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ENERGY EFFICIENCY
IN THE U.S. ECONOMY

TECHNICAL REPORT ONE

ENERGY, EMISSIONS, AND SOCIAL CONSEQUENCES OF TELECOMMUTING

May 1994

This report was initially prepared and transmitted to Congress in December 1993 to fulfill requirements under Section 413(2) of the Energy Policy Act of 1992. The report is being published in its present format to facilitate making it available to interested parties. A minor calculational error identified in the earlier report has been corrected in this report. This change does not alter the general results or conclusions contained in the earlier report.

This report is based on a study prepared by Oak Ridge National Laboratory, Lawrence Berkeley National Laboratory, and Global Telematics and cofunded by the U.S. Department of Energy's Office of Policy, Planning, and Program Evaluation and Office of Energy Research.

CONTENTS

Tables

Figures

Executive Summary

Purpose

This study was prepared in response to Section 2028 of the Energy Policy Act of 1992, which required the Department of Energy, in consultation with the Department of Transportation (DOT), to "conduct a study of the potential costs and benefits to the energy and transportation sectors of telecommuting." Telecommuting has been defined as the partial or complete substitution of telecommunications services for transportation to a conventional workplace (DOT, 1993).

Available estimates indicate that the number of telecommuters in the United States is substantial and has been growing rapidly. A 1992 survey found that 3.3 percent of the workforce—4.2 million employees—were telecommuters in 1992, a 27-percent increase over 1991 (DOT, 1993). Not counting those who are self-employed or working on contract, the numbers have grown from 0.4 million in 1990 to 1.4 million in 1991 and 2.4 million in 1992. There is strong evidence that advances in computing and telecommunications technologies have played a central role in this rapid growth. Projections cited by DOT indicate that there may be 10 million telecommuters by the year 2000, more than 30 million by 2010, and nearly 50 million by 2020 (DOT, 1993). The consequent reduction in highway travel could significantly help ameliorate the growing problems of traffic congestion, air pollution, and petroleum dependence.

In April 1993, DOT published a thorough report on the *direct* effects of telecommuting—that is, the safety, energy, and emissions effects of those commuters who switched from commuting to working at home or in a local telecommuting center (DOT, 1993). The DOT study, entitled *Transportation Implications of Telecommuting*, focused on the 10-year period ending in 2002, and it deliberately excluded *indirect* effects of the reduction in traffic on the remaining traffic, though it specifically acknowledged the potential importance of such indirect effects. Noting the complexity of such indirect effects, DOT also recognized that removing commuters from congested roads and improving traffic flow might attract additional drivers who previously were not using these roads, thereby countering the hoped-for benefit of reduced congestion. Rather than attempt to estimate both the beneficial indirect effects of congestion relief *and* the countervailing effects from induced travel ("latent demand"), the DOT study chose "to develop estimates only for the time, energy, pollution, safety, and cost savings directly associated with trips replaced by telecommuting," allowing readers to use their own judgment concerning the potential effects of congestion reduction and latent demand. However, the DOT report emphasized the potential importance of these indirect effects, particularly to emissions and energy impacts, and it noted that "these factors are among the largest uncertainties in estimation of the transportation impacts of telecommuting, given a projection of the amount of telecommuting which will occur." (DOT, 1993)

This study builds and expands on the firm foundation provided by the DOT study by examining the indirect effects of telecommuting on urban traffic and exploring the broader social impacts of advances in telecommunications technology and investments in telecommunications infrastructure. To consider the effects of widespread telecommuting, this report considers a longer time horizon—to the year 2010. Specifically, this study considers the following:

- The implications for energy use, emissions, and highway needs of the effects of widespread telecommuting on urban traffic congestion, latent travel demand, and urban sprawl (Chapter 1)
- The potential social impacts of widespread telecommuting (Chapter 2)
- The broader relationships between telecommunications and transportation, and the implications for technology initiatives like the national "information highway" (Chapter 3)

Projecting to the year 2010 and beyond becomes increasingly speculative, but it is necessary in order to explore what kind of effects telecommuting could have if it becomes truly widespread.

Principal Conclusions

By reducing transportation use, telecommuting can help reduce some of the social costs of travel. These costs include traffic congestion, the added time lost in congested as opposed to free-flowing traffic, emissions that degrade air quality, emissions that may contribute to climate change, the risks of depending on imported fuels, and the deaths, injuries, and property damage that result from traffic accidents. Telecommuting will not completely solve any of these problems, but it can be an important part of their solution.

Substantially increased levels of telecommuting can produce significant benefits in the form of reduced traffic delays, motor fuel consumption, highway capacity expansion requirements, and emissions. As documented in the Department of Transportation study, telecommuters will reduce their transportation fuel use and vehicle emissions because they will be driving fewer miles. However, these positive direct effects of telecommuting will be both offset and supplemented by the indirect effects of telecommuting—the results of the various other transportation-related changes that are likely to occur as telecommuting becomes more and more widespread. These indirect effects are the following:

- **Improved Traffic Flow.** Because of reduced congestion, the remaining vehicles on the highway will operate more efficiently. Better traffic flow and fewer stops and starts will reduce fuel use and emissions.
- **Latent Demand.** People who previously avoided using their vehicles because traffic was too congested will start driving more because telecommuting has lessened this congestion. This will tend to offset the direct reductions in fuel use and emissions.
- **Increased Urban Sprawl.** As close proximity to a central workplace diminishes in importance, telecommuters will feel freer to live farther from urban centers. This geographic expansion of cities will lead to longer drives when these workers do use their vehicles, and it will require additional highway construction.

This study indicates that the energy and emissions benefits of telecommuting are not likely to be entirely offset by latent travel demand or by the geographical expansion of cities. Perhaps half the potential reduction in vehicle-miles traveled (VMT) directly attributable to telecommuters will be replaced by new traffic, induced by lower levels of congestion and higher average speeds. But reduced congestion and higher speeds will create indirect benefits in terms of lower average emissions and fuel consumption rates. From a fuel-use perspective, this indirect benefit appears sufficient to offset impacts from the third indirect effect, additional travel brought about by increased suburbanization.

Thus, for vehicle travel and fuel use, the overall combined indirect effects of telecommuting appear to offset about half of the direct benefits. This estimate varies depending on the specific assumptions made regarding the effects of telecommuting on highway capacity expansion, latent demand, and urban sprawl. However, in no case do the benefits of telecommuting completely disappear. Figure ES–1 depicts the potential energy impacts of telecommuting, including the direct and indirect effects included in this study.

Estimates of the net effects of telecommuting on vehicle emissions vary considerably by type of pollutant. Because carbon dioxide (CO_2) emissions are primarily dependent on vehicle fuel consumption, estimated effects on CO_2

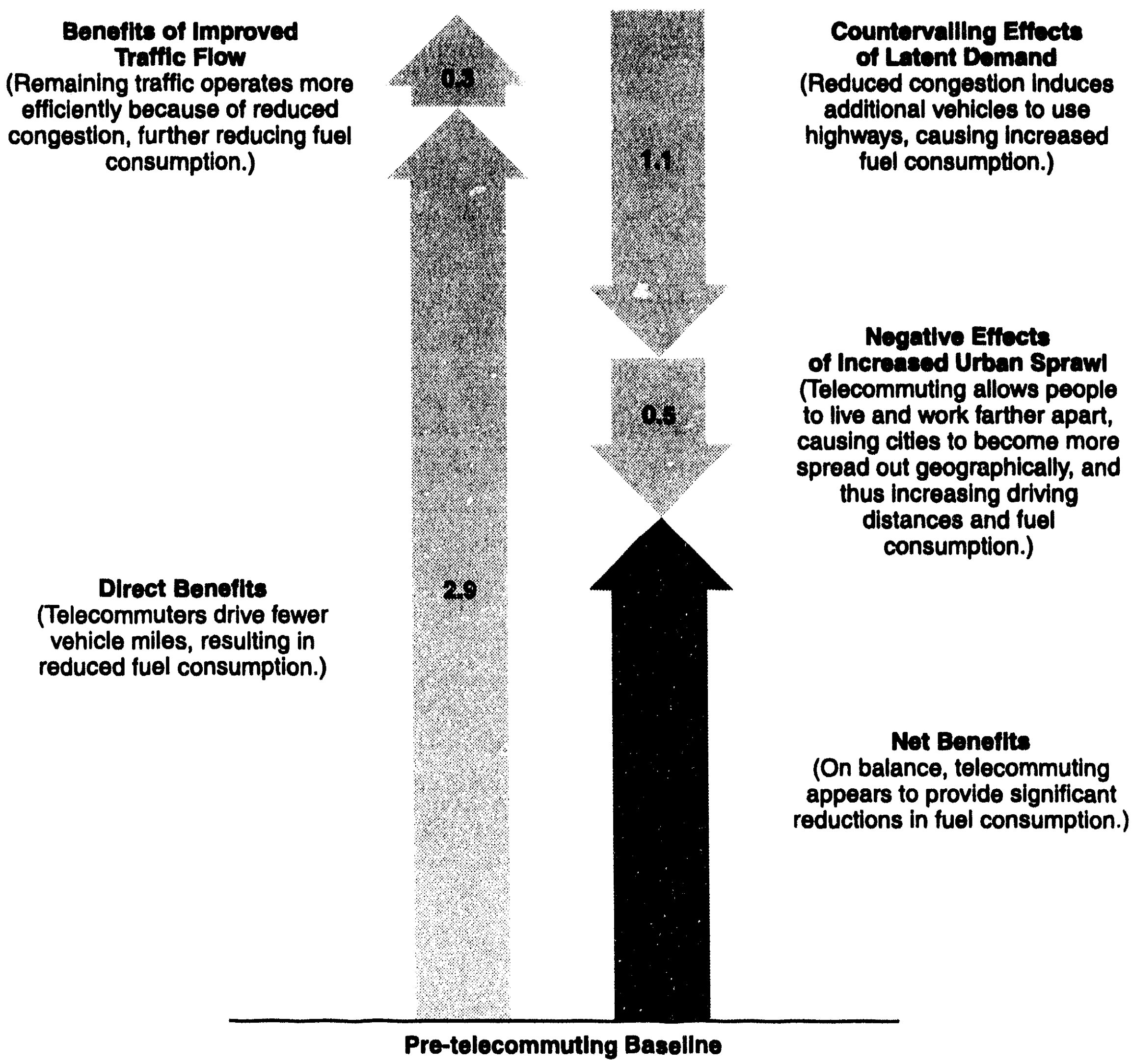

Figure ES–1. Direct and Indirect Effects of Telecommuting on Fuel Consumption Under Department of Energy "Alternative" Scenario, 2010 (billion gallons of gasoline)

emissions are similar to those for fuel consumption. Indirect reductions in nitrogen oxide (NO_x) emissions appear to be negligible, while indirect reductions in hydrocarbon (HC) and carbon monoxide (CO) emissions can be as great as or greater than direct reductions. Variations are due primarily to the emissions characteristics of vehicles under different operating conditions (that is, the level of congestion and average speeds). It should be noted, however, that the relationships between vehicle emissions per mile and operating conditions are still quite poorly understood, and results in this area should be treated with caution. The emissions estimates presented in this analysis are best interpreted as indicative of the direction that the net effects are likely to take.

Substantial levels of telecommuting will also reduce the need for highway capacity expansion, creating savings of capital, maintenance, and urban land. To the extent that reduced travel and congestion lead to reductions in highway capacity expansion, the benefits of telecommuting will shift from reductions in congestion to reductions in highway-related costs.

Telecommuting and its benefits will be concentrated in the largest, most congested, and most polluted urban areas. One-fifth to one-fourth of the reductions in traffic delays, emissions, and highway needs are likely to occur in the country's two largest urban agglomerations: the New York and Los Angeles metropolitan areas. Half of the benefits are likely to accrue to the 10 largest cities, and 90 percent to the 75 largest. Thus, the greatest benefits will occur where they are most needed.

By creating an alternative to the traditional peak-hour journey to work, telecommuting should reduce the cost of other strategies, such as congestion pricing and parking fees, that tax or discourage travel during peak periods. Thus, technological advances or investments in telecommunications infrastructure that facilitate telecommuting should not only lead to direct and indirect transportation benefits, but they may also have a synergistic beneficial effect on other transportation strategies that may be required to cope with growing traffic congestion, urban air pollution, and national petroleum dependence.

The exact nature of the social effects of widespread telecommuting—and, indeed, whether they will be positive or negative—are not well understood because telecommuting is such a recent phenomenon and because research in the area is scarce. The high levels of telecommuting considered in this study could have significant effects on people's perception of work and the separation of home and workplace, on the family through greater presence of adults in the home, and on residential communities because of a greater presence of adults during daytime hours. Other potentially important issues raised by widespread adoption of telecommuting concern disparities between high- and low-wage telecommuters, differences between workers with the option to telecommute and those for whom telecommuting is not feasible, and the rights of management to oversee and supervise work in the home.

Improved telecommunications technology and infrastructure can lead to increased travel, but they are likely to do so primarily by stimulating economic growth and improving the efficiency and quality of transportation services. Such improvements contribute to productivity throughout the economy. Advances in telecommunications are also likely to increasingly shift the economy toward information sectors as opposed to goods production. Telecommunications improvements are also likely to reinforce trends toward the dispersal of economic activities and population.

Future Levels of Telecommuting

Projections of future telecommuting activity used in this study are based on the DOT study, which assumed increasing prevalence of telecommuting among information workers—"individuals whose primary economic activity involves the creation, processing, manipulation, or distribution of information" (DOT, 1993). There are 73 million U.S. information workers today, and this number is expected to grow to about 80 million by 2002 and exceed 85 million by 2010 (DOT, 1993). The DOT study projected an increasing prevalence of telecommuting among these workers—from 2.8 percent (2 million) in 1992 to 18 percent (about 15 million) in 2002, and to 40 percent in 2010 (nearly 30 million).

Although the DOT study provided projections of numbers of telecommuters beyond 2002, it estimated telecommuting impacts only through 2002, using two alternative projections: its original projection (15 million telecommuters in 2002) as an upper bound, and half that number as a lower bound. The key features of these projections are shown in Table ES–1. Both projections assumed that the percentage of telecommuters working at home will decline from 99 percent in 1992 to about 50 percent by 2002, that a correspondingly increasing percentage will work at telecommuting centers,

Table ES–1. Telecommuting Trends Projected in Department of Transportation Study

	1992	1997	2002
Number of Telecommuters (millions)	2.0	3.1–6.2	7.5–15.0
Percent of Labor Force	1.6%	2.3–4.6%	5.2–10.4%
Percent of Telecommuters at Home	99.0%	73.4%	49.7%
Percent of Telecommuters at Local Centers	1.0%	25.7%	50.3%
Average Days per Week	1–2	2–3	3–4

Source: DOT, 1993.

and that the average number of days per week of telecommuting will increase from between 1 and 2 in 1992 to between 3 and 4 by 2002. By 2002, the number of vehicle-miles *not* traveled by telecommuters is projected to be between 17 and 35 billion. Although obviously a great many vehicle-miles, it is only 1 to 1.5 percent of the total U.S. vehicle travel projected for 2002.

The DOT telecommuting study distinguished five types of telecommuters, with each type of telecommuter forgoing a commute trip of different length or frequency. Commuters are assumed to have a round-trip length of 21.4 miles. Those who work at home avoid all 21.4 miles, while those using regional telecommuting centers have a 9-mile round-trip to those centers and thus avoid only 12.4 miles of commuting. Each category of telecommuter and its corresponding telecommuting frequency in days per week are shown in Table ES–2.

The distribution used in the DOT study is quite different from the current pattern of telecommuting, implying a substantial shift toward working in "regional" centers and away from working in the central business district (CBD). In fact, most urban workers do not work in the CBD, and most commuting is now "suburb to suburb." For these reasons, it is useful to consider an alternative distribution of telecommuters for the year 2010 that is essentially the same as today's patterns.

Table ES–2. Distribution of Telecommuters by Category

Category	Frequency[a] (days per week)	1992[b] (percent)	2002[b] (percent)	2010[c] (percent)
	DOT Assumptions			
Home to CBD	2 to 3.1	84.00	47.06	45
Regional Ctr./CBD	2 to 4.1	0.06	1.18	1
Regional Ctr./ Home	4 to 3.8[d]	0.37	15.30	17
Full-Time Home	5	15.00	2.63	2
Full-Time Regional	5	0.57	33.83	35
	Alternative Assumptions			
Home to Office	2 to 3.1	84.00	81	80
Local Ctr./Office	2 to 4.1	0.06	0	0
Local Ctr./Home	4 to 3.8[d]	0.37	2	2.5
Full-Time Home	5	15.00	15	15
Full-Time Local	5	0.57	2	2.5

[a]Range reflects projected change in frequency between 1992 and 2002.
[b]From DOT, 1993.
[c]Assumed.
[d]Number of days at regional center declines slightly through time because of slight increase in home-based telecommuting.

This study projects telecommuting market penetration for the 339 largest U.S. cities (about two-thirds of the Nation's population), considering in separate scenarios both distributions of telecommuters by category shown in Table ES–2. The same projection of total numbers of telecommuters is used in these two scenarios—17.7 million in 2005 and 29.1 million in 2010 (Table ES–3). This projection is generally consistent with the DOT "upper bound" projection for 2002, which projected 15.0 million telecommuters in that year. In both of these scenarios, this study foresees a dramatic increase in telecommuting over the next two decades, but projections of telecommuting miles "avoided" (the direct reduction in miles traveled by telecommuters) differ considerably depending on the assumed patterns of telecommuting behavior.

Table ES–3. Projections of Telecommuters and Telecommuting Miles

	Actual	Projected	
	1988	2005	2010
Telecommuters[a]			
Information Workers as % of All Workers	54.8	60.0	61.1
Telecommuters as % of Information Workers	1.3	27.8	44.9
Telecommuters as % of All Workers	0.7	16.7	27.4
Number of Telecommuters (million)	0.5	17.7	29.1
Telecommuting Miles Avoided (billion)			
DOT Scenario	1.1	36.4	59.3
Alternative Scenario	1.1	41.1	67.4

[a]Telecommuter estimates are consistent with DOT "upper bound" estimates; these estimates are used in both scenarios of telecommuter distribution by type.

Direct and Indirect Effects of Telecommuting

In accord with the findings of most existing analyses of the travel behavior of telecommuters, the DOT study assumed that telecommuters themselves would not increase their travel to replace the vehicle-miles they saved by telecommuting. As a result of this reduction in travel by telecommuters, DOT estimated that there would be modest beneficial effects on energy use, emissions, and safety over the next decade (Table ES–4).

In addition to the time, fuel, and pollution saved by telecommuters themselves, their absence from the highways improves traffic conditions for the remaining motorists. Indeed, widespread telecommuting appears to have significant potential to reduce vehicle travel in congested urban areas and to mitigate the undesirable side-effects of traffic congestion: the improved traffic flow of all vehicles would further reduce energy use and emissions. Because the vehicles still commuting far outnumber those of telecommuters, small indirect benefits per vehicle can add up to relatively large total benefits.

This study attempts to account both for indirect effects of telecommuting on traffic flow and for latent demand effects. Rather than operating at a national scale, the method is applied at the metropolitan statistical area (MSA) level. It

Table ES–4. Direct Effects of Telecommuting on Transportation Estimated in Department of Transportation Study

Factor	1992	1997	2002
Vehicle Miles Saved (billions)	3.7	10.0–12.9	17.6–35.1
Passenger VMT Saved (percent)	0.2	0.5–0.6	0.7–1.4
Commuting VMT Saved (percent)	0.7	1.6–2.0	2.3–4.5
Fuel Saved (million gallons)	178	476–619	840–1,679
Gasoline Saved (percent)	0.25	0.6–0.8	1.1–2.1
Value of Gasoline Saved (1990$)	203	543–706	958–1,914
Emissions Reduction (percent)			
Nitrogen Oxides (NO_x)	0.23	0.6–0.8	1.1–2.2
Hydrocarbons (HC)	0.31	0.8–1.1	1.4–2.7
Carbon Monoxide (CO)	0.36	1.0–1.3	1.7–3.4
Annual Hours Saved per Telecommuter	77	93	110
Total Annual Hours Saved (millions)	156	444–577	826–1,652

Note: All estimates are annual.
Source: DOT, 1993.

makes use of recent research on the relationships between vehicle travel, capacity, and congestion. Available studies allow these effects to be quantified for only the higher order highway systems: freeways, expressways, and principal arterials. The necessary analyses have not been done for lesser streets and roads. There will certainly be effects of reduced commuting on these lower order systems, however, and this should introduce a degree of conservatism into the estimates presented here. In addition, telecommuting travel is likely to be almost entirely a reduction in peak-period travel. Consistent with the areawide, average measures used, however, the effects are estimated as a reduction in total daily travel. It is likely that this approach *underestimates* the effect of telecommuting on traffic congestion because travel reductions will be concentrated in the peak periods when congestion is worst. Nonetheless, the method does reflect the important relationships that seem to be present, uses state-of-knowledge information on the aggregate relationships, and allows for varying most critical parameters about which there is substantial uncertainty.

The study constructs 16 scenarios to assess effects under a range of assumptions about telecommuting levels, indirect effects, and emissions levels. The scenarios represent the different combinations of the following four variables:

- Future year: 2005 versus 2010
- Types of telecommuting: DOT (1993) assumptions versus alternative assumptions (maintaining current patterns)
- Urban structure: inclusion or exclusion of a dispersion effect on urban density (that is, whether or nor urban sprawl is increased)
- Emissions: universal use of reformulated gasoline and 2004 inspection and maintenance requirements (low emissions) versus neither (high emissions)

While latent demand and urban sprawl tend to reduce the direct benefits of telecommuting on emissions, energy use, and traffic delays, the indirect effects of telecommuting on the remaining traffic stream restore some of those benefits. By accounting for these effects, this analysis indicates that indirect effects are not likely to eliminate the anticipated benefits of telecommuting.

The lower levels of traffic caused by expanded telecommuting reduces the need for additional highway capacity. Depending on the scenario, construction of 2,900 to 4,500 freeway lane-miles, and 4,400 to 6,700 lane-miles of principal arterials is avoided through 2010 because of increased telecommuting (Table ES–5). The cumulative (undiscounted) cost savings range from $13 billion to almost $20 billion through 2010.

Reduced congestion leads to increased average speeds and reduced hours of traffic delays. In general, most speed changes are in the vicinity of an increase of 0.5 mile per hour. Nonetheless, the reduction in delay is significant, ranging from a 3- to 5-percent reduction in total hours of delay for each urban area. Overall reductions in 2010 are in the vicinity of 140 million to 210 million hours annually. (Direct time savings to telecommuters are not included in these estimates.) Although telecommuting does not appear to be a panacea for urban traffic congestion, it clearly has important benefits, especially considering the substantial amount of avoided capacity expansion. Although there is 3 to 7 percent additional travel undertaken by others that would not have been taken in the absence of telecommuting—additional travel that "takes back" some of the indirect benefits of telecommuting—it is itself an economic benefit of telecommuting because of its value to the additional travelers. This study does not try to estimate the *value* of this "induced" vehicle travel.

Table ES–5. Projected Changes in Commuter Travel Time, New Highway Construction, and Fuel Use Resulting From Increased Telecommuting, 2010

	Department of Transportation Telecommuting Assumptions		Alternative Telecommuting Assumptions	
Factor	Adjusted for Increased Urban Sprawl	Not Adjusted for Increased Urban Sprawl	Adjusted for Increased Urban Sprawl	Not Adjusted for Increased Urban Sprawl
Reduced Delay (million hrs./yr.)	141	184	160	208
Highway Costs (billion 1990$)	13	17.5	14.9	19.9
New Freeways (lane-miles)	2,900	3,900	3,300	4,500
New Arterial Hwys (lane-miles)	4,400	5,900	5,000	6,700
Total	**7,300**	**9,800**	**8,300**	**11,200**
Fuel Savings (million gal.)				
Direct	1,171	1,560	1,336	1,775
Indirect	171	223	194	251
Total	**1,342**	**1,783**	**1,530**	**2,026**

Note: For estimates of fuel savings, "direct" reductions include the effects of latent demand.

The largest, most congested cities benefit the most from the effects of telecommuting. This is both because the city size distribution is skewed, and because the greatest benefits tend to occur where congestion is worst. Figure ES–2 illustrates the cumulative distribution of reduction in annual vehicle-hours of delay. The urban areas were ranked in descending order of daily vehicle-miles of travel on higher order highway systems. About one-fourth of the total reduction in delay occurs in the two largest cities: Los Angeles and New York. The 10 largest cities account for half of the delay reduction benefits; the 75 largest cities account for 90 percent. For the vast majority of the smaller 339 urban areas included in this analysis, indirect benefits are small and latent-demand effects are small or nonexistent.

The net emissions effects of telecommuting appear to be generally beneficial, but not large (Table ES–6). The DOT study estimated reductions of HC and NO_x on the order of 100,000 tons for direct effects in the year 2002. Reductions of CO are larger, on the order of 1 million tons, because of the greater mass of CO emissions. Emissions of lesser magnitudes are estimated in this study: tens of thousands of metric tons for HC and NO_x and on the order of 100,000 tons for CO. This is due in part to this analysis' use of lower rates of

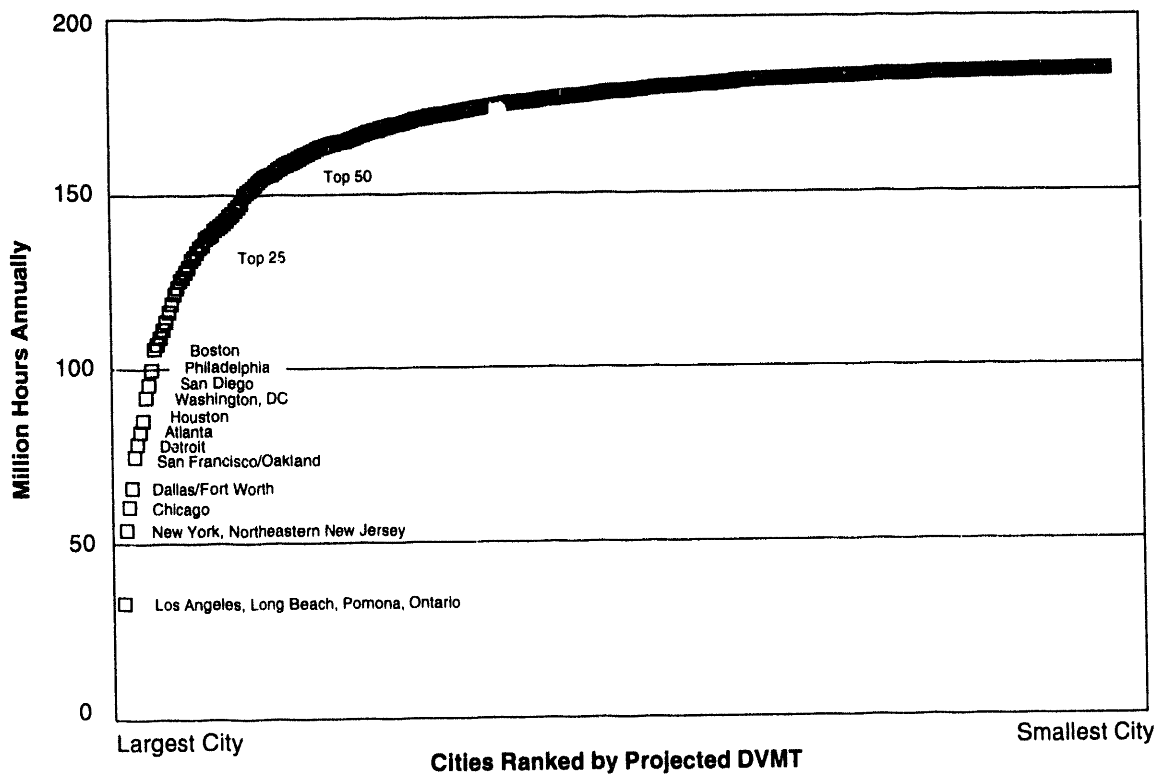

Figure ES–2. Projected Reduction in Traffic Delays in 339 Urban Areas as a Result of Telecommuting, 2010

emissions, based on EPA's MOBILE5 model and taking into account the more stringent emissions standards of the 1990 Clean Air Act Amendments it embodies. It is also because latent demand cuts direct emissions benefits roughly in half and because estimated indirect benefits are relatively small. While decreased congestion appears to reduce emissions of HC and CO, very minor increases in NO_x emissions are usually projected. This is because, for all pollutants, emissions first decrease with increasing speed and then increase at higher speeds, but NO_x emissions begin to rebound at lower speeds compared with HC and CO emissions. Over the range of speeds projected for the cities in this analysis, reductions in NO_x emissions (largely on arterials) because of increased speeds roughly offset increases (on freeways and expressways) so that the net effect is approximately nil. In light of mounting evidence that the current state of the art in projecting emissions in actual traffic conditions is

Table ES–6. Projected Changes in Emissions Resulting From Increased Telecommuting, 2010 (metric tons per year)

	Department of Transportation Telecommuting Assumptions				Alternative Telecommuting Assumptions			
	Adjusted for Increased Urban Sprawl		Not Adjusted for Increased Urban Sprawl		Adjusted for Increased Urban Sprawl		Not Adjusted for Increased Urban Sprawl	
Pollutant	**Low Emis.**	**High Emis.**	**Low Emis.**	**High Emis.**	**Low Emis.**	**High Emis.**	**Low Emis.**	**High Emis.**
Carbon Monoxide (CO)								
Direct	-85,300	-112,900	-113,700	-150,500	-97,300	-128,800	-129,300	-171,200
Indirect	-43,400	-140,100	-56,700	-183,100	-49,200	-158,900	-64,000	-206,700
Total	**-128,700**	**-253,000**	**-170,400**	**-333,600**	**-146,500**	**-287,700**	**-193,300**	**-377,900**
Nitrogen Oxides (NO_X)								
Direct	-33,800	-40,600	-45,000	-54,100	-38,500	-46,300	-51,200	-61,600
Indirect	-200	100	-300	200	-300	100	-300	200
Total	**-34,000**	**-40,500**	**-45,300**	**-53,900**	**-38,800**	**-46,200**	**-51,500**	**-61,400**
Hydrocarbons (HC)								
Direct	-14,200	-17,300	-18,900	-23,000	-16,200	-19,700	-21,500	-26,200
Indirect	-4,600	-11,500	-6,000	-15,000	-5,200	-13,000	-6,800	-17,000
Total	**-18,800**	**-28,800**	**-24,900**	**-38,000**	**-21,400**	**-32,700**	**-28,300**	**-43,200**
Carbon Dioxide (CO_2)								
Direct	-8,700,000		11,600,000		-9,900,000		13,200,000	
Indirect	-1,500,000		1,900,000		-1,700,000		2,200,000	
Total	**-10,200,000**		**13,500,000**		**-11,600,000**		**15,400,000**	

Note: "Low Emis." and "High Emis." refer to two vehicle-emissions scenarios. The low-emissions scenario assumes universal use of reformulated gasoline and 2004 inspection and maintenance requirements; the high-emissions scenario assumes neither. All "direct" changes include the effects of latent demand.

seriously inadequate, all the emissions results presented here should be viewed with caution.

Reduced congestion has a small, but positive, effect on vehicle fuel economy. Overall, fuel economy increases with increasing vehicle speed up to an optimal velocity and then decreases with increasing speed, primarily because of aerodynamic drag. The precise shape of the curve and location of the optimal fuel-economy speed depends on vehicle technology. Indirect energy savings, however, are quite small relative to direct energy savings resulting from telecommuting.

Sensitivity of Indirect Effects to Key Parameter Values

The projected indirect effects of telecommuting strongly depend on the degree to which telecommuting actually reduces traffic congestion. Therefore, it is important to test the modeling results to see if the reduction in traffic congestion is significantly affected by changes in key assumptions. The *capacity expansion* factor (the percent change in lane-miles added for a 1-percent change in lane-miles needed) plays a major role in determining the degree to which traffic congestion will worsen over time. This affects delays, speeds, fuel use, and emissions, and it directly determines the savings in highway capacity construction. The *latent-demand* factor and the *elasticity of trip lengths* with respect to total transportation cost together determine the degree to which vehicle travel will increase in response to reduced congestion and reduced commuting. The analysis explored the sensitivity of the modeling results to these three key factors. The base case values of these parameters were varied from plus or minus 20 percent to plus or minus 33 percent to create a meaningful range of possible values.

Although certain effects are very sensitive to changes in the parameter values, in no case do the benefits of telecommuting disappear, as shown in Table ES–7. In general, increasing the parameters affecting the rebound of vehicle travel in response to telecommuting (latent demand) tends to erode the benefits of telecommuting, as would be expected. However, even in the worst case considered, there are still nontrivial benefits.

