Impacts of Center-Based Telecommuting on Travel and Emissions: Analysis of the Puget Sound Demonstration Project

Dennis K. Henderson
Patricia L. Mokhtarian

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University of California Transportation Center

108 Naval Architecture Building
Berkeley, California 94720
Tel: 510/643-7378
FAX: 510/643-5456

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Dennis K. Henderson
Patricia L. Mokhtarian

Institute of Transportation Studies
University of California, Davis
Davis, CA 95616

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IMPACTS OF CENTER-BASED TELECOMMUTING ON TRAVEL AND EMISSIONS: ANALYSIS OF THE PUGET SOUND DEMONSTRATION PROJECT

DENNIS K. HENDERSON and PATRICIA L. MOKHTARIAN
Institute of Transportation Studies, University of California—Davis, Davis, CA 95616, U.S.A.

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Abstract—Center-based telecommuting has many hypothesized benefits. To determine its value as a transportation demand management strategy, however, its travel-related benefits must be established quantitatively. This research provides the first analysis of the impacts of center-based telecommuting on individual travel behavior and emissions, using travel diary data from the Puget Sound Telecommuting Demonstration Project. An analysis of personal vehicle usage for this small sample of workers showed that the number of vehicle-miles traveled (VMT) was reduced significantly as a result of center-based telecommuting (from 63.25 miles per person-day on non-telecommuting days to 29.31 miles on telecommuting days). The reductions in weekday VMT comprise significant reductions in commute-related VMT with insignificant changes in non-commute-related VMT. The number of personal vehicle trips did not change significantly. In essence, center-based telecommuters behave as conventional commuters in terms of their number of trips, but are more similar to home-based telecommuters in terms of VMT reductions. The significant reduction in VMT translates into a 49% decrease in oxides of nitrogen (NO_x) emissions and a 53% decrease in particulate matter (PM) emissions comparing telecommuting days to non-telecommuting days for the small sample. Because the number of daily trips was not impacted by telecommuting, the levels of emissions associated with the cold start process, total organic gases (TOG) and carbon monoxide (CO), were essentially unaffected. Of course, region-wide impacts will be much smaller when the proportion of telecommuters in the workforce and the frequency of telecommuting is considered. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Telecommuting in its various forms is becoming an increasingly common alternative work arrangement. A telecommuting center, or telecenter, is defined as a facility where employees (from single or multiple organizations) share workspace and equipment for the purpose of reducing the length of the commute from the employee's home to the workplace. In the past, policy-makers have been reluctant to accept center-based telecommuting as a transportation control measure (TCM) because it still requires a commute (albeit a shorter one) to a work site (Mokhtarian, 1991). It is easy to construct examples in which the transportation and/or air quality impact is negative. Recently, however, at least some air quality regulations allowed credit for center-based as well as home-based telecommuting. For example, Rule 2202 of the South Coast (California) Air Quality Management District (AQMD, 1996) states that vehicle trip emissions credits (VTEC) will be granted for vehicle-miles traveled (VMT) reduction programs, which may include telecommuting centers. Nevertheless, these types of policies relating to telecommuting as a TCM are being implemented based on speculation as to their potential air quality benefits, with no empirical confirmation of those benefits.

Support for telecommuting is offered by the Federal Government for many other reasons in addition to transportation benefits. Some of the stated objectives include: reduced individual and family stress, possibilities for improved customer service, environmental and energy conservation benefits, and reduced facility costs (U.S. GSA, 1995). These objectives *imply* that center-based telecommuting will provide beneficial impacts to both transportation and air quality; to date, however, no empirical data have been available to support this.

