mode, industry, and region. Even more important, the research has necessarily focused on overall transportation or highway capital spending, without distinguishing how productivity effects can differ depending on the type of highway improvement, intensity of highway use, or level of congestion. (Recent unpublished research by Jones et al. at Oak Ridge National Laboratory and Eberts at Upjohn Institute applies measures of highway accessibility rather than highway capital stock as the explanatory factor in productivity studies.)
2. *Treatment of changes over time.* The research to date has necessarily been retrospective, examining past trends. The marginal impact of future highway spending may be different, as business technologies and facility location patterns continue to evolve, as intensities of use and congestion grow on significant urban roads and inter-urban links, and as the mix of future projects changes.
3. *Nonvaluation of individual and consumer impacts.* Estimates of aggregate productivity impacts reflect producer cost and output changes, but generally place no value on improvements in nonbusiness travel affecting consumer (shopping) activities and personal (social and recreation) time. They also place no value on environmental benefits, which are similarly not included in the national income and product accounts.

Overall, then, we cannot be sure that the *marginal* benefits to productivity associated with current and *future* projects will be the same as the *average* benefits to productivity associated with *past* highway spending.

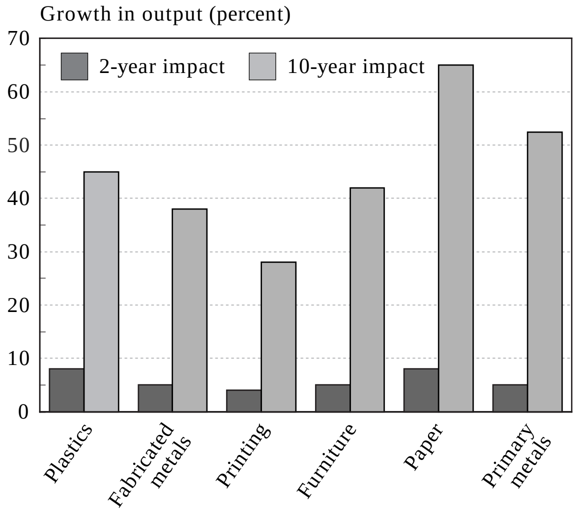
MEASURING TOTAL ECONOMIC EFFECTS

In order to measure the total economic implications of transportation infrastructure investments, the project-specific effects described in the preceding section need to be taken into consideration. These project effects in themselves, however, do not represent a full economic analysis. Changes in costs and productivity affecting an industry at the project level have broader economic repercussions for the locality or region. To show total U.S. macroeconomic effects of transportation investments, the national labor force availability also needs to be considered when calculating regional effects.

Thus, a bottom-up approach starting at the project-specific level can be applied to represent national macroeconomic effects of transportation investments. Accessibility and other direct effects are important determinants of regional macroeconomic changes; the combination of regional changes determines national economic effects, subject to national labor force and other constraints. Total national economic effects can therefore be calculated from specific transportation investment information.

The direct project-level changes in regional productivity and cost competitiveness can have implications for longer term forecasts of regional economic growth. Such forecasts can be generated by regional simulation and forecasting models that reflect inter-industry linkages and their effects over time on trade, production costs, wage rates, and other productivity factors. A few examples of the application of regional economic simulation models to evaluate major transportation improvements are studies of the Netherlands (Evers et al. 1987) and Wisconsin (Weisbrod and Beckwith 1992). In this paper, we provide an example for the REMI model for Indiana. The application of such models is illustrated in figure 6, which shows how a constant 10% reduction in highway transportation costs would affect economic model forecasts of industry growth.

FIGURE 6 Forecast of Business Growth Due to a 10% Reduction in Highway Travel Cost



Source: REMI (Regional Economic Models, Inc.) simulation model for Indiana.

In this example, the cost reductions increase employment through key interactions in the economy. These economic linkages are captured in the structure of the economic model. The highway cost decrease has the direct effect of reducing production costs. Lower production costs increase business activity in the region, as export and local market shares increase for the affected industries. Output increases to supply internal and external demand, and more workers are hired to produce the additional output. As employment increases, wage rates are driven up. Workers migrate into the region, lured by the additional employment opportunities and higher wages, and their additional spending has a further positive effect on economic activity. All variables in the economy are interrelated, and are solved simultaneously by the economic model.

By comparing figure 6 with figure 1, it becomes apparent that the ultimate effects of highway improvements on business output (and hence income creation) may not necessarily reflect the pattern of highway impact on total business costs. These results also show how long-term and short-term impacts on business growth can be different. Therefore, it becomes important to understand the competitive context of industries and locations affected by highway improvements. Any estimation of economic effects that simply equates cost reduction impacts with business growth impacts, ignoring demand response factors, may be subject to substantial error.

Furthermore, the multiregional U.S. model configuration can be used if major transportation investment results in a fiscal stimulus for the entire country. In that case, an increase in overall employment can cause the Federal Reserve to raise interest rates, in order to maintain the labor force utilization at the non-accelerating inflation rate of unemployment. For example, direct transportation investments for a national highway development program can be input separately for each affected region into a multiregional U.S. model. Then, the model can be solved, accounting for economic changes within each region, competitive effects among regions, and national labor force constraints. Thus, the total national economic effect of specific transportation projects can be obtained using a bottom-up approach, where direct changes on a geographically disaggregate level determine variations in state or local economic activity, which sum up to national-level total economic changes (Treyz and Treyz 1996).