Increasing the value of the capacity factor has the effect of changing benefits in reduced delay into savings in highway construction. About 17,000 fewer lane-miles are constructed at a savings of $30 billion (in undiscounted 1990 dollars and not including the costs of operating, maintaining, and repairing the additional capacity). The latent-demand parameter has a smaller effect on delay, roughly proportional to the net change in vehicle travel. Assuming base values of all the parameters, the net change in vehicle travel is -4.7 percent for a removal of telecommuting miles equivalent to 10.3 percent of vehicle travel. Reducing the latent-demand elasticity raises the net VMT reduction to -5.6 percent, while increasing it reduces the net change to -3.8 percent. Similarly, hours of delay are reduced by 105 million, 160 million,

Table ES–7. Sensitivity of Estimated Telecommuting Effects to Variations in New Highway Capacity, Latent Demand, and Urban Density Parameters (Tested Separately)

Parameter	High Case	Base Case	Low Case
	Net Reduction in Annual Vehicle Travel (percent)		
New Highway Capacity	-5.7	-4.7	-3.9
Latent Demand	-3.8	-4.7	-5.6
Urban Density	-4.3	-4.7	-5.0
	Annual Delay Reduction (million hours)		
New Highway Capacity	0	160	275
Latent Demand	105	160	222
Urban Density	150	160	169
	Total Highway Construction Avoided (billion 1990$)		
New Highway Capacity	30	15	7
Latent Demand	13	15	17
Urban Density	14	15	16
	Lane-Miles of Construction Avoided		
New Highway Capacity	16,750	8,300	4,000
Latent Demand	7,400	8,300	9,300
Urban Density	7,750	8,300	9,000
	Annual Fuel Savings, Indirect/Direct (billion gallons)		
New Highway Capacity	0/1.6	0.2/1.3	0.5/1.1
Latent Demand	0.1/1.1	0.2/1.3	0.3/1.6
Urban Density	0.2/1.2	0.2/1.3	0.2/1.4
	Annual Criteria Pollutants, Indirect/Direct (thousand metric tons)		
Nitrogen Oxides (NO_X)			
New Highway Capacity	0/-57	0/-46	-2/-39
Latent Demand	0/-38	0/-46	0/-55
Urban Density	0/-43	0/-46	0/-49
Hydrocarbons (HC)			
New Highway Capacity	0/-24	-13/-20	-24/-17
Latent Demand	-8/-16	-13/-20	-18/-24
Urban Density	-12/-18	-13/-20	-14/-21
Carbon Monoxide (CO)			
New Highway Capacity	0/-157	-159/-129	-304/-109
Latent Demand	-100/-106	-159/-129	-226/-154
Urban Density	-149/-120	-159/-129	-169/-137

Note: The sensitivity analysis used the "Alternative" telecommuting scenario for 2010 that assumed increased urban sprawl and no use of reformulated gasoline or of 2004 inspection and maintenance requirements. Each parameter was changed individually while holding the other two constant. For fuel and emissions estimates, "direct" reductions include the effects of latent demand.

and 222 million in the high elasticity, base, and low elasticity cases, respectively. The effect on emissions is similar; benefits are reduced but not eliminated. The effect of changing the urban-sprawl parameter is similar but much less pronounced.

Choosing all of the most extreme values for each of the three parameters, surprisingly, the net change in VMT is similar (Table ES–8). Because latent demand depends on a change in the level of congestion, when congestion does not decrease latent demand is not evident. When it is assumed that capacity expands in step with travel demand (capacity factor equals 1), there is no increase in congestion. Thus, all the savings are in reduced highway construction and in the direct effects. Using all of the lowest values greatly increases congestion, but also greatly diminishes the effects of latent demand and urban density. Because of the higher congestion levels, indirect effects play a much greater role in the total effects. Indirect fuel-use effects are still only about one-third of the direct effects, and indirect reductions in NO_x emissions remain relatively minor. Indirect reductions in HC and CO emissions, however, become considerably greater than the direct effects.

Table ES–8. Estimated Effects With Highest and Lowest Values of Three Key Parameters (Combined)

Effect	Highest	Lowest
Net Reduction In Annual Vehicle-Miles Traveled (percent)	-4.6	-5.3
Annual Delay Reduction (million hours)	0	400
Total Highway Construction Avoided (billion dollars)	$24	$8
Annual Fuel Savings, Indirect/Direct (billion gallons)	0/1.3	0.7/1.5
Annual Criteria Pollutants, Indirect/Direct (thousand metric tons)		
Nitrogen Oxides (NO_x)	0/-45	-3/-52
Hydrocarbons (HC)	0/-19	-36/-22
Carbon Monoxide (CO)	0/-127	-449/-145

Note: For fuel and emissions estimates, "direct" reductions include the effects of latent demand.

Social Effects of Telecommuting

The social effects of telecommuting will occur and be judged in the larger context of advances in telecommunications as well as other changes that effectively restructure workplace interactions. It may be difficult to distinguish the effects that are specific to telecommuting. Currently, telecommuting is not widespread, and its social effects are relatively localized. Individual telecommuters, their work organizations, their families, and, to a lesser extent, their communities currently are affected. If telecommuting becomes a widespread working strategy, the effects—both positive and negative—will become more varied and their scale will become larger, affecting individuals, the workplace, families, communities, and the Nation.

The following issues may become particularly important: separation between home and work; increasing fractionalization of the workforce and society at large; and changes in neighborhood and community interactions. Telecommuting from home blurs existing boundaries between home and work. Employees' abilities to separate (or escape) from their work and employers' abilities to invade their employees' homes may change the nature of home and work lives. Within the workplace, three major classes of personnel may develop: those who voluntarily telecommute and derive the benefits of autonomy, flexibility, and freedom from interruptions; those for whom telecommuting is required and who may not experience the advantages of the privileged class of telecommuters or have access to the benefits packages associated with long-term employment in an office setting; and those for whom telecommuting is not an option. Widespread telecommuting may enhance the safety and spirit of neighborhood and community life, though these effects may not be distributed consistently throughout a region or the country because the varying composition of communities may be associated with different levels of telecommuting. Finally, widespread telecommuting may change patterns of residential and commercial development, in part because proximity of the workplace to the labor force would diminish in importance.

Telecommunications and Transportation

Increased potential for telecommuting is the most direct and obvious effect that advances in telecommunications may have on transportation, yet there are broader relationships between telecommunications and transportation. Policies designed to advance telecommunications technology and to enhance investment in telecommunications infrastructure can have effects on transportation reaching beyond telecommuting. It is likely that changes as significant as the broadband information superhighway would increase the use of telecommunications not just for telecommuting but also for education, shopping, medical care, and recreation.

In some cases, telecommunications can be complementary to transportation, with increases in one leading to increases in the other. Telecommunications can enable new activities to occur that would otherwise not have existed, or it may reduce the cost or enhance the performance of the transportation system, thus stimulating demand. In other cases, telecommunications may substitute for physical movements, partially or completely replacing transportation services.

Many of the ways in which improved telecommunications can lead to increased travel result from the positive effect of advanced communications on economic growth. If one were to compare transportation effects at a constant level of economic growth, these complementary effects would disappear. Most of the other ways in which telecommunications can increase travel are the result of reductions in the cost or improvements in the quality of transportation services. These improvements contribute to productivity throughout the economy. Telecommunications are essential to hub-and-spoke transportation systems (such as those that dominate commercial air passenger and freight systems) and are also critical to just-in-time manufacturing.

1. Energy and Emissions Consequences

Introduction

Telecommuting has been defined as the partial or complete substitution of telecommunications services for transportation to a conventional workplace (DOT, 1993). By implication, telecommuters work at home or very close to home.[1] Available estimates indicate that the number of telecommuters in the United States is substantial and has been growing rapidly. A 1992 survey found that 3.3 percent of the workforce, 4.2 million employees, were telecommuting in 1992, a 27-percent increase over 1991. Not counting those who are self-employed or working on contract, the number of telecommuters has grown from 0.4 million in 1990 to 1.4 million in 1991 and 2.4 million in 1992. Advances in computing and telecommunications technologies have undoubtedly played a central role in this rapid growth. More than 70 percent of telecommuters use telephone answering machines, 36 percent own personal computers, 46 percent are reimbursed by their employers for long-distance calls, 16.2 percent use modems, and 7.4 percent use fax machines (DOT, 1993).

With dramatic advances in telecommunications and computing on the horizon, the potential for future telecommuting appears to be enormous. Projections cited by the Department of Transportation (DOT) indicate that by the year 2000 there may be 10 million telecommuters, more than 30 million by 2010, and nearly 50 million by 2020 (DOT, 1993). The consequent reduction in highway travel could significantly help ameliorate the growing problems of traffic congestion, air pollution, and petroleum dependence.

In April 1993, DOT published a thorough report, entitled *Transportation Implications of Telecommuting*, on the *direct* impacts of telecommuting—that is, the safety, energy, and emissions impacts of those commuters who switched from commuting to working at home or in a local telecommuting center

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[1] In a slightly different definition, Mokhtarian (1993) emphasizes the location of work rather than the substitution of telecommunication services: "I will refer to telecommuting as working from home, or a location close to home, instead of travelling to a conventional work location." This definition allows the possibility of other reasons for working at home besides the ability to substitute telecommunications for physical presence. This chapter assumes that advances in telecommunications technology and infrastructure are a motivating factor for telecommuting, though not necessarily the sole cause.

(DOT, 1993). *Indirect* effects of the reduction in traffic on the remaining traffic were deliberately not included, though the potential importance of such indirect effects was specifically noted in the DOT report:

> One view is that removal of telecommuters' vehicles from the highway will, in the aggregate, reduce overall congestion. Benefits are then substantially larger than the energy, pollution, and safety gains associated directly with telecommuters' absence, since all vehicles on those now less-congested roads will operate more efficiently, cleanly and safely, and the occupants will suffer less delay.

Noting the complexity of such indirect effects, DOT recognized that removing commuters from congested roads and improving traffic flow might attract additional users:

> On the other hand, it is often perceived that attempts to increase capacity through construction of additional roads seems to stimulate traffic growth—latent demand—that quickly vitiates any gains. A similar argument could be applied to the telecommuting case: the telecommuters might simply be replaced on the highways by other people, formerly users of transit or members of carpools, who observe that congestion has moderated to a point just below their threshold of pain and return to their automobile. In this case the telecommuter still saves time, but the net societal benefits (in terms of VMT congestion, energy, pollution, etc.) vanish.

Rather than attempt to estimate both the beneficial indirect effects of congestion relief *and* the countervailing effects of latent travel demand, the DOT study chose "to develop estimates only for the time, energy, pollution, safety, and cost savings directly associated with trips replaced by telecommuting," thus allowing readers to use their own judgment concerning the uncertain and controversial potential effects of congestion reduction and latent demand:

> No adjustment is made either for compensation due to latent or induced travel demand, or for reduced overall congestion. . . These factors are among the largest uncertainties in estimation of the transportation impacts of telecommuting, given a projection of the amount of telecommuting which will occur.

This study builds and expands on the firm foundation provided by the DOT study. This chapter explores the potential indirect, as well as direct effects, of telecommuting on energy use and emissions, taking into account telecommuting's likely effects on travel behavior, traffic congestion, new highway construction, urban sprawl, and latent demand for highway use. First, it briefly reviews the key findings of the DOT study. Then it presents a methodology for exploring the indirect effects of telecommuting on traffic congestion and travel in 339 U.S. urban areas. The computer-modeling method begins with the same forecast of future levels of telecommuting used by DOT, but for 2010 in order to investigate the effect of that year's projected high level of telecommuting on what are likely to be very congested highways. Finally, this chapter presents the results of the modeling analysis.

DOT correctly pointed out the uncertainties involved in an analysis such as this one. Relationships between congestion and highway capacity expansion, between capacity and latent demand, between telecommuting and household travel and locational behavior, and between traffic flow, energy use, and emissions are only beginning to be well understood. To a large degree, these relationships will depend on specific local conditions and policy. Rather than developing a separate framework for forecasting effects in each locale, this study develops an aggregate model that reasonably represents the known theoretical relationships, and it quantifies those relationships using available information, incorporating local-level data where possible. Recognizing that many of the key relationships are poorly understood, this study varies critical parameter values to test how sensitive the results are to them. The goal is to correctly identify the direction and order of magnitude of the most important effects.[2]

Subsequent chapters of this report move beyond the quantifiable effects of telecommuting. Chapter 2 reviews the potential social impacts of widespread telecommuting—how it could affect individuals, the workplace, families, neighborhoods, and even the Nation as a whole. Chapter 3 considers the broader relationship between telecommunications and transportation, as well as the implications for technology initiatives like the national "information highway."

[2]In the case of emissions, the correct order of magnitude of effects may be indescribable. Recent analyses of emissions indicate that rare events of extreme acceleration or emissions from a small fraction of poorly maintained vehicles may account for a majority of total highway emissions (Sierra Research, 1993; Guensler, 1993). These studies suggest that speed versus emissions relationships derived from laboratory data based on standard test cycles may seriously underestimate total emissions (NRC, 1991). The precise relationship between congestion and extreme emissions episodes is not known.

Direct Effects of Travel Reduction by Telecommuters

In its April 1993 study, the Department of Transportation provided an extensive review of the history and current scope of telecommuting in the United States (DOT, 1993). The study also contained a thorough analysis of the factors that may affect future levels of telecommuting in the United States and presented a forecast of the potential for future telecommuting. It then quantified the likely *direct* effects of increased future telecommuting on vehicle travel, travel-time savings, energy use, and emissions and discussed a range of other possible effects. The study noted that estimates of the future level and effects of telecommuting are highly uncertain. The chief conclusions of the DOT study were as follows:

- Telecommuting is now practiced by approximately 2 million workers and could reach 7.5 million to 15 million by 2002.
- Telecommuting could provide significant transportation-related public benefits in this decade.
- The actual extent and effect of telecommuting in any particular region will depend strongly on the local transportation environment and travel-demand measures.
- Direct energy, air-quality, safety, and time benefits of telecommuting will be increased as the level of congestion is reduced.
- The congestion and air-quality improvements potentially attainable through telecommuting could be substantially diminished if telecommuters removed from the highway are replaced by the emergence of latent travel demand.
- Telecommuting could stimulate urban sprawl and have other adverse impacts on land use and public transportation.
- Factors that will affect the growth of telecommuting include employers' uncertainty about its benefits and the considerable time and effort inherently required to bring about major changes in workstyles and business practices.
- Telecommunication services and equipment are adequate for most current telecommuting, but high-bandwidth capabilities will be needed in the future and would be beneficial now.

- Government agencies can play a significant role in facilitating and encouraging telecommuting.
- Telecommuting can be an effective tool for managing travel demand, but cannot be mandated.
- Continuing research is needed to clarify telecommuting costs, benefits, and future effects.

In projecting future levels of telecommuting, the DOT study relied on a projection developed by the Telecommuting Research Institute (Nilles, 1991). This projection assumed that "information workers," who currently comprise 50 to 60 percent of all U.S. workers, are the sole market for telecommuting. It projected an increasing prevalence of telecommuting among these workers—from 2.8 percent (2 million) in 1992 to 18 percent (15 million) by 2002, and eventually increasing to 40 percent by 2010 and more than 60 percent by 2030. (The DOT study only used this projection to 2002 in its analysis.) To create a range reflecting uncertainty about the future course of telecommuting, the DOT study used the original projection (15 million telecommuters in 2002) as an upper bound and took half that number as a lower bound. The key features of this projection are shown in Table 1–1.

The DOT study projected not only a dramatic increase in the number of telecommuters, but also a major change in the conditions under which they work. Whereas today nearly all telecommuters work at home, the projection on which the DOT study was based projected only half will be working at home by 2002. The remainder were expected to be working in satellite

Table 1–1. Telecommuting Trends Projected in Department of Transportation Study

	1992	1997	2002
Number of Telecommuters (millions)	2.0	3.1–6.2	7.5–15.0
Percent of Labor Force	1.6%	2.3–4.6%	5.2–10.4%
Percent of Telecommuters at Home	99.0%	73.4%	49.7%
Percent of Telecommuters at Local Centers	1.0%	25.7%	50.3%
Average Days per Week	1–2	2–3	3–4

Source: DOT, 1993.

telework centers set up or paid for by employers. In accord with the findings of most existing analyses of the travel behavior of telecommuters, the DOT study assumed that telecommuters themselves would not increase their travel to replace the vehicle-miles they saved by telecommuting.

By 2002, according to the DOT estimate, telecommuters are projected to save between 17 billion and 35 billion vehicle-miles traveled (VMT) per year. Although obviously a great many vehicle-miles, this is only 1 to 1.5 percent of the total vehicle travel projected for 2002. Total highway vehicle travel in the United States in 1991 has been estimated at almost 2.2 trillion vehicle-miles. There are four main reasons why telecommuting is projected to be only a small percentage of this total in 2002. First, households account for about 75 percent of total highway vehicle travel—1.5 trillion vehicle-miles in 1988 (EIA, 1990). Second, the journey to work accounts for about 32 percent of household vehicle-miles (Hu and Young, 1992). These two points imply that only about one-fourth of all vehicle-miles are potentially replaceable by telecommuting. Third, only about 5 to 10 percent of the labor force is projected to be telecommuting by 2002. Finally, many telecommuters are expected to telecommute less than full time.

As the estimated reductions in vehicle travel are not large, neither are the estimated direct effects on fuel use or emissions (see Table 1–2), given that these are obtained by dividing VMT by average fuel economy (in miles per gallon) and by multiplying VMT by average emissions rates (in grams per mile), respectively. In 1990, highway vehicles consumed 108 billion gallons of motor fuel (DOT, 1991), while the estimated "upper bound" projected savings for 2002 are almost 1.7 billion gallons. Estimated direct emissions reductions are also not trivial, but a relatively small percentage of the total. "Upper bound" estimates of emissions reductions in 2002 range from 2.2 percent (for nitrogen oxides to 3.4 percent (for carbon monoxide). Estimated reduced emissions in the "upper bound" case are shown in Table 1–3.

Safety improvements were projected as directly proportional to the reduction in VMT by assuming constant accident rates and death rates per VMT. This resulted in a projected annual savings of 815 lives in the "upper bound" case and 117,700 accidents avoided. Again, while these savings are important, they are only a small part of the projected totals for the entire highway system.

Time savings were estimated by assuming a constant round-trip time of 44.8 minutes per urban commuter and 22.4 minutes per rural commuter, resulting in a total of 1,652 million hours saved in 2002 in the "upper bound" case.

Table 1-2. Direct Effects of Telecommuting on Transportation Estimated in Department of Transportation Study

Factor	1992	1997	2002
Vehicle Miles Saved (billions)	3.7	10.0–12.9	17.6–35.1
Passenger VMT Saved (percent)	0.2	0.5–0.6	0.7–1.4
Commuting VMT Saved (percent)	0.7	1.6–2.0	2.3–4.5
Fuel Saved (million gallons)	178	476–619	840–1,679
Gasoline Saved (percent)	0.25	0.6–0.8	1.1–2.1
Value of Gasoline Saved (1990$)	203	543–706	958–1,914
Emissions Reduction (percent)			
Nitrogen Oxides (NO_x)	0.23	0.6–0.8	1.1–2.2
Hydrocarbons (HC)	0.31	0.8–1.1	1.4–2.7
Carbon Monoxide (CO)	0.36	1.0–1.3	1.7–3.4
Hours Saved per Telecommuter	77	93	110
Total Hours Saved (millions)	156	444–577	826–1,652

Note: All estimates are annual.
Source: DOT, 1993.

Table 1-3. "Upper Bound" Emissions Reductions From Telecommuting Estimated in Department of Transportation Study (metric tons)

Pollutant	1992	1997	2002
Nitrogen Oxides (NO_x)	11,852	41,061	111,479
Total Hydrocarbons (HC)	14,571	50,468	137,047
Carbon Monoxide (CO)	98,753	342,118	928,836

Source: DOT, 1993.

The DOT study estimated only the direct effects of telecommuting—that is, the VMT reduction, fuel savings, and emissions reductions due to the reduced vehicle-miles of telecommuters themselves. It did not consider the effect of removing vehicles from the road on overall traffic congestion and the indirect benefits this may produce in terms of increased speeds, reduced delays for remaining motorists, improved fuel economy, and possibly reduced emissions. On the one hand, the DOT study pointed out that these indirect benefits could be substantial relative to the estimated direct effects, especially in congested cities. On the other hand, the DOT study did not estimate the "take back" effects of telecommuting that could offset some of the direct benefits:

- Encouragement of additional vehicle travel (also referred to as the stimulation of latent demand) because of the reductions in traffic congestion and delays
- The likelihood of longer average trip lengths and, thus, increased travel because reduced demand for commuting could encourage the geographic expansion of urban areas (urban sprawl)

Numerous case studies of highway capacity improvements have noted that construction of additional roads or lanes sometimes stimulates traffic growth so much that the expected amelioration of traffic congestion is not realized. Similarly, removing telecommuters from the traffic stream and thereby improving traffic flow may make vehicle travel more attractive to others not currently traveling by auto. As the DOT report observed, estimating indirect effects without also accounting for latent demand would probably be misleading.

DOT limited its examination of potential telecommuting effects to the next decade. While projecting to the year 2010 and beyond becomes increasingly speculative, it is worth exploring what kind of effects telecommuting could have if it becomes truly widespread. If traffic congestion continues to increase over time as well, the importance of telecommuting's indirect effects would increase considerably. By looking to the years 2005 and 2010, this study examines conditions under which indirect effects are likely to be substantial.

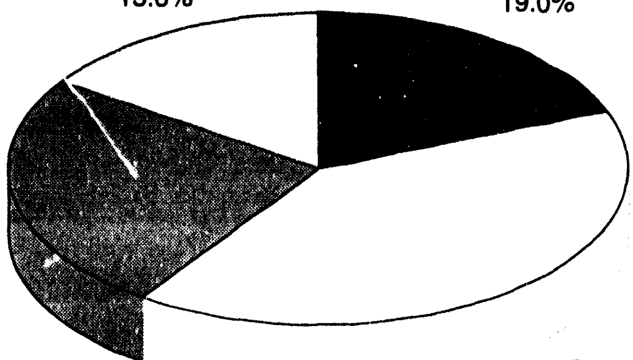
Methodology for Exploring the Effects on Traffic Congestion, Energy Use, and Emissions

This section describes a methodology for estimating the indirect effects of telecommuting on traffic congestion and delay, emissions, and motor fuel use. (Full technical details are included in the appendix.) The method allows highway capacity expansion to be related to the degree of congestion and also allows traffic levels to increase in response to reduced congestion. The method also reflects the fact that, as the requirement to commute is reduced, the need for a central location is diminished, permitting urban geographic expansion—that is, increased urban sprawl. Lower urban densities lead to longer average trip lengths and some increase in vehicle travel. In this analysis, relationships are included between traffic volumes per lane-mile and average speed, as well as between average speeds, energy use, and emissions. Because most of these relationships are not yet fully understood, the effects of varying key parameter values on the projections are examined. This creates a wider range of forecasts, reflecting the dependence of effects on where and how telecommuting takes place and on critical factors that are not now well understood.

The analysis is based on projections of employment, daily traffic volumes, and lane-miles for 339 U.S. urban areas. Two categories of higher order highways are considered: interstates, other freeways, and expressways; and principal arterials. In 1991, these two types of roads accounted for almost three-quarters of a trillion vehicle-miles—more than one-third of all U.S. vehicle-miles, and almost 60 percent of all urban vehicle travel (Figure 1-1). Although confining the analysis to only the higher order urban highways may underestimate the effects of telecommuting, they are the only systems for which the necessary data on congestion, delay, and speeds are available. They are also the systems that have the majority of traffic congestion.

Overview of the Method

The method described here attempts to account both for indirect effects of telecommuting from improved traffic flow and from latent demand. It makes use of recent research by the Texas Transportation Institute (TTI) on the



Source: U.S. Department of Transportation, Federal Highway Administration, "Highway Statistics 1991," Washington, DC.

Figure 1–1. Distribution of Highway Vehicle Travel by Type of Highway, 1991

relationships between vehicle travel, capacity, and congestion to estimate the indirect effects of reduced vehicle travel on delay and highway capacity expansion. The method also makes use of recent work by Oak Ridge National Laboratory's Center for Transportation Analysis on the relationship of highway capacity to the demand for vehicle travel. These two empirical aggregate relationships are the basis for the analysis of the indirect effects of telecommuting on emissions and energy use:

- The relationship between the ratio of daily vehicle-miles traveled (DVMT) to highway capacity and annual delays caused by congestion
- The relationship between highway capacity utilization and the demand for vehicle travel

The combination of these effects into an iterative process for estimating latent demand and congestion is described in Figure 1–2.

The process for estimating indirect and direct effects begins with 1988 baseline estimates for each of 339 metropolitan statistical areas (MSAs) of employment, vehicle travel, the shares of total VMT occurring on the two

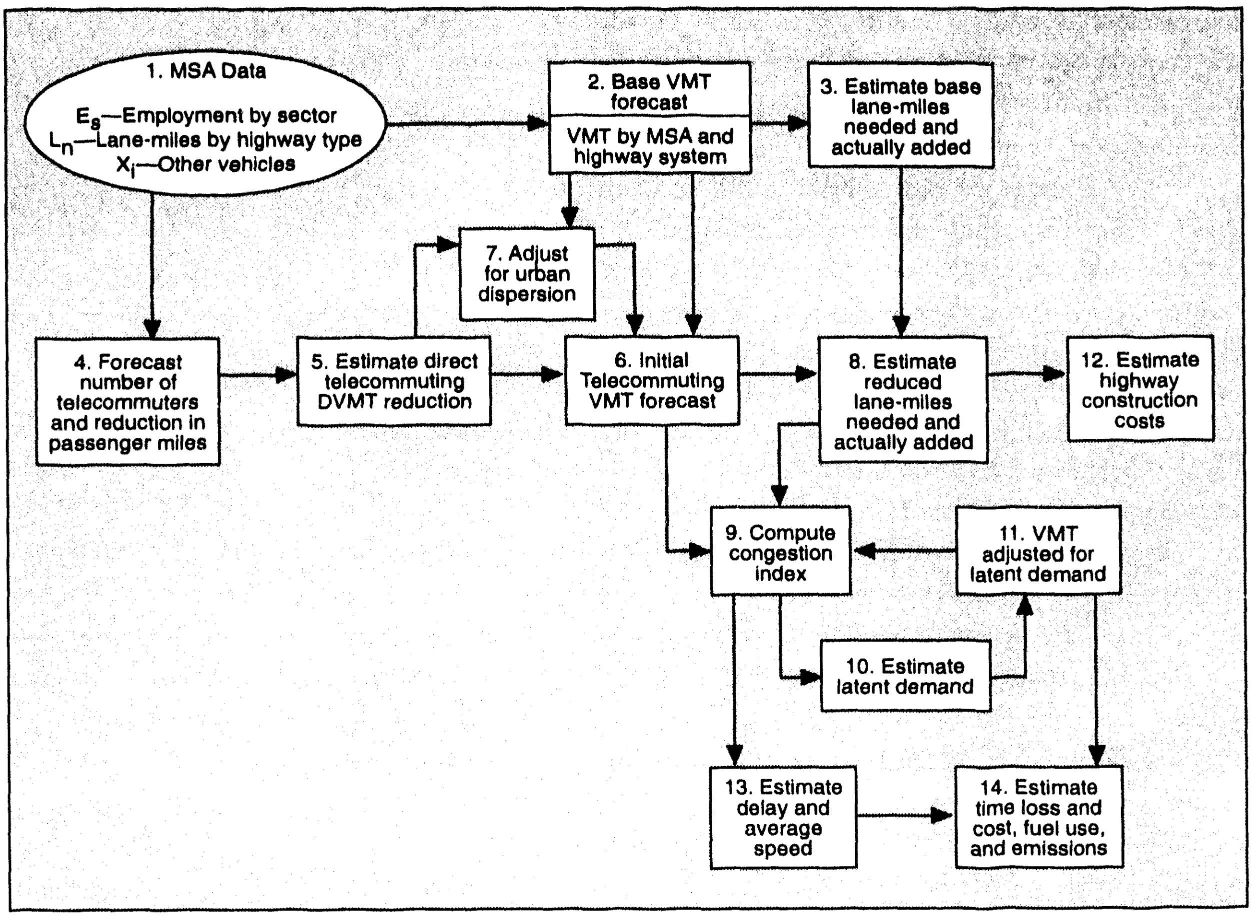


Figure 1–2. Process for Estimating the Direct and Indirect Effects of Telecommuting

highest order functional highway types, and an inventory of lane-miles for these highways (box 1 in Figure 1–2). These baseline characteristics are then forecast for the years 2005 and 2010, based on past and expected future trends in the absence of additional telecommuting (box 2). Given this base case projection of vehicle travel, capacity expansion required to hold areawide congestion constant is estimated and used to project how many additional lane-miles would have to be constructed in the absence of increased telecommuting (box 3) (Schrank, Turner, and Lomax, 1993).

Historical relationships are used to estimate the number of lane-miles that will be added as a function of the number of lane-miles needed to hold traffic congestion constant. Historical data suggest that less than the needed number of lane-miles will be added, so that traffic congestion will increase over time as travel demand increases. This forecast of travel, capacity, and congestion becomes the base case from which changes that are due to increased telecommuting are measured.

To obtain the number of telecommuters in each city, this analysis applies projections of the fraction of workers who will telecommute (based on the 1993 DOT telecommuting study) to the employment projections for each MSA. Following the DOT methodology, total employment is distributed between information workers and others, and telecommuters are estimated as a percentage of information workers (box 4). Multiplying this total by an average trip length per telecommuter, and by the average number of days per week telecommuted, gives an estimated direct reduction in commuter-miles for each urban area. The number of telecommuter-miles is converted to commuting vehicle-miles avoided by dividing by the average vehicle occupancy (box 5). An initial estimate of vehicle travel under expanded telecommuting is the original projection of VMT minus the estimated avoided miles (box 6). This may then be adjusted to take into account the effect of reduced commuting requirements on the dispersion of population in the MSA (box 7).

The forecast of VMT under the telecommuting case can then be compared with base case forecasts of lane-miles added to compute the reduction in lane-miles needed and added because of telecommuting (box 8). Highway capacity is increased over time as a function of the level of demand. In the base case, with higher levels of VMT than the telecommuting case, more highway lane miles are likely to be constructed. Thus, in the telecommuting case, traffic congestion will decrease, but not as much as if the same amount of highway capacity had been added as in the base case. On the other hand, fewer miles of highway will have to be constructed, saving both dollars and land.

With the projected supply of highway miles and VMT, an index of congestion can be computed (box 9). The areawide Roadway Congestion Index (RCI), developed by researchers at the TTI (Schrank, Turner, and Lomax, 1993), is used. The RCI has been more extensively used than any other measure of areawide traffic congestion, and its relationship to such key performance measures as delay and average speed has been explored (Turner, 1992). It is likely that reduced congestion will encourage a certain amount of travel that would not have occurred otherwise. This effect on latent demand is forecast based on a relationship between the supply of highway capacity and total vehicle travel estimated in a previous statistical analysis of VMT in

339 U.S. cities (Miaou et al., 1990) (box 10). The estimate of latent demand on VMT is then computed (box 11). Given this new estimate of vehicle travel, the RCI is recomputed.

Final impacts can now be estimated. The forecast of additional lane-miles is then used to estimate highway construction costs (box 12), and the index of congestion is used to predict hours of delay and average speeds on each of the two highway system types in each of the 339 MSAs (box 13). Finally, estimates of vehicle travel and average speed are used to forecast emissions, using speed-correction factors derived from the Environmental Protection Agency's (EPA) MOBILE5 model, and to forecast fuel consumption, using data from An and Ross (1993) and Davis and Strang (1993) (box 14). Direct effects of telecommuting are estimated by subtracting fuel consumption and emissions rates with and without increased telecommuting, and multiplying by the total number of VMT. Indirect effects are estimated by multiplying the *net* change in vehicle travel (VMT avoided by telecommuters minus the effects of urban population density and latent demand) times average fuel use and emissions rates adjusted for changes in congestion and average speeds. Finally, approximate dollar values are used in some cases to translate effects into 1990 dollars for a rough comparison of the magnitude of effects.