Home-based telecommuting eliminates the commute trip entirely for many participants. Recent empirical studies have demonstrated that home-based telecommuting reduces both the number of daily trips and VMT, leading to substantial savings in personal vehicle emissions (Mokhtarian *et al.*, 1995; Henderson *et al.*, 1996; Koenig *et al.*, 1996). However, home-based telecommuting may not be appropriate for every worker whose job permits it. Several factors may limit one's ability to telecommute successfully from home (Bagley *et al.*, 1994). There may not be adequate space, there may be distractions, and it may be more difficult to avoid destructive behavior such as overeating, smoking or substance abuse. With one or more of these factors present, it may be more advantageous for an employee to telecommute from a center. In addition to removing the undesirable elements that may be present at the home, telecommuting centers may also offer more opportunity for social or professional interaction. From the employer's point of view, the telecommuting center has many potential advantages as well. The job may require specialized equipment that is too expensive to provide for all telecommuting employees, but which can be shared at a center. The center also provides a more controllable environment for working. Worker and property liability issues, as well as the need to protect proprietary information, may be more effectively managed at a center. Because these advantages of a center may make telecommuting a viable option for a larger number of employees, it is important to perform empirical analyses of the travel and emissions impacts of center-based telecommuting to determine what long-term effects may result as it is implemented on a large scale.

The research presented here involves the first empirical analysis of the travel and emissions impacts of center-based telecommuting. Data from the Puget Sound Telecommuting Demonstration Project are analyzed and compared for three groups: home-based telecommuters, center-based telecommuters, and a comparison group. This study first determines whether center-based telecommuting provides quantitatively measurable transportation benefits. The travel activity of the sample is then used as an input to the California Air Resources Board's emissions models EMFAC7F and BURDEN7F to estimate the impacts of center-based telecommuting on personal vehicle emissions levels.

The travel behavior analysis can be conducted in two different ways depending on the focus of the study. The first way focuses on personal vehicle use. It is the (drive alone) personal vehicle (PV) use that has the largest impact on emissions. It is reasonable to assume that many, if not most, ride-sharing trips would still take place without the telecommuter, and that telecommuting would have no emissions impacts on those trips. Therefore, it is the changes in (personal) vehicle-miles traveled (VMT) and the number of PV trips that are important in such an analysis. The second way focuses on all modes used and thus, on changes in person-miles traveled (PMT) and in the number of trips (including all modes). In an analysis of this type, alternative mode trips are important because they allow the impacts of telecommuting on future demand for these modes to be investigated. Mode choice impacts can have both positive and negative outcomes (Mokhtarian, in press). On the negative side, carpools and vanpools might dissolve if telecommuters drop out, and transit operators may lose revenue in the near term. On the positive side, trips made closer to home may shift to non-motorized modes such as cycling and walking. In this study, analysis will be primarily applied to the trips made with personal vehicles. However, mode choice impacts are also studied for the center-based group to some extent.

It is important to note that the findings presented here result from the analysis of a small group, and should be considered an early indication of possible outcomes, rather than the definitive outcome of center-based telecommuting. The primary goal of this research is to identify some general trends of center-based telecommuting and to develop a methodology applicable to future travel analyses. The reported impacts represent percent reductions in travel and emissions for the telecommuters themselves, not for the population as a whole. These impacts are measured by comparing days on which the participants telecommuted (from either home or a center) with non-telecommuting weekdays. Further, the sample consists of work days for full-time workers only, not a random sample of the regional population. Also, when the *level* of telecommuting is considered, that is, the percentage of work days that employees actually telecommute, the weekly savings will be a much smaller proportion of total weekday travel and an even smaller proportion of total travel. Thus, these findings represent average per-capita weekday impacts for early adopters of center-based telecommuting; the aggregate (or overall, region-wide) impacts are determined by scaling these reductions by the proportion of telecommuters in the workforce and accounting for the frequency at which telecommuting takes place.

Although center-based telecommuting currently involves a small percentage of overall commute trips, the findings from this research will provide a much needed indication of whether or not those activities offer air quality benefits. With the data and methodology presented here, policy-makers will begin to have the ability to implement appropriate TCMs based on rigorous analysis, rather than speculation.

PUGET SOUND DATA

The data used for this study are from the Puget Sound Telecommuting Demonstration Project conducted between 1990 and 1991 by the Washington State Energy Office. The original data set contains travel diary information provided by 104 telecommuters (both home-based and center-based) from about 20 public and private organizations and 41 comparison group members who were (for the most part) similar non-telecommuting employees of the same organizations. The center-based telecommuters in the project used the Washington State Telework Center in North Seattle. The center was close to a child care facility and had convenient freeway and mass transit accessibility. Site selection criteria for the center specifically included availability of transit service, adequate parking, and proximity to residential neighborhoods and retail shops (Bagley *et al.*, 1994).