CONCLUSION: SELECTING APPROPRIATE ECONOMIC IMPACT MEASURES

Highway improvements can affect overall transportation costs for businesses, including traveling costs, logistic and scheduling costs, and other costs related to supplier accessibility or market scale effects. A variety of analysis methods can be used to assess the current or past magnitude of these overall costs. The challenge for highway planning, however, is to adequately reflect the magnitude of business cost savings and productivity increases when estimating the benefits of planned new highway improvements. Such benefits can be much more than just the simple time savings due to faster trips, as estimated from a network model. This is especially true if the highway improvements provide affected businesses with new opportunities for logistic efficiencies, scale economies, or broader supplier access.

Key Findings

It is important for local, state, and federal decisionmakers to identify the appropriate level of spending for highway infrastructure and the appropriate projects to maximize social benefits. Traditional methods used to value transportation user benefits and economic benefits for specific highway projects, based on simple calculations of savings in travel time and vehicle operating expense, can understate total project benefits by missing other important aspects of productivity enhancement. Current research on productivity is at a sufficiently aggregate level so as to miss potentially important location-specific aspects and congestion relief elements of needs for highway system development, which may affect future benefits from highway improvements (in ways different from past benefits of highway investment). Methods are emerging for identifying and assessing accessibility market and logistic benefits of highways, and they may be applicable for local highway studies as well as for broader government policy analyses.

While it is not possible or practical to engage in sophisticated modeling for all of the elements of economic impact for every highway project, it is nevertheless important and possible to recognize the breadth and nature of potential impacts during the decisionmaking process.

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Positive Externalities and the Public Provision of Transportation Infrastructure: An Evolutionary Perspective

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ABSTRACT

Do transportation systems, comprising infrastructure, service, and use, produce external benefits? If they do, should positive externalities be accounted for in the evaluation of infrastructure investments? This paper argues that while direct, technological, external benefits from transportation are difficult to find, meaningful positive externalities can arise from transportation systems in at least two ways. First, transportation infrastructure can reduce preexisting negative externalities, and the reduction of external cost must be considered an external benefit. Second, because transportation is essentially a derived demand its effects are broadly diffused throughout the primary markets that induce transportation demand. To the extent that changes in transportation infrastructure induce positive externalities in these primary markets, external benefits should be attributed to transportation.

A ONE-SIDED EXTERNALITIES DEBATE?

The general discussion on externalities of transportation—be they monetary or technological—usually concentrates on negative effects. In this paper, we concentrate on positive effects, although

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most scholars would question their existence—and in most cases they are right if the external effect is defined purely on a technological basis, leaving out monetary effects.

Consequently, most of the approaches used to evaluate the effects of externalities relate to the difficulty of pricing negative technological external effects.[1] We may distinguish between:

- The *resource approach*. The value of the externality is defined by the corresponding resource price of the private market, which in most cases relates to prices for damage or repair.
- The *avoidance approach*. The value of the externality is defined by the possibility of substituting the resource, the technology, or the good in question for a resource, technology, or good without the external properties.
- The *risk approach*. The value of the externality is defined by the discounted expected monetary value based on an evaluation of risk.
- The *utility approach*. The value of the externality is defined by the willingness to pay in order to reduce negative effects.

The scientific argument behind this apparent one-sidedness—which only accounts for negative effects—is that the positive effects of transportation investments are immediately captured by markets, unless market failure impedes it, whereas most negative effects remain external. This view is reflected in most of the literature.[2] Policy measures not correcting for this asymmetry must necessarily lead to allocation failures.

The most intuitive examples of negative externalities might be the adverse effects of infrastructure, for example, dividing up a landscape or vehicle emissions. It is very difficult to imagine external benefits (e.g., the beauty of a bridge in the case of infrastructure) or something comparable to "positive emissions." The very abstract concept of mental maps derived from a high degree of mobility and facilitating extended interaction spaces might be useful, though very unlikely.

The question is: what is ground zero? To what sort of alternative do we compare the existing transportation system? If we know the reference point, all effects "below" may be referred to as negative externalities, all effects "above" as positive externalities. Of course we know that this objective reference point does not exist, and there is no chance to objectively derive it. Thus, reductions in negative externalities may be considered as net positive externalities.

A more challenging issue seems to be that transportation demand is derived from other markets. If external effects exist in these "primary markets," they are in a causal sense transferred from one place to another. This link is not restricted to geographical locations; it may also refer to other metrics, that is, product space. The capacity of these links may be an important factor in the transfer of externalities. At the limit, without the transfer no market would exist and, thus, no externality issue.

In this paper, we investigate the external benefits of transportation stemming from spatial transfers from one primary market to another or from supply to demand. From what is known about spatial analysis (Blum 1996), it is clear that once markets or points of production and consumption are linked by means of interaction (i.e., transportation in geographical markets, substitutive exchange in product markets), the derived transportation demand (or transfer) function reflects excess demand and supply as well as underlying externalities. Furthermore, the effect will depend on the degree of perfection of these markets, that is, the more they are monopolized, the smaller the transfer effect.

Let us look at some intriguing examples:

- A vaccine prevents the spread of a disease once a sufficient proportion (below 100%) of a population has been vaccinated. Thus, all those who are not vaccinated benefit from an external benefit. If such a vaccine is shipped into a new market, external benefits emerge there, and their

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[1] The willingness to pay for reduced noise normally differs from costs for technological improvements in cars or actual costs incurred in the medical sector.