Clearly, this method is highly simplified and aggregated. Numerous omitted factors will affect the relationship between telecommuting and its effects on society. Serious questions have been raised about the usefulness of aggregate measures for predicting the effects of changes in traffic flow and emissions. The use of average daily numbers may understate the relationship between telecommuting and congestion, because congestion is most severe during peak rush hour periods. Nonetheless, the method does reflect the important relationships understood to be present, uses state-of-knowledge information on aggregate relationships, and allows for varying most critical parameters about which there is substantial uncertainty. Three of the more critical and potentially controversial issues—namely, the quantification of areawide traffic congestion, the projection of the nature and extent of telecommuting in the future, and the relationships between average speeds and emissions and fuel consumption—are discussed in the following subsections. Full technical details are included in the appendix.

Measuring Roadway Congestion

One of the most important relationships in this analysis is that between traffic congestion and vehicle travel per lane-mile of highway. The Roadway Congestion Index developed by traffic engineers at the TTI is based on the number of daily vehicle-miles traveled (DVMT) per lane-mile of highway. The RCI expresses the actual density of daily vehicle travel relative to a level historically associated with areawide congested conditions. The TTI researchers have applied the RCI measure to traffic conditions in 50 U.S. cities in a series of 5 widely studied and cited research reports (Schrank, Turner, and Lomax, 1993). The RCI is defined by the following equation,

$$RCI = \frac{[(DVMT_F/LM_F) \times VMT_F + (DVMT_A/LM_A) \times VMT_A]}{[13{,}000 \times VMT_F + 5{,}000 \times VMT_A]}$$

where VMT_F is total annual VMT on freeways and VMT_A is total annual VMT on principal arterial highways in the urban area. The TTI researchers explain the meaning of their congestion index as follows:

> An RCI value of 1.0 or greater indicates that congested conditions exist areawide. It should be noted that urban areas with areawide values less than 1.0 may have sections of roadway that experience periods of heavy congestion, but the average mobility level within the urban area could be defined as uncongested. The RCI analyses presented in this report are intended to evaluate entire urban areas and not specific locations. (Schrank, Turner, and Lomax, 1993)

The TTI's RCI is key to two parts of this model. First, it is used to forecast the expansion of capacity necessary to hold traffic congestion constant at base year levels. Later, given predictions of capacity expansion and vehicle travel demand, it is used to forecast hours of delay caused by congestion and average highway speeds.

Forecasting Levels of Telecommuting

Projections of future telecommuting in this study are based on the DOT study estimates, which, in turn, are based on a forecast by Nilles (1991) that assumes increasing prevalence of telecommuting among "information workers." Information workers are defined as "individuals whose primary economic activity involves the creation, processing, manipulation, or distribution of information" (DOT, 1993). Information workers are distinguished from those in agriculture, industry (manufacturing), and service sectors. The DOT analysis estimates that there are 73 million U.S. information workers today and that this number will grow to about 80 million by 2005 and exceed 85 million by 2010.

The information provided in the DOT study was used to approximate the Nilles forecast for the years 2005 and 2010. Logistic curves were fitted to the DOT forecast (which stopped at the year 2002) and used to extrapolate projections to 2005 and 2010. The telecommuting adoption curves, as illustrated in Figures 1–3 and 1–4, show information workers as a percent of all workers, increasing to about 60 percent by 2005 and about 61 percent by 2010. Adoption of telecommuting by information workers increases to about 28 percent by 2005 and to 45 percent by 2010. The total number of telecommuters in each city is forecast as the product of these shares and total employment.

The DOT study also distinguished five categories of telecommuters, again based on Nilles' analysis. This is important, as the DOT study pointed out, because each type of telecommuter forgoes a commute of different length and frequency. Commuters are assumed to have a round-trip length of 21.4 miles. Those who work at home avoid all 21.4 miles, while those using regional telecommuting centers have a 9-mile round-trip to those centers and thus avoid only 12.4 miles of driving. Each category of telecommuter and its corresponding telecommuting frequency in days per week are shown in Table 1–4. This study hypothesizes an eventual distribution for the year 2010, and interpolates between the DOT estimates for 2002 and the assumed distribution for 2010 to derive a distribution for 2005.

The distribution used in the DOT study is quite different from the current pattern of telecommuting, implying a substantial shift toward working in regional centers versus the central business district (CBD). In fact, most urban workers do not work in the CBD, and most commuting is now suburb-to-suburb. For these reasons, this study hypothesizes an alternative distribution of telecommuters that is essentially the same as today's patterns. The traditional workplace is called an "office" rather than a CBD. To estimate to the years 2005 and 2010, this study assumes a simple progression to 80 percent part-time home, 2.5 percent each for home-to-regional center and full-time regional center, and a continuation of 15 percent full time at home. Because this report assumes that the typical telecommuter has the same average trip length as the

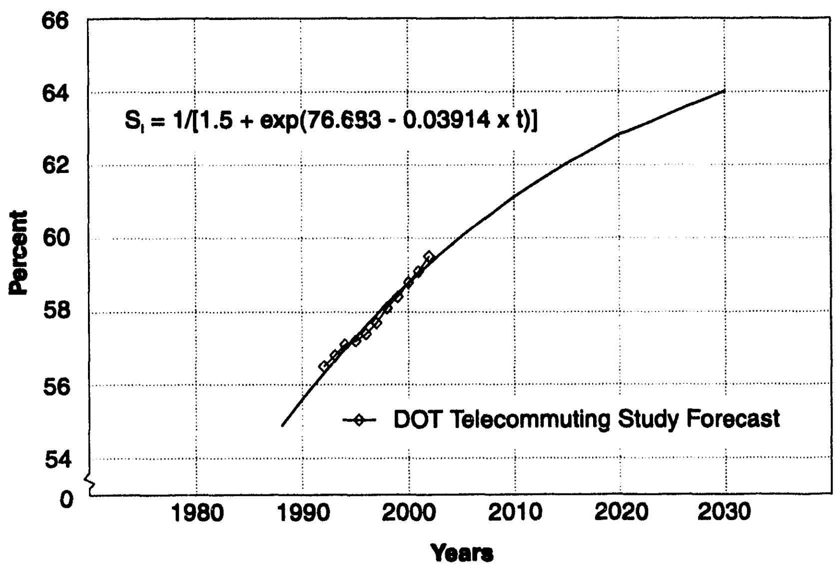


Figure 1–3. Information Workers' Projected Share of Total U.S. Work Force

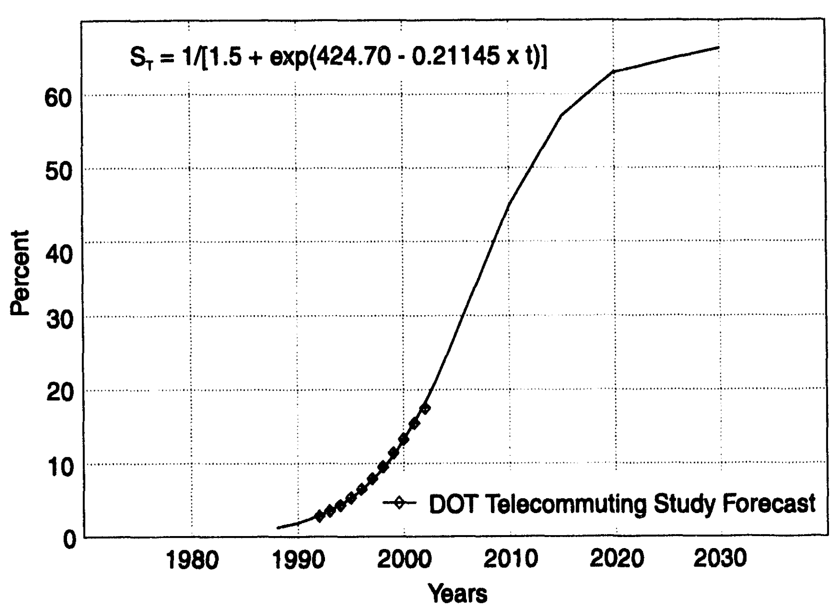


Figure 1–4. Projected Percentage of Information Workers Who Telecommute

Table 1–4. Distribution of Telecommuters by Category

Category	Frequency[a] (days per week)	1992[b] (percent)	2002[b] (percent)	2010[c] (percent)
	DOT Assumptions			
Home to CBD	2 to 3.1	84.00	47.06	45
Regional Ctr./CBD	2 to 4.1	0.06	1.18	1
Regional Ctr./ Home	4 to 3.8[d]	0.37	15.30	17
Full-Time Home	5	15.00	2.63	2
Full-Time Regional	5	0.57	33.83	35
	Alternative Assumptions			
Home to Office	2 to 3.1	84.00	81	80
Local Ctr./Office	2 to 4.1	0.06	0	0
Local Ctr./Home	4 to 3.8[d]	0.37	2	2.5
Full-Time Home	5	15.00	15	15
Full-Time Local	5	0.57	2	2.5

[a]Range reflects projected change in frequency between 1992 and 2002.
[b]From DOT, 1993.
[c]Assumed.
[d]Number of days at regional center declines slightly through time because of slight increase in home-based telecommuting.

typical commuter (21.4 miles round-trip, the U.S. average for 1990), it is not necessary that the commute trip be between the periphery and the CBD, just that it be a typical metropolitan area commute.

For each city, the number of telecommuters is multiplied by the average commute trip distance per day and the average number of days commuted per week to determine the weekly miles of travel forgone because of telecommuting. This is converted to a change in DVMT for a typical workday by dividing by 5. Because not all commuters travel by highway, the change in DVMT is multiplied by the share of commuting trips that used highways in 1990—91.4 percent (Hu and Young, 1992). Finally, the result is divided by the average commuter vehicle occupancy, 1.1, which assumes that telecommuters' vehicle occupancy rates are the same as the average for all commuters.

Telecommuting is likely to provide reductions almost exclusively in peak-period travel. Consistent with the areawide average measures used, however, the effects are estimated as a reduction in total daily travel. It is likely that this approach *underestimates* the impact of telecommuting on traffic congestion because travel reductions will be concentrated in the peak periods when congestion is worst.

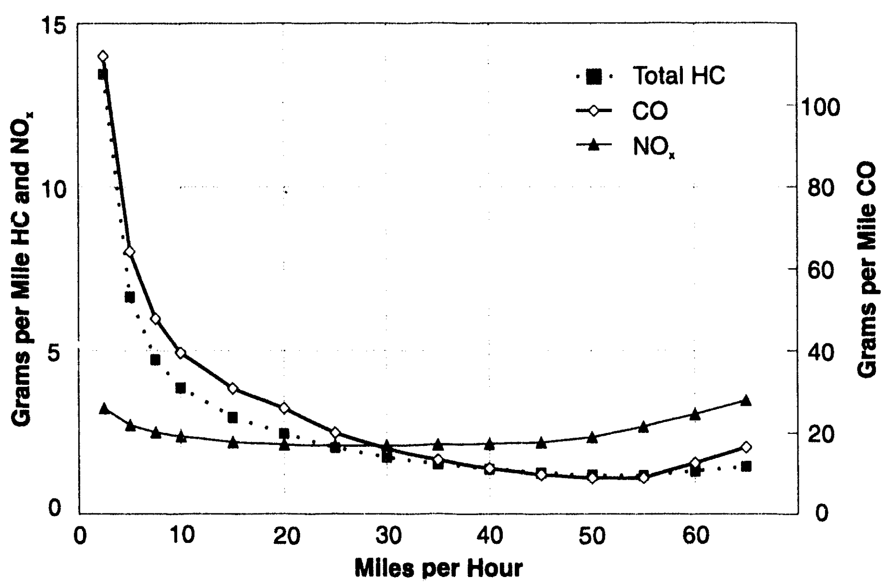
Estimating Fuel Use and Emission Rates as a Function of Speeds

Though recent evidence has cast doubt on the accuracy of emissions projections based on average speeds (Guensler, 1993), speed adjustment factors still represent the best practice in estimating the effect of changes in traffic flow on emissions levels. Baseline emissions estimates for light-duty motor vehicles are based on the Federal Test Procedure (FTP), which consists of a series of stops and starts with an average speed of 19.6 mph. Emissions rates for vehicles at speeds other than that of the FTP are estimated by multiplying the FTP emissions rate by the appropriate speed-correction factor (SCF). SCFs, developed by EPA and the California Department of Transportation, are derived by a statistical regression of fuel consumption against average speed for cycles other than the FTP. Thus, they represent a relationship between average speed, not cruising speed, and emissions. This is precisely the relationship needed in this analysis to relate average system speed to emissions and fuel use.

This study uses the speed-versus-emissions relationships for the total traffic stream based on the EPA MOBILE5 model. Because the numbers are intended to represent the effects of speed on mixed traffic, a weighted average of the relationships between speed and fuel economy of light- and heavy-duty vehicles is appropriate (Guensler, Washington, and Sperling, 1993). Future emissions levels will vary depending on the level of controls required. In particular, use of reformulated gasoline and strict inspection and maintenance programs have significant effects on emissions levels and will almost surely be implemented in urban areas that fail to attain national ambient air quality standards. Certainly, not all of the 339 urban areas included in this analysis will be required to implement reformulated gasoline and inspection and maintenance programs. To create a range of estimates of emissions effects, this study uses MOBILE5 to develop two sets of speed-versus-emissions curves for each of the two forecast years. The first is the MOBILE5 baseline projection, and the second assumes use of reformulated gasoline and implementation of the year 2004 inspection and maintenance standards.

In general, emissions decrease rapidly with increasing speeds, up to about 20 miles per hour (mph) (Figure 1–5). Beyond that point, emissions become increasingly insensitive to speed until a minimum emissions level is reached. The minimum emissions speed differs for the three criteria pollutants included in this assessment. Emissions of hydrocarbons (HC) and carbon monoxide (CO) tend to be lowest between 45 mph and 60 mph. Nitrogen oxides (NO_x) emissions, however, bottom out in the vicinity of 30 mph and begin increasing afterwards. As a result, increases in average speeds on many higher order roadways could increase rather than decrease emissions of NO_x.

The emissions effects produced by this analysis must be treated as approximations that are only indicative of the nature of the true effects. Researchers have recently come to understand the serious shortcomings of emissions inventory models such as MOBILE5 for forecasting emissions in real-world conditions. A recent study concluded that inventory models may underesti-



Note: Projection assumes no use of reformulated gasoline or 2004 inspection and maintenance requirements.

Figure 1–5. Projected Average Emissions From All Vehicles as a Function of Average Speed, 2010

mate real-world HC emissions by a factor of 2 to 4 and that substantial errors may well exist in the forecast of other criteria pollutants (NRC, 1991). Recent research on the relationship between traffic flow and emissions has shown that rare events of extreme acceleration and a minority of poorly maintained vehicles account for the majority of emissions. Nonetheless, the relationship between speed and emissions, as represented in MOBILE5, represents the current state of the art in emissions modeling. Readers should interpret the projections with great caution, however, and probably give credence to only the general direction and approximate magnitude of estimated impacts.

Vehicle fuel economy is strongly related to average speed. At lower speeds (below 40 to 50 mph), the relationship is due to a strong correlation between the number of acceleration episodes and idling periods and average speeds (Murrell, 1980). At higher average speeds, fuel economy approaches that achieved in steady-state cruising at constant speed. Overall fuel-economy increases with increasing speed up to an optimal velocity and then decreases with increasing speed, primarily because of increasing aerodynamic drag.[3] The precise shape of the curve and location of the optimal fuel-economy speed depends on vehicle technology. Steady-state fuel economy is higher than test-cycle fuel economy at low speeds, but the two tend to converge as speed increases.

A function fitted to a hybrid of the test-cycle and steady-state data is used to project changes in fuel consumption for this analysis (Figure 1–6). Up to 50 mph, the curve based on test-cycle data is used. For 50 mph and beyond, the steady-state curve is used. The combined curve increases from about 10 mpg at 7 mph, to 25 miles per gallon (mpg) at 25 mph, to a maximum of 31 mpg at about 48 mph, declining to 26 mpg at 65 mph. The hypothetical car on which this curve is based gets 20.1 mpg on the EPA city cycle and 32.7 mpg on the highway cycle, for an EPA rating of 24.3 mpg.[4] Using 24.3 mpg as an estimate of the in-use fuel economy implies an equivalent EPA test-cycle rating of 28.6 mpg. In 1993, the average EPA fuel economy for passenger cars was 28.0 mpg and for light trucks was 20.8 mpg, giving a combined average of 25.0 mpg (Murrell, Hellman, and Heavenrich, 1993). Thus,

[3]Because aerodynamic drag increases with the square of velocity, it eventually dominates other forces opposing the motion of the vehicle.

[4]The EPA rating is a weighted harmonic mean of the city and highway fuel economy numbers, using weighing factors of 55 for city and 45 for highway. In-use fuel economy tends to be about 15 percent lower than the EPA ratings.

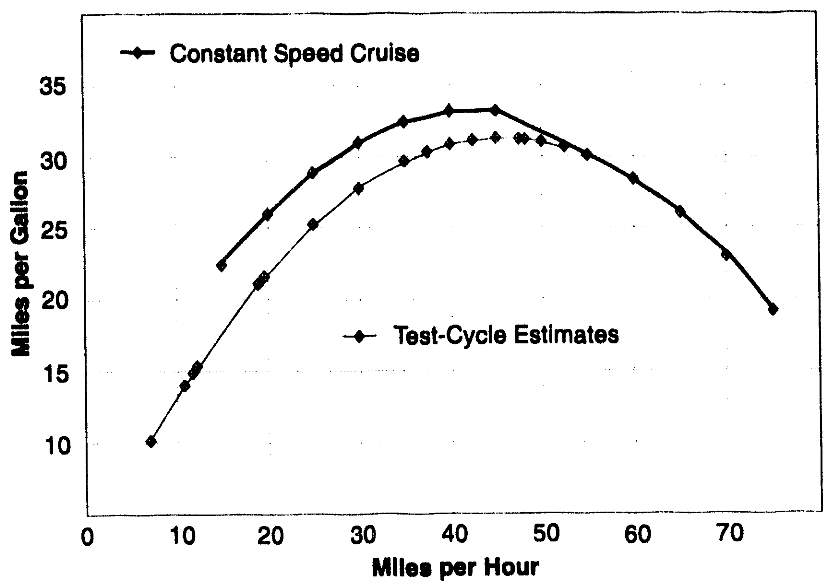


Figure 1–6. Estimated Relationship Between Average Speed and Fuel Economy

the fitted curve is a reasonable representation of onroad fuel economy for *new* automobiles today.

The Federal Highway Administration (FHWA) estimated average in-use fuel economy for *all* vehicles as 16.4 mpg in 1990 (DOT, FHWA, 1991). Using the equivalent of 24.3 mpg for all traffic would be equivalent to a 44-percent increase in realized fuel economy. The Energy Information Administration (EIA) projects a 10-percent increase in onroad fuel economy over 1990 levels for light-duty vehicles by 2005 and a 15-percent increase by 2010. Using the EIA light-duty vehicle improvement for all vehicles in 2005, and extrapolating to a 25-percent improvement by 2010 implies an average of 18.0 mpg for all vehicles in 2005, and 20.5 mpg in 2010. Thus, for indirect fuel savings in the year 2005 analysis, mpg projected by the quadratic function is discounted by a factor of 0.75, and for the 2010 analysis it is multiplied by 0.85. For direct fuel savings, this report assumes that telecommuters are using light-duty vehicles. The EIA projection is an average of 20.6 mpg in 2005 and 23.2 mpg in 2010 projected by extrapolation, implying correction factors for direct fuel savings of 0.85 in 2005 and 0.95 in 2010.

Emissions of carbon dioxide (CO_2), the principal greenhouse gas, are a direct function of gasoline consumption. CO_2 emissions are estimated at 19.2 pounds per gallon (2.3 kilograms per liter).

Quantifying Effects

The effects of telecommuting consist of time savings to telecommuters and other travelers due to changes in traffic delay, fuel savings due to a net reduction in VMT and a change in efficiency produced by increased speed, reduced emissions levels (total HC, CO, and NO_x), and the avoided costs of highway construction and maintenance.

Time costs are quantified as hours of delav (increased or decreased) and also in terms of dollars by multiplying by an assumed value of time of $10 per hour (Chui and McFarland, 1987).[5] Fuel costs are measured in gallons and translated into dollars using the 1990 average price of gasoline—$1.41 per gallon in 2005 and $1.51 per gallon in 2010 (EIA, 1993). Because State and Federal taxes are not true costs, but transfer payments, $0.30 per gallon is subtracted from the projected prices to account for motor fuel taxes. Emissions are measured in metric tons and can be valued at either the avoided cost of alternative pollution control measures (Greene and Duleep, 1992) or estimates of their damage (Wang, Sperling, Olmstead, 1993). (Typical values are shown in the appendix.) Because of the large uncertainties concerning the value of pollution reduction, this study emphasizes the tons reduced, rather than their value. Highway construction and maintenance costs are the avoided costs of highway capacity that does not need to be constructed because of reduced travel volumes. Average national costs per lane-mile are based on the average cost of widening—that is, adding lanes to existing facilities. This is expected to be the most common form of capacity expansion in urban areas in the future. Values of $2.5 million per lane-mile and $1.3 million per lane-mile are used for freeways and arterials, respectively.

[5]$10 per hour is the equivalent of Chui and McFarland's estimate inflated to 1990 dollars.

Results of the Modeling Analysis

This section presents an analysis of several scenarios of future effects of telecommuting in which latent demand and indirect effects are accounted for. The results indicate that latent demand effects are significant but do not eliminate the energy and environmental benefits of telecommuting and that indirect benefits are also substantial and, in some cases, are of the same magnitude as direct benefits.

Although the size of the latent demand effect is sensitive to key assumptions, it appears that for every vehicle-mile removed from highways by telecommuting, about half a vehicle-mile will be added because of latent demand. In addition, telecommuting is estimated to have a small effect on regional spatial structure—increasing urban sprawl. This also contributes to the "rebound" in travel, but to a lesser extent than latent demand.

While the effects of latent demand and urban sprawl tend to reduce the direct benefits of telecommuting on emissions, energy use, and traffic delays, the indirect effects of telecommuting on the remaining traffic stream tend to restore some of those benefits (a phenomenon anticipated by the DOT study). For a given level of commuting, the total net benefits appear slightly smaller than the direct benefits estimated in the DOT study, which did not attempt to account for latent demand or other indirect effects. By accounting for these effects, this study indicates that these effects are not likely to eliminate the anticipated benefits of telecommuting.

Because this analysis has been conducted at the level of individual MSAs, it is possible to consider the distribution of telecommuting effects across cities. The results suggest that benefits are likely to be highly concentrated in the largest cities. The two largest urban areas, New York and Los Angeles, by themselves account for 25 percent of the estimated total reduction in traffic delays. This is due both to the quantity of vehicle travel in these cities and to the degree of traffic congestion. The 75 largest cities account for 90 percent of the total reduction in hours of traffic delays. For the vast majority of the smaller 339 urban areas included in this analysis, indirect benefits are small and latent demand effects are small or nonexistent. (In the methodology used here, if there is no areawide traffic congestion, there is no latent demand.) Thus, latent demand effects and the offsetting indirect benefits are highly concentrated in the largest urban areas where problems of traffic congestion are most severe.

Telecommuting Scenarios

In this study, 16 scenarios were constructed to assess effects under a range of assumptions about telecommuting levels, indirect effects, and emissions levels. The scenarios represent the different combinations of the following four variables:

- Future year: 2005 versus 2010
- Types of telecommuting: DOT (1993) assumptions versus alternative assumptions (maintaining current patterns)
- Urban structure: inclusion or exclusion of a dispersion effect on urban density (that is, whether or not urban sprawl is increased)
- Emissions: universal use of reformulated gasoline and 2004 inspection and maintenance requirements (low emissions) versus neither (high emissions)

In addition, one of the scenarios was tested to determine the sensitivity of the projections to three critical elasticity parameters: road capacity expansion as a function of capacity needs, latent demand as a function of congestion, and average urban trip lengths as a function of total transportation costs. Sensitivities were tested in the 2010, "alternative" telecommuting patterns, high-emissions scenario (including the urban sprawl effect).

Telecommuting Forecasts for 2005 and 2010

The projection of telecommuting market penetration for the 339 cities included in this analysis foresees a dramatic increase in telecommuting over the next two decades (Table 1–5). Although information workers as a percentage of all workers increases only slightly—from 55 percent in 1988 to 60 percent by 2005 and 61 percent by 2010—telecommuting among information workers increases dramatically—from less than 2 percent in 1988 to 28 percent by 2005 and 45 percent by 2010. As a result, the number of telecommuters grows from just half a million in 1988 to 17.7 million by 2005 and 29.1 million by 2010. Approximately two-thirds of the Nation's population resides in the 339 cities included in this analysis.

As discussed earlier, projected telecommuting miles differ considerably depending on the assumed patterns of telecommuting behavior (see Table 1–5). The original DOT "upper bound" scenario projected 15.0 million commuters in 2002, which is generally consistent with the extension of that

Table 1–5. Projections of Telecommuters and Telecommuting Miles

	Actual	Projected	
	1988	2005	2010
Telecommuters[a]			
Information Workers as % of All Workers	54.8	60.0	61.1
Telecommuters as % of Information Workers	1.3	27.8	44.9
Telecommuters as % of All Workers	0.7	16.7	27.4
Number of Telecommuters (million)	0.5	17.7	29.1
Telecommuting Miles Avoided (billion)			
DOT Scenario	1.1	36.4	59.3
Alternative Scenario	1.1	41.1	67.4

[a]Telecommuter estimates are consistent with DOT "upper bound" estimates; these estimates are used in both scenarios of telecommuter distribution by type.

scenario in 2010 used here. The alternative scenario used here reaches substantially higher numbers of telecommuters in 2010.

Highway Capacity Effects and Congestion

The forecast on which this analysis is based projects growth rates of vehicle travel averaging just under 2 percent per year through 2010. This level is somewhat low for a national forecast by historical standards. From 1970 to 1990, total highway travel in the United States increased at an average annual rate of 3.4 percent. If growth rates exceed the 1.8-percent-per-year rate used for this forecast, congestion will worsen more rapidly and the indirect benefits of telecommuting, as well as the offsetting effects of latent demand, would be increased.

Increased travel increases traffic congestion, creating a demand for expansion of highway capacity. As explained above, the methodology used here does not expand capacity rapidly enough to hold congestion constant. Instead, an elasticity of 0.8 is used to project annual additions of lane-miles as a function of the number of lane-miles that would be required to hold congestion levels constant at the previous year's level. Thus, congestion will continue to worsen, in general, as vehicle travel grows. The base year (1988) average roadway congestion index value for the 339 cities was 0.76. The RCI values for New York and Los Angeles were 1.12 and 1.58, respectively. Allowing for capacity additions, but before taking into account the effect of increased telecommuting, in 2010 the average value increases to 0.81, while the RCIs for the two largest cities grow to 1.26 and 1.96. The reduced travel brought about by increased telecommuting causes the RCIs for New York and Los Angeles to drop to 1.18 and 1.87, respectively. Accounting for the rebound effects of latent demand raises them to 1.22 and 1.92, respectively. Thus, latent demand lessens the beneficial effect of telecommuting on congestion, but does not eliminate it.

Highway capacity expansion requirements are computed with and without increased telecommuting.[6] The difference represents highway lane-miles that do not need to be constructed because of the lower levels of traffic due to expanded telecommuting. Depending on the scenario, construction of 2,900 to 4,500 freeway lane-miles, and 4,400 to 6,700 lane-miles of principal arterials, is avoided through 2010 because of increased telecommuting (Table 1–6). The cumulative (undiscounted) cost savings range from $13 billion to almost $20 billion through 2010.[7]

Effects on Hours of Delay and Average Speeds

Reduced congestion caused by telecommuting leads to increased average speeds and reduced hours of traffic delays. In general, speed changes are less than 1 mile per hour, with most increases being in the vicinity of 0.5 miles per hour. Nonetheless, the delay reduction is significant, ranging from a 3- to 5-percent reduction in total hours of delay for each urban area. Overall reductions in 2010 are about 140 million to 210 million hours annually (Table 1–6). (Direct time savings to telecommuters are not included in these estimates.) Although telecommuting will not eliminate urban traffic congestion, it clearly has important benefits, especially considering the substantial amount of avoided capacity expansion. However, there is 3 to 7 percent additional travel

[6]Because capacity requirements with increased telecommuting are computed before adjusting for latent demand (but after adjusting for decreased urban density), the lane-miles required will be somewhat underestimated. This will result in a small overestimation of savings on highway construction but a small underestimation of the congestion benefits of telecommuting.
[7]The discounted present value of these savings would be lower.

Table 1–6. Projected Changes in Commuter Travel Time, New Highway Construction, and Fuel Use Resulting From Increased Telecommuting, 2005 and 2010

	Department of Transportation Telecommuting Assumptions		Alternative Telecommuting Assumptions	
Factor	Adjusted for Increased Urban Sprawl	Not Adjusted for Increased Urban Sprawl	Adjusted for Increased Urban Sprawl	Not Adjusted for Increased Urban Sprawl
		2005		
Reduced Delay (million hrs./yr.)	87	115	98	129
Highway Costs (billion 1990$)	4.9	6.4	5.4	7.2
New Freeways (lane-miles)	1,800	2,400	2,000	2,700
New Arterial Hwys. (lane-miles)	2,600	3,600	3,000	4,000
Total	**4,400**	**6,000**	**5,000**	**6,700**
Fuel Savings (million gal.)				
Direct	706	947	798	1,069
Indirect	95	125	107	140
Total	**801**	**1,072**	**905**	**1,209**
		2010		
Reduced Delay (million hrs./yr.)	141	184	160	208
Highway Costs (billion 1990$)	13.0	17.5	14.9	19.9
New Freeways (lane-miles)	2,900	3,900	3,300	4,500
New Arterial Hwys. (lane-miles)	4,400	5,900	5,000	6,700
Total	**7,300**	**9,800**	**8,300**	**11,200**
Fuel Savings (million gal.)				
Direct	1,171	1,560	1,336	1,775
Indirect	171	223	194	251
Total	**1,342**	**1,783**	**1,530**	**2,026**

Note: For estimates of fuel savings, "direct" reductions include the effects of latent demand.

undertaken by others that would not have been taken in the absence of telecommuting. This additional travel "takes back" some of the indirect benefits of telecommuting, but is itself an economic benefit of telecommuting because of its value to the additional travelers. This report does not attempt to estimate the value of this induced vehicle travel.

Most of the benefit of reduced congestion and delay accrues to the largest, most congested cities. Figure 1–7 illustrates the cumulative distribution of reduction in annual vehicle-hours of delay. The urban areas were ranked in descending order of daily vehicle-miles of travel on higher order highway systems. About one-fourth of the total reduction in delay occurs in the two

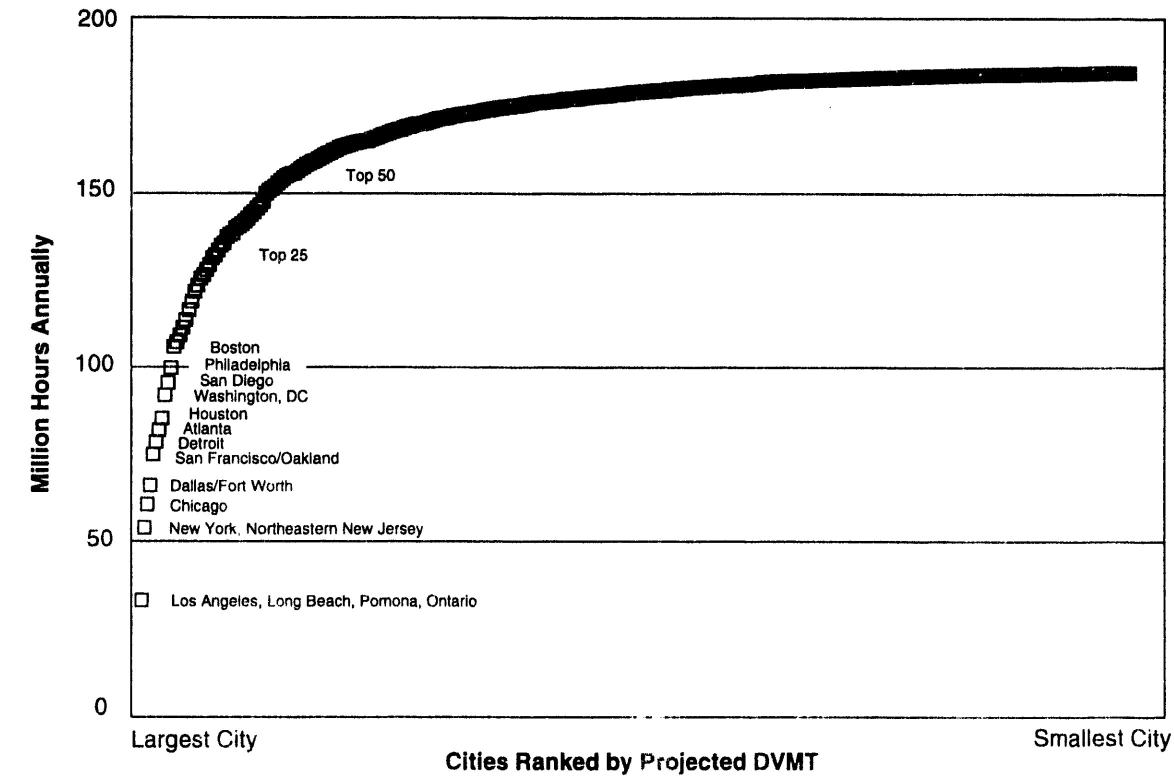


Figure 1–7. Projected Cumulative Reduction in Traffic Delays in 339 Urban Areas, as a Result of Telecommuting, 2010

largest cities: Los Angeles and New York. The 10 largest cities account for half of the delay reduction benefits; the 75 largest cities account for 90 percent.