Although every telecommuter in the Demonstration Project was expected to participate in the evaluation, compliance with that expectation varied and hence there is some self-selection bias in the data analyzed here. Further, it is not known whether the telecommuters in this project were representative of all the telecommuters in the region, and it *is* known (and discussed later) that these telecommuters are not representative of the general workforce in some important ways. Thus, caution should be used in extrapolating these results to the entire population of telecommuters and to the workforce as a whole. It is anticipated that improved data sets will be available in the future as telecommuting becomes more widely adopted and less 'experimental' in nature.

The travel diary data contains information on a trip-by-trip basis. The information for each trip includes the origin and destination, beginning and ending trip times, purpose, approximate trip length as reported by the respondent, and mode used. If a personal vehicle was used, respondents also reported the beginning and ending odometer reading, the number of passengers, and the vehicle make, model and year.

The data were collected in multiple waves before and after telecommuting began. However, a thorough review of the data revealed that, to maintain the largest sample of telecommuting data, it was best to compare travel behavior on telecommuting days and non-telecommuting days for the pure telecommuters and the comparison group, without regard to whether a participant's day fell in the 'before' or 'after' waves. For a more detailed overview of the data, refer to Henderson *et al.* (1994) and Quaid and Lagerberg (1992).

The analysis presented here involves comparing the travel behavior and emissions of the 72 people who were recruited to telecommute, and did, with the 33 comparison group members who never telecommuted. Isolating these groups allows a comparison of the same sample and provides greater certainty in conclusions on whether observed changes in travel behavior and emissions are actually due to telecommuting. Past analysis of the data focused on the telecommuting group as a whole, including both the home-based and center-based telecommuters in a single group which was analyzed against the comparison group (Henderson *et al.*, 1996). However, because of the need to quantify the impacts of center-based telecommuting it is valuable to focus on these participants as a separate group. The impacts of telecommuting on the center-based group may then be compared to the home-based and comparison group to determine similarities and differences among the groups. Thus, the telecommuting sample was further divided into 63

Table 1. Distribution of trips across groups

	Center-based				Home-based				Comparison	
	NTC day		TC day		NTC day		TC day			
	Trips	P-days	Trips	P-days	Trips	P-days	Trips	P-days	Trips	P-days
PV trips	95	28	53	13	868	231	228	52	649	150
All trips	118	28	53	13	1191	281	237	54	780	166
No PV trips made	—	0	—	0	—	50	—	39	—	16

home-based and nine center-based telecommuters. A single outlier was discovered in the center-based group. The participant reported a 63-mile trip to a telecommuting center compared to an 8-mile regular commute. It appeared that this participant may have taken a trip to visit the center rather than for the purpose of telecommuting. The participant was excluded from the study, and the final sample size of the center-based group was 8.

Weekend data and household member data were excluded due to infrequent and unreliable reporting. Thus, this study only addresses the travel impacts of telecommuting on the work days of participants directly recruited for the project. Previous trip diary-based studies of telecommuting impacts have faced similar problems with the collection of weekend and household member data. However, the limited results that are available do not support the hypothesis that household trips increase with telecommuting. On the contrary, there is some indication that trips for household members decline as well, for potentially a variety of reasons (Hamer *et al.*, 1991; Pendyala *et al.*, 1991).

A necessary penalty for excluding the household members from the analysis is that some accuracy is lost in evaluating the emissions impacts of telecommuting. Because it is the participants' trip-making patterns that are being followed and not the trips made using a given household vehicle, it is possible that some engine starts will be classified as cold starts when, in reality, the vehicle was used by someone else for an intermediate trip and a hot start actually occurred. Therefore, the number of cold starts made by the participant may be somewhat overestimated in this analysis. However, when the ratio of vehicles to licensed drivers is close to one, as is typically the case, little switching of vehicles among household members is likely to occur. Further, to the extent that this overestimation occurs equally across telecommuting days and non-telecommuting days, the estimated impact of telecommuting should not be greatly affected. In future studies, it is desirable (though difficult) to obtain a complete, reliable set of household travel data to minimize this problem.

