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METHODOLOGICAL ISSUES IN THE ESTIMATION OF THE TRAVEL, ENERGY, AND AIR QUALITY IMPACTS OF TELECOMMUTING

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Abstract—This paper addresses methodological issues in the estimation of travel-related impacts of telecommuting, based on findings from eight telecommuting pilot programs. Several of the studies address energy use (both travel-related and home-based) and one provides information on emissions of air pollutants. These findings are analyzed as well. Travel impacts examined include weekday person- and vehicle-miles saved due to a reduction in commuting, overall weekday travel reductions, and other changes in travel patterns for the telecommuter and the household. Some important issues regarding the estimation of these impacts, their use outside of the pilot programs, and their use in estimating energy savings or reductions in emissions are discussed. In particular, it is cautioned that early, short-term findings from small programs with participants unrepresentative of the population as a whole may change considerably as telecommuting moves into the mainstream.

1. INTRODUCTION

Telecommuting is often cited as a promising strategy for reducing travel demand. Regional air quality regulations (e.g., the South Coast Air Quality Management District Rule 15 and the Bay Area AQMD Regulation 13 in California) and in some cases, state and federal policy (e.g., the State of Washington's 1991 commute trip reduction law and the Federal Flexible Workplace Program) support the promotion of telecommuting as one approach to reducing peak-period vehicle trips. However, although empirical data on the transportation, energy, and air quality impacts of telecommuting are mounting, answers to a number of important questions currently rest on scanty evidence. Furthermore, the relationships between telecommuting and those impacts are more complex than is generally realized, and are changing over time.

This article examines existing empirical findings with respect to the impacts of telecommuting on travel, energy use, and air quality. These findings were generated by several telecommuting pilot projects that included evaluations of the transportation-related impacts of telecommuting. In all, eight studies, representing a total sample of 382 telecommuters, were analyzed. Four of these studies were located in California, two in other western states (Arizona and Washington), one on the east coast, and one in the Netherlands. The studies took place over a 6-year period, between 1986 and 1992. Sample sizes and methodologies for each of these studies are presented in the following section. For additional background on the studies, the reader is referred to Handy and Mokhtarian (1993b) and to the individual references relating to each project. Not all studies have analyzed the air quality and energy impacts, but most studies make reference to these potential benefits of telecommuting. We demonstrate the complex relationship among telecommuting and its travel, air quality, and energy impacts, and illustrate the need for a careful linkage among them. Although the evaluation methods and the reporting of data vary considerably with respect to quality and comprehensiveness, collectively, these studies represent the best efforts to date at analyzing the travel and travel-related impacts of telecommuting.

The content of this article is organized as follows. First, the methods used to analyze the impacts of telecommuting in the studies are compared against a research ideal. Second, the reported travel impacts are examined, including savings in commute travel and total weekday travel as well as other changes in travel patterns. Third, energy impacts due to travel savings and increased household consumption are presented, followed by a description of the implications for air quality. Possible long-term impacts, for which little evidence currently exists, are also outlined. Factors affecting impacts of telecommuting in the future are examined. Finally, key findings are summarized.

2. PROGRAM EVALUATION METHODS

The methods used to evaluate the transportation impacts of the eight programs studied here vary widely, from simple questionnaires to full travel diary surveys. The sophistication of the method is related to the intent of the analysis. In some cases, transportation impacts were the primary concern of the evaluators (e.g., the State of California, the Netherlands); in others, the travel savings were taken for granted and the evaluation focused on the impact of telecommuting on work quality and satisfaction (e.g., Bell Atlantic, Arizona/AT&T). Differences in evaluation methodologies may drive some of the differences in findings between studies.

Several hypotheses regarding the short-term potential impacts of telecommuting on travel have appeared in the literature (e.g., Mokhtarian, 1991b; Salomon, 1985) and are addressed to varying degrees by the studies analyzed here. These hypotheses, relating to the impacts of telecommuting on work and nonwork travel, mode choice, trip chaining, time of day of travel, destination, and person making the trip, highlight the complicated nature of tripmaking behavior and hence the complexity of the effects of telecommuting on that behavior. Fully analyzing those effects, then, requires a complex methodology.

The ideal evaluation method would include travel diary surveys before and after the start of the telecommuting program. Travel diary surveys collect data on nonwork travel as well as the commute trip, and provide data on travel mode, destination (and thus, distance), time of day, and travel time. For the evaluation of telecommuting, such a survey should cover both telecommuting days and nontelecommuting (i.e., regular commuting) days. A full 7-day diary would permit an analysis of the shifting of trips not only between telecommuting and nontelecommuting days but also between weekdays and weekends. Surveys before and after the start of the program allow for an evaluation of changes that have occurred. Multiple after-surveys would allow for an evaluation of how these changes evolve over time: do the initial impacts taper off as the novelty wears off or do the impacts increase as people become accustomed to telecommuting?

In addition to the telecommuters, household members should also be surveyed. The household member surveys will reveal changes in trip responsibilities among household members that might occur as a result of telecommuting (e.g., the telecommuter now does the grocery shopping on his or her telecommuting day). These surveys also permit a more accurate analysis of emissions impacts by providing a complete picture of the trips made by a given household vehicle, not just the telecommuter's use of that vehicle. Without data from the entire household, for example, it would not be possible to determine whether an auto trip by a telecommuter involved a hot start or a cold start.

Finally, a control group of nontelecommuting employees (and their household members) should be surveyed as well. The control group's behavior will reflect background changes affecting everyone, and thus will provide a base against which the travel characteristics of the telecommuters can be compared. For example, a sizable increase in gasoline prices, or a nationwide recession, could be competing explanations for an observed reduction in discretionary travel after telecommuting begins. Having a control group permits the effects of such broadly applicable factors to be isolated from the effects specific to telecommuting.

Although this approach is ideal from a research perspective, it poses a severe burden to the respondent. Before and after (panel) surveys suffer from a number of problems (Kitamura, 1990). Respondents to the first survey (wave) may drop out of the program, move away, or simply fail to complete subsequent waves, resulting in *attrition*. Such attrition is probably selective: that is, dropouts may differ materially from "stayers". To the extent this is true, the generalizability of the results is weakened. Those respondents who do complete later waves are subject to *panel fatigue*: a decline in accuracy in recording their trips as time goes on. A related problem is *panel conditioning*, whereby the fact of participating in the panel and early responses themselves influence later responses. Fatigue and conditioning effects across waves are not likely to be serious when several months elapse between each wave. However, fatigue and conditioning effects within wave can be substantial—the more so the longer each survey period runs. As a result, the researcher must make a trade-off between the complexity of the analysis that can be performed (which depends on the comprehensiveness of the data) and the quality of the data collected.

Table 1 displays the sample sizes and evaluation methodologies of the eight studies analyzed here. Three of the studies embody many of the elements of the ideal evaluation. The *State of California Pilot* study (Pendyala et al., 1991; Sampath et al., 1991, 1992) used a 3-day travel diary, administered to telecommuting state employees, their adult (i.e., driving age, 16 years or over) household members, and to a control group of nontelecommuting state employees and their driving-age household members. Two surveys were administered, the first 0 to 6 months before the start of telecommuting and the second 10 to 13 months after. Although 137 telecommuters completed the "before" survey, only 73 of these also completed the "after" survey; it is not clear how many telecommuters were still participating at this time but failed to complete the second survey.