Effects on Fuel Use and Emissions

As shown in Table 1–6, direct fuel savings (after taking the effects of latent demand into account) far outweigh the indirect savings. Estimated indirect effects are on the order of 100 million to 150 million gallons in 2005, while direct effect estimates range from 0.7 billion to 1.1 billion gallons. The ratios are similar in the year 2010, with combined effects estimated at 1.3 billion to 2.0 billion gallons annually. Emissions of CO_2 are proportional to fuel use, with combined reductions in 2010 estimated at about 15 million metric tons (Table 1–7).

Table 1–7. Projected Changes in Emissions Resulting From Increased Telecommuting, 2005 and 2010 (metric tons per year)

	Department of Transportation Telecommuting Assumptions				Alternative Telecommuting Assumptions			
	Adjusted for Increased Urban Sprawl		Not Adjusted for Increased Urban Sprawl		Adjusted for Increased Urban Sprawl		Not Adjusted for Increased Urban Sprawl	
Pollutant	**Low Emis.**	**High Emis.**	**Low Emis.**	**High Emis.**	**Low Emis.**	**High Emis.**	**Low Emis.**	**High Emis.**
	2005							
Carbon Monoxide (CO)								
Direct	-51,400	-68,100	-69,000	-91,400	-58,100	-77,000	-77,900	-103,100
Indirect	-2,900	-8,200	-3,600	-9,900	-3,300	-9,200	-4,000	-11,100
Total	**-54,300**	**-76,300**	**-72,600**	**-101,300**	**-61,400**	**-86,200**	**-81,900**	**-114,200**
Nitrogen Oxides (NO_X)								
Direct	-20,400	-24,500	-27,300	-32,900	-23,000	-27,700	-30,800	-37,100
Indirect	100	100	100	100	100	100	100	200
Total	**-20,300**	**-24,400**	**-27,200**	**-32,800**	**-22,900**	**-27,600**	**-30,700**	**-36,900**
Hydrocarbons (HC)								
Direct	-8,600	-10,400	-11,500	-14,000	-9,700	-11,800	-13,000	-15,800
Indirect	-300	-700	-400	-900	-400	-800	-400	-100
Total	**-8,900**	**-11,100**	**-11,900**	**-14,900**	**-10,100**	**-12,600**	**-13,400**	**-15,900**
Carbon Dioxide (CO_2)								
Direct	5,200,000		7,000,000		5,900,000		7,900,000	
Indirect	800,000		1,100,000		900,000		1,200,000	
Total	**6,000,000**		**8,100,000**		**6,800,000**		**9,100,000**	
	2010							
Carbon Monoxide (CO)								
Direct	-85,300	-112,900	-113,700	-150,500	-97,300	-128,800	-129,300	-171,200
Indirect	-43,400	-140,100	-56,700	-183,100	-49,200	-158,900	-64,000	-206,700
Total	**-128,700**	**-253,000**	**-170,400**	**-333,600**	**-146,500**	**-287,700**	**-193,300**	**-377,900**
Nitrogen Oxides (NO_X)								
Direct	-33,800	-40,600	-45,000	-54,100	-38,500	-46,300	-51,200	-61,600
Indirect	-200	100	-300	200	-300	100	-300	200
Total	**-34,000**	**-40,500**	**-45,300**	**-53,900**	**-38,800**	**-46,200**	**-51,500**	**-61,400**
Hydrocarbons (HC)								
Direct	-14,200	-17,300	-18,900	-23,000	-16,200	-19,700	-21,500	-26,200
Indirect	-4,600	-11,500	-6,000	-15,000	-5,200	-13,000	-6,800	-17,000
Total	**-18,800**	**-28,800**	**-24,900**	**-38,000**	**-21,400**	**-32,700**	**-28,300**	**-43,200**
Carbon Dioxide (CO_2)								
Direct	-8,700,000		11,600,000		-9,900,000		13,200,000	
Indirect	-1,500,000		1,900,000		-1,700,000		2,200,000	
Total	**-10,200,000**		**13,500,000**		**-11,600,000**		**15,400,000**	

Note: "Low Emis." and "High Emis." refer to two vehicle-emissions scenarios. The low-emissions scenario assumes universal use of reformulated gasoline and 2004 inspection and maintenance requirements; the high-emissions scenario assumes neither. All "direct" changes include the effects of latent demand.

The local area emissions effects of telecommuting are generally beneficial, but not large. The DOT study estimated reductions of hydrocarbons (HC) and nitrogen oxides (NO_x) on the order of 100,000 tons for direct effects in the year 2002. Carbon monoxide (CO) reductions are larger, on the order of 1 million tons, due to the greater mass of CO emissions. Emissions of lesser magnitudes are estimated in this study. This is due in part to the use of lower rates of emissions, based on EPA's MOBILE5 model and the more stringent emissions standards of the 1990 Clean Air Act Amendments. It is also due, however, to the fact that latent demand cuts direct emissions benefits roughly in half, and because estimated indirect benefits are relatively small. As illustrated in Figure 1–5, the relationship between average speed and emissions is quite flat over the range of speeds forecast for higher order roads in the 339 cities included in this analysis. Between 25 and 60 miles per hour, small speed changes (on the order of 0.5 miles per hour) produce very small changes in emissions rates (hundredths of a gram per minute for HC and NO_x, tenths of a gram per mile for CO). The result is that direct and indirect effects are of approximately the same magnitude (tens of thousands of metric tons for HC and NO_x and roughly 100,000 tons for CO), and none are extremely large (Table 1–7).

While decreased congestion caused by telecommuting appears to produce reduced emissions of HC and CO, very minor increases in NO_x emissions are projected. For all pollutants, emissions first decrease with increasing speed and then increase at higher speeds. However, compared with HC and CO emissions, NO_x emissions begin to increase at lower speeds. Over the range of speeds predicted for the cities in this analysis, reductions in NO_x emissions (largely on arterials) due to increased speeds roughly offset increases (on freeways and expressways) so that the net effect is approximately nil.

As pointed out earlier, recent analyses of motor vehicle emissions in actual traffic have seriously called into question the ability to forecast emissions with inventory models such as MOBILE5. In light of mounting evidence that the current state of the art in projecting emissions in actual traffic conditions is seriously inadequate, the emissions results projected here should be viewed with caution. Perhaps all that can be reasonably asserted is that the emissions effects are probably beneficial.

Sensitivity to Key Parameter Values

The projected indirect effects of telecommuting strongly depend on the degree to which telecommuting actually reduces traffic congestion. Sensitivity of the results to three key factors was explored. The *capacity expansion factor* (the percent change in lane-miles added for a 1-percent change in lane-miles needed) plays a major role in determining the degree to which traffic congestion will worsen over time. This affects delays, speeds, fuel use, and emissions, as well as directly determines the savings in highway capacity construction. The *latent demand factor*, as a function of congestion, and the *elasticity of trip lengths*, with respect to total transportation cost, together determine the degree to which vehicle travel will increase in response to reduced congestion and reduced commuting. The base case values of these parameters were varied from plus or minus 20 percent to plus or minus 33 percent to create a meaningful range of possible values (Table 1–8).

First, each parameter was changed individually, while holding the other two constant. Next, two cases were considered using the extreme values that give the largest and smallest congestion effects. All were tested using the 2010 projections for the "alternative" telecommuting scenario, with high emissions levels and adjusted for increased urban sprawl.

Although certain effects are very sensitive to changes in the parameter values, in no case do the benefits of telecommuting disappear (Table 1–9). In general, increasing the parameters affecting latent demand in response to telecommuting tends to erode the benefits of telecommuting, as would be expected. However, even in the worst case considered, there are still significant benefits.

Table 1–8. Parameter Values Used in Sensitivity Analysis

Case	New Highway Capacity	Latent Demand	Urban Sprawl
High	1.0	-0.67	-1.2
Base	0.81	-0.50	-1.0
Low	0.6	-0.33	-0.8

Table 1–9. Sensitivity of Estimated Telecommuting Effects to Variations in New Highway Capacity, Latent Demand, and Urban Density Parameters (Tested Separately)

Parameter	High Case	Base Case	Low Case
	Net Reduction in Annual Vehicle Travel (percent)		
New Highway Capacity	-5.7	-4.7	-3.9
Latent Demand	-3.8	-4.7	-5.6
Urban Density	-4.3	-4.7	-5.0
	Annual Delay Reduction (million hours)		
New Highway Capacity	0	160	275
Latent Demand	105	160	222
Urban Density	150	160	169
	Total Highway Construction Avoided (billion 1990$)		
New Highway Capacity	30	15	7
Latent Demand	13	15	17
Urban Density	14	15	16
	Lane-Miles of Construction Avoided		
New Highway Capacity	16,750	8,300	4,000
Latent Demand	7,400	8,300	9,300
Urban Density	7,750	8,300	9,000
	Annual Fuel Savings, Indirect/Direct (billion gallons)		
New Highway Capacity	0/1.6	0.2/1.3	0.5/1.1
Latent Demand	0.1/1.1	0.2/1.3	0.3/1.6
Urban Density	0.2/1.2	0.2/1.3	0.2/1.4
	Annual Criteria Pollutants, Indirect/Direct (thousand metric tons)		
Nitrogen Oxides (NO_X)			
New Highway Capacity	0/-57	0/-46	-2/-39
Latent Demand	0/-38	0/-46	0/-55
Urban Density	0/-43	0/-46	0/-49
Hydrocarbons (HC)			
New Highway Capacity	0/-24	-13/-20	-24/-17
Latent Demand	-8/-16	-13/-20	-18/-24
Urban Density	-12/-18	-13/-20	-14/-21
Carbon Monoxide (CO)			
New Highway Capacity	0/-157	-159/-129	-304/-109
Latent Demand	-100/-106	-159/-129	-226/-154
Urban Density	-149/-120	-159/-129	-169/-137

Note: The sensitivity analysis used the "Alternative" telecommuting scenario for 2010 that assumed increased urban sprawl and no use of reformulated gasoline or of 2004 inspection and maintenance requirements. Each parameter was changed individually while holding the other two constant. For fuel and emissions estimates, "direct" reductions include the effects of latent demand.

Increasing the sensitivity of highway capacity expansion to reductions in travel has the effect of changing benefits in reduced delay into savings in highway construction. With the capacity factor at 0.6, delay is reduced by 275 million hours over the base case, but with the capacity factor at 1.0 (capacity expanded to hold congestion levels constant over time), reduction in delay is essentially zero (Figure 1–8 and Table 1–9). In other words, the method assumes that because telecommuting will gradually decrease the growth rate of travel, investment in highway infrastructure will also be made at a lower rate. Because a capacity factor of 1.0 implies that congestion (as measured by the RCI) will be held constant at the 1988 level, there is no difference in congestion between the base case forecast and the telecommuting projections. There is a substantial difference, however, in the construction of highway capacity (Figure 1–9 and Table 1–9). About 17,000 fewer lane-miles are constructed at a savings of $30 billion.[8] The latent demand parameter has a

[8]This is undiscounted 1990 dollars and does not include the costs of operating, maintaining, and repairing the additional capacity.

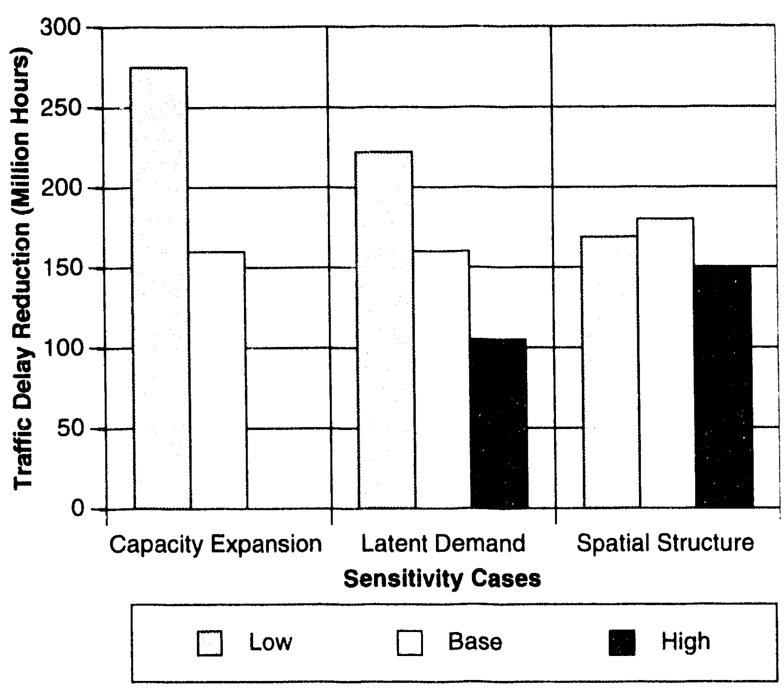


Figure 1–8. Sensitivity of Reduction in Traffic Delays to Three Critical Parameters

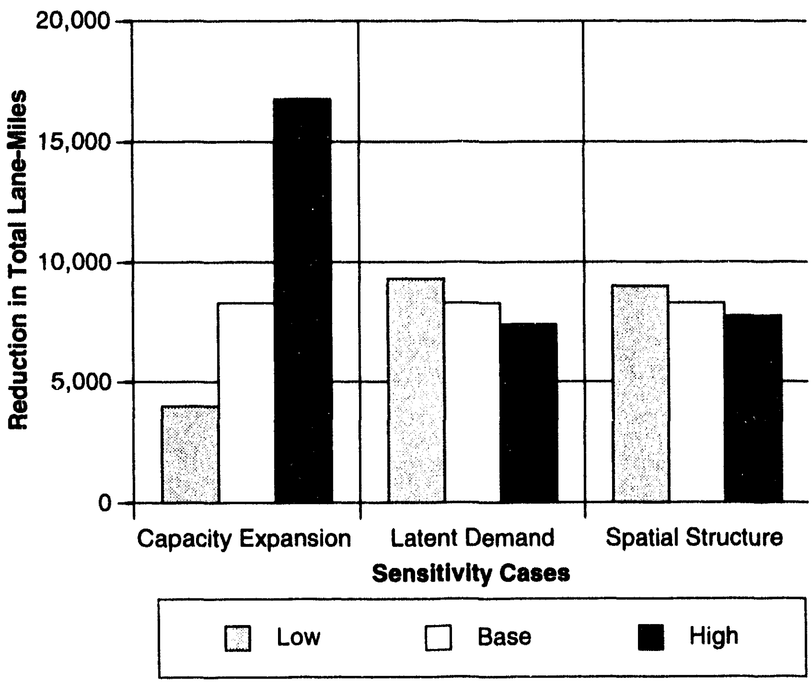


Figure 1–9. Sensitivity of Highway Capacity Expansion to Three Critical Parameters

smaller effect on delay, roughly proportional to the net change in vehicle travel. Assuming base values of the parameters, the net change in VMT is -4.7 percent, for a removal of telecommuting-miles equivalent to 10.3 percent of vehicle travel. Reducing the latent-demand elasticity to -0.33 raises the net VMT reduction to -5.6 percent, while increasing it to -0.67 reduces the net change to -3.8 percent. Similarly, hours of delay are reduced by 105 million, 160 million, and 222 million in the high elasticity, base, and low elasticity cases, respectively. The effect on emissions is similar; benefits are reduced but not eliminated. The effect of changing the urban-sprawl parameter is similar but much less pronounced.

If all of the most extreme values for each of the three parameters are chosen, surprisingly, the net change in VMT is nearly identical (Table 1–10). Because latent demand depends on a change in the level of congestion, latent demand is not evident when there is no decrease in congestion. As explained above, when it is assumed that highway capacity expands in step with travel demand (capacity factor equals 1) there is no increase in congestion. Thus, all

Table 1–10. Estimated Effects With Highest and Lowest Values of Three Key Parameters (Combined)

Effect	Highest	Lowest
Net Reduction In Annual Vehicle-Miles Traveled (percent)	-4.6	-5.3
Annual Delay Reduction (million hours)	0	400
Total Highway Construction Avoided (billion dollars)	$24	$8
Annual Fuel Savings, Indirect/Direct (billion gallons)	0/1.3	0.7/1.5
Annual Criteria Pollutants, Indirect/Direct (thousand metric tons)		
Nitrogen Oxides (NO_x)	0/-45	-3/-52
Hydrocarbons (HC)	0/-19	-36/-22
Carbon Monoxide (CO)	0/-127	-449/-145

Note: For fuel and emissions estimates, "direct" reductions include the effects of latent demand.

of the savings are in reduced highway construction and in the direct effects. Using all of the lowest parameter values greatly increases congestion, but also greatly diminishes the effects of latent demand and urban density. Because of the higher congestion levels, indirect effects play a much greater role in the total effects. Indirect fuel-use effects are still only about one-third of the direct effects, and indirect reductions in NO_x emissions remain relatively minor. Indirect HC and CO emission reductions, however, become considerably greater than the direct reductions.

Conclusions

Substantially increased levels of telecommuting can produce significant benefits in the form of reduced delays, fuel consumption, needs for highway capacity expansion, and emissions. Telecommuting alone cannot completely solve any of these problems, but it should help. The direct benefits of telecommuting are not likely to be entirely offset by latent travel demand, or by the geographical expansion of cities. Perhaps half the potential reduction in vehicle-miles will be replaced by new traffic, induced by lower levels of congestion, reduced commuting requirements, and higher average speeds. But reduced congestion and higher speeds will create indirect benefits in terms of lower average emissions and fuel consumption rates that compensate somewhat for the induced vehicle travel. Indirect reductions in fuel use are likely to be a small fraction of direct fuel savings, and indirect reductions in NO_x emissions appear to be negligible. Indirect reductions in HC and CO emissions, however, can be as great or greater than direct reductions. Lower expenditures for additional highway capacity and less land devoted to increased lane-miles will be additional benefits. The only factor that could eliminate the indirect fuel-use and emissions benefits of telecommuting is if one assumes that highway capacity will expand fast enough to keep traffic congestion from increasing. In this case, savings on avoided highway construction from telecommuting increase and the latent demand effect disappears, increasing the direct benefits.

Telecommuting and its benefits will be concentrated in the largest, most congested, and most polluted urban areas. One-fifth to one-fourth of the reductions in traffic delays, emissions, and highway demands are likely to be obtained in the country's two largest urban agglomerations. Half the benefits are likely to accrue to the 10 largest cities, and 90 percent to the 75 largest. Thus, the greatest benefits will occur where they are most needed. It is likely that the method used here tends to underestimate indirect benefits, considering that it is based on areawide average conditions and that telecommuting VMT reductions should be concentrated during peak traffic periods.

By creating options and alternatives to the traditional peak-hour journey to work, telecommuting should reduce the cost of other strategies, such as congestion pricing and parking fees, that tax or discourage travel during peak periods (Schroeer and Kessler, 1993). Conversely, policies that discourage driving will tend to dampen the latent demand effect that reduces the direct benefits of telecommuting. Thus, policies that facilitate telecommuting not only should lead to direct and indirect transportation benefits, but also may provide synergistic beneficial effects with other transportation strategies that are implemented to cope with growing traffic congestion, urban air pollution, and national petroleum dependence.

2. SOCIAL IMPLICATIONS

Introduction

Telecommuting is not yet a common practice, so its social effects are relatively localized, affecting the individual telecommuters, their work organizations, their families, and, to a lesser extent, their communities. If telecommuting becomes a more widespread working strategy, the variety and magnitude of its effects could grow much larger, affecting in both positive and negative ways individuals, the workplace, families, communities, and the Nation.

This section discusses past, present, and projected social effects (both direct and indirect) of telecommuting. Examining the social effects of telecommuting is difficult for several reasons. First, the pace of technological change is so rapid that the context within which social effects should be assessed is always shifting. Second, particularly with regard to the workplace, it is difficult to distinguish the effects of telecommuting from the effects of other factors, such as telecommunications advances, flexible work hours, employee empowerment, corporate restructuring or, more generally, economic recession. Third, the scarcity of studies on the social effects of telecommuting, particularly of long-term studies, makes it difficult to assess past and present social effects, much less to project future social effects. Most of the available literature speculates on possible effects; only a small percentage documents actual effects.

Existing social impact studies tend to focus on telecommuting at a very small scale. For instance, pilot or demonstration projects generally are of limited duration, and they involve relatively small geographic areas (for example, single metropolitan areas). Such studies do not provide a solid foundation on which to base generalizations about the social implications of widespread telecommuting either within those metropolitan areas or in larger regions. Their value is particularly limited in addressing possible effects at the national level. Consequently, this report raises issues that may become extremely important in the future, though it cannot forecast accurately how these issues may be resolved. Among these issues is the potential for widespread telecommuting to exacerbate societal fractionalization within the workplace and in society at large. Widespread telecommuting also may alter conceptions about home and the workplace, as distinctions between formerly separate sets of activities and expectations disintegrate. As discussed in Chapter 1, spatial patterns of residential and corporate development may follow a different path—toward greater urban sprawl—if a substantial proportion of the population telecommutes regularly than if the percentage of telecommuters remains small. Furthermore, the institutional structure of workplaces may change substantially to adapt to the conditions and needs presented by widespread telecommuting.

The social effects of telecommuting can be positive or negative, and the same effects can be judged differently by different people. People's judgments of the overall effects of telecommuting depend on how they value the relative importance of different specific effects and on how they combine (weigh and rank) those aspects of telecommuting they deem positive and negative. This chapter seeks to make neither specific valuations nor overall judgments. In the policy realm, though, such valuations are of critical importance, and the specific types of effects (especially negative effects) may highlight opportunities or the need for mitigation or regulation. For example, the potential for increases in the use of telecommuting as a condition of employment—which could either amplify social inequities or create a new class of workers who do not receive many of the protections or benefits of full-time employment—may spur specific policy or regulatory measures.

Workplace Implications

This section highlights the implications of telecommuting for productivity, organizational structure, and other factors such as employee morale and turnover. that influence the functioning and composition of organizations. The discussion is primarily from the perspective of corporate organizations, not the perspective of the individuals who make up those organizations, though those perspectives often overlap or are intertwined. (The following section focuses on the implications of telecommuting on individual telecommuters.)

Telecommuting already has been adopted formally and informally at numerous organizations; for increasing numbers of workers, "virtual offices" (organizations with no physical or central office) are a reality. Among the social benefits associated with telecommuting are enhanced employee morale, reduced employee stress, productivity improvements, and increased creativity (Gleckman et al., 1993; Hammer, 1990; Kelly and Gordon, 1986; and DOT, 1993). These kinds of benefits border on the intangible; they are hard to define and difficult to measure with precision. In addition, these benefits may vary depending on the unit of analysis (for example, individual employees, workgroups, or organizations), and they do not appear in isolation—certain benefits to some individuals or classes of worker may produce costs to other individuals or classes of worker. The Washington State Energy Office demonstration study makes the point that a telecommuter's productivity gains seem to stem primarily from reduced interruptions (Heifitz, 1992). However, telecommuting has yet to be analyzed as a means of improving productivity by reducing workplace interruptions; telecommuting may be neither the most cost-effective nor the most equitable way to reduce interruptions or improve individual productivity.

Telecommuting raises issues that relate to the equipment necessary for its implementation. Specialized equipment or services may be required for working at home or at telecommuting centers, including computers, modems, facsimile machines, additional telephone lines, electronic mail services, and subscriptions to on-line information sources. A major issue is, and will be, how these expenses are to be borne and how the benefits of using the equipment are to be shared. For example, employers may encourage or require their employees to provide the necessary equipment if they work away from the office. Not all individuals can afford such equipment and services, particularly when rapid technological advances quickly make equipment and software obsolete. Those employees who can afford equipment and services personally would be providing items that benefit employers (who may not distribute those benefits to employees). On the other hand, if employers provide equipment and services, individuals may use them in off-hours for personal purposes such as shopping at home, accessing electronic bulletin boards, or downloading data for purposes unrelated to work. Particularly in the public sector, where equipment is purchased with taxpayers' funds, the argument can be made that employees should not be allowed to make personal use of such items.

Other issues that arise from home (or nonoffice) use of personal or company equipment or services include the following: liability for equipment maintenance, damage, or theft; liability for adverse health consequences of equipment use (such as the possible effects of repetitive motions or of exposure to video display terminals); and taxes (such as the legitimacy of claiming deductions for the purchase of equipment, especially if that equipment also is used for personal purposes). In addition, telecommuting raises other issues, such as excessive or increased expectations of productivity; employer monitoring of employees; compensation, promotion, and benefits; and inclusion in, or exclusion from, informal information exchanges that occur within the workplace that help to create and maintain organizational culture (Deal and Kennedy, 1982 and DOT, 1993).

Although telecommuting typically refers to working at home, a broader definition encompasses working at a satellite worksite (or regional telecommuting center) that is equipped with personal computers and telecommunications equipment and that is located closer to an employee's home than is the employer's central office. Experience with this type of telecommuting remains limited, and research on regional telecommuting centers is relatively scarce. In addition, it is not clear if the satellite centers that have been studied were planned to maximize their use by locating them close to telecommuters and to public transportation. A few studies have found that satellite centers potentially can be successful but that measures to reduce their cost and increase their use are necessary (Quaid and Lagerberg, 1992). Mokhtarian (1991), who also emphasizes the financial costs associated with starting telecommuting centers, notes that their air-quality and transportation impacts should be assessed (a subject that is addressed in Chapter 1 of this report).

Whether at home or at satellite centers, telecommuting enables employees to conduct much of their work without face-to-face interaction, which produces both positive and negative effects. Efficiency and productivity may increase, but working group morale may decline. Telecommunications, particularly broad-band technologies, potentially can substitute for some of the lost face-to-face contact. Once installed, the infrastructure to support broad-band technologies makes possible additional information and communications services that could support expanded telecommuting. Currently, broad-band technologies are expensive to install, and services that use them, such as videoconferencing, are too expensive to use as routine substitutes for typical telephony or face-to-face communication. Because their use is so limited, information on worker satisfaction with broad-band technologies as substitutes for face-to-face interactions typically comes from small, specialized groups who may be testing and developing particular systems. Anecdotal evidence suggests that worker use of and satisfaction with broad-band technologies is variable (Brittan, 1992). It also remains to be seen whether the costs of such services will decrease to levels that allow their widespread use in the office, for telecommuting, or for residential use.

Productivity

If telecommuting does not enable individual and organizational productivity to be at least as good as nontelecommuting productivity, then it is unlikely to become a long-term, established practice. Unfortunately, although telecommuting frequently is said to enhance productivity (for example, Long, 1987; Yarnell, 1989; and Strazewski, 1990), productivity is not easily defined or measured. Many conceptual definitions focus on labor yields—in amounts or values of goods—over time (for example, Skinner, 1986; Curtin, 1993; Duke, 1992; and Gullickson, 1992) and not on total productivity. In practice, productivity often proves very difficult to measure for individuals and workgroups. The Washington State Energy Office study of a telecommuting demonstration project emphasized that people who supervise professional staff have trouble specifying how productivity can be measured (in performance evaluations, for instance) (Quaid and Lagerberg, 1992). Thus, discussions of enhanced productivity resulting from telecommuting should be grounded by clear definitions of productivity and how it is measured. Without such clear definitions, productivity remains an amorphous concept, study results may be ambiguous, and findings from different studies may not be comparable.

Because productivity can refer to individuals, workgroups, and organizations, the productivity effects of telecommuting may vary according to which of these units is of interest. There is growing evidence that telecommuting may enhance organizational productivity (Gleckman et al., 1993; Hammer, 1990; and Roach, 1993). At a more micro-level, however, the distribution of productivity impacts across workers may be uneven. The Washington State Energy Office study (Heifitz, 1992) revealed that telecommuters, their coworkers, and their supervisors agreed that individual telecommuters' productivity increased, at least on their telecommuting days. Telecommuters reported greater increases in their productivity than did either their coworkers or supervisors. However, coworkers' productivity may not have improved, which raised questions about the overall productivity of workgroups. In some instances, colleagues of telecommuters acquired additional burdens on telecommuting days since they had to cover, or fill in, for telecommuters. Some colleagues thought that these additional burdens were valuable as training for positions with increased responsibility. Others simply felt put-upon by the need for them to take on additional responsibilities, which was one reason why nontelecommuters sometimes resented telecommuters. Nontelecommuters' self-reported productivity levels varied. In some cases, because there were fewer distractions at the office when individuals were telecommuting, productivity increased on telecommuting days. In other cases, colleagues reported decreased productivity.

One result of these differences in productivity is that policymakers and corporate managers who wish to use productivity as a measure of the effects of telecommuting may have to rank the importance of different kinds of productivity. The Washington State Energy Office study underscores the dynamic and interactive nature of many working environments. In assessing the advantages and disadvantages of telecommuting, it is important to recognize that benefits for telecommuters may not translate automatically into benefits for the entire work group.

Another issue relating to productivity is causality. It may be impossible to distinguish the effects of telecommuting on productivity from the effects of accompanying changes in corporate attitudes, management approach and structure, and other organizational restructuring. Further, it may be too soon to tell how long already observed changes in productivity may persist or what additional changes in productivity may occur.

Corporate Structure

Telecommuting may influence corporate structure by altering the interactions and roles of classes of personnel in the workplace, by establishing links between job classification and the ability to telecommute, and by revealing a company's underlying attitude or philosophy that caused it to undertake telecommuting.

Telecommuting, perhaps together with the adoption of other telecommunications technologies, can affect the roles that managers play and the levels of autonomy and control that different categories of workers experience. For example, because high-technology information tends to flow from the bottom up, middle managers, who traditionally disseminate information from the top down, either may be less in demand or they may find that their roles change as the use of telecommuting increases (for example, Long, 1987; Roach, 1993; and Zemke, 1987). Managers' or supervisors' abilities to check on employees who are working at home, particularly when work schedules do not conform with office schedules, may be more limited than in an office setting.

Links between job classification and telecommuting may appear primarily as equity issues. One example concerns which categories of workers—based on job class, job description, and personality characteristics—are deemed good candidates for telecommuting. It is important to understand that much work does not lend itself to telecommuting. The DOT study (1993) suggested that 45 percent of the U.S. work force potentially could telecommute at least part time, and a Dutch study suggested that 37 percent of all jobs in The Netherlands could be performed through telecommuting for at least 20 percent of working hours (Weijers, Meijer, and Spoelman, 1992). As the economy continues its relative shift toward services and information, the fraction of work that potentially could lend itself to telecommuting is projected to increase (DOT, 1993), but it is likely that much work will never lend itself to telecommuting.

Some research suggests that benefits such as working at home with less direct supervision and fewer interruptions than at the office, as well as being able to tailor work schedules to account for individual energy levels, to prepare children for school, or to run midday errands, also are distributed differently through the workforce. The benefits appear to be greater for professionals (who, in early studies of telecommuters, tended to be male) than for clerical workers (who have tended to be working mothers), where the perceived solution to conflict between child care and employment may be illusory (Risman and Tomaskovic-Devey, 1989).

Corporate attitudes toward and reasons for telecommuting also can affect the distribution of effects in the workplace. A recent study (Tomaskovic-Devey and Risman, 1993) indicates that employers view telecommuting by their professional workers differently than they view telecommuting by their clerical workers. Professional telecommuting tends to be viewed as a reorganization of work that allows additional flexibility and an increase in the capacity for uninterrupted work, thereby improving productivity. In these circumstances, telecommuting becomes a way of motivating and retaining staff who are relatively skilled and already relatively autonomous. Clerical telecommuting tends to be viewed as an option for reducing costs, often using subcontract work or piece-rate work done totally at home, and often with loss of benefits packages. The study found that fear of reduced management control was more likely to hinder clerical than professional telecommuting; this differentiation was attributed to the high degree of autonomy already extant among the professional staff. Although the study did not specifically discuss making telecommuting a condition of employment, the researchers' review of previous work and their findings imply that this would occur for clerical and not professional work. Although Tomaskovic-Devey and Risman did not specifically discuss gender in the two work forces in this study, their earlier work implies that clerical telecommuters have tended to be working mothers with young children and professional telecommuters have tended to be male (Risman and Tomaskovic-Devey, 1989).