Table 1 tabulates the trips taken by the three groups. The *center-based* telecommuting group consists of eight participants with 13 person-days of data on TC days and 28 person-days of data on NTC days. In this context, a person-day is defined as a day on which a participant kept record of his or her trips. The *home-based* telecommuting group consists of 63 participants with 91 person-days (including days on which no trips were made) of data on telecommuting days (TC days) and 281 person-days of data on non-telecommuting days (NTC days). Finally, the *comparison* group has 33 members with 166 person-days of data reported. It is noteworthy that personal vehicle (PV) trips were made by the home-based telecommuters on only 57% (52 out of 91) of their TC person-days, whereas 82% of their NTC person-days involved personal vehicle use. The comparison group reported PV use on 90% of their person-days, and the center-based group used a PV at least once on 100% of their TC and NTC days.

INDIVIDUAL ANALYSIS OF CENTER-BASED PARTICIPANTS

The center-based telecommuting group is small, consisting of only eight participants. However, a total of 171 trips were reported, which allows a quantitative investigation of the changes in travel behavior due to telecommuting. The average daily commute-related

VMT and number of commute trips are analyzed to determine changes in behavior between NTC and TC days, including changes in mode choice. Because the sample is small, the investigation is performed on an individual basis where the findings offer some interesting insight. It is important to note that the accuracy of these results is limited by the available travel diary data: the frequency at which the reported behavior occurs is unknown. However, a study of center-based telecommuting in California is currently underway at U.C. Davis which will provide data on the frequency of occurrences of the participants' various types of commute patterns. That study, when complete, will refine the early findings presented here.

After disaggregating the average daily VMT into commute-related and non-commute-related VMT, center-based telecommuting was found to reduce the daily commute VMT for all but one of the participants (Table 2). This participant, along with three others, provided some useful insight as to what types of individual behavior may occur as a result of center-based telecommuting. The activities of the four participants are discussed in detail below.

In the case of participant no. 1, the one-way commute length was only reduced by 1 mile (7 miles to 6 miles) when driving to the telecommuting center. The participant reported commute travel on 4 NTC days (eight trips, counting each direction), and 1 TC day (two trips). On 1 of the 4 NTC days, the participant went home at lunch time (two more trips, resulting in the 2.5 average commute trips per day shown in the table). However, the participant also went home for lunch on the single TC day (resulting in an 'average' of four daily commute trips), and the average daily commute VMT increased from 15.5 miles on NTC days to 24.0 miles on TC days. This illustrates the limitation of this data set since it is not known, in general, how frequently the participant returns home at lunch time either when commuting conventionally or when commuting to a center.

Only one respondent (participant no. 2) used multiple modes to commute to the regular workplace. This activity occurred on two of the four NTC days reported. The average daily travel for those 4 days was 73.0 miles (including all modes), with 39.5 of those miles taking place in the personal vehicle. On the single TC day reported by that respondent, only a personal vehicle was used to travel to and from the telecommuting center with a commute VMT of 28.0 miles for that day. Even though it is unknown whether this participant always drives alone to the center, the reduction in commute distance is large enough such that, when averaged across multiple days, the average daily personal vehicle-miles traveled was reduced (from 39.5 miles to 28.0 miles per day). Thus, even though alternative modes were not chosen as a result of center-based telecommuting, transportation and emissions benefits were still realized since the personal vehicle VMT was reduced by 29% for that individual.