The *Puget Sound* study (Quaid & Lagerberg, 1992) employed a similar method. Two-day travel logs were completed by telecommuters, a control group of employees, and household members of driving age for both groups. Three such surveys were administered, at the beginning, in the middle (about 6 months into the program), and at the end of the 12-month pilot project. Of 286 telecommuters originally selected for the project, 63 completed all three travel diaries, while 26 control households also completed all three diaries. The results presented here are the preliminary findings reported to date. Further cleaning and analysis of the travel diary data are underway, and final published results may differ somewhat from those discussed here.

The *Netherlands* study, that evaluated two separate telecommuting programs (Hamer et al., 1991; 1992), also used a relatively comprehensive evaluation method. A 7-day travel diary was administered to the telecommuters and their adult (i.e., 18 or older) household members. One "before" survey was administered and four "after" surveys were administered at 3-month intervals, for a total of five waves in the first program; only four waves were completed in the second program. These multiple waves allowed for a testing of changes in the impacts of telecommuting over time and were also used by the evaluators to artificially increase the size of the sample by pooling the surveys from each

Table 1. Sample sizes and methodologies used in studies examined

	Sample Size	Before (B) & After (A)	All Trips (Diary)	Multiday	Household	Controls
State of California	73	1 B, 1 A wave	✓	3 days	✓	✓
Puget Sound	63	1 B, 2 A waves	✓	2 days	✓	✓
Netherlands	30	1 B, 3–4 A waves	✓	7 days	✓	
SCAG	18	(✓)*	partial	partial day		
San Diego	34	(✓)*	partial	partial day		
Arizona/AT&T	99	(✓)*				
Bell Atlantic	50	(✓)*				
REB	15	(✓)*				

*(✓) Indicates that a before-and-after comparison (primarily of commute-travel impacts) was implicitly derived from "after" assessments of commute length and frequency of telecommuting.

wave. No control group was included in the two studies, as the researchers felt that these employees would have very little incentive to participate in the evaluation because they were not also participating in the telecommuting program.

A reservation should be made about the Netherlands study. The Dutch (and other European) travel patterns are much different from those in the United States. The role of the automobile is not as prominent in Europe and consequently, demand management technologies are likely to have differential effects. Thus, the impacts of telecommuting on travel in the Netherlands may not be directly comparable to the U.S. experience. However, that study is included here for several reasons. First, a major emphasis of this article is on the need for methodological rigor. The Dutch study is among the most rigorous conducted to date, and as such deserves attention. Second, an international perspective is broadly useful, and in particular the Netherlands experience with telecommuting provides an important balance to that of the U.S. precisely because of its contrasting policy environment. Third, the Dutch study qualitatively corroborates and enhances the insights offered by the U.S. studies. And finally, note that quantitative results from that analysis are incorporated here only with respect to comparing commute lengths of telecommuters to the regional average (Table 2), where the findings are consistent between the two countries.

In contrast, the most basic approach consisted of a simple questionnaire of telecommuters with respect to their commute distance to work. This approach was used in the *Arizona/AT&T* (Behavior Research Center, Inc., 1990), *Review and Evaluation Branch* (a branch of the Department of Social Services of the State of California—REB, 1992), and *Bell Atlantic* (Wycech & Cuddington, 1991) studies. Nonwork travel was not evaluated, no control group was included, and household members were not surveyed. The assumption used to calculate transportation impacts in these studies is that travel decreases by the round-trip commute distance on telecommuting days. The fact that not all telecommuters would otherwise drive to work is not always factored into the impact calculations. Because the travel benefits of telecommuting were largely taken for granted, very simple methods were used to evaluate travel impacts and greater attention was devoted to evaluating the impacts on work quality and satisfaction.

The *Southern California Association of Governments* (SCAG—Mokhtarian et al., 1988) and *San Diego* (Mokhtarian, 1991 and forthcoming) studies used more complex questionnaires which asked about commute distance and mode, but also attempted to evaluate the impacts on nonwork travel by asking telecommuters to record any trips made during normal work or commute hours on their most recent telecommuting day. For each of those trips, respondents indicated whether, if they had not telecommuted, the same place would have been visited at the same time, at a different time on the same day or on a different day, whether a different place would have been visited instead, whether that activity would not have taken place, or whether someone else would have made the trip. This question, although hypothetical, allows for some evaluation of the possible generation of nonwork trips on telecommuting days (at least during normal work and commute hours). No control group or household members were surveyed in these two studies.

Table 2. Telecommuters' commute distance, mode split, and vehicle-miles

	Average Roundtrip Commute Distance (mi)	Percent Drive-Alone	Commute Vehicle-Miles Saved/ Telecommuting Occasion	Regional Average Two-Way Commute Distance (mi)	Ratio of Telecommuters' to Regional Commute Distance	Sample Size
State of California	39.0	81%	31.6	21.6	1.81	73
Puget Sound	36.0	63%	22.7	20.0	1.80	63
Netherlands					2.00	30
SCAG	42.0	67%	28.1	18.0	2.33	18
San Diego	38.8	79%	30.7	21.6	1.80	34
Arizona/AT&T	31.1	74%	23.0			99
Bell Atlantic	40.0					50
REB	30.0					15
Weighted average	36.1	74%	26.3		1.87	382

Most of these studies used a variety of other techniques to collect data from telecommuters, though usually to evaluate impacts other than travel impacts. The Puget Sound Study, for example, used questionnaires, focus groups, case studies, informal observation, and follow-up interviews as well as the travel diaries. The SCAG study used selection surveys, before and after attitude surveys, telephone interviews, timesheets, receptionist logs, round table discussions, and personal interviews to evaluate the telecommuting program. These multiple sources sometimes allowed the researchers to compare estimates of various impacts based on different sources and thus to draw conclusions about the probable margin of error in the data.

A few studies were careful to screen respondents to ensure that unusual or inappropriate cases were omitted from the analysis. For example, the Netherlands study omitted data from households that experienced "unusual circumstances" during a particular wave, such as an illness, a residential move, or maternity leave, that may have caused abnormal travel patterns at that time. In the San Diego study, 5 out of 34 cases were eliminated from the analysis of commute travel impacts because it was determined that these telecommuters would not have made a commute trip had they not been telecommuting, an issue discussed further in Section 3.1. In addition, data from three respondents who had stopped telecommuting 3 to 7 months before the survey and three who could not recall the most recent telecommuting day were discarded from the analysis of nonwork trip impacts. The lack of consistency between studies with respect to the screening of respondents prior to the analysis may further muddy a comparison of the findings.

3. TRAVEL IMPACTS

3.1. Change in commute travel

The personal commute travel saved per telecommuting occasion is equivalent to the telecommuter's usual round-trip commute distance. (A telecommuting occasion, or telecommuting person-day, is defined as a day on which a given individual telecommutes). In the studies reviewed, the savings range from 30 to 45 person-miles, with an average (weighted by sample size) across studies of 36.1 person-miles per telecommuting occasion (Table 2, first column).

However, not all person-miles eliminated will result in a decrease in vehicle-miles. For example, if a participant telecommutes instead of taking the bus to work, the bus still makes its trip and no vehicle-miles are eliminated. Thus, in general, only those commute trips that would have been drive-alone trips will reduce vehicle-miles. For the five studies that provide mode split data, the percent of drive-alone trips ranges from 63% to 81%. If mode split is factored in, the commute savings drops to an estimated 23 to 31 vehicle-miles per telecommuting occasion. The weighted average distance times the weighted average mode share results in an average of 26.3 vehicle-miles saved per telecommuting occasion (Table 2).