These authors also found that managers tend to view either professional or clerical work as suitable for telecommuting; only a quarter of their sample considered both types of work suitable (Tomaskovic-Devey and Risman, 1993). Managers who thought that telecommuting might improve the quality of worklife generally favored professional telecommuting work options and opposed clerical ones. Professional telecommuting also was endorsed by managers who believed that telecommuting would increase productivity. Managers who believed that telecommuting would reduce labor costs (but not necessarily other costs) were much more likely than others to favor clerical telecommuting. Most of the managers surveyed worked for companies that had not yet allowed telecommuting but were aware of it as a potential option.

Other Issues

From an employer's perspective, telecommuting is an option that can be used to recruit or retain valuable employees. Telecommuting also enables an employer to draw upon a labor pool that, because of location, nonwork responsibilities, disability, or limited access to transportation, may not be available otherwise. The cost of this labor may be lower than in the employer's nearby labor market.

Telecommuting also equips employers with additional options to improve staff productivity and, perhaps, to reduce costs. Employees who telecommute full time do not require expenditures for office space, parking, and perhaps other services. Telecommuting can enable reductions in expenses if employees who telecommute part time can coordinate schedules and share office space on days when they do not telecommute.

Telecommuting provides opportunities for certain categories of employees to work productively when they would not be able to do so at the office. For instance, people with permanent or temporary disabilities may reduce or eliminate commuting travel and its associated personal costs in time and inconvenience. (At the same time, some of these workers, particularly those with permanent disabilities, may be deprived of the esprit de corps, face-to-face interaction, and other social benefits derived from working in an office setting.) It also is possible that, for people who find commuting travel not just a cost but a real barrier, telecommuting may increase the chance of finding and holding satisfying jobs. However, if these employees are responsible for purchasing or maintaining the necessary equipment, this option may not be realistic.

Implications for the Individual

Perhaps the most universal effect of telecommuting on individuals is increased time efficiency: the individual telecommuter may be able to work more efficiently at home, save time that would otherwise be spent driving to and from an office, and have more (and possibly more flexible) time to spend on personal or family matters. In the workplace, increased time efficiency may be deemed beneficial by workers, their supervisors, and corporate executives. However, rather than reducing the workload, increased time efficiency may have exactly the opposite effect. Workers and their managers may set higher daily productivity goals (sometimes with a diminished work force), potentially with the effect of increasing rather than decreasing the stress associated with pressures to accomplish tasks. In addition, people in the United States are working more hours now than they were in the 1950s and 1960s (Schor, 1991), and widespread adoption of telecommuting may amplify that trend, suggesting that the pressures of work could increase even more. It is worth noting that telecommuting may enable more of these additional work hours to be spent at home instead of in an office.

The degree to which individuals are affected positively or negatively by telecommuting may depend on the choices they make in adopting that practice. For instance, the ability to telecommute is affected by geography. The locations of telecommuting centers, the availability of public transportation to them, and the ease of personal transportation to them influence the degree to which the telecommuting centers truly are accessible. Geography may play an important role in urbanized areas (especially in terms of public transportation options) as well as in suburban and rural locales. For example, the usage of urban and suburban telecommuting centers may be affected by their relationship with popular transit modes and stops as well as the location's reputation for safety. Similarly, in rural environments, telecommuting centers may not be viable because they may be impossible to site in a location that would be convenient for many people to use.

Further, whether telecommuting is an employee's or employer's choice influences its effects on individuals:

- Employers considering allowing voluntary telecommuting have a number of concerns, including potential disruption of work schedules, difficulty in supervising and managing work being performed offsite, possible reductions in computer or other information security, and needs to change organizational culture to make voluntary telecommuting successful. Thus employers may not allow telecommuting, limit which of their employees may telecommute (Tomaskovic-Devey and Risman, 1993), or place restrictions on employee activity during telecommuting days (for example, requiring employee presence during specified hours, or requiring employees to check in at specified intervals).
- Employees considering voluntary telecommuting also have a number of concerns, including reduced contact (in person, and not through camera lenses) with coworkers or with office politics, reduced visibility and opportunity while telecommuting, less access to business support services, the possibility of overworking while telecommuting, the need for the discipline of an office environment, and a blurring of boundaries between work and home life. In addition, an employer who restricts employee activity during telecommuting days may create additional concerns or make telecommuting unattractive. Thus some employees who are offered the opportunity to telecommute may not do so.
- An employer who makes telecommuting a condition of employment for some or all employees is more likely to be motivated by controlling costs than by attracting and retaining workers. Therefore, that employer may be more likely than others to restrict the telecommuting employee's flexibility to ensure that the anticipated savings are realized.

It is possible that distinctive classes of workers develop: the privileged class, which may choose to telecommute; the class that must telecommute as a condition of employment; and the class that has no option to telecommute. This tiered system could amplify class-related rifts in the workplace and in society generally.

The issue of workplace surveillance already has received public attention (for example, Lacayo, 1991; and Schwartz and Galen, 1992). For example, supervisors reportedly eavesdrop on randomly selected telephone company employees to ensure that operators perform their jobs well and courteously. Employers also may count automatically the number of keystrokes certain employees make in a particular period of time. Telecommuting, and telecommunications in general, raise broad issues of concern with regard to workplace surveillance. First, growing technological sophistication may enhance the ability of employers to "watch" their employees in increasingly unobtrusive ways (whether the employers overtly or covertly undertake surveillance), potentially creating and perpetuating mutual feelings of suspicion and mistrust in the workplace. Second, these surveillance techniques may invade the homes of telecommuters, potentially raising legal, political, and social questions. Related to the second point is the possibility that employers may expect—and verify through surveillance—telecommuters to achieve higher productivity levels than office workers who perform the same jobs.

Another privacy issue involves information. Telecommunications technologies amplify existing issues pertaining to the privacy of information. Enormous amounts of personal data are collected and stored on a wide variety of data bases (for example, census, health, and health insurance information). Questions arise regarding who has access to those data bases (for example, organizations, such as government agencies and individuals within those organizations who may use those data from their homes or other locations), the measures that can and should be implemented to protect individual privacy, and whether there are situations in which individual privacy is secondary to a potential benefit to a group of individuals. For telecommuters, perhaps the major issues involve the ability to access such data bases from their homes and the safeguards that will be implemented to ensure the privacy of that information.

While telecommuting may decrease individuals' privacy in some ways, it also may enhance privacy in others. Telecommuters who are able to work from home are likely to encounter many more opportunities for privacy than are their coworkers at the office.

Implications for Family Interactions

If telecommuting truly becomes widespread, it may alter the nature of homelife and worklife throughout the Nation by blurring the distinction between homelife and worklife. This shift could have both positive and negative consequences.

By providing workers with flexibility in scheduling activities and in choosing where to do them, telecommuting enables parents to be present while their children are at home, or relatives to be present while infirm family members are at home. If a family member requires some form of active care, caregiving could conflict with work. This conflict could reduce the attractiveness of telecommuting to employers, if not to employees. However, where the employees' presence, rather than active care, is all that is required, telecommuting may permit some families to reduce their needs for child care or nursing care outside of the home. It nevertheless is possible that even the presence of a spouse, elderly parent, or child who needs no active care may inhibit an employee's ability to work effectively.

Telecommuting also may alter relationships among family members. For example, Kelly and Gordon (1986) suggest three potential scenarios when both spouses work at home. They suggest that good relationships will improve; weak relationships could be stressed, perhaps to the breaking point; and borderline relationships could experience either result. However, empirical data (especially long-term data) to support these hypotheses are lacking.

Implications for the Neighborhood and Community

Telecommuting is touted as a mechanism for enhancing neighborhood and community spirit and safety because it allows adults to be present in neighborhoods and communities during the day. As an example, telecommuters may be able to participate in neighborhood and community activities or events in which, as full-time office workers, they previously were unable to participate. Working parents of "latchkey" children may gain a sense of ease and security knowing that one or more neighbors are available for their children to call on in an emergency. Neighborhood security also may increase when more adults are present. At the same time, the diversions or conditions of the home work environment (for example, visiting children, neighborhood noise, a lack of neighborhood security) may prevent telecommuting employees from working effectively.

The potential benefits of telecommuting for neighborhoods and communities may not be realized; they almost certainly will not be experienced consistently or uniformly. Two major factors constitute barriers to the full realization of neighborhood and community benefits. First, many telecommuters work at home part time. The variability and possible uncertainty associated with the schedules that part time telecommuters may keep likely will diminish the value—particularly in terms of reliability—of having more adults at home in a neighborhood. Second, the total number of telecommuters may not constitute the critical mass necessary for providing neighborhood benefits, especially in certain communities. Communities inhabited largely by blue-collar, production workers are unlikely to be filled with many telecommuters. Similarly, there may be an urban-suburban differentiation of telecommuting patterns. There have been attempts to use telecommuting centers as sources of renewal and economic development for inner cities and rural areas (DOT, 1993).

Telecommuting could have a significant effect on land-use patterns, potentially contributing to urban sprawl (DOT, 1993; also Chapter 1 of this report). The effects on sprawl may depend on the form of telecommuting. Part-time telecommuting may support a continuing trend for people to move farther out into rural areas and press for transportation infrastructure improvements, which are a major contributor to sprawl. If telecommuting is a full-time activity, engaged in primarily through satellite centers, the transportation infrastructure in rural areas is likely to remain unchanged and the rural areas therefore may remain unattractive to commuters (Nilles, 1991).

At the neighborhood level, the various forms of telecommuting could have diverse effects. Full-time telecommuting centers are likely to encourage the development of stores and services to support the centers and their employees (DOT, 1993). This development goal is key to some telecommuting centers that have been started to help rejuvenate inner city neighborhoods. The success of this policy is dependent on other variables, such as the perceived safety of the neighborhood, accessibility to the center, and existing services and stores. These variables may influence private companies seeking to site telecommuting centers to deem small cities more attractive than large cities, thereby placing the burden of establishing inner city telecommuting centers on the public sector. Consequently, inner cities may lose the opportunity to create jobs and increase the tax base via telecommuting centers, and many small cities may not be prepared to handle the resultant growth caused by the centers (DOT, 1993).

Conclusion

Social issues related to telecommuting that may become particularly important are separation between home and work, increasing fractionalization of the workforce and society at large, and changes in neighborhood and community interactions. Telecommuting from home blurs existing boundaries between home and work. Employees' abilities to separate (or escape) from their work and employers' abilities to invade their employees' homes may change the nature of home and work lives. Within the workplace, three major classes of personnel may develop: those who voluntarily telecommute and derive the benefits of autonomy, flexibility, and freedom from interruptions; those for whom telecommuting is required and who may not experience the advantages of the privileged class of telecommuters or have access to the benefit packages associated with long-term employment in an office setting; and those for whom telecommuting is not an option. This three-tiered system may amplify existing rifts among categories of personnel in the workplace and among social classes. If telecommuting proceeds at its current, relatively low level, it may not have major consequences for many neighborhoods or communities, because there may not be a critical mass of telecommuters to effect changes. However, widespread telecommuting may enhance the safety and spirit of neighborhood and community life. These effects may not be distributed consistently throughout a region or the country, because the varying composition of communities may be associated with different levels of telecommuting. Finally, widespread telecommuting may change patterns of residential and commercial development, in part because geographic proximity of the workplace to the labor force would diminish in importance. Large office buildings also may tend toward obsolescence.

3. TELECOMMUNICATIONS AND TRANSPORTATION

Introduction

As discussed in Chapter 1, telecommuting reduces transportation use and thus reduces some of the social costs of travel. These costs include traffic congestion, time lost in congested traffic, emissions that degrade air quality and may contribute to climate change, the risks of dependence on imported fuels, and the death, injuries, and property damage that result from traffic accidents. Other methods exist for reducing these costs, including improving vehicle fuel economy, switching to nonpetroleum fuels, using more effective vehicle emission control technologies, adding safety features to vehicles, and encouraging people to use public transportation or to travel at less congested times. However, each of these methods has obvious costs as well as benefits. Telecommuting presents a particularly attractive option for reducing some of these costs because it allows some commuters to avoid rush-hour traffic and may improve work conditions or productivity at little or no additional cost (as discussed in Chapter 2). People whose work would permit telecommuting might voluntarily forgo some work trips without additional incentives, thereby providing a low-cost option for commuters and metropolitan areas to ameliorate serious problems.

The benefits and costs, actual as well as potential, of telecommuting have obviously depended on advances in telecommunications. However, as discussed in this chapter, telecommunications has broader relationships with transportation and effects on transportation that go beyond those of telecommuting. In many cases (such as telecommuting), the dominant effect of telecommunications is to substitute for transportation, and thus provide reductions in travel, energy use, and emissions. In other cases, telecommunications and transportation act as complements, with an increase in the use of one leading to an increase in the use of the other. In still other cases, there is no direct relationship between telecommunications and transportation; telecommunications enables new activities to occur, or it enables lower costs, higher efficiency, or better performance of existing activities. In its enabling role, telecommunications tends to increase economic growth, which tends to increase the amount of travel over the long term, all else being equal.

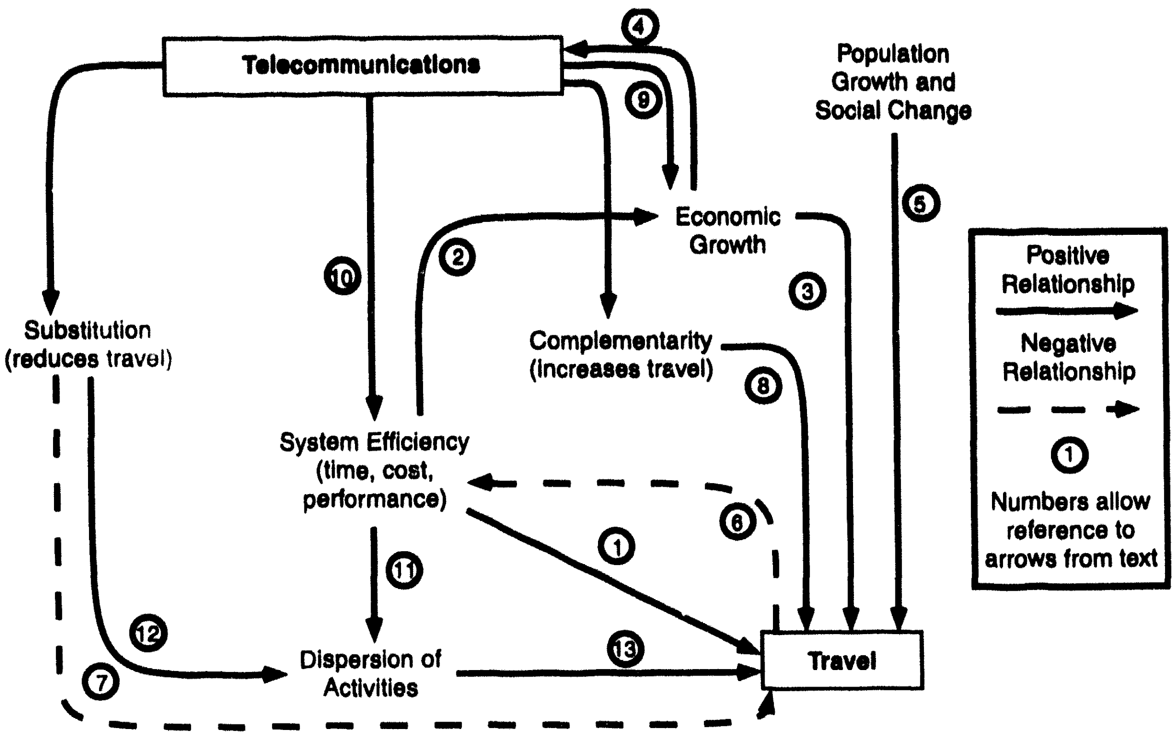
Recently, there has been much discussion within the Federal Government and among the public about making major improvements in the Nation's telecommunications infrastructure, in part to provide additional opportunities for telecommuting (National Telecommunications and Information Administration, 1993). This discussion has been couched primarily in terms of developments such as a national information infrastructure—an information superhighway that would connect all residences and offices in the Nation. Such developments would make existing telecommunications services available to more people, make other services less expensive, allow demonstrated technologies to perform more effectively, and encourage the development of new services and technologies. It is likely that these changes would increase the use of telecommunications not just for telecommuting but for other activities such as education, shopping, medical care, and recreation. For this reason, it is worth examining whether such investments might have effects not just on telecommuting, but on transportation generally.

This chapter examines in a qualitative manner the various relationships between telecommunications and transportation—for both passenger travel and freight travel—and then assesses some of their implications for the effects of an information superhighway. The relationships are complex, and data to analyze them are currently limited—as well as difficult and expensive to collect. Furthermore, telecommunications technologies are changing so rapidly that individuals and organizations often are still adjusting to an existing (but recently introduced) technology even as they adopt a new one. For these reasons, a quantitative analysis of the relationships is extremely difficult. This chapter provides an overview of relationships that might be quantified in the future.

Telecommunications and Passenger Travel

Transportation System Efficiency and Economic Growth

Figure 3–1 illustrates relationships between telecommunications and passenger vehicle travel. These relationships operate through telecommunications' direct effects on the demand for travel and its indirect effects on the efficiency, cost, and performance of the transportation system. Compared with telecommuting, which primarily affects commuting travel, telecommunications as a whole effects the entire transportation system, including virtually all travel, at all locations and times of day.



Note: Solid arrows in the figure indicate positive relationships between the variables that they link—that is, an increase in the variable at the tail of the arrow is linked to an increase in the variable at the arrow's head, and a decrease in one to a decrease in the other. Dashed arrows indicate negative relationships—an increase in the variable at the tail of the arrow is linked to a decrease in the variable at the arrow's head, and vice versa.

Figure 3–1. Relationships Between Telecommunications and Passenger Vehicle Travel

Travelers differ in the emphases they place on the various elements of system efficiency, but for most people the time required to travel is most important, followed by the cost of making a trip (Greene, 1992). All else being equal, traffic congestion reduces system efficiency by increasing the amount of time required for a trip. An increase in travel time becomes a cost increase when people or employers place value on travelers' time. Traffic congestion also reduces vehicle operating efficiency, which increases fuel consumption and cost, as well as wear and tear on the vehicle. Increases in fuel cost, vehicle cost, transit fares, and highway tolls also increase the cost of the transportation system and can do so independently of congestion.

A decrease in transportation system efficiency (or an increase in cost with no change in efficiency) tends to discourage travel (Figure 3–1, arrow 1). Some users may decide to forgo some activities that require trips, or take shorter trips, or seek other ways of interacting. People may choose to shop at nearer locations, visit friends less frequently, seek an apartment closer to where they work, or telecommute. If people are required to continue with one activity, such as commuting, despite its increased time or cost, they may reduce the time they spend on other activities that require travel. Or they may reduce the cost or time of other travel by combining trips, changing routes, or switching to other transportation modes, depending upon the options available and the manner in which the transportation system efficiency decreased.

By the same token, an increase in system efficiency tends to make travel more attractive than before, whether caused by lower fuel costs, improved vehicle efficiency, or reduced congestion. People may decide to engage in more activities that require trips, they may be willing to take longer trips for their current activities, or they may be willing to make trips more frequently (Figure 3–1, arrow 1). In addition, an increase in transportation system efficiency is equivalent to a decrease in the total cost of travel (including time and monetary costs). This decrease tends to stimulate economic growth by allowing the savings in travel costs to be used in other activities (arrow 2).

Transportation system efficiency is determined by a variety of factors in addition to telecommunications (telecommunications impacts on system efficiency are discussed below). Investments in system infrastructure, vehicles, and fuel supplies improve system efficiency, encourage more travel, and make it possible to meet additional demand. The workings of markets and public policies also affect transportation system efficiency by affecting the cost of travel, the supply and cost of vehicles and fuels, and the amount and type of investment made in infrastructure.

Economic growth tends to increase the aggregate demand for both travel (Figure 3–1, arrow 3) and telecommunications (arrow 4). Growth tends to create new activities that require transportation for access, as well as additional demand for telecommunications. Population growth tends to increase the aggregate demand for travel and telecommunications, as do some social changes, such as the increasing percentage of married women who are employed (arrow 5). Together, these are strong forces for increasing the amount of travel. Between 1970 and 1990, automobile transportation, measured by vehicle-miles traveled (VMT), grew at an average annual rate of 2.6 percent. Between 1982 and 1990, this average annual growth rate increased to 3.3 percent (Davis and Strang, 1993).

When an increase in travel creates congestion or makes congestion worse, it degrades system efficiency (Figure 3–1, arrow 6). Not only does congestion exist in most major metropolitan areas in the United States, but as discussed in Chapter 1, the average investment in additional transportation infrastructure needed to maintain present levels of congestion, especially in urban areas, is not keeping pace with the demand for travel (Shrank, Turner, and Lomax, 1993). Thus, congestion is increasing.

Potential Substitution of Communications for Travel

People substitute telecommunications for travel when they find it more convenient or less expensive in terms of time or money. Because commuting tends to be concentrated during periods of peak traffic congestion, the potential to save time and reduce stress is one motivation for employees to telecommute. Similarly, as traffic congestion increases at major shopping centers, shopping in person becomes less attractive and ordering merchandise by phone or from catalogs becomes more attractive. When people exercise these options to substitute telecommunications for travel, they eliminate trips (Figure 3–1, arrow 7), which (considering this activity in isolation) results in fewer cars being on the road during peak periods, less congestion, less fuel being burned, fewer emissions, and potentially fewer accidents.

In some cases, telecommunications does not eliminate a trip but, instead, shortens it. For example, as discussed in Chapter 1, there have been some efforts to develop regional telecommuting centers that allow employees to commute to a suburban location and telecommute from there to their main office (DOT, 1993). Telecommunications also permits such services as branch banking and automatic teller machines, which allow depositors to use banking services without making a trip to the central office. Again, all else being equal, less fuel is burned, there are fewer emissions, and probably fewer accidents occur. Because trips are not eliminated, the effect on congestion of substituting for only part of a trip is uncertain, though it probably reduces congestion. However, substitution for only part of a trip does not eliminate the short periods of high emissions that result from the cold start of an automobile engine with or without emission controls.

Some telecommunications substitutions for travel do not involve conscious individual choice between the two options. For example, when people choose electronic depositing of paychecks or government benefit checks, the transactions occur automatically. People may still make trips to the bank to receive cash on days when the deposits are made, but they no longer have to make trips for the sole purpose of making the deposit, so some trips are eliminated. Again, there is less driving during afternoon peak travel periods, less fuel burned, reduced emissions, and probably fewer accidents (Figure 3–1, arrow 7).

When telecommunications replaces travel, it reduces the time and cost required for a business or household to engage in its present set of activities. The time and money released by the substitution become available for other activities, some of which may involve travel that offsets the reduction from substitution. In effect, the reduced cost of transportation is an improvement in system efficiency (Figure 3–1, arrow 6) that permits economic growth (arrow 2) which increases travel (arrow 3). However, unless all of the newly available time and resources are used in travel, which is unlikely, the net effect of substitution should be to reduce travel (arrow 7).

Potential Complementarity

Some uses of telecommunications increase the use of transportation, either directly or indirectly, in what economists call a complementary relationship (Salomon, 1986). The general concept of complementarity is the notion that an improvement in telecommunications leads to more long-distance interaction and to more people becoming more familiar with more activities at more locations, increasing the prospects that people eventually will follow up some of their contacts with trips. Alternatively, people meet once face-to-face, use telecommunications to develop and maintain a relationship, and at some future time travel for another face-to-face meeting; had the relationship not been maintained, the trip for the second meeting would not have occurred. In other words, telecommunications encourages long-distance relationships, which may involve greater travel to maintain than short-distance relationships. This is apart from the effects of increased numbers of relationships allowed by telecommunications, which falls into the category of increased economic activity.

Complementarity increases the demand for travel (Figure 3–1, arrow 8). All else being equal, this increase tends to degrade system efficiency (arrow 6).

Telecommunications as Enabling Technology

Often a firm or household adopts a telecommunications technology for reasons that have nothing to do with transportation. For example, background examinations of different sectors of the economy conducted as part of this study (Hillsman and Cowell, 1993; Tom Lehman and Associates, 1993; Research and Planning, Inc., 1993; and Dunau Associates, 1993) found that organizations often adopt telecommunications to improve the quality of service they provide their customers, to reduce the cost of activities, or to make themselves more effective. This type of re-engineering of an organization's activities to improve productivity, customer service, or cost of service appears to be a major reason for adopting telecommunications technologies (Davenport, 1993). By making more efficient use of resources, the introduction of telecommunications into different activities contributes to economic growth (Figure 3–1, arrow 9), which in turn increases the demand for travel (arrow 3).

Telecommunications is not a perfect substitute for travel. The experience of "being there" differs from the experience of interacting via telecommunications, and many activities require at least some amount of physical interaction or face-to-face contact to be successful. The cost of transportation can be sufficiently high that it prevents some activities from occurring. When an improvement in telecommunications technology allows telecommunications to substitute for enough transportation that these activities become possible (but not for all of the transportation), then the increased use of telecommunications leads to an increase in economic activity (Figure 3–1, arrow 9) and to an increase in travel (arrow 3).

Once telecommunications technologies are in place for one purpose, they become available for other purposes, including those that involve transportation. Thus, when a government agency or private firm re-engineers document flow using telecommunications within the office, it makes documents available in electronic form. Employees then can work with the documents in that form while telecommuting if they have the necessary equipment at home, even though the decision to re-engineer document flow may not have considered this possibility.

Potential for Transportation System Efficiency Improvements and Feedback Effects

An improvement in telecommunications technology can have several effects on transportation system efficiency. The most direct of these involves the application of telecommunications technology to improve the system's performance (Figure 3–1, arrow 10). Synchronization of traffic control signals, timing of vehicle entrances onto freeways, and use of reverse-lane signals all apply telecommunications to improve traffic flow and reduce travel time, though the technical sophistication and effectiveness of these applications varies widely. The Intelligent Vehicle-Highway Systems (IVHS) initiative is intended to develop and use other telecommunications technologies to further improve transportation system efficiency (IVHS America, 1992); these include such applications as electronic collection of tolls, which is intended to reduce delays at toll plazas, and real-time monitoring of traffic flows to allow real-time adjustments to traffic-control systems. In addition, some people consider the increased use of microelectronics to improve vehicle and engine performance as an application of telecommunications to improve transportation system efficiency (Salomon, 1986). All else being equal, these applications of telecommunications should reduce delay and thereby improve transportation system performance.

Individuals also can use telecommunications to improve system efficiency from their own perspective, if not that of the system as a whole. Telephoning a store to make sure that it is open or that a product is in stock can save an unnecessary trip, as can calling a friend or an office before paying a visit. Individuals who listen to radio traffic reports at home or in their vehicles can modify their travel behavior to avoid congested areas or allow additional time for a trip. Again, some IVHS technologies are intended to improve the information available to drivers and make it easier for drivers to use it.

Telecommunications also has indirect effects on system efficiency, resulting from its effects on travel. When there are congested periods on the system, reducing travel during these periods (Figure 3–1, arrow 7) reduces delays and the resulting cost of lost time, thereby improving system efficiency (arrow 6). Thus, telecommuting would reduce travel and improve system efficiency if nothing else changed. However, as discussed in Chapter 1, if there is latent demand for transportation (demand that is not now being met because of poor system performance, usually congestion), then a reduction in travel that improves system performance might make it possible to meet some of that latent demand. Travel would increase (arrow 1) and system performance would degrade (arrow 6), but would probably still be improved over what existed before the initial substitution of telecommunications for travel.

Similarly, the complementarity and enabling relationships between telecommunications and travel can increase the amount of travel (Figure 3–1, arrows 9, 3, and 8). If these increases occur during congested periods, they will degrade system performance (arrow 6). This degraded performance should reduce some of the travel increase brought about by the telecommunications, as well as other travel; this, again, is reflected in arrow 1. If there is no congestion, or if the increase in transportation occurs during uncongested periods, then increased travel would have no significant positive or negative effect on system efficiency, and arrow 6 would not apply.

Effects of Transportation System Efficiency and Telecommunications on Urban Expansion and Travel

In the long run, the substitution of telecommunications for transportation may increase the geographic dispersion of activities (the urban-sprawl effect discussed in Chapter 1) within a region (Figure 3–1, arrow 12). When telecommunications reduces the number of trips required for an activity (as in telecommuting), or reduces the length of trips required, it reduces the cost of interaction between individuals and activities located at one place and those located at another. In other words, substitution acts as an improvement in transportation system efficiency. If nothing else changes, then the reduced cost of interaction would enable the activities to be located farther apart and interact as before. Although activities relocate for a variety of reasons (many of which have nothing to do with transportation system efficiency), a more efficient transportation system allows them to consider sites that are farther away than they would have considered with a less efficient system. Over time, reductions in traffic congestion, lower fuel costs, or lower driving costs all should tend to encourage greater dispersion of activities and households within a region (arrow 11) (Hu and Young, 1992; Pisarski, 1992; Giuliano, 1989).

As activities become more dispersed, the amount of travel required to conduct them as before increases (Figure 3–1, arrow 13). These longer trips are now easier to make or less costly than before because of the improved system efficiency. For example, while average commuting distance in the United

States between 1983 and 1990 increased from 8.54 to 10.65 miles—a 25-percent increase—the average commuting time increased only from 18.20 to 19.65 minutes—an 8-percent increase. This was a result of an increase in average commuting speed from 28.15 to 33.34 miles per hour, which offset much of the additional distance (Hu and Young, 1992). Newman and Kenworthy (1988; 1989) analyzed 32 cities worldwide, including 10 in the United States, and found decreased traffic congestion and higher travel speeds to be strongly associated with longer trips, increased travel, and higher energy consumption. Over time, increases in population and economic growth can lead to increased travel in areas where activities have dispersed (arrows 3 and 5), increasing congestion and the cost of the longer trips—and thus countering the efficiency gains that helped spur the geographic expansion (arrow 6).

Summary and Observations

The overall pattern of interactions described above is complex and contains both positive and negative feedback loops. The most important relationships are as follows:

- There are strong forces leading to increases in both travel and telecommunications. With expansion of transportation capacity lagging behind the increased demand for travel, traffic congestion is increasing.
- An improvement in transportation system efficiency makes travel more attractive, but additional travel offsets some of the improvement in system efficiency. A reduction in system transportation system efficiency, in turn, makes travel less attractive.
- Telecommunications can substitute for travel, but can also stimulate additional travel. Telecommunications can be applied directly to transportation systems to improve their efficiency, which would stimulate travel. Whether the net effect of increasing telecommunications use is to reduce or to increase travel from what it otherwise would be is case-specific, and effects cannot be generalized at present.
- Reductions in the cost of interaction, whether through improvements in transportation system efficiency or through the substitution of telecommunications for part of the travel required, create opportunities for activities to disperse. Over time, if these reductions persist, some of these opportunities are realized. When realized, they tend to increase some demands for travel

and reduce others, with the net effect probably being a small increase in travel.