[2] The analysis of negative externalities of transportation in Germany reveals costs that vary between 44 bn DM and 221 bn DM p.a. (IWD 1996). Growth effects are mostly analyzed within the framework of production models (Blum 1982). External benefits have been reported in Germany by Aberle (1992, 1994), who especially stressed the spatial aspects, the aspects of market integration, and cost savings; however, it has been argued that these benefits are not external at all as they are included in the allocation via the price system.

level will depend on demand that, again, will be partly influenced by transportation costs—which makes the institutional setting of the transportation market of crucial importance.

- Knowledge produced in one region is transferred to another region by means of commerce: the level of external benefits in the sense of spontaneous adjustments to the economy will depend on the intensity of this transfer, and it will be difficult to capture these effects from the beginning because of the existence of non-knowledge or uncertainty (Knight 1921). Market integration, however, triggered by the same transport system may produce sufficient information to grasp the issue and internalize it.
- The existence of a transportation system allows production and consumption nodes to interact, enabling them to produce economies of scale and of scope, and network economies. According to the new growth theory, they are external to the firm and can only be captured once sufficient information is available.
- Visitors to a resort island benefit from the beauty of nature, depending on the number of people allowed on the island.

All these external benefits are surpluses in the transportation demand system; in the price-volume diagram, a social transportation demand function with a higher reservation price reflects the level of demand if all positive externalities were properly accounted for by the individuals.

The structure of the rest of this paper is as follows: the next part classifies goods according to demand and supply characteristics; then, a model is proposed to link the characteristics of goods to varying congestion levels, a dominant characteristic of the use of infrastructure. Finally, we show that this classification provides new insights into the way infrastructure allocation is organized and costs and benefits are evaluated.

INFRASTRUCTURE, PUBLIC GOODS, AND EXTERNALITIES

Public Goods

Following the classic definition by Samuelson (1954, 387), goods are public "which all enjoy in common in the sense that each individual's consumption of such a good leads to no subtraction from any other individual's consumption of that good." As a consequence, consumers cannot be *excluded* from consumption and there exists no *rivalry* for consumption.

In this definition, the *pure public goods* are one pole of a continuum that extends to *pure private goods* at the other end. It was quickly discovered, however, that ideal public goods rarely exist in reality and that private allocation is possible once mechanisms can be found that:

- prevent the free use of these public goods, and
- force groups to reveal their preferences, at transaction costs that do not reduce demand to zero.

Symmetrically, pure private goods are also only an ideal counterpart to the ideal public good; the spectrum between these poles may be seen as a continuum that we will address later. This leaves unresolved the question of what type of good a road really is, for instance. In fact, it is easy to find roads or other types of infrastructure that can be positioned at different points on this continuum. The following observations may serve as a first challenge to the easy categorization of infrastructure:

- there is no such thing as rivalry per se; it depends on congestion and thus may vary widely for the same infrastructure. Once a motorway is filled to capacity, the situation is different from when it was empty.
- exclusion depends on the relative weight of transaction costs that vary in space and time. Some of these transaction costs are "natural," while some are created in order to force the revelation of preferences.
- the quality of the public good may depend on location, that is, a constant quality and/or quantity is not guaranteed.[3]

In fact, we see that given a fixed infrastructure capacity, exclusion reduces congestion and therefore also rivalry.

Our main argument is as follows: the quality of a public good is not only a supply-side characteristic but also relates to demand (i.e., preferences). As

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[3] Security is an example of the thinning out of a public good in a spatial setting (Blum and Dudley 1991).

a consequence, the usual one-dimensional classification of goods from pure public to pure private no longer applies. This interaction of supply and demand was implicitly mentioned by Buchanan (1965) when defining the optimal size of a club good.[4] In fact, the issue of optimal size of a club relates to the problem of how to measure in real terms what goods people want if the market principle is not completely applicable. The club good then is characterized by the ability to exclude consumers, but no rivalry in consumption exists. It is worth noting that:

- All club goods can be declared public goods if capacity is set above zero price demand. For transportation, this is often the case for a highway in a sparsely populated area.
- The same holds true for private goods, if the government floods the market with free goods (i.e., if mass transit is declared free, as is the case in some European cities).
- Club goods can be changed into private goods, that is, by selling individual seats instead of selling to groups in a charter flight.
- A true public good cannot be turned into a club or a private good. If it is not a true public good, however, then privatization is possible if control and exclusion costs become manageable, e.g., decoding units in the field of communications.

It becomes clear from the arguments given above that capacity and how it is used may be key to the proper categorization of goods.

Categories of Externalities

External effects are impacts of activities in one market on another market without compensation.[5] They affect the property rights of persons not participating in the latter market. A distinction can be made between *externalities of cost* that are, by definition, captured by a market, and *technological externalities* (Scitovski 1949/50), where the activity in one market affects the individual production or the individual utility function in another market without a transfer through the market mechanism. The transfer may be prevented because of missing institutional arrangements: in the case of external diseconomies, there is no automatic incentive to capture these effects; in the case of external economies, market imperfections may prevent inclusion in the price system.

Incentive Structure and Externalities

If positive external economies are produced by the existence of infrastructure, changes in land prices, for example, occur as consumer demand (use) increases. Even if the initial externalities have been internalized, there is no guarantee that all effects stemming from this change in demand (and thus congestion) are accounted for—be they positive or negative—by transaction costs.[6] Thus, institutional arrangements may play a decisive role. Positive external economies may be sufficiently strong to overcome the level of transaction costs that inhibits internalization directly, or that may trigger the formation of new institutional arrangements. However, what happens if these changes are not feasible because the institutional arrangement has been adapted? What happens—in the sense of the initial discussion—if the necessary volume of vaccines cannot be transported because the infrastructure capacity is inadequate or too expensive (or both), if information exchange is incomplete because the flow of goods is hindered, or if visitors cannot access the empty island?