Several points should be noted. First, the relationship between person-miles and vehicle-miles reduced is not always straightforward. The estimation of vehicle-miles just presented makes the assumption that the mode split of commute trips eliminated due to telecommuting is the same as the overall commute mode split; that is, that telecommuting "borrows" mode share proportionally from all modes. The San Diego study analyzed mode split for commute trips before and after telecommuting and found it to be virtually constant. This may not generally be the case, however. For example, in the second phase of the Netherlands study, nearly all telecommuting occasions replaced transit or biking trips rather than car trips. As a result, telecommuting did not lead to any reduction in automobile travel. This study suggests that the most difficult trips are eliminated, which will often be those made by nonautomobile modes. Researchers have also hypothesized that if telecommuters drop out of a carpool, the carpool may disintegrate, leading to an increase in vehicle-miles-traveled (VMT). However, the San Diego study found no evidence of termination of carpool arrangements due to telecommuting, and all of the studies reviewed here showed an overall decrease in VMT (or, for the second Netherlands study, no increase). Nevertheless, there may be individual instances of negative impacts on VMT due to changes in mode choice.

Second, there is a wide range in commute distance within each study. For example, in the San Diego study, distances ranged from 3 to 50 miles. There is also variation in the frequency distribution of commute distance among studies. For example, in the SCAG study, 11% of telecommuters lived 10 miles or less from work and 39% lived more than 20 miles away, while in the Arizona/AT&T study, 25% of workers lived 10 miles or less from work and only 24% lived more than 20 miles away (Fig. 1). It is also important to note how commute distances of telecommuters compare to the average commute distance for the region in which they live and work. The regional average round trip distance itself varies between 18 and 22 miles. Furthermore, the ratio between the average commute for telecommuters and the regional average differs between studies, with average commute distances for telecommuters ranging from 1.8 to 2.3 times the regional average (Table 2). The use of an average distance per telecommuting occasion masks this variation among telecommuters, organizations, and regions.

The fact that telecommuters have substantially longer commutes on average than other workers in the region suggests that early adopters of telecommuting may be unrepresentative of the pool of potential telecommuters in many ways. Of particular interest here, telecommuting pilot programs that are implemented for transportation-related reasons (all of the programs reviewed here were at least partly implemented for transportation-related reasons) may explicitly or implicitly bias participation toward those with longer commutes. As telecommuting becomes more widely adopted, it is expected that the average commute length for telecommuters will drop closer to the regional average.

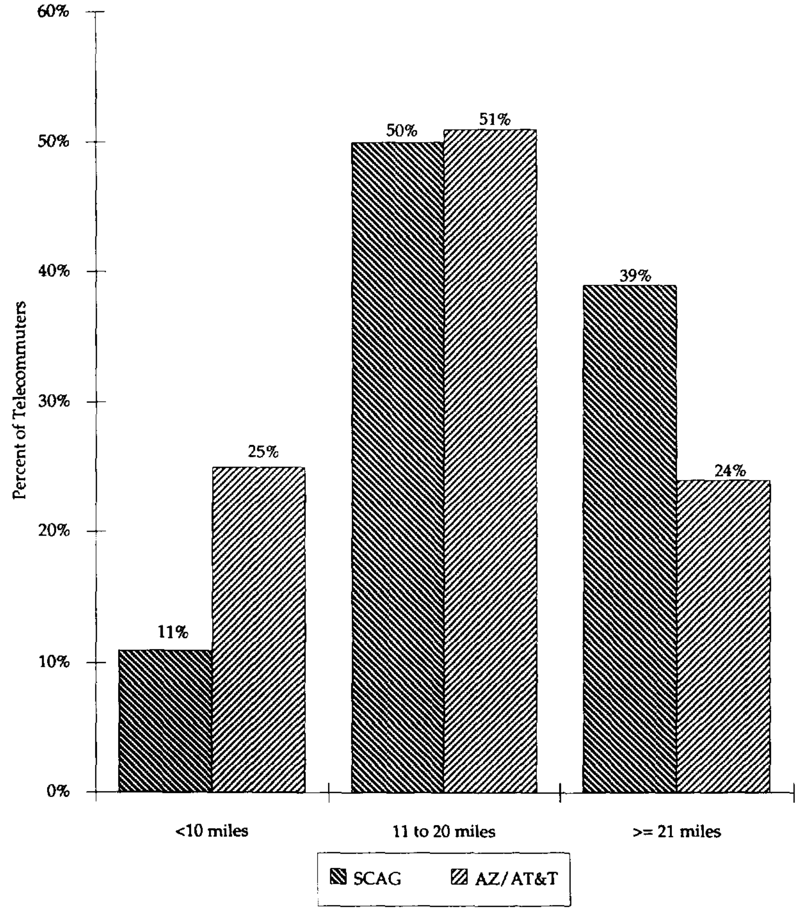

Fig. 1. Frequency distribution of commute distance.

Thus, it is important to realize that using the factors presented here to project future travel savings due to telecommuting may overpredict those impacts.

Impacts may also be overpredicted if not all telecommuters actually eliminate a work trip when they telecommute. In the San Diego study, for example, five telecommuters did not eliminate their commute trip: a nontrivial 15% of the (admittedly small) sample of 34. These cases involved three telecommuters who worked at home during pregnancy and while recovering from surgery (who would not have worked without the telecommuting opportunity), one who switched from part-time to full-time (whose commuting days did not change), and one who worked at home part of the day and at the office part of the day (whose trips thus shifted but did not decrease). Whereas this finding does not directly affect the estimation of the impact per telecommuting occasion, it points to the need to carefully define telecommuters and telecommuting occasions to ensure that the impact is ascribed only to cases where commute trips are eliminated.

3.2. Change in total weekday travel

It has been suggested that telecommuting, while reducing commute travel, could lead to increased noncommute travel. For example, Salomon hypothesized in 1985 that "the substitution of telecommunications for travel is of minor importance, because, even if it happens, it will be offset by the human desire to exercise mobility." The idea is that mobility not only serves the function of getting one to places but that it also fulfills a desire to move around freely, to be acquainted with the physical, social and "informational" environment (Salomon & Koppelman, 1992). Thus, after working at home for a few hours or a few days, one may invent reasons to get out and go somewhere for a change of scenery (a phenomenon commonly referred to as "cabin fever").

An increase in noncommute travel might occur due to any number of factors: a psychological need for mobility, the availability of a vehicle to another household member, or the direct stimulation of travel for work-related activities such as trips to the post office (Mokhtarian, 1991b). Any increases in noncommute travel by telecommuters or their household members would at least partly offset savings due to decreases in commute travel. As a result, it is important to evaluate the impact of telecommuting on total travel, not just commute travel. However, to minimize the burden on the respondent (as discussed in Section 2), most studies that examine the total travel impacts at all focus on weekday travel alone. This is a crucial point in understanding the reported results, as is considered further in Section 3.3.