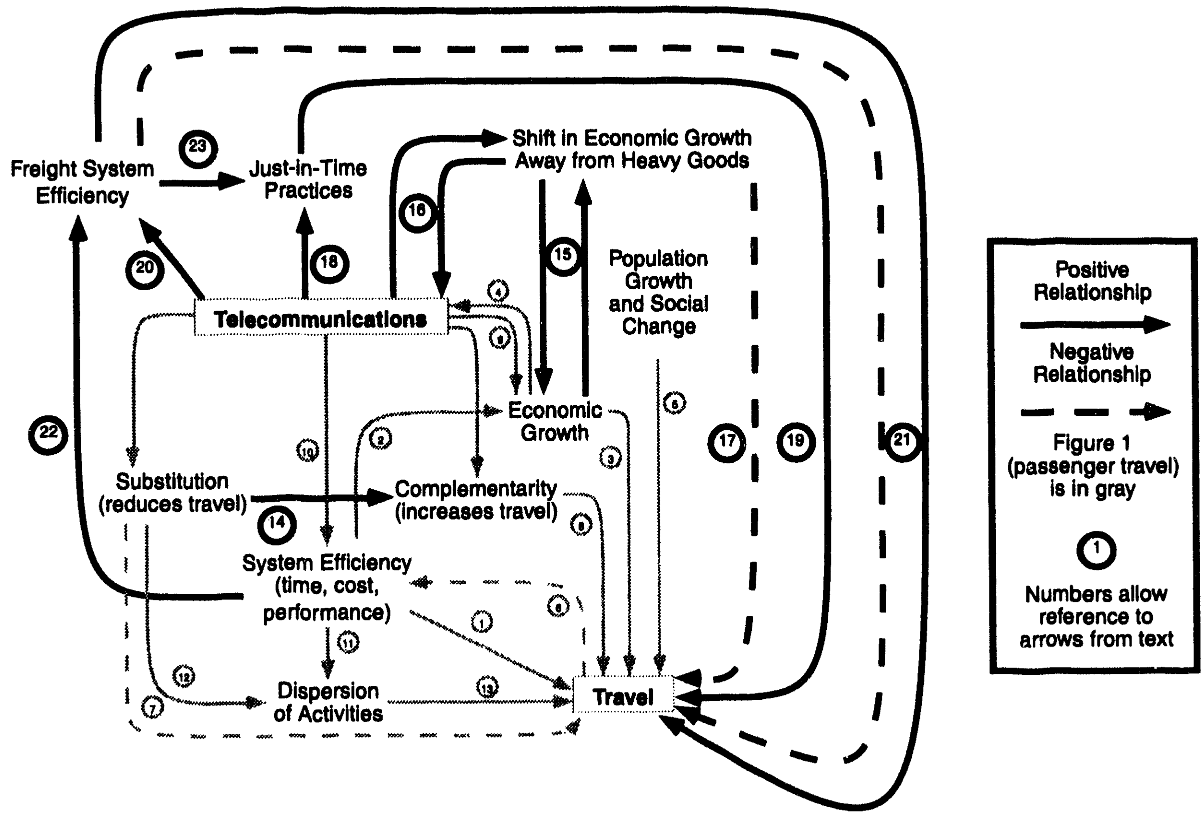
- Many of the paths by which telecommunications increase travel are through their effect on economic growth. If one were to evaluate telecommunications impacts on travel after accounting for this growth, it appears likely that increased use of telecommunications yields net reductions (that is, reductions in the travel intensity of economic activity).

The uncertain effect of telecommunications on travel does not mean that carefully targeted applications of telecommunications to reduce travel or to improve system efficiency cannot be effective, especially in the short term. It does mean that these efforts must be considered carefully, and their short-term results interpreted carefully.

In light of the foregoing, any policy efforts to promote adoption of telecommunications technologies in order to reduce travel should also consider measures that complement this "carrot" (in providing alternatives to travel) with "sticks" to discourage travel, especially relatively low-value travel. Such measures include a variety of approaches to charging travelers the full social costs of their travel, such as by pricing fuel, emissions, or the travel itself (for example, through road pricing) accordingly (Schroeer and Kessler, 1993).

Telecommunications and Freight Transport

Many of the same transportation systems used to move passengers also move freight. Thus, the same processes portrayed in Figure 3–1 affect freight movements and the effect of telecommunications on freight transportation. However, there are additional relationships between freight and telecommunications, which Figure 3–2 depicts overlaid on the relationships shown in Figure 3–1. These additional relationships involve complementarity between telecommunications and some freight travel, anticipated structural shifts in the Nation's economic activity, increased adoption of new manufacturing and logistical strategies, and the potential for telecommunications to enhance freight system efficiency separately from overall system efficiency.



Note: Solid arrows in the figure indicate positive relationships between the variables that they link—that is, an increase in the variable at the tail of the arrow is linked to an increase in the variable at the arrow's head, and a decrease in one to a decrease in the other. Dashed arrows indicate negative relationships—an increase in the variable at the tail of the arrow is linked to a decrease in the variable at the arrow's head, and vice versa.

Figure 3–2. Relationships Between Telecommunications and Freight Vehicle Travel

Substitution and Complementarity Between Telecommunications and Freight

Although telecommunications offers opportunities to substitute for increased passenger travel, it offers few opportunities to substitute for freight. The primary area for substitution is in the transmission of information: information storage media (paper documents, diskettes, tapes) can be transported as freight; or the information can be transmitted using telecommunications technologies (facsimile, cable, broadcast), thereby eliminating freight. Because the amount of freight for which telecommunications can substitute appears to be a tiny fraction of the freight shipped in the United States, no attempt has been made to depict potential substitution of telecommunications for freight in Figure 3–2.

Some activities that substitute telecommunications for passenger travel can cause an increase in freight transportation. A person who purchases goods such as clothing at a store usually takes the purchase home in a car, transporting both persons and goods. If the same person purchases the same goods from a catalog by telephone, he or she has reduced personal travel, but the goods are delivered by mail or parcel carrier as freight. If the goods arrive by mail, it is likely that no additional travel was required, but if they arrive by private carrier, then it is likely to have generated some additional freight travel (Figure 3–2, arrow 14). However, when freight travel substitutes for passenger travel in this manner, it is unclear whether the combined impacts (on travel, energy use, and emissions) are positive or negative.

Relationships to Economic Structure and Output

Economic growth, population growth, and social change are powerful drivers for increasing freight travel, just as they are for passenger travel. As population grows and incomes increase, demand for goods and services also increases (Figures 3–1 and 3–2, arrows 3 and 5). As production increases, the amount of resources and products to be moved also increases (Figures 3–1 and 3–2, arrow 3). When individuals spend a larger share of their incomes and save less, current demand for goods and services also increases.

As the economy has grown, the shares of the economy that extract resources and manufacture goods have decreased, even though their absolute size has been increasing. In constant 1987 dollars, the U.S. gross domestic product (GDP) increased from $1.99 trillion to $4.86 trillion between 1960 and 1991; the amount of this attributable to goods increased from $1.0 trillion to $1.88 trillion, but decreased as a share of GDP from 50 percent to 39 percent (Department of Commerce, 1992). This shift has occurred for a number of reasons, including reductions in the energy and materials intensity of the economy, maturation of markets for many manufactured goods, and the emergence or rapid growth of activities that deliver products but do not manufacture them in the traditional sense. This last group of activities includes health services, education, much of the entertainment industry, and many business and financial services. As these shifts have occurred, growth in sectors such as services and information processing have become increasingly responsible for the Nation's economic growth. The two arrows labeled 15 in Figure 3–2 indicate the reinforcing relationship between economic growth and growth of these sectors.

Some of the enabling characteristics of telecommunications technologies discussed earlier under passenger travel have contributed to this shift, as organizations apply these technologies to improve service or productivity. At the same time, existing or anticipated demand for telecommunications services has stimulated technological and policy changes that, in turn, have reduced the cost of telecommunications and made their use more attractive in new applications. The two arrows labeled 16 in Figure 3–2 indicate the reinforcing relationship between telecommunications and the shift of the economy toward services and information.

Although agriculture, resource extraction, and manufacturing activities are larger than before and are generating more freight than before (Figure 3–2, arrow 3), the relative shift of the economy away from these activities and toward services means that relatively less freight is being moved now than would have been (Figure 3–2, arrow 17). All else being equal, this relative shift means that freight travel contributes less to congestion and other societal costs of transportation than it would have if the shift had not occurred. Advances in telecommunications can be expected to promote this shift.

Potential Effects on Industrial Operations

Historically, mass production systems of manufacturing have involved the production, storage, and delivery of materials, parts, and products in large quantities (Womack, Jones, and Roos, 1990). Large, infrequent bulk shipments have been well-suited to railroad and waterborne transportation, which were the dominant transportation modes when mass production began to develop in the early 1900s. A shipment of sheet steel would arrive at the factory of an automobile component manufacturer, be placed in inventory, and drawn down as production required. The shipment would be large enough to accommodate production until the next shipment. Similarly, the manufacturer would store the product until enough had been produced to ship to the factory engaged in the next step of the production process, where it would be stored again. Once the final product had been assembled, it would be stored until enough was ready for a large shipment to another region of the country. The high costs of holding inventory could be justified by the savings from shipping in bulk, the cost of changing production dies, and other characteristics of the production process (Womack, Jones, and Roos, 1990).

In response to some of the limitations of historical mass production philosophies, some Japanese automobile manufacturers developed alternative philosophies that, for a number of reasons, reduce the amount of materials, parts, and product held in inventory. One of the characteristics of these "lean" production systems is that they require supplies to be produced and delivered as needed, rather than produced ahead of time and stored either until needed or until low-cost transportation between suppliers and assemblers is available. Lean production systems view the buffer that inventories provide as both an added cost and a barrier to improving the quality and cost of the product.

Lean production involves much more than "just in time" delivery, including a high degree of coordination between suppliers and product assemblers. Much of this coordination requires changes in an organization's outlook and approach to problem-solving (Womack, Jones, and Roos, 1990). Frequent interaction between component supplier and final manufacturer is required to coordinate component design with product design and to solve problems relating both to design and manufacturing quality. Telecommunications technology might substitute for some of the necessary face-to-face interaction. The logistical coordination of production and delivery schedules, while probably simpler to manage than the coordination of design and quality, also requires increased use of telecommunications as an enabling technology (Figure 3–2, arrow 18). The need for parts may be monitored electronically, the order placed electronically, the shipment of parts from supplier scheduled and dispatched electronically to the precise workstations where needed, and the parts invoiced, inspected, accepted, and paid for electronically. At least one major retailing chain has adopted the same general approach to retailing, linking major suppliers of goods to point-of-sale terminals in its stores, allowing them to track sales, schedule production, and plan deliveries (*Forbes*, 1992a).

Shortening delivery cycles increases the number of freight trips and decreases the size of shipments. In the Japanese automobile industry, 52 percent of the suppliers to lean-production automobile assembly plants were delivering supplies daily in 1982, and an additional 31 percent were delivering hourly;

only 16 percent were delivering weekly (Womack, Jones, and Roos, 1990). By contrast, in the U.S. automobile industry in 1983, 70 percent of suppliers were delivering more than a week's supply of parts at once, a figure that had fallen to 20 percent by 1988; however, only 10 percent of U.S. suppliers were delivering on an hourly or daily basis by 1988. Although Womack, Jones, and Roos do not discuss the transportation requirements for such short cycle times, it is likely that many of the hourly and daily deliveries require the use of trucks rather than rail or barge. Thus, the number of highway trips would increase and, for the same locations of suppliers and assemblers, energy consumption would increase because of the higher energy consumption per ton-mile for trucks compared to rail or barge (Davis and Strang, 1993). Air shipments would involve even higher rates of energy consumption.

Although the larger land area and lower population density of the United States may make delivery cycles as short as those in Japan uneconomic, there is some scope for U.S. manufacturers to adopt lean production systems, and some have already begun to do so. Doing so would tend to increase freight vehicle travel (Figure 3–2, arrow 19) and degrade the performance of a congested transportation system (arrow 6 in Figures 3–1 and 3–2). In addition, holding the location of the suppliers and assemblers constant, the shift to more frequent delivery of parts by truck, or even by rail, is likely to increase the cost of making the deliveries.

Potential for Freight System Efficiency Improvements

Telecommunications has the potential to improve freight system efficiency (Figure 3–2, arrow 20), independent of its effect on overall transportation system efficiency (arrow 10 in Figures 3–1 and 3–2). Examples include the following:

- Planning, scheduling, and operating hub-and-spoke freight systems, which offer the potential to reduce freight system costs while improving service to customers. This coordination has been essential to the successful emergence and growth of the airborne package express industry since the late 1970s.
- Use of bar coding and global positioning systems to track individual vehicles or shipments. These and similar technologies allow shippers and freight carriers to monitor demand as packages are picked up and to reschedule delivery equipment if the incoming data indicate a need to do so.

- Onboard monitoring of engine performance and driver behavior. This allows carriers to detect and correct declines in vehicle performance or use that increase cost.
- Real-time dispatching and rerouting of vehicles that pick up or deliver freight, in response to changes in customer demand. This has the potential to improve customer service, reduce the need to dispatch additional vehicles, avoid delays resulting from traffic congestion, and notify system dispatchers when delays are unavoidable to reduce uncertainty about operations and delivery.
- Electronic maintenance and checking of vehicle and driver credentials and conditions. This has the potential to reduce delays at truck weigh stations or other inspection points, improve performance of tax-collection and permitting-enforcement systems, and allow the freight carrier to file paperwork electronically.
- Electronic data interchange. This provides the supplier or shipper with information about an order in standardized format that facilitates interaction with the freight carrier, as well as between freight carriers when a shipment requires more than one carrier (Kuby and Reid, 1992).

Many of these applications of telecommunication technology have been demonstrated successfully in existing freight systems. Others are in widespread but not universal use. The potential benefit of many of these applications is probably greater than their present use might suggest, because it takes time for firms to become familiar with a new technology and discover options that it might enable. The IVHS initiative includes developments and demonstrations of most of these applications (IVHS, 1992).

Improvements in freight system efficiency have several possible effects. Some of the applications of telecommunications listed above will reduce delays, redundant trips, or the number of vehicles required to provide a given level of service. In this case, freight traveling could remain the same but be delivered with less freight travel (Figure 3–2, dashed arrow 21). When there is congestion but no significant compensating latent demand, this reduction in freight travel would improve transportation system efficiency (Figures 3–1 and 3–2, arrow 6), and further improve freight system efficiency (Figure 3–2, arrow 22). As with passenger travel, the improvement in transportation system efficiency also would induce additional travel for both freight and passengers (Figures 3–1 and 3–2, arrow 1); latent demand would offset some of the improvement in transportation system efficiency, though probably not all of the improvement in freight system efficiency.

An improvement in freight system efficiency that lowers costs and, especially, improves reliability would make just-in-time delivery practices more attractive to potential shippers. The use of such practices would increase (Figure 3–2, arrow 23) as would the amount of freight travel (arrow 18). Improvements in freight system efficiency also could induce additional freight travel, either directly, as illustrated by the emergence of air package express services (solid arrow 21), or indirectly, by reducing the cost of interaction and allowing activities that ship freight to be farther apart than they are now (dashed arrow 21 and arrows 6, 11, and 13). In both cases, the amount of freight shipped might remain the same, but the amount of freight travel would increase. The improvements in freight and general transportation system efficiency would contribute to economic growth (Figures 3–1 and 3–2, arrow 2).

Effects on the Geographic Location of Extraction, Processing, and Manufacturing

As noted earlier, a switch to just-in-time practices tends to increase the number of trips required for supplying a processing or manufacturing plant, to shift many of these from rail or barge transportation to highways, and to increase the cost of transportation both because of the mode shift and the increase in frequency. The increase in cost would give the suppliers incentive to relocate production to be nearer the assemblers (Figures 3–1 and 3–2, arrow 12), and it has been argued that effective just-in-time manufacturing requires close proximity of suppliers and manufacturers (Kenny and Florida, 1992). Such relocation would reduce dispersion of activities and travel (Figure 3–1, arrow 11), and it would offset some of the effects of shifting modes and increasing the numbers of shipments.

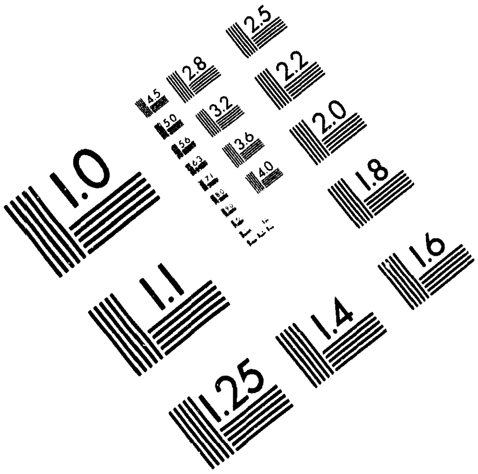
Over time, as growth in population and the economy increase the amount of passenger and freight travel, and as investments to maintain present transportation efficiency lag behind these increases, traffic congestion is likely to increase, and freight system efficiency is likely to decline. This would tend to reduce the attractiveness of just-in-time practices (Figure 3–2, arrow 23) and forestall some of the increase in freight travel that might result if they were adopted more widely. The more general deterioration in system efficiency, however, is likely to increase the collocation of activities within urban areas (Figures 3–1 and 3–2, arrow 10).

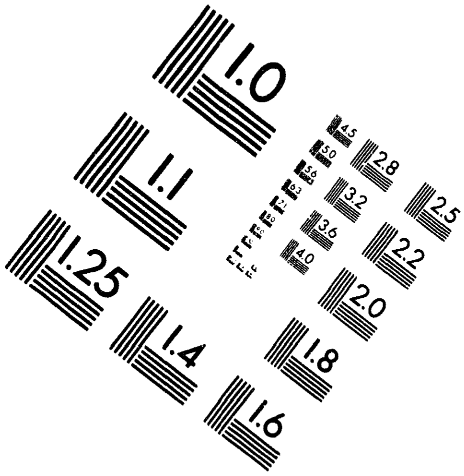
Although telecommunications offers opportunities to improve freight system efficiency independently of transportation system efficiency, as described earlier (Figure 3–2, arrow 23), the long-term potential for these improvements to offset decreasing performance of the general transportation system seems questionable. VMT for combination (heavy) trucks is only 6.3 percent of that for automobiles and only 4.5 percent of total VMT (Davis and Strang, 1993). Moreover, although truck VMT is increasing faster than total VMT, a disproportionate share of truck VMT occurs outside of urban areas. Even large improvements in freight system efficiency may be swamped by declines in the efficiency of the larger urban transportation system.

Summary

The most important relationships between telecommunications and freight travel are as follows:

- The opportunity to directly substitute telecommunications for freight movements is limited.
- There is potential for more effective use of telecommunications to support increased use of just-in-time practices in manufacturing and retailing. These practices increase freight vehicle travel. However, they also are expected to increase industrial efficiency, competitiveness, and economic growth.
- Long-term shifts in the structure of the U.S. economy toward information and service activities, driven in part by improvements in telecommunications technologies, are reducing the freight intensiveness of the economy. Increases in the Nation's freight transportation are smaller than they would have been without these shifts.





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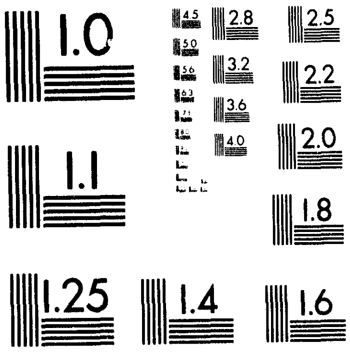

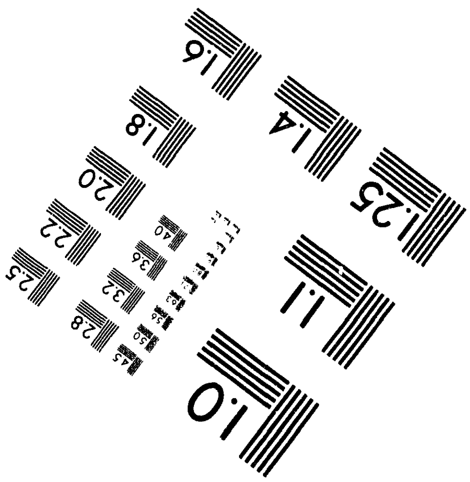

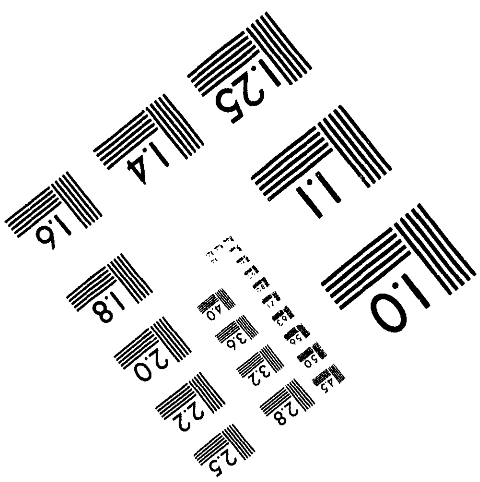

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Implications of an "Information Superhighway" for the Energy and Environmental Effects of Vehicle Travel

Various proposals have been made for developing an "information superhighway" in the United States. The technical details of such a superhighway remain uncertain, as do key issues of financing, ownership, operation, pricing, and extent of regulation. Nevertheless, it is an example of a major telecommunications technology and infrastructure change. Potential uses of the superhighway remain highly speculative, but the following have been discussed:

- Increased levels of activities that are already being conducted in some form or another using telecommunications, but that might be conducted less expensively or more effectively with improved telecommunications. These activities include information searches of remote databases, retrieval of text from on-line libraries, communication by electronic mail, videoconferencing, and shopping from home.
- New activities that can be foreseen based on existing or likely technology and that would be made either technically feasible or less expensive by improved telecommunications. "Movies-on-demand" has probably received the most discussion in the press, but interactive videoconferencing and interactive shopping also have been suggested. Generally speaking, these activities would enhance the use of telecommunications for entertainment, education, communication, information gathering and delivery, and shopping.
- New activities that cannot be accurately foreseen, either because the technology needed to deliver the service—beyond the basic telecommunications service—has not yet been developed, because, as with any technology, the possibility exists to use it in ways that the developers did not anticipate, or because the demand for the activity is uncertain.

It is anticipated that an information superhighway would facilitate telecommuting by making it easier and less expensive for people working at home to use information that resides on computers maintained by their employers or by other information repositories; by allowing people to perform more of their work tasks at home; by providing higher quality telecommunications services, such as videotelephony or videoconferencing, that would allow work at home to include more of the kinds of interactions that occur between employee and co-workers, or between employee and customers; and by promoting growth in information activities that lend themselves to telecommuting. Although the specific form of the information superhighway and the services it would provide are as yet unknown, the superhighway clearly will improve the ability of firms and governments to use telecommunications to offer services, and it will improve the ability of individuals to use telecommunications to receive services. The cost of services should decrease, and the variety and quality of services should increase.

An information superhighway would not be the only source of improvements in the cost and availability of telecommunications services. As the development of the cellular telephone industry illustrates, there is substantial opportunity for wireless telecommunications to reduce the costs of some telecommunications services, create new economic activities, and transform others. Because wireless telecommunications can more easily maintain contact with moving vehicles, wireless technologies are likely to be more important in transportation operations than would an information superhighway.

With this as background, it is possible to sketch some of the implications of the information superhighway for the energy use and environmental impacts of the Nation's vehicle travel, noting that although the information superhighway would have most of its effects by telecommunications, not all of the effects of improved telecommunications can be attributed to the development of an information superhighway.

Implications for Telecommuting

In general, an information superhighway would increase the amount of work that can be done via telecommuting, and it would make telecommuting more acceptable and easier to perform. First, an information superhighway seems likely to create new kinds of employment in information processing, and it seems likely to make some present employment more information intensive. Thus, the superhighway would increase growth in the kinds of work that lend themselves to telecommuting. Second, by enabling new telecommunications technologies, and by decreasing the cost or improving the performance of existing technologies, an information superhighway could make more existing work amenable to being performed via telecommuting. As examples:

- A common obstacle to telecommuting appears to be the concern of supervisory personnel that they cannot check up on telecommuters when they are not at the office (DOT, 1993; Quaid and Lagerberg, 1992). Improved, less expensive videoconferencing might alleviate some of this concern, and it might allow employees whose work involves frequent interaction with other people to conduct some of these interactions from home. The information superhighway is widely expected to enable video telephony and videoconferencing services that are less expensive and of higher quality than at present. If this happens, some interactions that now require face-to-face contact could become possible using telecommunications instead, and some additional work could be done by telecommuting instead of at an office.

- Much of the re-engineering of document flow within businesses and government agencies creates video images whose transmission requires higher capacity telecommunications than now exist to most residences. An information superhighway is expected to provide the necessary capacity to allow people who use those documents in their workplaces and have the necessary computer equipment at home to retrieve the documents and use them at home. The added telecommunications capacity would allow more work to be done at home and make more work amenable to telecommuting.

- As firms undertake re-engineering of their work and begin to question long-standing practices and assumptions, some are concluding not only that re-engineering can reduce the need for middle management, but also that telecommunications and re-engineering can reduce the need for office space (*Forbes*, 1992b). At present, the interest in reducing office space seems concentrated among firms whose employees spend a good deal of time in the field with clients and who spend a relatively small amount of time in their offices. However, major improvements in telecommunications could make it possible for more employees to perform a greater share of work away from their offices and lead more employers to want to provide fewer employees with office space.

For these reasons, it is likely that developing an information superhighway would allow a greater proportion of work to be performed via telecommuting than at present. According to assessments by the Department of Transportation (DOT, 1993) and the results of this study described in Chapter 1, the greater use of telecommuting would reduce fuel consumption, emissions, and other societal costs of transportation.

The amount of telecommuting that actually results will depend on the willingness of employers to allow employees to telecommute and on the perception by employees that the benefits of telecommuting are greater than the risks of not being present at the office (DOT, 1993). In addition, although the information superhighway may make it possible for a supervisor to use videoconferencing or other services to check up on a telecommuting employee, this may not encourage telecommuting as much as it might seem. As discussed in Chapter 2, part of the benefit of telecommuting to both employers and employees is improved productivity of the telecommuter; telecommuters and supervisors both attribute this improvement to the employee's being able to work away from the normal interruptions of the office (Quaid and Lagerberg, 1992). An information superhighway that makes such interruptions via telecommunications easier, by making the quality of the interaction higher, could reduce some of the benefit of telecommuting.

Implications for Passenger Travel

Although an information superhighway would encourage telecommuting and thereby reduce passenger travel, it would have other effects as well. Most notably, by providing a substantial improvement in telecommunications technology, the superhighway is likely to encourage decisions to disperse activities not just within metropolitan areas (Garreau, 1991), but to remote areas with lower costs of labor (Howland, 1993) or land, or higher quality of life (*Forbes*, 1992b). When the activity being relocated is a business or other employer, it seems likely that much of the interaction between the activity and its former surroundings would be maintained using telecommunications, especially where telecommunications is now in use. When the activity being relocated is a household, increased dispersion would likely increase household passenger travel. Telecommunications cannot substitute for transportation in some activities—such as taking children to sports activities, visiting parks, or going out for dinner—though it might provide some alternatives that families prefer instead. If new residential areas are developed at lower densities, the amount of travel required to maintain these activities after dispersion increases is likely to be higher than before.

An information superhighway is expected to increase the ease and quality of shopping from home, and thereby reduce some passenger travel for shopping. The potential also exists for telecommunications to substitute for travel in education and to displace some leisure activities that now involve travel. These changes would offset some of the other increases in travel brought about by dispersion, and they make the net effect of an information superhighway on household passenger travel uncertain.

In the most congested areas where travel may be undesirable due to traffic delays or discouraged by public policy to minimize adverse environmental impacts, the existence of an information super highway should facilitate the substitution of telecommunications for travel. In this way, it could reduce the costs of policy measures designed to reduce vehicle travel.

Implications for Freight Movements and Economic Structure

Telecommunications has limited potential to substitute for freight travel, primarily in cases where electronic transmission enables people to dispense with shipping information storage media. An information superhighway is expected to allow more of this potential to be realized, but the overall effect of such substitution on the amount of freight being shipped will be very small. Similarly, an information superhighway is expected to lead households to do more shopping from home, which will lead to an increase in small-parcel freight to deliver the goods purchased. Again, the effect on travel is likely to be small.

An information superhighway would allow freight carriers to operate more efficiently, probably reducing the travel intensity of freight movement and almost certainly making freight movement less expensive than it would be without the superhighway. These changes would improve economic efficiency and tend to increase economic growth, which would increase the amount of freight being shipped.

The superhighway also would enable more firms to adopt just-in-time practices, which would increase freight vehicle travel but also improve these firms' competitiveness. This again should increase economic growth and further increase the amount of freight being shipped.

An information superhighway is likely to cause an even greater shift in the Nation's economy away from manufacturing, resource extraction, and resource processing activities and toward services and information. This shift will reduce future increases in the amount of freight being shipped, and probably will be the superhighway's dominant effect on freight movements.

APPENDIX. METHODOLOGY FOR ESTIMATING EFFECTS OF TELECOMMUTING

This appendix presents technical details of the methodology outlined in Chapter 3 for estimating the indirect and direct effects of vehicle travel reductions due to telecommuting in 339 metropolitan statistical areas (MSAs). The process, as diagramed in Figure A–1, begins with 1988 baseline estimates for each of 339 MSAs of employment, vehicle travel, the shares of total vehicle-miles traveled (VMT) occurring on the two highest order functional highway types, and an inventory of lane-miles for these highways (box 1 in Figure A–1). These baseline characteristics are then forecast for the years 2005 and 2010, based on past and expected future trends in the absence of additional telecommuting (box 2). Given this base case projection of vehicle travel,

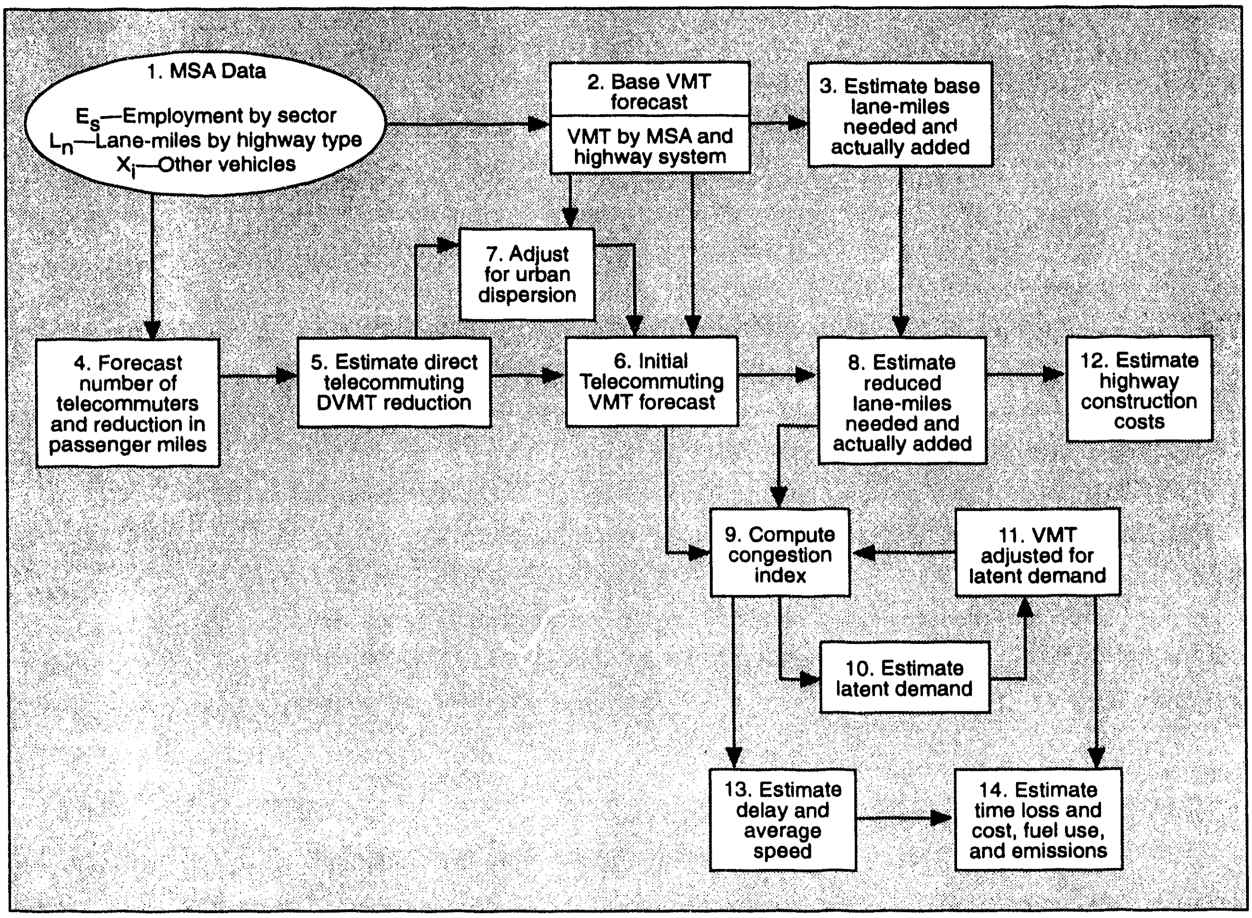

Figure A–1. Process for Estimating Direct and Indirect Effects of Telecommuting

capacity expansion required to hold areawide congestion constant is estimated and used to project how many additional lane-miles would have to be constructed in the absence of increased telecommuting (box 3) (Schrank, Turner, and Lomax, 1993).

Historical relationships are used to estimate the number of lane-miles that will be added as a function of the number of lane-miles needed to hold traffic congestion constant. Historical data suggest that less than the needed number of lane-miles will be added, so that traffic congestion will increase over time as travel demand increases. This forecast of travel, capacity, and congestion becomes the base case from which changes that are due to increased telecommuting are measured.