Participant no. 7 reported an average of four commute trips per day on the 2 reported TC days (due to trips home for lunch on both days). The same participant reported trips on a total of 4 NTC days, none of which included a trip home for lunch. Although the commute length was reduced (from 65 miles on NTC days to 8 miles on TC days), which has beneficial impacts on some pollutants, the number of PV engine starts increased,

Table 2. Center-based telecommuters' individual commute behavior (per-day averages)

	NTC days		TC days	
Participant	Commute VMT	Commute trips	Commute VMT	Commute trips
1	15.5	2.5	24.0	4
2	39.5 (PMT = 73)	2.0	28.0	2
3	73.0	2.0	6.0	2
4	105.2	2.0	20.0	2
5	32.0	2.0	26.0	2
6	19.0	2.0	14.0	2
7	65.0	2.0	8.0	4
8	40.7	0.67	40.0	2
Average	48.7	1.90	20.8	2.5

which has negative impacts on others. Because two of the eight participants (25%) made trips home for lunch while telecommuting from the center, future studies should continue to monitor these trips to ensure that their impacts remain small relative to the overall impacts of telecommuting.

A fourth participant with particularly interesting travel behavior was participant no. 8. Although this participant reported a regular commute length of 61 miles and a commute to the telecenter of 20 miles, it was found that telecommuting had virtually no effect on the average daily commute VMT (decreasing the average daily commute VMT from 40.7 miles to 40.0 miles). For this participant, three NTC days of travel were reported, along with a single TC day. On the TC-day, a single round-trip commute to the center was made with a length of 40 miles. Only 1 of the 3 NTC days included a trip to work and back, thus contributing 122 miles of commute-related travel for 3 days of trips, resulting in an average daily commute length of 40.7 miles. This participant had a substantial amount of work-related trips and VMT on the days for which no commute was reported. Both of those days included two work-related trips, one with 135 work-related miles and the other with 108 work-related miles. Therefore, because of the high proportion of off-site work days, telecommuting was found to have little effect on this participant's *average* daily commute. However, without knowing the actual frequency of days on which the employee makes the regular commute trip, works off-site, or works at the telecenter, the overall impacts are difficult to measure with accuracy. Also, it is unknown if, for this participant, a TC day typically replaces a regular commute day or an off-site work day, further adding to the uncertainty of the finding.

These scenarios illustrate the importance of individual commute patterns (and the frequencies at which they occur) in understanding whether telecommuting from a center has a positive or negative transportation effect for a particular employee. The following situations should be considered as cases where telecommuting from a center may increase VMT and emissions. In a case where a regular commute does not typically involve a personal vehicle, but the trip to the telecommuting center does, VMT and emissions may increase. Also, if increased travel (commute-related or non-commute-related) is stimulated by using the center, negative impacts may occur. For example, if a cafeteria is normally available to employees at the regular work place, but not at the telecommuting center, PV trips to the home or some other location may be generated. Finally, knowing the frequency of a participant's travel behavior is important to establish an appropriate baseline measure of NTC day travel for comparison with TC day travel. These considerations allow the true impacts of telecommuting to be qualitatively evaluated on an individual level. Some programs may wish to screen out counterproductive cases at the outset. However, if allowed, such cases are likely (as here) to remain in the minority and the aggregate impact on VMT and emissions is likely to remain positive. Nevertheless, it is important to monitor the occurrence of these types of cases; corrective measures may be needed if they become too frequent.

The factors just mentioned can perhaps be significantly modified by attempting to train employees to be efficient telecommuters. If employees understand one of the objectives of the work arrangement to be reducing vehicle emissions, they may choose to use modes other than the personal vehicle to get to the center. They may also bring a lunch or walk to a nearby location to eat at lunchtime.

ANALYSIS OF TRAVEL BEHAVIOR

The impacts of telecommuting from a home and from a center are based on an analysis of eight travel indicators, each divided by the number of person-days in the respective group to obtain a per person-day average. The eight indicators are: number of commute trips, number of non-commute trips, number of trips, commute VMT, non-commute VMT, VMT, number of cold engine starts and number of hot engine starts. Disaggregating trips into hot and cold engine starts is important because cold engine starts generate emissions that are an order of magnitude higher than hot engine starts. Thus, it is important to measure the impacts of telecommuting on cold starts in particular. It should be noted that the number of person-days represented in the denominator is the combined number of person-days in the sample on which PV trips were made and days on which no trips at all were made. Days on which strictly non-PV modes were used are not included because their effect on each measure would be to reduce its value (by increasing the denominator). Since the travel on those days is not represented in the numerator, it should not be represented in the denominator. However, the days on which no trips of any kind were recorded *are* included in the denominator, as the elimination of travel due to telecommuting is precisely the outcome of interest in this study. To the extent that a given telecommuter would virtually never travel by personal vehicle (e.g. the telecommuter does not own a car, and takes transit or walks everywhere), the impacts of telecommuting are slightly overstated by including such a case (because the reduction in travel due to telecommuting would have no emissions impact). However, the impact of such cases (if any in fact exist) is expected to be negligible.