Two approaches to estimating the impact of telecommuting on total weekday travel have been used. The first approach, employed in the State of California, Puget Sound, and the Netherlands studies, involved multiple-day travel diary surveys both before and after the start of the telecommuting program. This approach provides a record of nonwork as well as work trips made during the survey period. Results from the State of California and Puget Sound studies, shown in Table 3, indicate that, surprisingly, total travel savings are slightly higher than commute savings alone. In the State of California study, total travel decreased by 40.5 person-miles on telecommuting days, of which 39 person-miles can be explained by the elimination of the commute trip. In the Puget Sound study, total travel decreased by 39 person-miles, of which 36 miles can be explained by the elimination of the commute trip. The ratios between total miles saved and commute miles saved were 1.04 (40.5 vs 39 person-miles) and 1.08 (39 vs 36 person-miles), respectively, or a weighted average of 1.06 (Table 3). In other words, total travel savings is about 6% higher than the savings in commute travel, or about 40 person-miles per telecommuting occasion, for the California State and Puget Sound studies.

The finding that total travel savings are greater than commute travel savings alone implies that noncommute travel actually decreases as a result of telecommuting. This is consistent with the first program in the Netherlands study, which also showed that nonwork travel decreased slightly from before telecommuting, by about 15%. However, in the second Netherlands program, no significant change in nonwork travel was found. By showing a slight decrease or no change in nonwork travel, these studies thus provide no support for the hypothesis that nonwork travel increases for telecommuters.

Table 3. Total travel savings on telecommuting days

	Person-Miles Traveled per Weekday						
	Before Telecommuting	After Telecommuting	Total Person-Miles Saved*	Total Percent Savings*	Commute Person-Miles Saved*	Ratio of Total to Commute PM Saved	Sample Size
State of California	53.7	13.2	40.5	75.4%	39.0	1.04	73
Puget Sound	52.0	13.0	39.0	75.0%	36.0	1.08	63
Weighted average	52.9	13.1	39.8	75.2%	37.6	1.06	136

*We emphasize that these numbers represent per-telecommuting-occasion savings on weekday travel, for employees who tend to live farther from work than average. See Section 3.3 for additional discussion.

There are several possible reasons for the observed decrease in noncommute travel. Perhaps the most likely reason is that nonwork activities normally linked to the work trip are potentially being shifted to regular commuting days or eliminated altogether. Or, as indicated in Section 3.5, the telecommuter may be finding new destinations closer to home at which to conduct nonwork activities. There may be a perceived threshold "cost" to getting dressed to go out. As a consequence of participating in a telecommuting pilot, there may be a heightened awareness of the need to reduce travel to mitigate congestion (an example of the panel conditioning described earlier). Panel fatigue could also be a factor: under-reporting is more likely to be a problem in the second survey—made during the telecommuting program—than in the first, or "before" survey. An increase in under-reporting in the second survey would show a decrease in travel that had not truly occurred. In the State of California study, the number of trips made by a control group of nontelecommuting employees also decreased between the first and second studies, although the decrease was statistically insignificant. Thus, it is possible that at least part of the apparent decrease in nonwork travel for telecommuters was due to respondent fatigue in this study. Finally, intentional falsification cannot be ruled out: when respondents know that telecommuting is being implemented as a trip reduction measure, there may be an incentive to under-report across the board, especially any trips made during hours the respondent was expected to be working.

The studies employing travel diary surveys also provide a basis for estimating the percentage of total weekday travel that the reduction in travel due to telecommuting represents. The California State and Puget Sound studies found similar savings of 75.4% (40.5 out of 53.7 person-miles saved) and 75% (39 out of 52 person-miles saved) per telecommuting occasion, respectively (Table 3). The Netherlands study found a savings of 14% to 16% per week, or about 58% to 67% per telecommuting occasion. The significant difference between this value and those of the two U.S. studies may result from significant differences in travel patterns in the two countries. Nevertheless, all three values are quite high, and deserve further discussion. These findings are interpreted in Section 3.3.

In the second approach to estimating the impact on total weekday travel, employed in the SCAG and San Diego studies, respondents recorded trips made during work and commute hours on their most recent telecommuting day and indicated whether or not the trip would have been made had they not been telecommuting. Less than one such trip was made on average per telecommuting occasion (0.9 trips for SCAG and 0.3 trips for San Diego), but only about 5% of these trips would not have been made if the telecommuter had worked at the office instead of home. In the SCAG study, this implies that only 0.04 nonwork trips are induced during work hours on telecommuting days, resulting in an additional 0.3 miles of travel. However, these studies did not ask about nonwork trips not made as a result of telecommuting; the methodology could not reveal a decrease in nonwork travel. Thus, the current available evidence points to relatively insignificant impacts on the amount of noncommute travel due to telecommuting.

Given the apparent insignificance of the impact of telecommuting on noncommute travel, it can be assumed that the savings in total weekday travel is equivalent to the savings in commute travel. Across all studies, this suggests that the average savings in total travel per telecommuting occasion is currently 36.1 person-miles (Table 2). However, the finding in the State of California and Puget Sound studies of a slightly higher savings in total weekday travel than in commute travel could be used to generate an optimistic estimate of the total weekday travel impact of telecommuting at present. Applying the ratio between total savings and commute savings from those studies of 1.06 to the weighted average commute savings across all studies generates an estimate of 38.3 total person-miles saved per telecommuting occasion.

The question of total savings in weekday vehicle-miles traveled is more complicated. Again, it can be assumed that the savings in total weekday vehicle-miles traveled is equivalent to the savings in commute vehicle-miles traveled. For an optimistic estimate of savings, the ratio of 1.06 applied to the weighted average commute vehicle-miles saved of 26.3 (Table 2) generates an estimate of 27.9 total vehicle-miles saved on average per telecommuting occasion. However, this approach assumes that mode split is constant for work and for nonwork travel. The State of California study showed that the percentage of trips made by automobile increased from 81.5% before telecommuting to 91.2% on telecommuting days (Pendyala et al., 1991), suggesting that a greater share of nonautomobile trips were eliminated. But in terms of miles of travel, rather than number of trips, the study showed a decrease of 75.4% in miles of travel by all modes (i.e., person-miles traveled), versus a decrease of 77.0% in automobile-miles traveled (Sampath et al., 1992). Given the small magnitude of this difference, it can be assumed that the ratio between total weekday savings and commute savings is about the same for both person-miles traveled and vehicle-miles traveled, although further research on this issue is warranted.

3.3. Discussion of observed travel impacts

Two general findings just presented require further discussion: the 75.2% savings in travel reported by the State of California and Puget Sound studies (Table 3) and the fact that noncommute travel did not increase—counter to the most-frequently expressed hypothesis about the potentially negative travel impacts of telecommuting.

A 75.2% reduction in person-miles traveled appears at first glance to be extravagant. After all, nationwide, commuting accounts for only 22.7% of total person-miles traveled, on average (Pisarski, 1992b). It is important to realize, however, that the latter number presumably covers all annual travel—including weekends, vacations, and travel by nonworkers—whereas the telecommuting finding applies strictly to weekday travel by workers. The average commute proportion of workers' weekday travel will be far higher than 22.7%.

It will not on average, however, be as high as 75.2%. As indicated in Section 3.1, the telecommuters in these studies live about twice as far from work as the regional average, and thus commuting will constitute a higher-than-normal proportion of their weekday travel (71.1% for the State of California and Puget Sound studies combined, as can be calculated from Table 3). Hence, these workers are clearly unrepresentative of the population as a whole. The extent to which they are unrepresentative of the population of potential telecommuters is more debatable (see Sections 7 and 8), but the authors believe that future telecommuters will tend toward more typical commute distances.