Seemingly, the ability to transfer externalities depends on the institutional setting of the transportation system, or more concretely, on the organization of infrastructure. We propose two classifications[7]:

1. The basic question of supply is to what extent—given a certain technology—rivalry exists and exclusion is possible. In the case of no rivalry and no exclusion, a public good is a given. The combination of exclusion without rivalry defines the club good. Both rivalry and exclusion are conditions for private procurement.

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[4] A club good is one where the members of the club enjoy a public good and others are excluded. Some argue that highways are a club good, since one needs a motor vehicle to be in the club that enjoys the good.

[5] See, for instance, Arrow (1970) and Cornes and Sandler (1993).

[6] The issue of transaction costs and their impact on externalities was recently discussed by Demsetz (1996), with a focus on possible internalization strategies of the public.

[7] For an example, see Blum and Mönius (1998).

2. The basic question of demand is what prices—given a certain capacity—are applicable or set, for example, by policymakers. For prices $q = 0$ we have a public good; for prices $q > 0$ we obtain a club or a private good.

The general structure is given in table 1; t_c are exclusion costs for club goods, t_p for private goods, $t_p > t_c$. It is evident that the actual exclusion prices for public goods are zero, as nobody is excluded; the hypothetical exclusion costs are extremely high. For example, if a single driver has random access to a public road system, under the institutional setting of a public good, his exclusion would be extremely costly to enforce—thus exclusion prices are zero and all drivers have free access. This dichotomy also holds for other types of goods: without a change of institutional setting, actual exclusion prices for a certain type of good are always higher than if the hypothetical exclusion mechanisms for another type of good had been chosen.

In table 1, rivalry and excludability characteristics of goods are matched with demand, where prices are given exogenously (e.g., set by politics). Examples are in parenthesis.

External Economies and Control Costs

If external economies and costs emerging from setup, exclusion, and rivalry, which we now call control costs, are characteristics of markets, two criteria permit us to classify the allocation of goods:

1. *Positive (external) economies*, that is, economies of scale, of scope, and network externalities imply that the yield increases more than proportionately with input. In many cases, these external economies are a direct consequence of market integration enabled by transportation or communications networks.
2. *Control* is the ability to monitor, exclude consumers, and manage a good; it depends on transaction costs and, thus, the institutional structure (Coase 1937; Williamson 1975) that influences internalization mechanisms.

With increasing use, congestion and thus rivalry may grow. It may be operationalized by the (positive) opportunity costs of supplying additional quantities to maintain the competition at the existing level. Furthermore, positive (external) economies may be reduced, thus lessening the "public" or "club" element in the good. Once total rivalry exists and results in the need to exclude additional consumers, either a pure club good or a private good emerges. Club goods are likely outcomes if joint consumption of the club can be maintained, otherwise a private good is likely.

Mobility facilitates the transfer of external benefits, which might otherwise go unrealized, from one place to another. Take, for instance, an underutilized mass transit system offered as a public good; users only pay marginal costs with fixed costs financed by general taxes. The externalities of one market can easily be transferred to another market. If a road with little congestion is privately

TABLE 1 Demand and Supply Categories of Markets

Demand/ Supply	$q = \mathbf{0}$	$q > \mathbf{0};\ q - t_c > \mathbf{0} > q - t_p$	$q > \mathbf{0};\ q - t_p > \mathbf{0}$
No exclusion, no rivalry	Public (neighborhood street)	— (not offered)	— (not offered)
Exclusion, no rivalry	Public* (highway, toll possible)	Club toll road	Private* or club (opera seats in the same row)
Exclusion and rivalry	Public* (congested highway, toll possible)	Club* (congested toll road)	Private (chewing gum)

* Asterisks show inefficient allocations, and the arrows give the direction of efficient change.

offered and users have to pay fixed costs, the transfer between markets will become more expensive and externalities will no longer spill over with the same intensity.

Once demand increases, congestion can be prevented by charging user fees and organizing clubs, for example, through electronic road pricing. If congestion continues to increase and the exclusion of some potential consumers becomes too expensive (they might revolt), the system will collapse—any transport then would have to become private. However, if with more funds invested in the system the system would produce above proportional yields (i.e., equal to carrying capacity), then these additional transactions could be offset and the system could remain stable.

It is clear that if external economies exist, they might overcome additional costs. This leads us to a model that allows us to formally delimit the different goods' characteristics.

CATEGORIZATION OF GOODS

The Basic Model

What is the path from private to club and public goods? Is it possible to derive functions that discriminate between these three categories? The following model is based on the assumption that if more than one person demands the same public good, a spillover occurs because of the non-exclusion principle. Economic efficiency is achieved when the sum of all individuals' marginal rates of substitution curves between this public good and all other private goods and equals the marginal rates of transformation for the infrastructure in question.