Analysis of telecommuting group versus comparison group

Before assessing the changes in emissions due to telecommuting, it is important to determine the extent to which the telecommuter and comparison groups are similar, independent of telecommuting. This analysis will be approached in two parts: first the comparison group will be examined against the center-based telecommuters, and then against the home-based telecommuters.

Analyzing the center-based telecommuters on NTC days versus the comparison group reveals two critical differences (Table 3). First, center-based telecommuters make 21.7% *fewer* trips than the comparison group (3.39 versus 4.33 per person per day). This translates into 13.1% fewer cold starts and 36.3% fewer hot starts. Second, center-based telecommuters have a 91% *higher* daily VMT (63.25 versus 33.12 miles per person-day). The difference in trips is marginally significant ($p = 0.058$) whereas the difference in VMT is statistically significant at a level less than 0.005 (see Table 5, lines 1–5, where the groups are numbered according to the labels of Table 3).

Examining the home-based telecommuters on NTC days against the comparison group identifies the same two basic differences. In this case, the home-based telecommuters make 13.2% fewer trips per day (significant at $p = 0.016$) and have 54.1% higher daily VMT (significant at $p < 0.005$). Thus, the home-based telecommuters are still different from the comparison group in these two areas, but are more similar (in terms of the overall average) than the center-based group.

The higher VMT for telecommuters (both home- and center-based) on NTC days is due to the fact that, on average, their commute length is more than twice as long as the comparison group's. It can be calculated from Table 3 that the average PV commute trip length on NTC days for the center-based group is 26.6 miles, for the home-based group is 21.5 miles, and for the comparison group is 10.4 miles. As for the smaller number of trips, it may be that because telecommuters spend considerably more time on a single

Table 3. Comparison of travel indicators across groups (personal vehicle only)

	Center-based		Home-based		
	NTC day 1	TC day 2	NTC day 3	TC day 4	Comparison 5
Person-days	28	13	231	89	150
Trips	3.39	4.08	3.76	2.56	4.33
Commute trips	1.93	2.46	1.87	0.24	2.05
Non-commute trips	1.46	1.62	1.89	2.33	2.27
VMT	63.25	29.31	51.03	17.12	33.12
Commute VMT	51.36	19.54	40.29	3.90	21.42
Non-commute VMT	11.89	9.77	10.74	13.22	11.73
Cold starts	2.39	2.77	2.52	1.31	2.75
Hot starts	1.00	1.31	1.24	1.25	1.57

trip—the commute—they have less time to spend on other discretionary trips than do the comparison group members.

Due to these important differences, the comparison group is not well matched to the home-based telecommuter group. However, since the center-based telecommuters still have a commute trip (on their TC days) that is reduced in length, it is useful to determine whether the group displays behavior more similar to the home-based group on their TC days or to the comparison group. Therefore, it is anticipated that an analysis of the center-based group's TC day travel against that of the home-based TC day group and the comparison group will provide some interesting findings.

Comparison of NTC and TC days for center-based telecommuters

Although the impacts of home-based telecommuting are not the focus of this analysis, it is useful to mention them, to provide a basis of comparison for the center-based impacts. Analysis of Table 3 shows that telecommuting caused a 31.9% reduction in the number of daily trips (comparing 3.76 trips per person-day on NTC days to 2.56 trips on TC days). This net reduction is the sum of a 32.2% decrease in total trips from the category of cold engine starts and a 0.3% increase from the category of hot starts. The daily VMT was reduced by 66.5% on TC days.