A final observation on this point is that the numbers presented are per telecommuting occasion. It was felt that this was the most practical unit to use, because the commute savings accrue on each occasion and because the average number of telecommuting occasions per week may change over time. But any attempts to extrapolate the impacts reported here to the aggregate level must factor in the percent of the workforce that is telecommuting (about 5.8% in California in 1991) and the average telecommuting frequency for those workers (about 1.2 days per week; Handy & Mokhtarian, in press). When this is done, the impact spread over a week will obviously be much smaller than that for a telecommuting day alone—even for an individual telecommuter, much less for the population as a whole. Applying these calculations to California, for example, leads to an estimate that in 1991 telecommuting resulted in a reduction of 0.51% of the statewide total VMT for cars and light-duty trucks (Handy & Mokhtarian, 1993c).

As for the second finding, how are these results from multiple studies, that noncommute travel does not increase to compensate for reductions in commute travel, reconciled with the hypothesized desire for mobility discussed above? The answer again likely lies with the longer-than-average commutes of the telecommuters in these samples. These long-distance commuters may well consider themselves to be traveling too much already (i.e., exceeding some desired travel time budget, due to external factors such as housing costs, a spouse's job location, or other locational constraints), and grateful for an opportunity to reduce absolutely the amount they travel.

It may be the case that telecommuters who live closer to work than, say, the regional average would be more likely to increase their noncommute travel than those who live farther away. If so, those increases would likely also "cancel out" a higher proportion of commute travel savings for those telecommuters (because their commutes are shorter). If telecommuting is adopted by more shorter-distance commuters in the future, then, these early findings on noncommute travel could change. However, situations in which any newly-generated travel exceeds the travel saved may still be the exception rather than the rule; that is, there may still be a significant net savings in travel in the aggregate. In any case, an important area for future research is to study the travel behavior particularly of shorter-distance commuters who telecommute. Re-analysis of existing data may provide some initial insight into this question.

3.4. Change in household travel

It has also been hypothesized that travel by members of the telecommuter's household might increase due to the increased availability of a car to household members or to a change in household responsibilities. This possibility was tested by both the State of California study and the Netherlands study. Both studies found a small but statistically significant decrease in travel by household members, however. In the State of California study, household members made 0.9 fewer trips per day at the end of the telecommuting program, or 23% fewer trips. In the first program of the Netherlands study, household members made 9% fewer trips; no significant change was found in the second program. One possible explanation is respondent fatigue; the State of California study found some evidence of under-reporting by household members in the "after" survey. Panel conditioning (heightened awareness of the need to reduce travel) may be a factor here, as well. Another possible explanation, however, as hypothesized by Pendyala et al., is that both telecommuters and their household members streamline their trip-making activity and visit destinations closer to home as a consequence of the learning process prompted by telecommuting. A conservative estimate of travel impacts would thus assume no reduction in household travel. There is no evidence that household travel increases. In view of the fact that at least in the U.S. studies, telecommuting households tend to have nearly one vehicle per licensed driver, the availability of the telecommuter's auto may be expected to have a negligible impact on household tripmaking.

3.5. Other Changes in travel patterns

As a result of telecommuting, several other changes in travel patterns may occur that could affect the amount of travel, and that will have implications for energy use and air quality impacts whether or not the amount of travel is affected.

3.5.1. Temporal changes. Telecommuting may influence not only the total amount of travel but also the timing of travel. The usual hypothesis is that trips will be shifted out of the peak. Because many (although not all) work trips are made during the peak, the elimination of commute trips due to telecommuting will reduce the proportion of trips made during peak hours, all else equal. In addition, telecommuters may shift some nonwork trips made during the peak into less congested times of day. However, the State of California study found that the share of nonwork trips in the peak period did not change; that is, telecommuters were not more likely to make nonwork trips during off-peak hours than before telecommuting or on nontelecommuting days. As a result, the State of California finding of a 63% decrease in peak-period trips per telecommuting occasion was due almost completely to the elimination of peak-period work trips. Similarly, the Netherlands study found a 19% decrease in peak-period trips (and a 26% decrease in peak-period distance) over a week, or a 79% decrease per telecommuting occasion.

3.5.2. Spatial changes. It can be hypothesized that telecommuters would tend to shift their destination choices closer to home than to work. Such changes in the short-term spatial distribution of trips have been observed. The State of California study analyzed the spatial distribution of destinations around the home and found that 42% of nonwork trips (home-based as well as nonhome-based) were made to destinations within 12.5 miles of the home after telecommuting, versus 35% of nonwork trips before telecommuting (Fig. 2). Unexpectedly, even on nontelecommuting days destinations were likely to be closer to home than before. The result was a contraction in the activity space of telecommuters. These travel changes were also associated with a substantial decrease in the

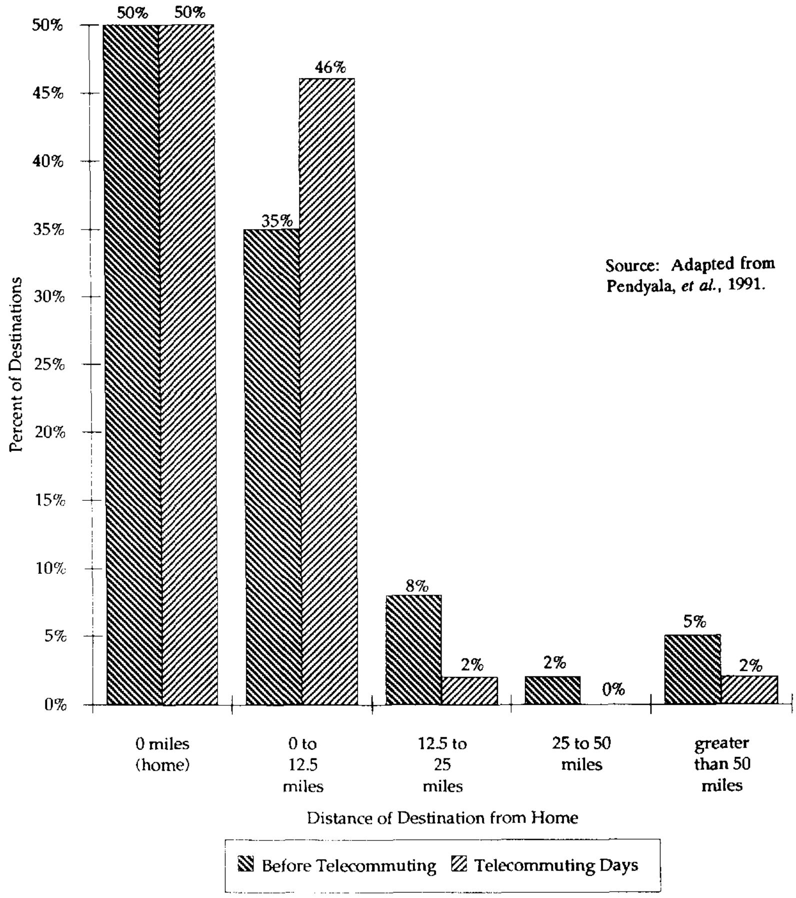

Fig. 2. Changes in spatial distribution of nonwork trips.

percentage of travel on freeways (from 49% on nontelecommuting days to 10% on telecommuting days) and a related decrease in average speed (from 29.9 mph on nontelecommuting days to 23.2 mph on telecommuting days).