Let us start with the maximization of a utility function for two goods, a private good x and a nonprivate good y—the latter of which may later turn out to be either a club or a public good:

$$\max{:}U(x,y). \tag{1}$$

This function is subject to a budget constraint:

$$q \cdot x + k \cdot y = B, \tag{2}$$

where q is the price of the private good, k is the control costs incurred by the household for the nonprivate good, and B is the budget. Let us assume that x satisfies the same needs as y, that is, x is the private substitute for a nonprivate y. Because of positive spillovers and with increased demand, unit costs fall:

$$k \rightarrow \frac{k}{\lambda}\ ,\ \lambda > 1, \tag{3}$$

where λ is an externality factor, for example, a participation index. Forming the Langrangian L and taking first derivatives, we obtain:

$$\frac{\partial L}{\partial x} = \frac{\partial U}{\partial x} + \mu \cdot q = 0, \tag{4}$$

$$\frac{\partial L}{\partial y} = \frac{\partial U}{\partial y} + \mu \cdot \frac{k}{\lambda} = 0, \tag{5}$$

$$\frac{\partial L}{\partial \mu} = q \cdot x + \frac{k}{\lambda} \cdot y - B = 0. \tag{6}$$

Nonprivate procurement would be preferred if:

$$\frac{\frac{\partial U}{\partial x}}{q} < \frac{\frac{\partial U}{\partial y}}{\frac{k}{\lambda}}. \tag{7}$$

If households are unable to distinguish between the utility stemming from x and y and if the good is either demanded totally or not at all because of indivisibility, we may derive for nonprivate procurement:

$$\lambda > \frac{k}{q}\ , \tag{8}$$

that is, positive external economies have to overcompensate for the relative costs of nonpublic allocation if they are to be beneficial. We may set $q = 1$ and simplify to:

$$\lambda > k\,. \tag{9}$$

Let us now assume that the system is more general. Following our description in the preceding part, three goods are available: a public good (y), a club good (z), and a private good (x). The respective costs or prices are k, p, and q. The system then becomes:

$$\max: U(x,y,z), \tag{10}$$

subject to

$$q \cdot x + k \cdot y + p \cdot z = B. \tag{11}$$

We start with an externality factor λ for the club good and an externality factor μ for the public good, $\mu > 1$. The choice for a public good becomes:

$$\frac{\frac{\partial U}{\partial z}}{\frac{p}{\lambda}} < \frac{\frac{\partial U}{\partial y}}{\frac{k}{\mu}}. \tag{12}$$

Again, we may simplify by assuming that households consider y and z to be identical. Then the system reduces to:

$$\lambda < \mu \cdot \frac{p}{k}. \tag{13}$$

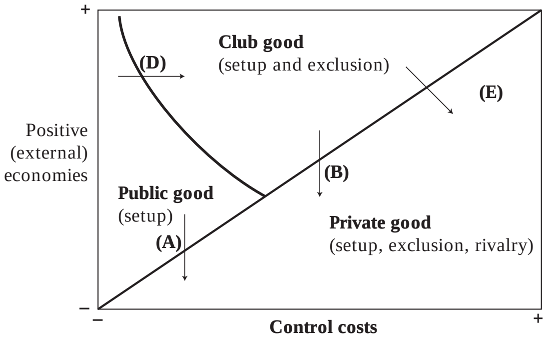
If we further assume that the offer of the (smallest possible) club good has to match the price of the private good, we may set $p = q$, and as $q = 1$:

$$\lambda < \mu \cdot \frac{1}{k}. \tag{14}$$

The delimitation between club goods and public goods is thus a hyperbola: the more positive externalities public goods comprise, the larger their domain.

Organization of Goods and the Impact of Congestion

FIGURE 1 The Two Dimensions of Goods Space



In figure 1, positive external economies and control (exclusion) costs are the two principal dimensions; the relationship is shown by a line from the lower left to the upper right corner. Above that line, the benefits supplying the good on a nonprivate basis exceed the unit costs of setup and exclusion under the institutional setting of a public or a club good. The lower triangle constitutes the region of private goods. Furthermore, the choice between public goods and club goods rests with the question of whether rising control costs can be offset by (external) benefits or not. If so, the public good is preferable, otherwise the club good becomes more advantageous. The delimitation is given by the hyperbola line from the upper left corner to the center. We see that:

- If (external) benefits decrease, then goods previously provided as public or club goods may have to become private as they no longer can win back their setup costs (A) or their exclusion costs (B).
- If control costs for public goods increase, then the provision as club goods (D) and, ultimately, as private goods (E) becomes more likely in order to overcome the rising costs of the now inefficient institutional arrangement.

Generally, any shift in congestion would amount to changes in control costs, which makes the efficient goods provision—as already shown in table 1—a function of demand and capacity. Furthermore, increased levels of congestion would impede market integration and reduce economies of scale and scope, and network economies, thus limiting the yield of the existing arrangement. We may argue that the two externality indices, λ and μ, are decreasing functions of congestion and that control costs, k, increase with congestion, because of their relation to rivalry and exclusion. Whereas private provision needs an optimal degree of utilization, this may be difficult to control in a public or a club environment. Overutilization would then lead to private arrangements unless it can be compensated for by falling unit control costs or additional externalities.

The bottom line of this argument is that externality problems may be solved in cases of congestion by changing the institutional structure, that is, by privatizing slots for road use as well as by actions that maintain the public good character of transportation infrastructure (e.g., expanding capacity). This is compatible with Knight's (1924) proposition that the implementation of Pigou-taxes can be avoided if congestion allows privatization.[8] Furthermore, this internalization may produce sufficient profits to induce additional traffic, which may be one reason why induced traffic is so difficult to forecast (Blum 1998).