The next area of interest is a comparison of the center-based telecommuters' travel behavior on their NTC days and their TC days. Tables 4(a) and 4(b) show comparisons of the center-based telecommuting group on their NTC days and their TC days. The figures in Table 4(a) represent travel indicators for personal vehicle trips only, whereas Table 4(b) presents travel for all modes of transportation used by the participants. The second column of figures for the center-based TC days is the same in both tables, because no travel by alternative mode was reported by this group on TC days. It should be noted that commute trip and VMT averages in the tables differ slightly from the averages reported in Table 2. In Table 2 the averages were calculated by averaging the individual per person-day figures, whereas in Tables 4(a) and 4(b), the averages were obtained by summing the trips and VMT for the entire sample of travel activity and then dividing by the total number of person-days. The two results would be the same only if each person had the same number of person-days and made the same number of commute trips in the sample.

Table 4(a). Center-based telecommuting group NTC day vs TC day (PV only)

	C-based NTC day	C-based TC day	Percentage difference
Number of trips	3.39	4.08*	20.4%
Number of commute trips	1.93	2.46*	27.5%
Number of non-commute trips	1.46	1.62*	11.0%
VMT	63.25	29.31**	-53.7%
Commute VMT	51.36	19.54**	-62.0%
Non-commute VMT	11.89	9.77*	-17.8%
Cold starts	2.39	2.77*	15.9%
Hot starts	1.00	1.31*	31.0%

*No significant difference from NTC day mean.
**Significant difference, $p \leq 0.002$.

Table 4(b). Center-based telecommuting group NTC day vs TC day (all modes)

	C-based NTC day (all modes)	C-based TC day (pv = all modes)	Percentage difference
Number of trips	4.21	4.08*	-3.1%
Number of commute trips	1.93	2.46*	27.5%
Number of non-commute trips	2.29	1.62*	-29.3%
VMT	68.93	29.31**	-57.5%
Commute VMT	56.79	19.54**	-65.6%
Non-commute VMT	12.14	9.77*	-19.5%

*No significant difference from NTC day mean.
**Significant difference, $p \approx 0.000$.

Analysis of Table 4(a) shows that center-based telecommuting decreased VMT by 53.7%, comprising a 50.3% decrease in total VMT due to decreasing the commute VMT and a 3.4% decrease due to non-commute VMT. Results of t-tests for each indicator showed that the total VMT and the commute VMT reductions were significant, whereas the reduction in non-commute VMT was not (see Table 5, line 1–2). The number of trips per person-day increased from 3.39 on NTC days to 4.08 on TC days, a 20.4% increase. This increase represents a 15.6% increase due to commute trips and a 4.7% increase due to non-commute trips. None of the three indicators was found to differ significantly between NTC days and TC days. As a result of the increase in the number of trips, the number of cold starts increased by 15.9% and the number of hot starts increased by 31.0%, neither differing significantly. Of course, the statistically negligible increase in the number of trips is expected to have small negative impacts on emissions; however, the significant reductions in VMT may result in net savings for all pollutants. In terms of the percent reduction, the VMT savings are less than the savings found for home-based telecommuting. However, Table 3 shows that the absolute distance saved due to telecommuting is approximately 34 miles for both groups. Thus, it should be kept in mind that the differences in the percent reductions of VMT are a function of the magnitudes of the numbers used in the calculations, whereas the absolute reduction in the level of emissions may be similar for the two groups.

Table 4(b) shows the differences in travel behavior with all modes of transportation taken into consideration. Because there was no alternative mode use on the center-based TC days, all of the indicators for that column remain unchanged. The only indicator that does not change for the center-based NTC days is the number of commute trips. This simply means that on NTC days, every commute trip involved a personal vehicle. The other five indicators are all higher on NTC days than in Table 4(a), and all are higher than for TC day travel. In spite of this, the statistical result does not change. The differences in the number of trips, number of commute (and non-commute) trips, and non-commute VMT are statistically insignificant, whereas the reductions in VMT and commute VMT are statistically significant. This further demonstrates that center-based telecommuting appears to be only effective at reducing daily VMT (primarily due to commute VMT reductions), and ineffective at reducing the number of daily trips. On the contrary, there is a small increase in both commute and non-commute trips. Although these increases are statistically insignificant, they suggest a trend to be monitored in future projects. The one-half trip increase in the number of commute trips in particular is indicative of the occasional tendency of center-based telecommuters to return home and then to work again during the course of a day.