To obtain the number of telecommuters in each city, this analysis applies projections of the fraction of workers who will telecommute (based on the 1993 DOT telecommuting study) to the employment projections for each MSA. Following the DOT methodology, total employment is distributed between information workers and others, and telecommuters are estimated as a percentage of information workers (box 4). Multiplying this total by an average trip length per telecommuter, and by the average number of days per week telecommuted, gives an estimated direct reduction in commuter-miles for each urban area. The number of telecommuter-miles is converted to commuting vehicle-miles avoided by dividing by the average vehicle occupancy (box 5). An initial estimate of vehicle travel under expanded telecommuting is the original projection of VMT minus the estimated avoided miles (box 6). This may then be adjusted to take into account the effect of reduced commuting requirements on the dispersion of population in the MSA (box 7).

The forecast of VMT under the telecommuting case can then be compared with base case forecasts of lane-miles added to compute the reduction in lane-miles needed and added because of telecommuting (box 8). Highway capacity is increased over time as a function of the level of demand. In the base case, with higher levels of VMT than the telecommuting case, more highway lane miles are likely to be constructed. Thus, in the telecommuting case, traffic congestion will decrease, but not as much as if the same amount of highway capacity had been added as in the base case. On the other hand, fewer miles of highway will have to be constructed, saving both dollars and land.

With the projected supply of highway miles and VMT, an index of congestion can be computed (box 9). The areawide Roadway Congestion Index (RCI), developed by researchers at the TTI (Schrank, Turner, and Lomax, 1993), is used. The RCI has been more extensively used than any other measure of areawide traffic congestion, and its relationship to key performance measures such as delay and average speed has been explored (Turner, 1992). It is likely that reduced congestion will encourage a certain amount of travel that would not have occurred otherwise. This effect on latent demand is forecast based on a relationship between the supply of highway capacity and total vehicle travel estimated in a previous statistical analysis of VMT in 339 U.S. cities (Miaou et al., 1990) (box 10). The estimate of latent demand on VMT is then computed (box 11). Given this new estimate of vehicle travel, the RCI is recomputed.

Final impacts can now be estimated. The forecast of additional lane-miles is then used to estimate highway construction costs (box 12), and the index of congestion is used to predict hours of delay and average speeds on each of the two highway system types in each of the 339 MSAs (box 13). Finally, estimates of vehicle travel and average speed are used to forecast emissions, using speed-correction factors derived from the Environmental Protection Agency's (EPA) MOBILE5 model, and to forecast fuel consumption, using data from An and Ross (1993) and Davis and Strang (1993) (box 14). Direct effects of telecommuting are estimated by subtracting fuel consumption and emissions rates with and without increased telecommuting, and multiplying by the total number of VMT. Indirect effects are estimated by multiplying the *net* change in vehicle travel (VMT avoided by telecommuters minus the effects of urban population density and latent demand) times average fuel use and emissions rates adjusted for changes in congestion and average speeds. Finally, approximate dollar values are used in some cases to translate effects into 1990 dollars for a rough comparison of the magnitude of effects.

The details of this methodology, including the specific equations and parameter values used, are explained below. This appendix first explains the RCI because of its key role in the method. Next, its relationships to capacity expansion are specified. The projection of future levels of telecommuting and telecommuting vehicle-miles is then described. This is followed by an explanation of how the "take-back" effects of latent demand and urban sprawl are computed. Methods for estimating hours of delay and average speeds are defined, followed by methods for forecasting fuel consumption and emissions as functions of average speeds. Finally, issues relevant to quantifying and valuing effects are discussed.

The TTI Index of Roadway Congestion

One of the most important relationships in this analysis is that between traffic congestion and vehicle travel per lane-mile of highway infrastructure. Traffic engineers at TTI have developed a measure of areawide traffic congestion based on the ratio of daily vehicle miles of travel (DVMT) per lane-mile (LM) of highway. Because this measure and its relationship to capacity expansion, traffic delays, and average speeds are critical to the methodology used in this study, it is important to understand the TTI congestion index. The principle of the RCI is to express the actual density of daily vehicle travel relative to a level historically associated with areawide congested conditions. The TTI researchers have applied the RCI measure to traffic conditions in 50 U.S. cities in a series of five widely studied and cited research reports (Schrank, Turner, and Lomax, 1993).

The RCI is defined by the following equation,

$$RCI = \frac{[(DVMT_F/LM_F) \times VMT_F + (DVMT_A/LM_A) \times VMT_A]}{[13{,}000 \times VMT_F + 5{,}000 \times VMT_A]} \qquad \text{A–1}$$

where VMT_F is total annual VMT on freeways and VMT_A is total annual VMT on principal arterial highways in the urban area. The TTI researchers explain the meaning of their congestion index as follows:

> An RCI value of 1.0 or greater indicates that congested conditions exist areawide. It should be noted that urban areas with areawide values less than 1.0 may have sections of roadway that experience periods of heavy congestion, but the average mobility level within the urban area could be defined as uncongested. The RCI analyses presented in this report are intended to evaluate entire urban areas and not specific locations (Schrank, Turner, and Lomax, 1993).

The TTI's RCI is key to two parts of this model. First, it is used to predict the expansion of capacity necessary to hold traffic congestion constant at base year levels. Later, given predictions of capacity expansion and vehicle travel demand, it is used to predict hours of delay caused by congestion.

Forecasting Lane-Miles of Capacity Needed

The RCI reflects areawide traffic conditions for a base year (1990 in the most recent TTI research report). In the 50 urban areas for which the TTI researchers have calculated the index, vehicle travel on freeway and principal arterial systems grew at average annual rates of 0.3 percent (Boston) to 9.2 percent (Salt Lake City) between 1987 and 1990 (Schrank, Turner, and Lomax, 1993). To avoid deterioration in performance, lane-miles must be added to both systems. As a measure of the demand for new highway capacity, TTI researchers have computed the additional lane-miles needed annually to maintain the 1990 congestion level, assuming that VMT growth continues at historical rates. Their method is used here to estimate the need for highway capacity expansion.

The TTI method assumes that vehicle travel growth will proceed at the same rate (*r*) on both freeway and arterial systems. Since daily vehicle travel (*DVMT*) is annual travel divided by 365, it too will grow at the rate of *r*. Substituting the new *DVMT* and *VMT* values in the equation for RCI,

$$RCI = \frac{[(r \times DVMT_F / LM_F) \times r \times VMT_F + (r \times DVMT_A / LM_A) \times r \times VMT_A]}{[13{,}000 \times r \times VMT_F + 5{,}000 \times r \times VMT_A]} \qquad \text{A–2}$$

yields a single equation in two unknowns, LM_F and LM_A. Although there are an infinite number of possible solutions, the most obvious, and that used in the TTI studies, is to assume equal relative increases in lane-miles for both types of systems. Thus, the new values of lane-miles are $r \times LM_F$ and $r \times LM_A$. This not only ensures that the RCI remains constant, but that the congestion level on each system also remains constant.

Forecasting Lane-Miles of Capacity Added

Lane-miles of freeways and principal arterials added to the metropolitan highway system are forecasted as a simple function of the lane-miles required to hold areawide congestion constant. Historical data presented in Schrank, et al. (1993) were used to estimate a regression equation relating additional annual lane-miles needed to maintain a constant level of congestion, as defined by the TTI areawide congestion index, and the average annual lane-miles actually added to the highway systems of 50 urban areas from 1987 to 1990. The regression was carried out using the logarithms of the lane-mile data in order to stabilize the variance of the data. Equations were estimated separately for freeways and principal arterials, and an estimate combining both highway types was made as well. Because intercept terms were generally not statistically significant, equations were also estimated without intercepts. Lane-miles needed is a highly statistically significant forecaster of average lane-miles added, but its explanatory power is modest, with R_2 values typically in the vicinity of 0.5. Dispersion of the data around the regression lines is illustrated in Figures A–2 through A–4.

The logarithmic model implies a constant elasticity relationship between lane-miles needed (m) and lane-miles added (M). The estimated freeway regression equation,

$$\log(M) = 0.655 + 0.641 \times \log(m) \qquad \text{(A–3)}$$

implies that every 1-percent increase in lane-miles needed will result in just over a 0.6-percent increase in lane-miles actually to be added. Ten freeway-miles needed results in an estimated 8.4 miles constructed, while 100 miles needed produces an estimate of 37 miles constructed. The estimated regression equation for principal arterials,

$$\log(M) = -0.254 + 0.863 \times \log(m) \qquad \text{(A–4)}$$

implies that a 1-percent increase in lane-miles needed will call forth an 0.86-percent increase in miles added. Ten miles needed of principal arterials would result in 5.7 miles constructed. One hundred miles needed would call forth 41 miles of arterials.

In neither equation are the intercept terms statistically significantly different from zero. Dropping the intercept terms results in estimates for the coefficient of the logarithmic term of 0.82 for freeways and 0.80 for principal arterials. These are not statistically significantly different from each other, suggesting that the freeway and arterial data can be pooled, and a single

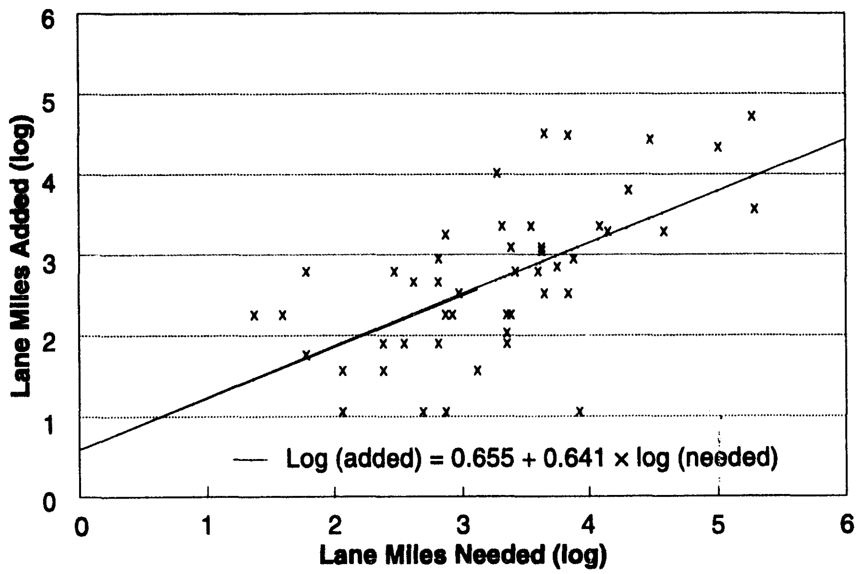

Figure A–2. Actual Average Annual Freeway Capacity Expansion Versus That Needed To Prevent Increased Congestion

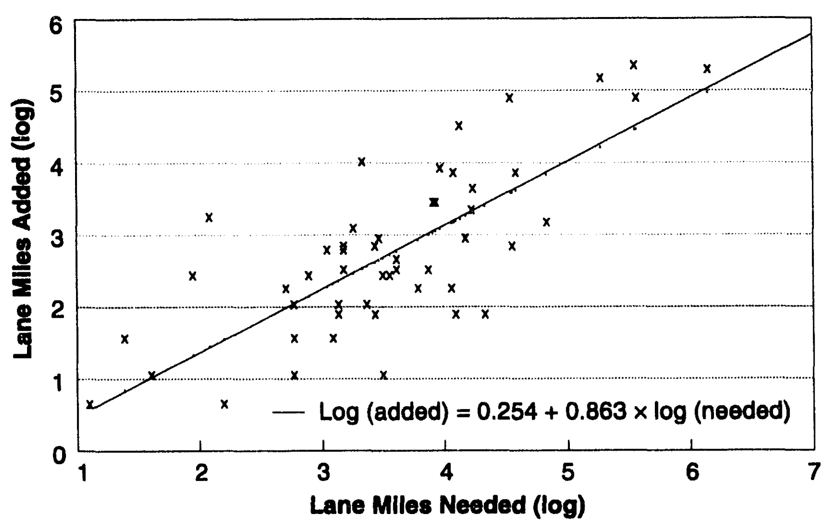

Figure A–3. Average Annual Principal Arterial Capacity Expansion Versus That Needed To Prevent Increased Congestion

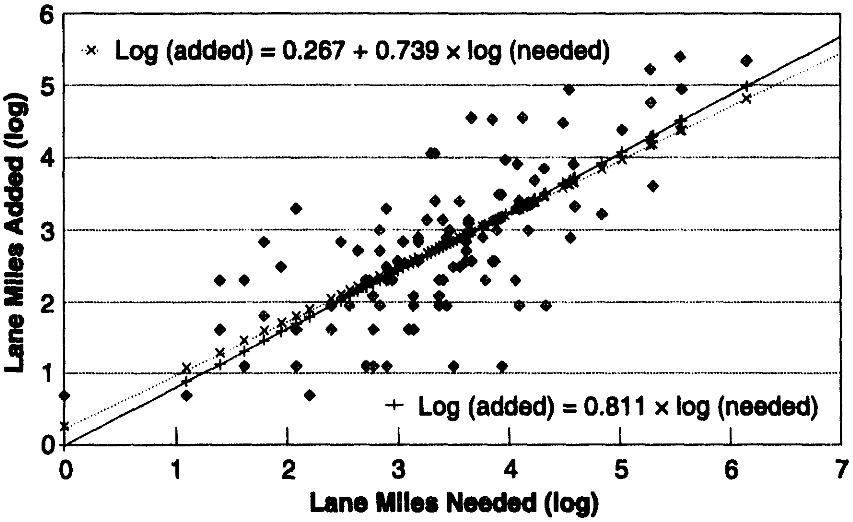

Figure A–4. Actual Average Annual Highway Capacity Expansion Versus Amount Needed To Prevent Increased Congestion

regression equation estimated for both. The resulting pooled regression equation,

$$M = m^{0.81} \qquad \text{(A–5)}$$

indicates an elasticity of about 0.8 for miles actually constructed with respect to miles needed to hold congestion constant. Because more complex versions of the model do not provide a statistically significant increase in explanatory power, the simple, pooled model is preferred.

A general property of the equation for projecting miles constructed is that the greater the miles needed, the smaller the proportion of the need that will be satisfied. Because miles needed is surely a function of city size (as well as the rate of *VMT* growth), the equations will tend to forecast congestion worsening at a faster rate in larger cities, other things equal. That is, smaller cities will tend to satisfy a greater proportion of their highway needs than larger cities, given the same rate of growth in vehicle travel.

In using this model, it is important to remember that it projects the average annual lane-miles added, assuming that transportation planners are attempting to keep congestion from deteriorating over the previous year's level. A significant error would be made if the equation were used to project the total lane-miles added over a period of time greater than one year. For example, suppose 1,000 lane-miles were needed to hold congestion constant over a period of 10 years. If one incorrectly raised 1,000 to the 0.81 power, an addition of only 269 lane-miles would be projected. The correct use of the model would be based on an *average annual* need of 100 lane-miles resulting in 41.7 miles being added in each of the ten years for a total of 417 added over the 10-year period.

Forecasting Levels of Telecommuting

Projections of future telecommuting in this study are based on the DOT study *Transportation Implications of Telecommuting* (DOT, 1993). DOT estimates are based on a forecast by Nilles (1991) that assumes an increasing prevalence of telecommuting among "information workers." Information workers are defined as "individuals whose primary economic activity involves the creation, processing, manipulation, or distribution of information" (DOT, 1993). Information workers are distinguished from those in agriculture, industry (manufacturing), and service sectors. DOT estimates that there are 73 million U.S. information workers today and that this number will grow to about 80 million by 2005 and exceed 85 million by 2010.

The information provided in the DOT study was used to approximate the Nilles forecast for the years 2005 and 2010. Logistic curves were fitted to the DOT data and used to extrapolate projections to 2005 and 2010. The curve for the share of total workers who are information workers (s_I) as a function of time (t) is

$$S_I = 1/[1.5 + \exp(76.683 - 0.03914 \times t)] \qquad \text{(A–6)}$$

and that for the share of information workers adopting telecommuting (s_T) is

$$S_T = 1/[1.5 + \exp(424.70 - 0.21145 \times t)] \qquad \text{(A–7)}$$

The values 1.5 in the denominators of these curves were inserted by assumption to force the shares to approach a limit of 2/3 (1/1.5) as t grows large. The other coefficients were fitted by ordinary least squares regression. The telecommuting adoption curves, as illustrated in Figures A–5 and A–6, show

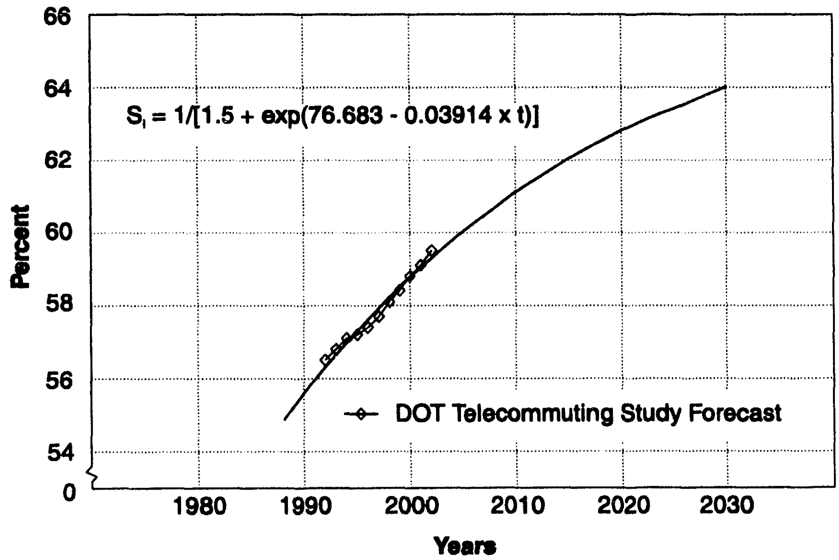

Figure A–5. Information Workers' Projected Share of Total U.S. Work Force

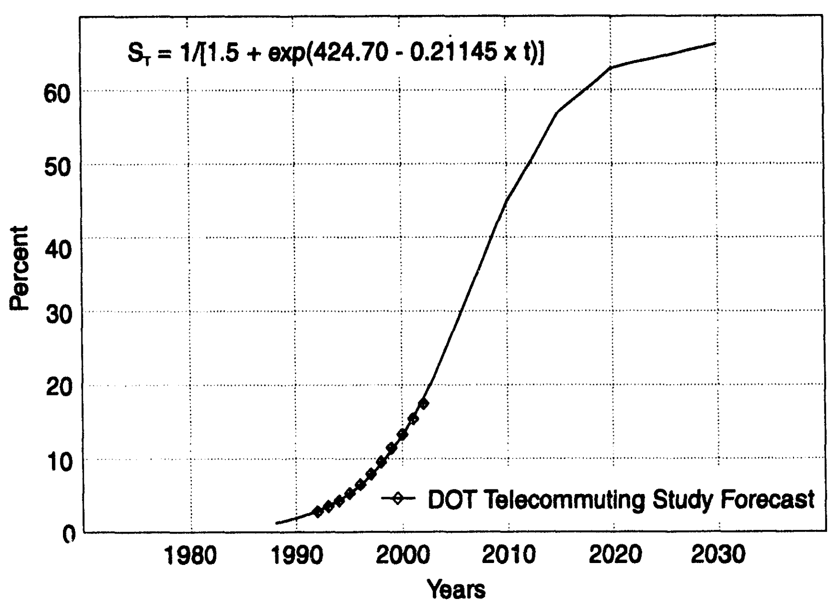

Figure A–6. Projected Percentage of Information Workers Who Telecommute

information workers as a percent of all workers increasing to about 60 percent by 2005 and nearly 63 percent by 2010. Adoption of telecommuting by information workers increases to about 28 percent by 2005 and to 45 percent by 2010. The total number of telecommuters (N_T) in each city is forecast as the product of the shares and total employment (N_W) in city c in year t.

$$N_T = N_W \times S_T \times S_I \tag{A-8}$$

The DOT study also distinguishes five types of telecommuters, again based on Nilles' analysis (Table A–1). This is important, as the DOT study points out, because each type of telecommuter forgoes a commute of different length and frequency. Commuters who travel to the urban center are assumed to have a round-trip length of 21.4 miles, while those using regional centers have a 9-mile round-trip commute. Each category of telecommuter and its

Table A–1. Distribution of Telecommuters by Category

Category	Frequency[a] (days per week)	1992[b] (percent)	2002[b] (percent)	2010[c] (percent)
		DOT Assumptions		
Home to CBD	2 to 3.1	84.00	47.06	45
Regional Ctr./CBD	2 to 4.1	0.06	1.18	1
Regional Ctr./ Home	4 to 3.8[d]	0.37	15.30	17
Full-Time Home	5	15.00	2.63	2
Full-Time Regional	5	0.57	33.83	35
		Alternative Assumptions		
Home to Office	2 to 3.1	84.00	81	80
Local Ctr./Office	2 to 4.1	0.06	0	0
Local Ctr./Home	4 to 3.8[d]	0.37	2	2.5
Full-Time Home	5	15.00	15	15
Full-Time Local	5	0.57	2	2.5

[a]Range reflects projected change in frequency between 1992 and 2002.
[b]From DOT, 1993.
[c]Assumed.
[d]Number of days at regional center declines slightly through time because of slight increase in home-based telecommuting.

corresponding telecommuting frequency in days per week is shown below. This study hypothesizes an eventual distribution for the year 2010, and interpolates between the DOT estimates for 2002 and the assumed distribution for 2010 to derive a distribution for 2005.

The distribution used in the DOT study is quite different from the current pattern of telecommuting, implying a substantial shift toward working in regional centers versus the CBD. In fact, most urban workers do not work in the CBD and most commuting is now suburb-to-suburb. For these reasons, this study hypothesizes an alternative distribution of telecommuters that is essentially the same as today's patterns. The traditional workplace is called an "office" rather than CBD. To project to the years 2005 and 2010, this report assumes a simple progression to 80 percent part-time home—2.5 percent each for home-to-regional center and full-time regional center, and a continuation of 15 percent full time at home. The Nilles projections assume a strong trend toward regional telecommuting centers. The scenario analysis below also assumes that telecommuter shares remain close to the 1992 distribution throughout the time period (the 1992 numbers are based on survey data). Because this report assumes that the typical telecommuter has the same average trip length as the typical commuter (21.4 miles round trip, the U.S. average for 1990), it is not necessary that the commute be between the periphery and the CBD, just that it be a "normal" urban commute.

Based on the total employment (E_c) of each city (c), we estimate the number of telecommuters (N_c) by multiplying E_c by the national share (S) of employees who telecommute.

$$N_c = S \times E_c \tag{A–9}$$

Let d_i be the average number of weekly telecommuting days for subgroup i, and l_i be the average round-trip commute. If s_i is the fraction of telecommuters belonging to subgroup i, then the average weekly telecommuting days (d) and average commute distance avoided per day (l) are

$$d = \Sigma_i s_i d_i \qquad l_c = \Sigma_i s_i l_i \tag{A–10}$$

The number of telecommuters is multiplied by the average commute trip distance per day and the average number of days commuted per week to determine the total reduction in weekly miles of travel foregone in city *c* because of telecommuting. This is converted to a change in *DVMT* for a typical workday by dividing by five. Because not all commuters travel by highway, the change in *DVMT* is multiplied by the share of commuting trips that used the highway mode in 1990—h = 91.4 percent (Hu and Young, 1992). Finally, the result is divided by the average commuter vehicle occupancy, *vo*, which assumes that telecommuters' vehicle occupancy rates are the same as the average for all commuters.

$$\Delta DVMT_c = (h \times E_c \times l_c \times d/5)/vo \qquad \text{(A–11)}$$

Telecommuting travel is likely to be almost entirely a reduction in peak-period travel. Because the effects are estimated solely as a reduction in total daily travel, the true impact of telecommuting on traffic congestion is likely to be underestimated.

To obtain a preliminary estimate of *DVMT* on higher order systems with telecommuting ($DVMT^*$) for each urban area, the fraction of daily travel that occurs on the higher order highway systems (*f*) is multiplied by $DVMT_c$ and subtracted from $DVMT_c$.[1] In other words, the fraction of all vehicle-miles that occur on higher order systems is assumed also to be the fraction of telecommuting-miles occurring on higher order systems.

$$DVMT^* = DVMT - (f \times \Delta DVMT) \qquad \text{(A–12)}$$

Given this new lower estimate of travel demand, the miles of highway capacity of class *h* in city *c* needed to hold congestion constant given increased telecommuting (m^*_{hc}) is recomputed. From this, equation A–5 is used to compute miles added, given increased telecommuting (M^*_{hc})

$$M^*_{hc} = (m^*_{hc})^{0.81} \qquad \text{(A–13)}$$

[1]This study assumes minimal or no telecommuting in the base year (1988) for city-wide VMT. This is consistent with survey results reported by DOT (1993), which indicate that recent growth in telecommuting has been explosive. In 1992, 2.4 million persons telecommuted as a part of their regular work, increasing from 1.4 million in 1991 and 0.4 million in 1990.

The savings in highway miles that do not need to be constructed due to reduced travel is then

$$\Delta M^{*}_{hc} = M_{hc} - M^{*}_{hc} \qquad \text{(A–14)}$$

Adding the new estimate of lane-miles constructed to the base year lane-miles gives a new estimate of highway capacity that is used in conjunction with $DVMT^{*}$ to derive a new estimate of the traffic congestion index, RCI^{*}.

Forecasting Latent Demand for Vehicle Travel

To forecast the effect of changes in traffic congestion on vehicle travel, we must have a model relating vehicle travel demand to the supply of highway capacity. National or state-level vehicle travel forecasting models have not included highway capacity as an explanatory variable (Southworth, 1986). A recent econometric forecasting model based on data from 339 U.S. urban areas includes a statistically significant relationship between highway capacity and *DVMT* (Miaou, Rathi, Southworth, and Greene, 1990). That study found that for urban areas with less than 2.15 lane-miles of higher order highway systems (freeways and expressways, and principal arterials) per 1,000 persons, the elasticity of *DVMT* with respect to additional lane-miles was 0.33. For urban areas with greater than 2.15 lane-miles of higher order systems per 1,000 persons, additional lane-miles had no statistically significant effect on *DVMT*.[2] Additionally, the study found no relationship between highway capacity and *DVMT* for cities of less than 100,000 population. The authors of this study interpreted as follows: Where there is insufficient supply of highway capacity (that is, areawide traffic congestion) increasing capacity leads to increased demand; and where the supply of capacity is adequate or more than adequate, it is not a constraint on travel, and increasing supply has no measurable effect on vehicle travel. This empirical result provides the relationship between highway capacity and vehicle travel needed to forecast the latent-demand effect.

[2]The authors note that 2.15 lane-miles per 1,000 persons is equivalent to a volume to capacity ratio of between 7,500 and 8,000 DVMT/LM in the primary highway system under 1987 conditions. This falls between the TTI researchers reference congestion levels for freeways (13,000 DVMT/LM) and principal arterials (5,000 DVMT/LM).

One more step is required to establish a relationship between traffic *congestion* (represented as the ratio of traffic volume to capacity) and travel demand. We can simplify the Miaou, et al. (1990) travel forecasting model as follows:

$$DVMT = K \times (LM/POP)^{\beta} \qquad \text{(A–15)}$$

where K represents the combined effects of all factors other than capacity, (LM/POP) is lane-miles of higher order roads per capita, and the constant elasticity $\beta = 0.33$.[3] To determine the elasticity of $DVMT$ with respect to the ratio $(DVMT/LM)$, rearrange equation A–15 to give

$$DVMT^{(1-\beta)} = K^{1} \times (DVMT/LM)^{-\beta} \qquad \text{(A–16)}$$

where $K^{1} = K(POP)^{-\beta}$ now includes the effect of POP. By implicit differentiation of equation A–16 the derivative and elasticity of $DVMT$ with respect to $(DVMT/LM)$ are obtained.

$$\begin{aligned}\eta &= K^{1} \times \{[-\beta \times (DVMT/LM)^{-\beta}]/[(1-\beta) \times DVMT^{1-\beta}]\} \\ &\quad \times [(DVMT/LM)/DVMT] \\ &= \beta/(1-\beta) \\ &= -0.33/0.67 \\ &\approx -0.5\end{aligned} \qquad \text{(A–17)}$$

This very useful result states that where there is latent demand, the elasticity of travel with respect to reduced congestion is -½. Because congestion has been defined in terms of $DVMT$ per lane-mile, this implies that one $DVMT$ removed by telecommuting in a congested urban area will be replaced by one-half a $DVMT$ of latent demand. This should be a long-run, rather than a short-run effect, because the key parameter ($\beta = 0.33$) was estimated using cross-sectional data for 339 cities. Finally, in urban areas with less than 7,500 $DVMT/LM$ (or, alternatively with $RCI < 1$) there will be no latent-demand effect of reduced travel because areawide congestion is not present.

[3]Miaou, et al. (1990) estimated their model in log transforms of the variables, which implies constant elasticities.

Changes in Location Patterns and Urban Density

Reducing the need to commute may lead to greater dispersion of urban spatial structure (urban sprawl), and lower population densities. This study allows for that possibility by making use of relationships derived from simple urban-economic models of population distribution (see, for example, Mills and Hamilton, 1991). Although the models make the simplifying assumption that each household commutes once per day to the CBD, they are based on a more general theory that describes the trade-off between land area and transportation costs. Given realistic assumptions about economic parameters, these simple models can be shown to imply a elasticity of the average trip length (given fixed frequency) within an urban area with respect to total transportation costs (including travel time) of about -1 (Greene, 1993). The increase in trip length results from decreases in population densities and is therefore a very long-run effect. This implies that, in the long run, a 10-percent reduction in total household transportation costs would produce about a 10-percent increase in the average length of trips taken by the household, yielding no net change in total miles traveled.

Telecommuters realize a substantial savings in transportation costs by virtue of the fact that they avoid a significant fraction of their work trips. An estimate of the change in total urban transportation costs is obtained by multiplying the reduction in daily vehicle miles due to telecommuting divided by total daily vehicle miles ($\Delta DVMT/DVMT$), by the variable costs of highway travel as a fraction of total costs. This, multiplied by the highway share of all urban travel, h[4], and divided by the average auto occupancy rate, vo. Variable costs include the traveller's time costs and all variable monetary costs, which are about 20 percent to 25 percent of the total monetary costs of vehicle ownership and operation (MVMA, 1992). Time costs are estimated by dividing an assumed value of time, $10 per hour (Chui and McFarland, 1987), by an average urban travel speed, 40 mph. Given a total monetary cost per mile of $0.40, this produces a variable cost share of approximately 50 percent. The resulting percent change in total urban vehicle travel, δ, is given by

$$\delta = (\Delta DVMT/DVMT) \times (VC/TC) \times (h/vo) \qquad \text{(A–18)}$$

[4]This approximation assumes that all urban travel modes have approximately the same total cost per passenger mile.

Long-run changes in urban density take decades to fully unfold. It may be that the rate of telecommuting adoption will outpace the rate of this change. If this happens, substantial benefits may be present during the adjustment process that will eventually disappear as urban structure adjusts.

The final estimate of vehicle travel is obtained by multiplying DVMT* times the ratio (RCI*/RCI) raised to the elasticity -0.5:

$$r \times DVMT = DVMT^{*} \times (RCI^{*}/RCI)^{-0.5} \times (1 + 5) \qquad \text{(A–19)}$$

The new *DVMT* is used to recompute the *RCI*, hours of delay, and average speeds for each urban area. Changes in speeds are then used to estimate changes in emissions and fuel consumption as explained above.

Estimating Total Hours of Delay

If the *RCI* is a valid indicator of the level of areawide congestion on an urban highway system, it should be a significant forecaster of the hours of delay experienced by motorists using the system. Schrank, Turner, and Lomax (1993) provide statistics on hours of delay in each of their 50 urban areas. These statistics are reported by states to the Federal Government, and are independent of the *RCI* measure (DOT, 1989). By regressing hours of delay against the *RCI* for each urban area, an equation can be estimated for projecting delay as a function of the *RCI*.

Traffic engineers distinguish two types of traffic delays: recurring delay caused by the inadequacy of highway capacity to accommodate peak traffic volumes, and incident delay caused by accidents, breakdowns, or other occurrences. Both are related to the level of traffic congestion.