CONCLUSION

Positive technological external effects[9] can spill over from supply to demand or from one market to another once the infrastructure is offered efficiently, that is, according to the level of congestion that influences setup, exclusion, and rivalry costs, as well as the yield through economies of scale and scope, and network economies in the primary markets. In the case of a pure private procurement—when demand reaches levels where public or club provision becomes unsustainable—pricing may even capture some of the external benefits as it forces people to reveal (to a greater or lesser extent) preferences (e.g., make the participants in the market pay for the externalities stemming from vaccines, from knowledge transfer, or from the amenities of an uninhabited island).

If, however, congestion is low, the emergence of external benefits is only possible if transfer is not "too expensive," as forcing users to pay the full price of infrastructure would completely eliminate the very transfers that generate positive external benefits.

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[8] The author is indebted to an anonymous referee for this valuable information.

[9] The concept can easily be transferred to monetary external effects.

Research Note

Sources of Error in Estimating Truck Traffic from Automatic Vehicle Classification Data

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ABSTRACT

Truck annual average daily traffic estimation errors resulting from sample classification counts are computed in this note under two scenarios. One scenario investigates an improper factoring procedure that may be used by highway agencies. The study results show consistent and substantial overestimates of truck traffic when truck counts are estimated using adjustment factors obtained from total traffic volume. In the second scenario, better estimates result when the required factors are obtained from a permanent automatic vehicle classifier exhibiting a pattern of truck traffic that is similar to the pattern at the sample count site. A limited research analysis of truck type estimation from sample counts is also presented in this note.

INTRODUCTION

Accurate knowledge of truck traffic has important implications for a variety of highway-related planning, design, and policy analyses (Weinblatt 1996). Estimates of truck annual average daily traffic (TAADT) and vehicle classification (VC) data for individual sections of roads are required to design pavements for the truck volume they will carry. The knowledge of what percentage of traffic is made up of trucks is also a required input for determining capacity and level-of-service provided by a road section (TRB 1994).

Only permanently employed automatic vehicle classifiers (PAVC) can provide accurate estimates of TAADT. However, limited resources available to highway agencies make it impractical to install PAVC on all sections of interest. Seasonal and short-period counts are therefore used to obtain estimates of TAADT and VC. Typically, state highway agencies carry out classification counts for a 48-hour period on weekdays. The factoring procedures currently used by various agencies for adjusting such counts to obtain TAADT estimates vary considerably and the unsophisticated factoring procedures used by many agencies can result in unsatisfactory estimation results (Weinblatt 1996).

This paper presents a number of observations regarding the temporal and spatial variations in truck traffic at several sites located in the Canadian provinces of Alberta and Saskatchewan. The main objective of this research note is to investigate TAADT estimation errors resulting from the use of inappropriate adjustment factors.

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AN OVERVIEW OF THE CURRENT PRACTICE OF TAADT ESTIMATION

Weinblatt (1996) studied seasonal and day-of-week factoring to improve estimates of truck vehicle-miles traveled (VMT). In that study, he reviewed currently used procedures in the United States for estimating annual average daily traffic (AADT) by vehicle classes. He found that classification counts are typically collected for a 48-hour period on weekdays (excluding Friday evenings). These counts are then used, without any seasonal or day-of-week adjustment, as the basis for distributing estimated AADT across vehicle classes. This procedure shows that the vehicle composition of traffic does not change with time. Since AADT is usually estimated from sample counts by applying total traffic volume factors, this procedure also implies that the number of trucks can be estimated by using total traffic volume factors that might have been obtained from an automatic traffic recorder.

Weinblatt's study indicates that the above-mentioned procedure of apportioning of AADT across vehicle classes can contribute to substantial errors in VMT estimates. The study claims that significantly better estimates of VMT for all classes of trucks and of AADT for combination trucks can be developed by using modified versions of the *Traffic Monitoring Guide's* seasonal and day-of-week adjustment factors (USDOT FHWA 1995). It makes several recommendations to reduce truck AADT and VMT estimation errors through categorization of highway sections and use of appropriate seasonal and daily adjustment factors.

A number of provincial highway agencies in Canada use daily and monthly adjustment factors to estimate TAADT from short-term classification counts. These adjustment factors, however, may be derived from automatic traffic recorders reflecting total traffic variation rather than truck traffic variation. The main intent of this note is to investigate TAADT estimation errors resulting from the use of such adjustment factors.

STUDY DATA

The VC data used in this study were supplied by Saskatchewan Highways and Transportation and Alberta Transportation and Utilities. Data were collected from October 1991 to December 1993. In total, eight PAVC sites representing a variety of highway types and traffic volumes were studied—seven from Saskatchewan and one from Alberta. Locations of these sites are described in table 1. The trucks were grouped into three classes: single-unit, single-trailer, and multi-trailer.