3.5.3. Sequential changes. Telecommuting also influences the sequencing of trips and may, in particular, lead to a reduction in trip chaining, or in other words, an increase in the percentage of single-stop trips. The State of California study found that on telecommuting days, 75% of the telecommuter's trips were single-stop, versus 50% on commute days (and 55% prior to telecommuting). This is not surprising, given the elimination of the work trip from the trip chain. It also helps explain the changes in the spatial distribution of destinations just described: instead of stopping at a store near work on the way home, a trip is made from home to a different store that is closer to home. On its own, this finding implies a shift to less efficient trip patterns. However, its impact is clearly outweighed by the decrease in commute travel that results from telecommuting and as previously discussed, it has apparently not resulted in an increase in nonwork travel.

3.6. Summary of transportation findings

The findings with respect to the transportation impacts of telecommuting are summarized in Table 4. The values presented in this table are the averages of the values generated by each available study weighted by the sample size of each study. The studies reviewed here clearly show that telecommuting results in a substantial net reduction in travel on telecommuting days: 26.3 vehicle-miles of commute travel and 75.2% of total

Table 4. Summary of transportation findings

	Weighted Average	Sample Size	Sources*
Round-trip commute distance	36.1	352	a, b, d, e, f, g, h
Percent drive alone	74%	287	a, b, d, e, f
Commute vehicle-miles saved per TC occasion**	26.3	287	a, b, d, e, f
Ratio of telecommuters' commute distance to regional average	1.87	218	a, b, c, d, e
Ratio of total person-miles saved to commute person-miles saved	1.06	136	a, b
Total person-miles saved per TC occasion**	38.3	352	a, b, d, e, f, g, h + ratio from a, b
Total vehicle-miles saved per TC occasion**	27.9	287	a, b, d, e, f + ratio from a, b
Percent of total person-miles saved**	75.2%	136	a, b

*a. State of California (n = 73); b. Puget Sound (n = 63); c. Netherlands (n = 30); d. SCAG (n = 18); e. San Diego (n = 34); f. Arizona/AT&T (n = 99); g. Bell Atlantic (n = 50); h. R.E.B. (n = 15).
**See footnote on Table 3 and Section 3.3 of the text.

person-miles of travel. However, the caveats of Section 3.3 must be kept in mind when attempting to generalize these findings beyond the original samples on which they are based.

4. ENERGY IMPACTS

4.1. Transportation energy impacts

Three methods have been used to estimate the impacts of telecommuting on transportation energy use. In the most simple method, an average fuel efficiency is multiplied by the average number of miles saved to yield an average number of gallons saved. The Arizona/AT&T study applied an assumed overall energy efficiency of 26 miles per gallon (mpg) to the average travel savings to estimate a savings of 1.2 gallons/telecommuting occasion. However, this estimate did not account for the difference between person- and vehicle-miles traveled. When mode share is factored in, the savings drops to 0.9 gallons per telecommuting occasion. The Puget Sound study applied a constant rate of 25 mpg to estimate savings of 1.4 gallons per telecommuting occasion, although it appears that mode split was also not factored into this estimation. With a drive-alone percentage of 63%, the fuel savings drop to 0.9 gallons per telecommuting occasion. Neither study explains the basis for the particular fuel efficiency value used.

Applying averages in this way may mask important individual differences and thus distort the estimate of total savings. A more accurate approach is to estimate fuel savings at the individual level, using each telecommuter's travel savings and self-reported fuel efficiency, and then to average the individual fuel savings. The SCAG study, using this approach, found a somewhat higher average savings of 1.4 gallons per telecommuting occasion, based on drive-alone commute miles. The sample average fuel efficiency was 24 mpg, similar to the Arizona/AT&T and Puget Sound values.

In the third approach, the State of California study estimated the fuel savings due to telecommuting as a side product of an air quality modeling effort, using the EMFAC 7E and BURDEN models (California Air Resources Board, 1990). The study found that average fuel efficiency decreased 3.5% – from 18.65 mpg before telecommuting to 17.99 mpg on telecommuting days. The lower average travel speeds that result from proportionately less travel on freeways on telecommuting days probably account for this decrease in efficiency. However, the energy savings of about 75% was nearly comparable to the savings in vehicle-miles, suggesting that the decline in efficiency has a relatively insignificant impact on the total energy savings. The estimated average fuel savings of 2.2 gallons per telecommuting occasion was significantly higher than savings suggested by the other studies (Table 5).

Differences between the estimated impacts from each of these studies are driven by

Table 5. Estimated travel energy savings

	Gallons per Telecommute Occasion	Average Miles per Gallon	Sample Size	Method Used	Source of mpg
Arizona/AT&T	0.9	26	99	avg miles saved/avg mpg	assumed value
Puget Sound	0.9	25	63	avg miles saved/avg mpg	assumed value
SCAG	1.4	24	18	avg of (miles saved/mpg)	computed value
State of California	2.2	18	73	EMFAC7E Air Quality Model	computed value
Weighted average	1.3	23.3	253		all values
		19.2	91		computed values only

differences in the travel savings and fuel efficiency found or assumed in each. For example, the fact that the gallons saved per telecommuting occasion for the Arizona/AT&T and the Puget Sound studies are equivalent masks the fact that the (assumed) fuel efficiency was lower and the travel savings higher in the Puget Sound study. The relatively low fuel efficiency in the State of California study is offset by a relatively long travel savings to generate a substantially greater average fuel savings per telecommuting occasion. As a result, it may be more appropriate to assume an average fuel savings per mile and apply this value to the average vehicle-miles saved, rather than assuming an average fuel savings per telecommuting occasion. This is especially true in view of the unusually high travel savings experienced by these early adopters of telecommuting, as previously discussed. In the SCAG and State of California studies, where fuel efficiency was determined on an individual basis, the weighted average fuel efficiency was 19.2 mpg.

4.2. Household and net energy impacts

Three studies attempted to estimate the impacts on household energy use due to telecommuting. Participants in the SCAG study were asked to estimate their use of energy in terms of hours of use of different appliances (e.g., heating/air conditioning, computers, stoves, lights). This method may overestimate energy use, in that decreases in office energy use were not accounted for. However, decreases in office energy use are expected to be small, given that the use of heating, air conditioning, and in some cases lights in the main office will not generally decline just because some employees are telecommuting. Hours of use were converted to energy using the average energy consumption of various appliances. Household energy use was estimated to have increased by 5.5 kilowatt-hours (kwh) per telecommuting occasion, considerably less than the 50.4 kwh per telecommuting occasion net travel savings (1.4 gallons, at 36.62 kwh per gallon; JALA, 1990).

The Puget Sound study reported increases in household energy use of 0.7 million British thermal units (MBtu) per year, although the method by which this value was estimated is not clear. As in the SCAG study, this energy increase is significantly lower than the transportation savings of 5.2 MBtu per year. When these values are converted to kwh per telecommuting occasion (using 293 kwh per MBtu and 26 telecommuting occasions per year, the Puget Sound average), the findings are consistent with those from the SCAG study: household energy use increased by 7.9 kwh per telecommuting occasion while transportation energy use decreased by 58.6 kwh per telecommuting occasion (Table 6).