> When congestion levels increase (creating higher *RCI* values), it is the recurring delay that is directly affected. While incident delay is not directly related to or caused by congestion, the delay resulting from incidents significantly increases under congested conditions. (Schrank, Turner, and Lomax, 1993)

Thus, it should not be surprising that as an empirical forecaster of congestion delay, the *RCI* does equally well at forecasting recurring and total delay. Reported hours of delay for freeways and principal arterials and categorized as recurring or incident-related were compiled for 50 urban areas by Schrank, Turner, and Lomax (1993). The relationships of both recurring and total delay per 1,000 *DVMT* to the *RCI* index are illustrated by Figures A–7 and A–8. Note that even cities with *RCIs* less than 1.0 experience both recurring and incident-related delays. Scaling hours of delay by vehicle travel volumes removes the effect of city size on delay hours.

Regression lines fitted to the data are also shown in Figures A–7 and A–8. The fit of the regression lines is equally good—$R^2 = 0.55$ for total delay and $R^2 = 0.56$ for recurring delay. Three U.S. cities fall far away from both lines, however: Orlando, Los Angeles, and San Diego. Omitting these cities and reestimating the regression equation increases the slope of the regression line by 30 percent (in Figure A–6, the regression in which the three cities were omitted is indicated by the symbol *x*). Because there is no specific reason for omitting Orlando, Los Angeles, and San Diego, however, the equation is estimated on the full sample for purposes of projection.

$$(DELAY/1{,}000\ \mathrm{DVMT}) = -6.57 + 12.43 \times RCI \qquad \text{(A–20)}$$

According to this equation, the elasticity of delay per 1,000 DVMT when the *RCI* = 1.0 is approximately 25. At an *RCI* of 1.55 (that of Los Angeles in 1990), the elasticity is only half as great.

It remains to scale up the delay rate forecasted by the previous equation to total hours of delay by multiplying by the daily DVMT.

$$TDELAY = (DELAY/1{,}000\ \mathrm{DVMT}) \times (DVMT/1{,}000) \qquad \text{(A–21)}$$

The correlation of reported hours of delay with those forecast by this method is illustrated in Figure A–9.

Estimating Average Speeds

To translate changes in traffic congestion into changes in fuel use and emissions, the effects on average speeds must be forecast. The relationship between traffic velocity and traffic density (vehicles per mile) is a well-studied area of traffic flow theory (Gerlough and Huber, 1975). The established engineering

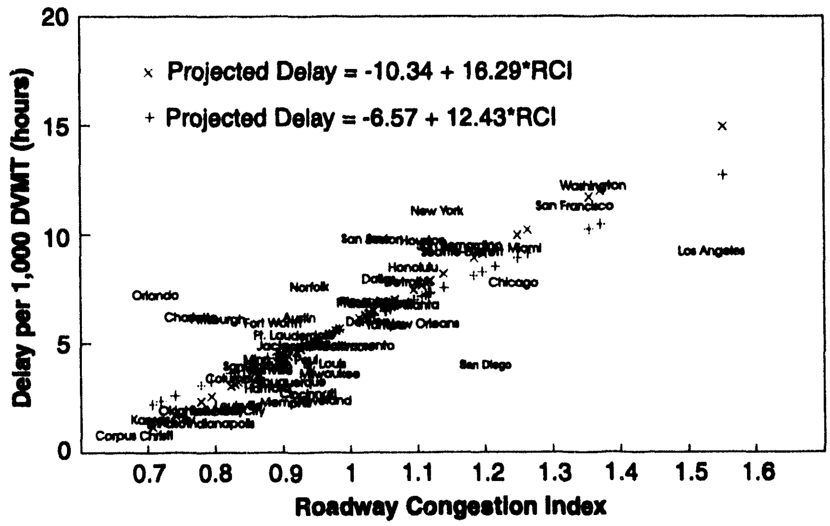

Figure A-7. Congestion Delay per Vehicle Mile Versus RCI

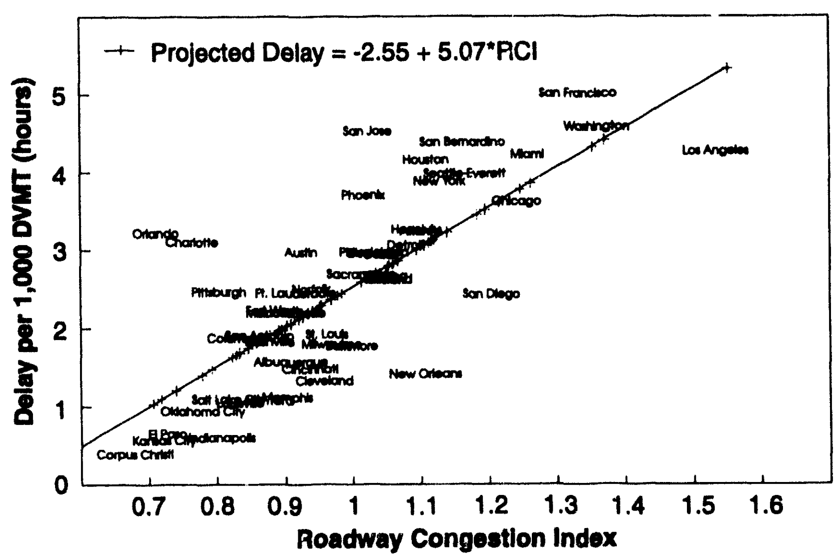

Figure A-8. Recurring Delay per Vehicle Mile Versus RCI

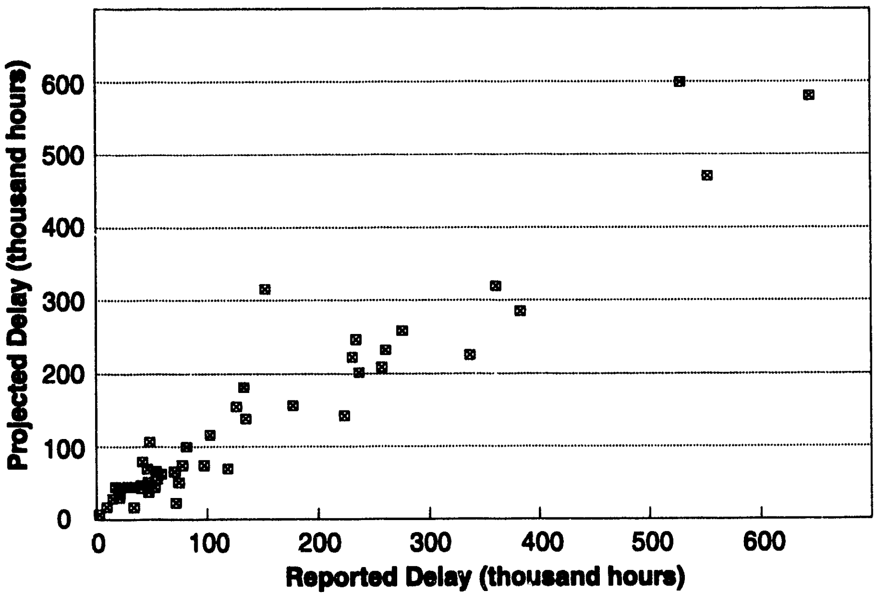

Figure A–9. Reported Versus Projected Total Annual Delay

relationships use exponential, linear, and piecewise linear functions to describe how speeds decline as traffic density increases. They are intended to represent the typical behavior of traffic on a particular road at a point in time. A relationship between average systemwide traffic flow (*DVMT*/*LM*) to average systemwide speed is needed. Appropriate estimates are presented in Schrank, Turner, and Lomax (1993) for freeways and principal arterials (Table A–2).

Exponential or linear curves can be readily fitted to the data in Table A–2. However, at very low or very high traffic levels, linear or exponential curves will produce unreasonable speed estimates. Instead, logistic curves were found to produce more reasonable results outside of the range of data in Table A–2. The curves indicate a substantial dropoff in speed as traffic flow increases above the levels where congestion sets in. As volume to capacity ratios increase over time, speeds will decrease as shown in Figure A–10.

Table A–2. Speed as a Function of Average Daily Traffic (ADT) per Lane

Functional Class	Parameters	Severity of Congestion: Moderate	Heavy	Severe
Freeway/Expressway	ADT/Lane[a]	15,000–17,500 (16,250)	17,501–20,000 (18,750)	Over 20,000 (20,250)
	Speed (mph)	38	33	30
Principal Arterials	ADT/Lane[a]	5,750–7,000 (6,375)	7,001–8,500 (7,750)	Over 8,500 (8,667)
	Speed (mph)	28	25	23

[a]Numbers in parentheses were those used in fitting curves to the data.
Source: Schrank, Turner, and Lomax, 1993.

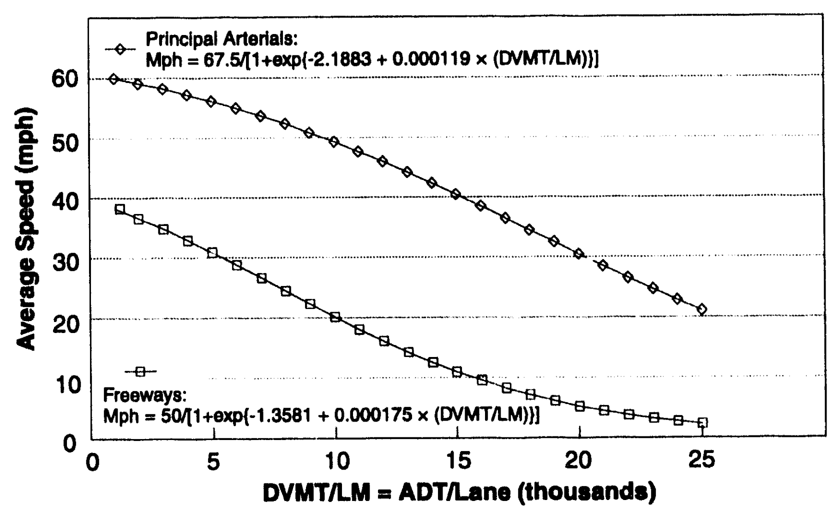

Figure A–10. Average Speed Versus Average Daily Traffic per Lane

Estimating Fuel Use and Emission Rates as a Function of Speeds

Though recent evidence has cast doubt on the accuracy of emissions projections based on average speeds (Guensler, 1993), speed adjustment factors still represent the best practice in estimating effects of changes in traffic flow on emissions levels. Baseline emissions estimates for light-duty motor vehicles are based on the Federal Test Procedure (FTP), which consists of a series of stops and starts with an average speed of 19.6 mph. Emissions rates for vehicles at speeds other than the FTP are estimated by multiplying the FTP emissions rate by the appropriate speed correction factor (SCF). SCFs developed by EPA and the California Department of Transportation (CALTRANS) are derived by a statistical regression of fuel consumption against average speed for cycles other than the FTP. Thus, they represent a relationship between average speed, not cruising speed, and emissions. This is precisely the relationship needed in this analysis to relate average system speed to emissions and fuel use.

This study uses the speed-versus-emissions relationships for the total traffic stream based on the EPA MOBILE5 Model. Because the numbers are intended to represent the effects of speed on mixed traffic, a weighted average of the speed fuel economy relationships of light- and heavy-duty vehicles is appropriate (Guensler, Washington, and Sperling, 1993). Future emissions levels will vary depending on the level of controls required. In particular, use of reformulated gasoline (RFG) and strict inspection and maintenance (I/M) programs have significant effects on emissions levels, and will almost surely be implemented in urban areas that fail to attain national ambient air quality standards. Certainly, not all of the 339 urban areas included in this analysis will be required to implement RFG and I/M programs. To create a range of estimates of emissions effects, MOBILE5 was used to develop two sets of speed-versus-emissions curves for each of the two forecast years. The first is the MOBILE5 baseline projection, and the second assumes use of RFG and implementation of the year 2004 I/M standards. The data are presented in Table A–3, and illustrated in Figures A–11 through A–14.

Even these simplified emissions relationships are nonlinear functions of speed. Over the range of speeds of interest in this study (approximately 20 mph to 65 mph), the *change* in emissions with a *change* in speed is approximately a linear function of speed. Formally, we let e represent emissions and v velocity,

Table A–3. Emissions Versus Speed for All Traffic Based on the MOBILE5 Model (grams per mile)

Speed (mph)	Baseline Scenario: Hydrocarbons	Baseline Scenario: Carbon Monoxide	Baseline Scenario: Nitrogen Oxides	RFG and I/M Scenario: Hydrocarbons	RFG and I/M Scenario: Carbon Monoxide	RFG and I/M Scenario: Nitrogen Oxides
2005						
2.5	14.31	117.56	3.39	6.27	42.24	2.47
5.0	7.01	67.17	2.87	3.10	24.93	2.12
7.5	4.97	49.76	2.64	2.23	18.61	1.95
10.0	4.06	40.79	2.50	1.84	15.21	1.83
15.0	3.10	31.53	2.32	1.41	11.56	1.69
20.0	2.57	26.43	2.22	1.16	9.52	1.60
25.0	2.13	20.55	2.21	0.97	7.46	1.58
30.0	1.83	16.66	2.20	0.84	6.09	1.57
35.0	1.62	13.90	2.22	0.75	5.14	1.58
40.0	1.46	11.85	2.25	0.68	4.45	1.60
45.0	1.34	10.30	2.31	0.63	3.95	1.65
50.0	1.27	9.56	2.47	0.60	3.73	1.78
55.0	1.26	9.63	2.83	0.58	3.79	2.03
60.0	1.41	14.05	3.22	0.63	5.46	2.32
65.0	1.57	18.56	3.69	0.70	7.20	2.67
2010						
2.5	13.03	109.64	3.17	5.07	31.48	2.07
5.0	6.49	63.23	2.67	2.54	19.07	1.78
7.5	4.63	47.23	2.45	1.84	14.46	1.64
10.0	3.80	38.96	2.32	1.53	11.94	1.54
15.0	2.92	30.49	2.16	1.17	9.18	1.42
20.0	2.43	25.72	2.07	0.97	7.60	1.34
25.0	2.00	19.78	2.06	0.8	5.88	1.32
30.0	1.72	15.83	2.05	0.70	4.73	1.31
35.0	1.51	13.03	2.07	0.62	3.94	1.31
40.0	1.35	10.96	2.09	0.56	3.36	1.33
45.0	1.24	9.38	2.14	0.51	2.95	1.37
50.0	1.17	8.61	2.30	0.49	2.76	1.48
55.0	1.15	8.67	2.62	0.48	2.81	1.68
60.0	1.29	12.17	2.98	0.51	3.79	1.92
65.0	1.42	15.76	3.39	0.55	4.83	2.22

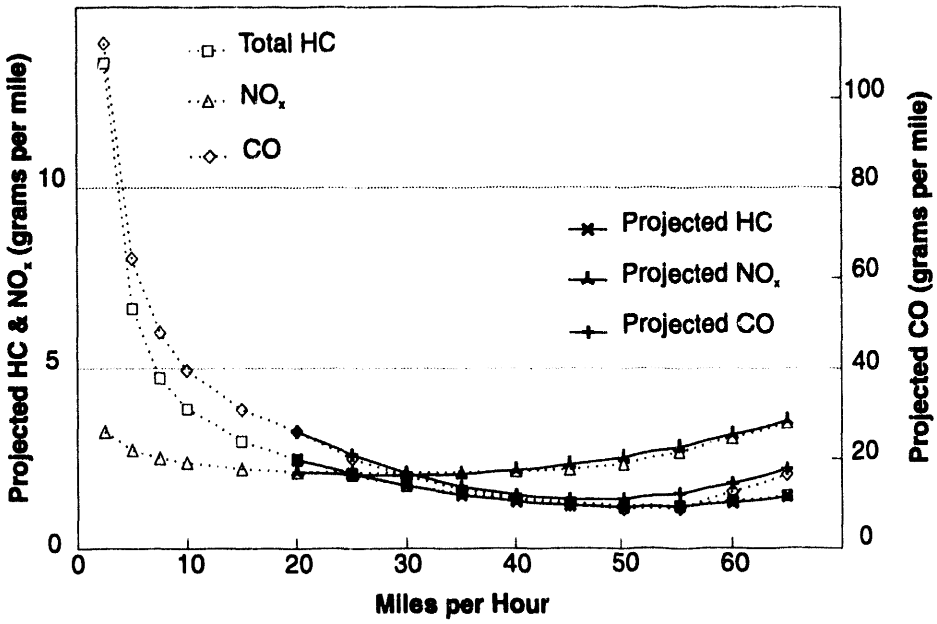

Figure A-11. Emissions as a Function of Average Speed: All Vehicles, Annual Average, MOBILE5 Baseline Projection, Year 2010

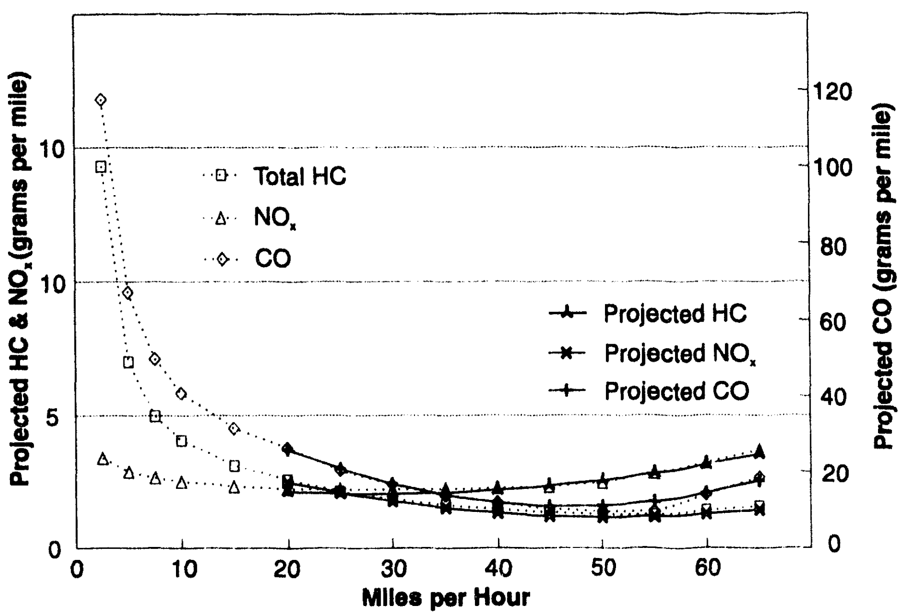

Figure A-12. Emissions as a Function of Average Speed: All Vehicles, Annual Average, MOBILE5 Baseline Projection, Year 2005

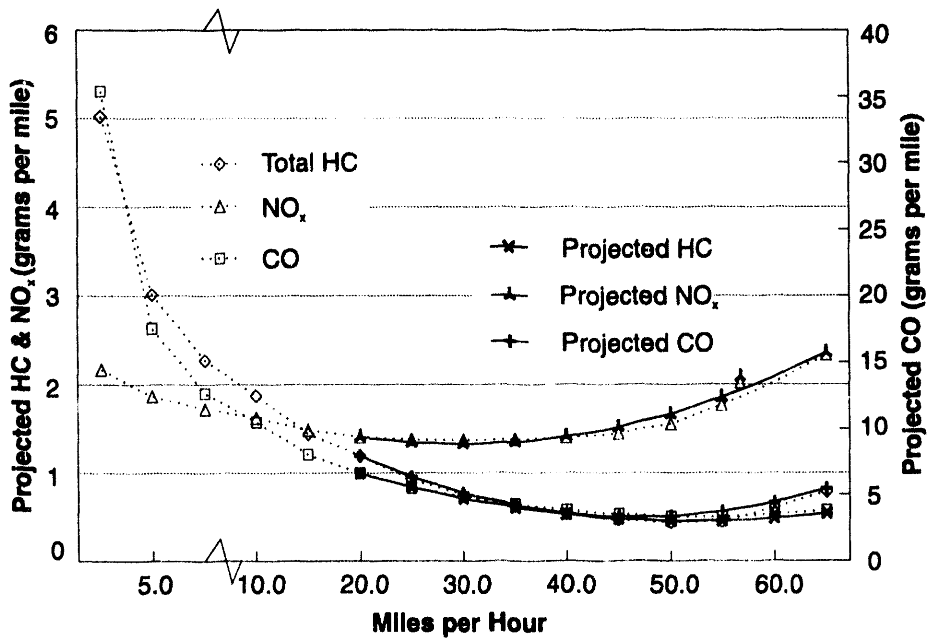

Figure A-13. Emissions as a Function of Average Speed: Low Emissions Scenario, Year 2010

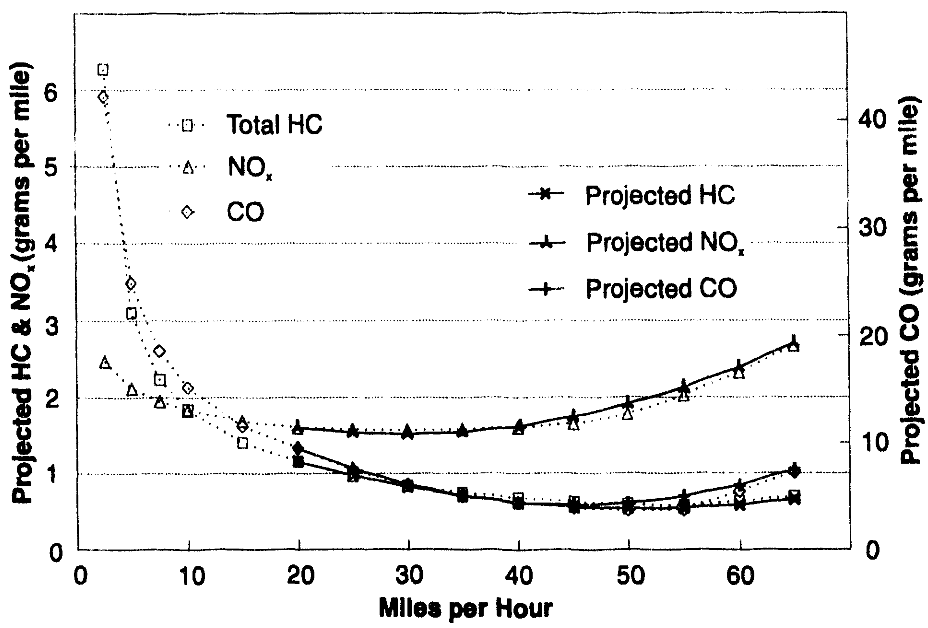

Figure A-14. Emissions as a Function of Average Speed: Low Emissions Scenario, Year 2005

$$\Delta e/\Delta v = A + B \times v \quad \text{(A-22)}$$

and for small changes in v,

$$e(v) = e(v_0) + \{A + B \times [(v-v_0)/2]\} \times (v-v_0) \quad \text{(A-23)}$$

Although equation A–22, using the parameters in Table A–4, fits the EPA MOBILE5 data exactly, the emissions effects produced by this analysis must be treated as gross approximations that are only indicative of the nature of the true effects. Researchers have recently come to understand the serious shortcomings of emissions inventory models such as MOBILE5 for forecasting emissions in real-world conditions. A recent study (NRC, 1991) concluded that inventory models may underestimate real-world HC emissions by a factor of 2 to 4, and that substantial errors may well exist in the prediction of other criteria pollutants. Recent research on the relationship between traffic flow and emissions has shown that rare events of extreme acceleration and a minority of poorly maintained vehicles account for a majority of emissions. Nonetheless, the relationship between speed and emissions, as represented in MOBILE5, represents the current state of the art in emissions modeling.

Table A–4. Parameters Relating Changes in Emissions Rates to Average Speed

	Baseline Scenario		RFG and I/M Scenario	
	A	B	A	B
2005				
Hydrocarbons	-0.15726	0.002978	-0.06860	0.001280
Carbon Monoxide	-2.16556	0.044851	-0.80515	0.016896
Nitrogen Oxides	-0.07734	0.002463	-0.06072	0.001890
2010				
Hydrocarbons	-0.14734	0.002763	-0.05635	0.001033
Carbon Monoxide	-2.02458	0.040704	-0.60628	0.012218
Nitrogen Oxides	-0.07015	0.002231	-0.05227	0.001605

Readers should interpret the projections with great caution, however, and probably give credence to only the general direction and order of magnitude of estimated effects.

Vehicle fuel economy is strongly related to average speed. At lower speeds (below 40 to 50 mph) the relationship is due to a strong correlation between the number of acceleration episodes and idling periods and average speeds (Murrell, 1980). At higher average speeds, fuel economy approaches that achieved in steady-state cruising at constant speed. Overall, fuel economy increases with increasing speed up to an optimal velocity, and then decreases with increasing speed, primarily because of increasing aerodynamic drag.[5] The precise shape of the curve and location of the optimal fuel economy speed depends on vehicle technology. Recently, An and Ross (1993) have estimated fuel economy for a hypothetical automobile with average characteristics over a variety of driving cycles used to test fuel economy and emissions. Plotting these points (labeled "avpwr" in Figure A–15) versus average test-cycle speed shows the expected pattern of increasing fuel economy with increasing speed. Data for fuel economy at steady-state cruising for a typical 1984 model year U.S. light-duty vehicle, taken from Davis and Strang (1993) is plotted on the same graph (labeled "84"). Steady-state fuel economy is higher than test-cycle fuel economy at low speeds, but the curves seem to converge as speed increases.

Quadratic functions appear to give a reasonable fit to the speed versus fuel economy data, as shown by the points labeled "S" and "T." A quadratic function fitted to a hybrid of the test cycle and steady-state data is used to project changes in fuel consumption for this analysis. Up to 50 mph, the test-cycle data points are used. For 50 mph and beyond, the steady-state data were added to complete the curve. The resulting curve increases from about 10 mpg at 7 mph, to 25 mpg at 25 mph, to a maximum of 31 mpg at about 48 mph, declining to 26 mpg at 65 mph. The hypothetical car on which this curve is based gets 20.1 mpg on the EPA city cycle and 32.7 mpg on the highway cycle for an EPA rating of 24.3 mpg.[6] Using 24.3 mpg as an estimate of the in-use fuel economy implies an equivalent EPA test-cycle rating of 28.6 mpg. In

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[5]Because aerodynamic drag increases with the square of velocity, it eventually dominates other forces opposing the motion of the vehicle.

[6]The EPA rating is a weighted harmonic mean of the city and highway fuel economy numbers, using weighing factors of 55 for city and 45 for highway. In-use fuel economy tends to be about 15 percent lower than the EPA ratings.

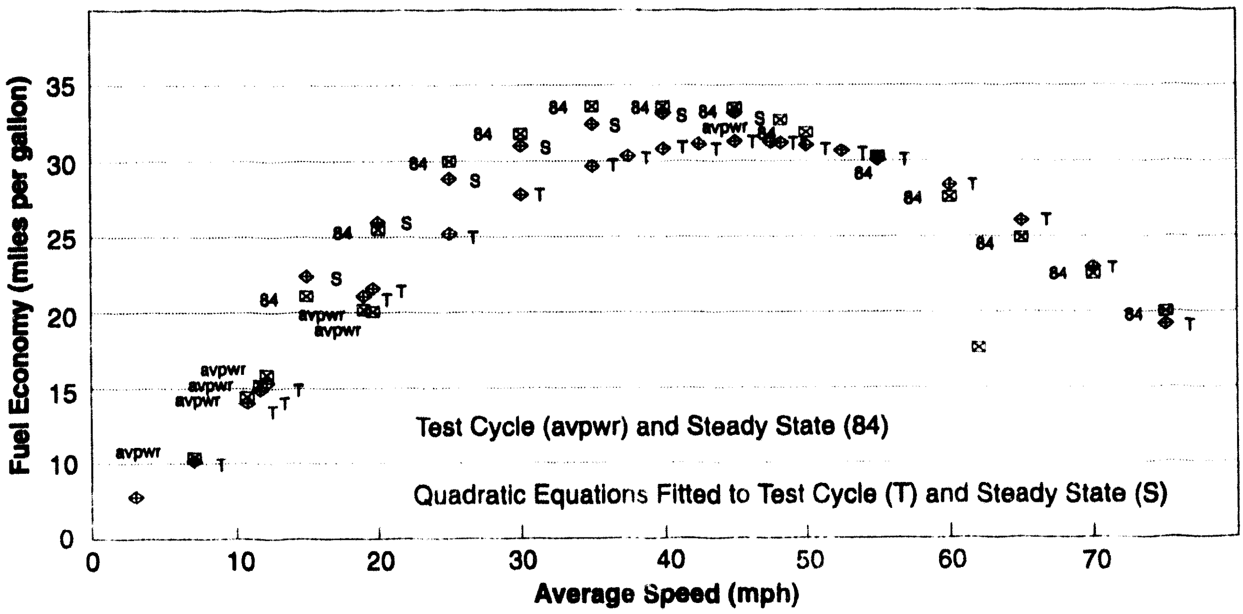

Figure A-15. Estimated Relationship Between Average Speed and Fuel Economy

1993, the average EPA fuel economy for passenger cars was 28.0 mpg and for light-duty trucks was 20.8 mpg, giving a combined average of 25.0 mpg (Murrell, Hellman, and Heavenrich, 1993). Thus, the fitted curve is a reasonable representation of onroad fuel economy for new automobiles today.

The Federal Highway Administration (FHWA) estimated average in-use fuel economy for all vehicles as 16.4 mpg in 1990 (DOT, FHWA, 1991). Using the equivalent of 24.3 mpg for all traffic would be equivalent to a 44-percent increase in realized fuel economy. The Energy Information Administration (EIA) projects a 10-percent increase in onroad fuel economy over 1990 levels for light-duty vehicles by 2005 and a 15-percent increase by 2010. Using the EIA light-duty vehicle improvement for all vehicles in 2005, and extrapolating to a 25-percent improvement by 2010 results in an average mpg for all vehicles of 18.0 in 2005, and 20.5 mpg in 2010 Thus, for indirect fuel savings in the year 2005 analysis, mpg projected by the quadratic function is discounted by a factor of 0.75, and for the 2010 analysis it is multiplied by

0.85. For direct fuel savings this report assumes that telecommuters are using light-duty vehicles. The EIA projection is an average of 20.6 mpg in 2005 and 23.2 mpg in 2010 (projected by extrapolation), implying correction factors for direct fuel savings of 0.85 in 2005 and 0.95 for 2010.

Quantifying Effects

The effects of telecommuting consist of time savings to telecommuters and other travelers because of changes in traffic delay; fuel savings because of a net reduction in VMT and a change in efficiency produced by increased speed; reduced emissions levels—total hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x); and the avoided costs of highway construction and maintenance.

Time costs are quantified as hours of delay (increased or decreased) and also in terms of dollars by multiplying by an assumed value of time of $10 per hour (Chui and McFarland, 1987).[7] Fuel costs are measured in gallons and translated into dollars using the 1990 average price of gasoline—$1.22 per gallon in 1988, increasing to $1.40 per gallon in 2005 and $1.55 per gallon in 2010 (EIA, 1993). Because State and Federal taxes are not true costs by transfer payments, $0.30 per gallon is subtracted from the projected prices to account for motor fuel taxes.

Emissions are measured in metric tons and can be valued at either the avoided cost of alternative pollution control measures (Greene and Duleep, 1992) or estimates of their damage (Wang, Sperling, and Olmstead, 1993). These are shown in Table A–5.

Highway construction and maintenance costs are the avoided costs of highway capacity that does not need to be constructed because of reduced travel volumes. Average national costs per lane-mile are based on the average cost of widening, that is, adding lanes to existing facilities. This is expected to be the most common form of capacity expansion in urban areas in the future. Cost estimates for lane additions to interstate, other urban freeways and

[7]$10 per hour is the equivalent of Chui and McFarland's estimate inflated to 1990 dollars.

expressways, and principal arterials, divided by the appropriate mileage of the systems (FHWA, 1991) are shown in Table A–6. Values of $2.5 million per lane-mile and $1.3 million per lane-mile are used for freeways and arterials, respectively.

Table A–5. Air Pollutant Cost Estimates per Metric Ton

Pollutant	Damage Cost[a]	Avoided Cost[b]
Nitrogen Oxides	$26,400	$2,000
Carbon Monoxide	$9,300	$300
Hydrocarbons	$18,600	$3,350
Carbon Dioxide	$10 to $100	—[c]

[a]Based on conditions in Southern California.
[b]Based on average U.S. conditions. Avoided costs for California are closer to damage costs.
[c]The NRC (1991) study classified options for mitigating greenhouse gas emissions into three categories: Low cost, $0-$9 per metric ton of CO_2 equivalent emissions; Moderate cost, $10-$99 per ton; and High cost, $100 or more per ton.

Table A–6. Estimated Average Highway Construction Costs per Lane-Mile (million 1990 dollars per lane-mile)

Highway Type	Outside Central City	Central City
Freeways and Expressways	$2.5	$3.7
Other Principal Arterials		
Divided	$1.4	$2.0
Undivided	$1.2	$1.6

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