TEMPORAL AND SPATIAL PATTERNS OF TRUCK TRAFFIC

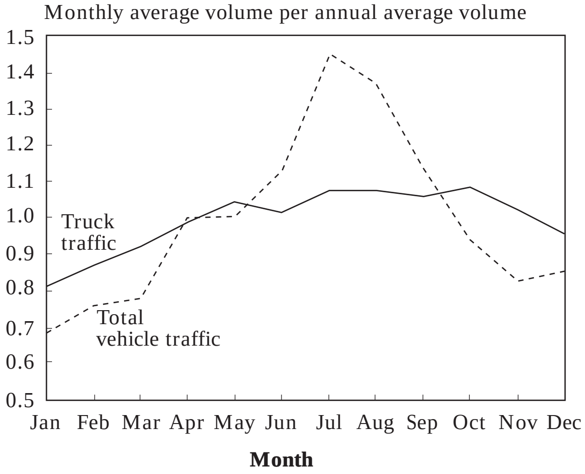
Numerous observations regarding temporal and spatial variations in truck type and truck volume were made from the study data. Figure 1 shows monthly and daily variations in truck volume at a number of study sites. Part (a) clearly indicates that there can be considerable differences between the patterns of truck traffic and total vehicle traffic. It may be noted that the y-axis in part (b) is the ratio of daily TADT (truck average daily traffic) and

TABLE 1 Location of AVC Study Sites

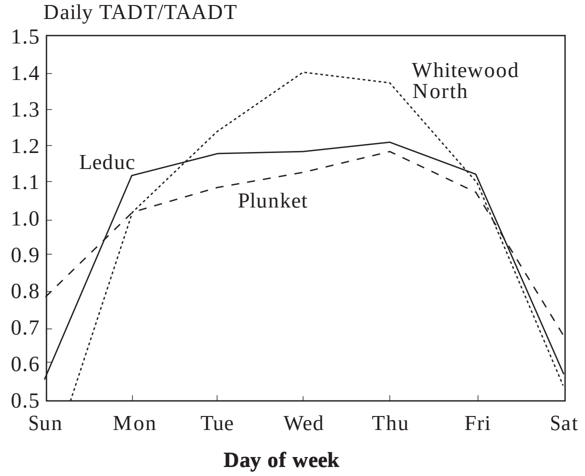
AVC site name	Location description
Indian Head	The 2 east-bound lanes on Highway 1 (the Trans-Canada highway), a 4-lane divided highway, 4.5 km west of Indian Head
Humboldt	The west-bound lane of Highway 5, a 2-lane highway, just east of Humboldt
Whitewood South	Both lanes on Highway 9, a 2-lane highway, 13.5 km north of junction with Highway 48
Whitewood North	Both lanes on Highway 9, a 2-lane highway, 7 km north of junction with Highway 1
Yorkton	The west-bound lane on highway 10, a 2-lane highway, 14.5 km south of Yorkton
Plunket	The west-bound lane on highway 16, a 2-lane highway, 12 km west of junction with Highway 20
Leduc, Alberta	The 2 north-bound lanes of a 4-lane divided highway, close to Leduc, Alberta
Regina	The 2 east-bound lanes on Highway 1 (the Trans-Canada highway), a 4-lane divided highway, just west of Regina.

FIGURE 1 Temporal Variation of Vehicle Traffic

(a) Monthly Variations of Vehicle Traffic at the Indian Head Site



(b) Daily Truck Volume Variations at Selected Study Sites



TAADT. Large variations in hourly truck traffic were also observed at all the automatic vehicle classifier (AVC) sites. Moreover, a remarkable variation in the percentage of trucks was observed during the busiest hours of operation. For example, during the 50 highest volume hours of the year at the Indian Head site, the percentage of trucks was observed to be between 3.5% and 13.5%. The average percentage of trucks over the entire year for this site was 20.5%.

The volume of truck traffic and the truck-type distribution was also found to vary spatially, i.e., from one location on the road network to another. The temporal patterns of truck traffic were observed to be considerably different from the corresponding patterns of total vehicular traffic at all the investigation sites.

ESTIMATION OF TAADT FROM 48-HOUR COUNTS

Equation 1 was used to estimate TAADT from 48-hour AVC counts:

$$\text{Estimated TAADT} = \frac{\text{STADT}}{\text{FACT}} \qquad (1)$$

where:

Estimated TAADT = estimate of truck annual average daily traffic,
STADT = average daily volume of trucksduring the sample 48-hour count, and
FACT = combined monthly and daily adjusment factor for the 48-hour period.

The sample automatic vehicle classifier data that simulated the 48-hour counts were generated from the continuously recorded vehicle classification statistics available from the permanent AVC sites. The sample counts consisted of every 48-hour period beginning at 12 p.m. (noon) on Monday, Tuesday, and Wednesday during the months of April through October.

Two scenarios were considered in this study for calculation of the adjustment factors. Scenario 1 assumed that the adjustment factors came from a permanent traffic counter reflecting total traffic variations rather than truck traffic variations. This scenario was simulated by obtaining total volume adjustment factors for the sample data from the same permanent AVC data that were used to generate the sample counts.

Scenario 2 assumed that the adjustment factors were obtained from a permanent AVC that has a pattern of truck traffic very similar to the pattern at the short-period count site. Such a scenario would occur under ideal situations where a transportation agency has a sufficient number of permanent AVCs to provide close matches to the patterns of truck traffic at the short-period count sites. Since the data were limited, this scenario was simulated by obtaining average adjustment factors for the sample data from the same permanent AVC data that were used to generate the sample counts.

Monthly and daily truck volume adjustment factors were calculated in the same manner as the volume adjustment factors were calculated for the estimation of AADT for total traffic (Gulati 1995). Estimation errors were calculated by using the following relationship:

$$\text{Error} = \frac{\text{Estimated TAADT} - \text{Actual TAADT}}{\text{Actual TAADT}} \times 100$$

Table 2 shows the mean, the standard deviation (S_e), and the range of estimation errors under Scenarios 1 and 2. As expected, the estimation errors under Scenario 1 are much larger than errors under Scenario 2. In the case of Scenario 1, the TAADT estimation errors did not follow a normal distribution, and positive mean errors indicated an overestimation of TAADT for all study sites. A careful examination of sample counts and the factors used in this scenario revealed that the positive mean error or the overestimation occurred mainly because of large differences between the traffic variation patterns for the total vehicular traffic and the truck traffic during weekdays. The weekday total volume factors used for estimation in this scenario had much smaller values (note that the factor appears in the denominator of Equation 1) than we would expect given the corresponding weekday truck volume factors that would have been used in the estimation procedure.