Table 6. Net energy savings per telecommuting occasion

	Travel Energy Reduction (kwh/TC occ)	Home Energy Increase (kwh/TC occ)	Home Increase as Percent of Travel Savings	Net Energy Savings (kwh/TC occ)	Sample Size
Puget Sound	58.6	7.9	13.5%	50.7	63
SCAG	50.4	5.5	10.9%	44.9	18
State of California	80.6	20.5	25.4%	60.1	73
Weighted average	68.1	13.6	18.8%	54.5	154

The State of California study (JALA, 1990) asked telecommuters and control group members to report their monthly home-energy bills. Again, this method does not account for possible decreases in energy use in the office. Telecommuters reported spending $10.87 more per month for energy at home than the control group, which translated (at an average cost of $0.08 per kwh in the Sacramento area) to 136 kwh more per month and 1600 kwh more per year. Assuming 1.5 telecommuting occasions per week (the average for this program) and 52 weeks per year, home energy use increased by 20.5 kwh per telecommuting occasion, considerably more than in the SCAG and Puget Sound studies. Because the State of California study found significantly greater transportation energy savings of 80.6 kwh per telecommuting occasion, the net energy savings of 60.1 kwh per telecommuting occasion is still greater than in the other two studies. However, the increase in home energy use as a percent of travel savings is about twice as high, suggesting that the net energy savings on a percentage basis is considerably less.

These studies suggest that household energy use increases represent between 11% and 25% of the travel energy savings. In other words, the net energy savings is 11% to 25% less than the energy savings due to travel. However, the differences among the studies and the limitations of the methods used (potentially unreliable self-reports) suggest that these percentages are at best rough approximations.

5. AIR QUALITY IMPACTS

The State of California study provides the only methodologically sound estimation to date of the impacts of telecommuting on air quality. The study estimates emissions of TOG, NO_x, and CO using the EMFAC 7E and BURDEN 7E air quality models (California Air Resources Board, 1990) and the data from the travel diaries with respect to number of trips, cold and hot starts, average speeds, and vehicle-miles-traveled for telecommuters before and after telecommuting. The decreases in emissions per day calculated by the model represented 61.3% of TOG emissions, 71.8% of NO_x emissions, and 71.6% of CO emissions (Table 7). The study compared these emissions savings to savings in vehicle-miles traveled and found them to be somewhat less on a percentage basis: 80%, 93%, and 93% of the 77% reduction in vehicle-miles-traveled, for TOG, NO_x, and CO, respectively. These differences are due to the decrease in average travel speeds and the proportional increase in cold starts on telecommuting days relative to nontelecommuting days that result from the changes in travel patterns described in Section 3.5.

6. POTENTIAL LONG-TERM IMPACTS

Several long-term impacts of telecommuting have also been hypothesized. However, none of the studies is of long enough duration to fully test the long-term effects; most surveys were administered within 6 to 12 months of the start of the telecommuting program. As a result, the existing evidence is inconclusive.

It has been hypothesized that automobile ownership may decline over time, for example, because telecommuters have a reduced need for automobile travel. The questionnaire used in the San Diego study (administered about 9 months into the program) asked telecommuters about their automobile ownership choices. No respondents in this study indicated that the number of automobiles that they owned had decreased. This is not surprising, in view of the fact that the program was a pilot, the relatively short time

Table 7. Reduction in emissions for the State of California Pilot Program

	Grams Reduced per Telecommuting Occasion	% of Total Emissions Reduced	Emissions Reduction as a % of VMT Reduction	Grams per Mile Reduced
TOG	70.2	61.3	80	1.7
NO_x	62.0	71.8	93	1.5
CO	581.2	71.6	93	14.4

frame involved, the fact that telecommuting was generally part time, and the need or perceived need for automobiles in the typical suburban environment.

Another potential impact is residential relocation to sites farther from the workplace, because longer commute distances can be compensated for by increased frequency of telecommuting. It has been hypothesized that such relocation may result in an increase in total travel. Given the decrease in commute costs resulting from the reduced frequency of commuting, residential location models suggest that the weight of distance to work would be reduced and hence that greater distances would be acceptable (Lund & Mokhtarian, in press). Clearly, if there is any desire to relocate, even unrelated to telecommuting, then all else being equal, the ability to telecommute can only influence that desire in the direction of increasing distance from, rather than movement toward, the workplace. Moreover, to the extent that such relocation is to less densely-settled areas, nonwork travel is likely to be affected as well, due to the reduced opportunities for various activities as density decreases. (However, forecasting the net impact on travel is complex: there may, for example, be a tradeoff between trip lengths and trip frequencies). In turn, such long-term changes may perpetuate if not increase dependence on the automobile, counteracting the hypothesis of decreased auto-dependence just discussed.

Empirically, a residential relocation effect has not appeared in the short-term studies reviewed here. The San Diego questionnaire asked telecommuters whether they had moved or were considering moving, and whether telecommuting had affected this decision. The results showed no conclusive evidence of a relocation effect, although two respondents indicated that they were considering moving considerably farther from work. Similarly, the State of California study found some inconclusive evidence of residential relocation to more distant locations for a small percentage of telecommuters. As for theory, a simple model of residential relocation due to telecommuting (Lund & Mokhtarian, in press) found that total commute-miles traveled after relocation was still lower than before telecommuting in all but the most extreme cases (nearly flat land price decay rates and low- to moderate-frequency telecommuting). Clearly, however, additional theoretical as well as empirical research is needed on this issue.

The system-wide impacts of telecommuting may not be a simple aggregation of individual-level impacts. If large numbers of commuters adopt the option to eliminate some of their work trips, to an extent that the demand for highway (or transit) and office space capacity is noticeably reduced, some new factors may come into play. Latent demand may be realized if level-of-service is improved and consequently, new trips may be generated or diverted from other destinations. Similarly, the increased supply of office (and parking) space may result in reduced costs, thus changing the weight of the some of the benefits motivating employers' participation in such work arrangements. This implies that the long-term evaluation of telecommuting impacts should take the system-wide effects into account.

7. TRENDS IN IMPACT FACTORS

The impact per telecommuting occasion on automobile travel, energy use, and air quality may change in the future, depending on a variety of factors. The impact of telecommuting on energy use and air quality is primarily driven by the impact of telecommuting on automobile travel. If the reduction in automobile travel per telecommuting occasion changes over time, then savings in energy use and air pollutant emissions will change as well.

7.1. Impact on travel

Changes in the automobile-travel impact can result from changes in average travel distances and/or changes in mode share for telecommuters. Average commute distances for telecommuters are likely to change in two ways over time. First, average commute distances for all workers have increased over time—nationwide, from 9.4 miles (one-way) in 1969 to 11.0 miles in 1990 (Hu & Young, 1992, Table 7). Second, current telecommuters tend to have substantially longer commutes on average than other workers in the region, as discussed in Sections 3.1 and 3.3 and shown in Table 2. As the level of telecommuting (in terms of the percent of workers telecommuting) increases over time, however, the ratio between the average distance for telecommuters and the average distance for all workers is likely to decrease. On the other hand, given a positive correlation between telecommuting and income (Handy & Mokhtarian, 1993c) and a positive correlation between income and commute distance (Federal Highway Administration, 1991), the average commute distance for telecommuters may remain somewhat higher than the average for all workers. Thus, the average commute distance for telecommuters is likely to decrease but to an equilibrium that is still higher than the average commute distance for all workers.

Mode share has also been changing for all workers, with the percent of work trips made by driving alone increasing over time (Pisarski, 1992b). Evidence shows that telecommuters are drawn proportionately from each mode. For example, in the Puget Sound telecommuting pilot program, 63% of telecommuters drove alone to work, versus 64% of comparison group workers (Quaid & Lagerberg, 1992). As a result, an overall increase in the drive-alone share should lead to an increase in the drive-alone share for telecommuters and to a greater reduction in automobile travel than before. In the future, it seems likely that telecommuters will be drawn from automobile users in even greater proportions, as congestion increases and automobile travel times deteriorate. Telecommuting may become a particularly attractive strategy for coping with congestion for those solo commuters with an aversion to transit and carpooling. Of course, growth in telecommuting might hinder growth in transit and carpooling. The net effect on automobile travel is thus uncertain, as distances may be decreasing but the share of automobile travel increasing.

In the long term, the role of telecommuting centers should be taken into account. Virtually no empirical data currently exist on the transportation-related impacts of telecommuting centers, although a number of demonstration projects are underway for which such data will be collected. Telecommuting centers obviously involve a commute trip of some type; the important questions are (a) how long a trip (compared to the normal commute); (b) the mode of the trip (e.g., if a new cold start is involved); (c) the frequency of the trip (e.g., will people telecommute from a center more often than from home); (d) the temporal and spatial characteristics of the trip (will it be at less congested times and/or places than the normal commute); (e) the alternative (home-based telecommuting, or not telecommuting at all).

7.2. Energy and air quality impacts

Even if the average amount of auto travel reduced per telecommuting occasion were to remain stable over time, impacts on energy use and air quality could be significantly affected. Travel speeds as well as travel distances affect energy consumption and emissions. Travel speeds for work trips have been increasing in recent years—contrary to expectations. For the U.S., average travel speeds for work trips by car increased from 31.7 mph in 1983 to 34.7 mph in 1990 (Pisarski, 1992a, Table 5). To the extent this trend continues, energy and air quality impacts of telecommuting will decrease, because energy efficiency increases with speed, at least up to a point. Trends in travel speeds may be very different in California, however, particularly in metropolitan areas. If travel speeds were to decrease over time as a result of increasing congestion, then energy use and air pollution emissions savings would increase per telecommuting occasion, even if distance does not increase, because travel will become less efficient. The upward trends in average speeds suggest near term decreases in telecommuting impacts but this trend is probably not sustainable into the long term.

Energy and air quality impacts will also be affected by changes in vehicle characteristics. The California Energy Commission forecasts that the average car and light duty truck fleet efficiency in California will increase from 20.2 mpg in 1992 to 23.4 mpg in

2011, an increase of nearly 16% (California Energy Commission, 1993). This suggests that the energy impacts of telecommuting might decrease by 16%, all else equal. Similarly, the standards for emissions will become stricter over time, thereby reducing emissions per trip and per mile, leading to a reduction in the emissions savings due to telecommuting. As a result, regulations to reduce the environmental impacts of automobiles will reduce the energy and air quality impacts of telecommuting.

On the positive side, the net increase in building energy consumption due to telecommuting is likely to decline over time, for two reasons. First, the computerized control of lights and heating/air conditioning in office buildings is likely to become more widespread in the future. If lights are automatically turned off and the heat automatically turned down when no one is in the telecommuter's regular office, then the energy used at home will tend to replace rather than augment the energy used in the office. Second, companies are likely to factor a distributed work force into their long-range facilities planning, and reorganize space to be more efficiently shared among workers.

All things considered, however, the long-term role of telecommuting as an energy- and air pollution-reducing policy will probably be less important than its role as a congestion-reducing policy.

8. SUMMARY

We analyze the transportation-related findings of eight telecommuting programs. These studies highlight the complexity of attempting to evaluate the individual and aggregate travel impacts of telecommuting. A typical simple evaluation is likely to focus primarily on average commute person-miles presumed to be eliminated by the telecommuter, possibly with a translation of those reduced miles to energy savings and pollution reduction. Yet the issues discussed throughout this article complicate that picture considerably. To summarize some key points presented earlier:

(a) It is generally only the drive-alone vehicle-miles that count as far as transportation, energy, and air quality impacts are concerned, assuming that carpool, vanpool, and transit vehicles would continue to be on the road despite the occasional absence of a telecommuter. Applying an overall drive alone mode share factor to the average number of person-miles reduced relies on the assumption that telecommuting borrows mode share proportionally from all modes. Whereas this is a reasonable assumption given present empirical findings, the impact of telecommuting on mode choice should be carefully examined in future studies.

(b) It is important to analyze the impact of telecommuting on total travel, not just commute travel, in view of the real possibility that at least some noncommute travel will be stimulated by the ability to telecommute. Although studies to date have not identified this effect, that may be because early adopters are longer-distance commuters, and hence perhaps more strongly motivated to reduce their overall travel, than later adopters will be.

(c) Thus, early adopters of telecommuting are unrepresentative of the general population – certainly in terms of commute distance and probably in other important ways. If telecommuting is attractive primarily to long-distance commuters, then the ultimate adoption of telecommuting (and hence, its transportation benefits) will be more narrowly restricted than anticipated. If, on the other hand, as the authors believe, people will adopt telecommuting for a variety of reasons of which transportation is only one (Mokhtarian & Salomon, 1994), then average commute distances (and hence, miles saved) of telecommuters will decline over time. Either way, the future aggregate transportation impacts of telecommuting will almost certainly be smaller than suggested by current data taken in isolation. Other impacts may be overstated as well.

(d) Not all "telecommuters" reduce travel. In many cases, the alternative to telecommuting is not working rather than making a conventional commute. In other cases, telecommuting occurs for part of the day, but a commute trip is still made, generally in the off-peak. This has some transportation, energy, and air quality benefits, but obviously not as much as elimination of the trip altogether. As these types of cases comprised

15% of the sample in one small study, more attention should be paid to this issue. It may be argued that a person should not be classified as a telecommuter unless the commute trip is reduced. In practice, however, that strict a test will probably not be universally applied. Thus, in translating future forecasts of the amount of telecommuting into the transportation impacts of that amount, it may be appropriate to apply a "deflation factor" to account for cases in which telecommuting did not impact travel at all.

(e) Relative reductions in energy consumption and emissions will generally be smaller than relative reductions in vehicle-miles traveled, due to the disproportionate contribution of cold starts to these factors, and due to the fact that (so far) average speeds for trips made on telecommuting days are lower (therefore generating emissions at a higher rate) than on nontelecommuting days. However, only one rigorous study of emissions impacts has been conducted to date. It would be useful to replicate this analysis across a number of settings, and especially to explore the air quality impacts of telecommuting centers, which are likely to involve vehicle commute trips. As technological advances lead to further improvements in vehicle fuel efficiency and emissions, the per-occasion reductions in fuel and emissions attributable to telecommuting will diminish.

(f) At least three studies have attempted to measure the increased energy use in the home due to telecommuting, and deduct that from the transportation energy savings. The increased energy used is far outweighed by the energy saved, but the three studies collectively suggest that the observed travel energy savings should be deflated by a factor of 19% to account for increases in home energy usage. However, as indicated in Section 7, those impacts are likely to diminish over time.

The collective findings presented here permit the development of tentative impact factors, that is, estimates of the transportation and related effects of telecommuting on a per-occasion basis (Handy & Mokhtarian, 1993b). These factors can be multiplied by an estimated number of telecommuting person-days at a particular point in time (e.g., Handy & Mokhtarian, in press) to calculate the aggregate transportation-related impacts of telecommuting at that point in time (e.g., Handy & Mokhtarian, 1993c).

One point of this article is that great care should be exercised in doing that. Those impact factors, uncertain even today, will undoubtedly change over time. To improve our understanding of telecommuting and its transportation, energy, and air quality impacts, it will continue to be imperative to conduct carefully designed empirical evaluations.

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