The standard deviation values for Scenario 2 given in table 2(b) could be used to make useful statistical statements about the estimation errors that followed a normal distribution with the mean equal to zero. For example, in the case of the Indian Head AVC site, 95% of the estimation errors would be expected to lie within ±12.15% (or ±1.96 S_e) of the mean value (which is zero).

ESTIMATION OF TRUCK-TYPE DISTRIBUTION

This study investigated the use of 48-hour AVC counts to estimate truck-type distribution. We found that there can be sizable differences between the *actual* truck-type distribution and the *estimated* truck-type distribution. For example, at the Indian Head site, where the actual average percentage of single-trailer trucks with five axles (April through October) was 34%, the 95% confidence interval of the 70 sample counts generated at this site had the lower bound of 17% and the upper bound of 51%—an interval width of 34%. A limited analysis involving frequency of counts indicated that increasing the frequency of 48-hour samples to two counts, taken at least one month apart, could reduce the estimation errors for truck-type distribution by a considerable margin. For the

TABLE 2 TAADT Estimation Errors Under Various Scenarios

(a) Scenario 1

Study site	Actual TAADT	Number of samples	Mean error (%)	Deviation (S_e) of errors (%)	Range of errors (%)
Leduc, Alberta	700	46	30.82	12.50	8.67 to 59.38
Indian Head	390	70	5.07	16.02	–32.58 to 35.87
Plunket	310	90	9.31	24.60	–33.25 to 64.29
Humboldt	170	73	17.23	21.37	–18.43 to 74.60
Whitewood North	130	65	23.43	20.12	–12.18 to 72.94
Whitewood South	100	95	33.77	30.43	–26.67 to 99.21

(b) Scenario 2

Study site	Actual TAADT	Number of samples	Mean error (%)	Deviation (S_e) of errors (%)	Range of errors (%)
Leduc, Alberta	700	46	0.0	4.0	–9.41 to 8.54
Indian Head	390	70	0.0	6.2	–14.78 to 14.17
Plunket	310	90	0.0	9.6	–26.74 to 22.64
Humboldt	170	73	0.0	11.9	–21.57 to 37.44
Whitewood North	130	65	0.0	7.7	–19.11 to 20.00
Whitewood South	100	95	0.0	7.2	–18.57 to 23.18

previous example of trucks at the Indian Head site, the width of the 95% confidence interval was reduced to 22% as compared with 34% for a single count.

CONCLUDING REMARKS

TAADT estimation errors are computed in this note under two scenarios. It is assumed in Scenario 1 that the adjustment factors come from a permanent traffic counter reflecting total traffic variation rather than truck traffic variation. The adjustment factors in Scenario 2 are assumed to have been obtained from a permanent AVC that has a pattern of truck traffic very similar to the pattern at the short-period count site. The statistical results shown in table 2 for the study sites indicate that consistent and substantial overestimates of TAADT are produced when truck counts are estimated using factors obtained from total traffic volume. The mean value (of plus and minus errors) is overestimated from 5% to 34% at the investigation sites. The width of the error interval (the difference between the highest and lowest error values, as shown in the range of errors in table 2) varies from nearly 50% to about 125% in this scenario.

In the case of Scenario 2, where appropriate adjustment factors are used, the expected width of the error interval is reduced to a large extent. In fact, when expressed in terms of the standard deviation (S_e) or the 95% confidence interval ($\pm 1.96\ S_e$), the magnitude of TAADT errors in this scenario is similar to the magnitude of AADT estimation errors for total traffic volume resulting from the Federal Highway Administration-recommended seasonal and day-of-week factoring procedures (USDOT FHWA 1995; Sharma et al. 1996).

Results of this study also indicate that the estimates of truck-type distribution from a single 48-hour count can be subject to a large margin of error. Increasing the frequency of counts to two or three in a year can be expected to reduce the error in the estimates of truck-type distribution. The effect of the frequency and duration of sample counts on the accuracy of volume and truck-type distribution remains poorly understood.

For highway capacity and level-of-service analysis, a traffic analyst requires data on the proportion of trucks in the traffic stream during the design (or peak) hour, which may be the 30th, 50th, or any other highest volume hour. The large variation of truck percentages during the highest volume hours, such as noted in this study for the Indian Head Site, may have significant implications for planning and design of highways.

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		TranStats
	☐	*Truck Movements in America*
	☐	*Federal Gas Tax: Household Expenditures, 1965–1995*
	☐	*Truck Shipments Across the Woodrow Wilson Bridge: Value and Tonnage in 1993*
	☐	*The Economic Importance of Transportation Services: Highlights of the Transportation Satellite Accounts, 1998*
☐		Travel Demand Forecasting 1997
	☐	Welfare Reform and Access to Jobs in Boston 1998

* Represents new product listing.

Customer name and title ______________________________

Organization ______________________________

Address ______________________________

City/state/country/zip code ______________________________

Telephone and fax numbers ______________________________

Email address ______________________________

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