Other comparisons

The next comparison of interest is the TC day travel for the two telecommuting groups. When the center-based TC days are compared to the home-based TC days, significant differences are found for four out of the eight variables (see Table 5, line 2–4). Not surprisingly, the center-based group made significantly more trips, commute trips, commute

Table 5. Significant differences for each comparison group combination

	Trips	C-trips	N-trips	VMT	CVMT	NVMT	Cold	Hot
1–2				SD	SD			
1–3								
1–4		SD		SD	SD		SD	
1–5	$p = 0.058$			SD	SD		SD	
2–3		SD		SD	SD			
2–4	SD	SD			SD		SD	
2–5								
3–4	SD	SD		SD	SD		SD	
3–5	SD	SD		SD	SD		SD	
4–5	SD	SD		SD	SD		SD	

Note: Empty cells denote 'no significant difference', at $p > 0.05$.

VMT and cold starts. These differences are obviously due to the fact that the center-based group continued to use their personal vehicles for commuting.

A very interesting finding is discovered by comparing the center-based group on their TC days to the comparison group (Table 5, line 2–5). There are no significant differences for any of the eight measures. This shows that these long distance commuters become statistically similar to average commuters on days when they telecommute from a center (to the extent that the comparison group represents average commuters).

Analysis of variance and additional t-tests

For the telecommuting groups, a two-way analysis of variance (ANOVA) can be performed to identify, for each indicator, significant person main effects (center-based versus home-based), day status main effects (NTC versus TC) and interaction effects. The person effect compares the center-based telecommuter sample to the home-based telecommuter sample for each measure to determine if the group means differ significantly. Similarly, the day status effect weighs the differences between the TC day and NTC day measures. The interaction effect indicates whether any change across day type differs by person type.

An assumption for the use of ANOVA is that the within-group variances be equal for each group. This criterion is satisfied for only two of the travel indicators, non-commute VMT and hot starts. Because the ANOVA results for the remaining indicators are not entirely rigorous due to this violation, the results are supported with *t*-tests between each pair of groups. These tests are able to account for unequal variances among groups where appropriate, and they provide completely rigorous statistical evidence to support (or refute) the ANOVA findings. *t*-Test results are presented in Table 5.

ANOVA results for main and interaction effects are displayed in Table 6. Because of the large number of comparisons, a convenient way to present the data is to illustrate them graphically, as shown in Fig. 1(a–h). All eight travel indicator variables are discussed below, where an α of 0.05 is used as the cut-off for determining significance.

Beginning with the average number of trips per person-day, the ANOVA result shows that the person main effect is insignificant, the day status main effect is significant, and the interaction effect is significant. This is a somewhat surprising result because the *t*-test (when comparing center-based to home-based workers on their TC days) showed a significant difference in the number of trips. However, the *t*-test result for this indicator showed that the significance of the differences in group means depended on the equality of variance result. That is, for equal variances, the difference was insignificant (p = 0.076), and for unequal variance, the difference was significant (p = 0.012). For this indicator, variances were determined to be unequal, explaining the reason for the incorrect ANOVA result (since equal variances are assumed when conducting an ANOVA test). Thus, the more valid inference from the *t*-tests collectively is that both main effects and the interaction effect are all significant. From Fig. 1(a) it is seen that trips decreased significantly for home-based telecommuters, and increased insignificantly for center users.

The next indicator of interest is the number of commute trips per person-day [Fig. 1(b)]. For this indicator, both main effects as well as the interaction effect are significant. In terms of commute trips, the two groups have entirely different impacts from telecommuting. The home-based group is able to eliminate its commute trips almost entirely on TC days, whereas the center-based group actually increases (insignificantly) the number of commute trips on TC days.

Table 6. ANOVA results

	Trips	C-Trips	N-trips	VMT	CVMT	NVMT	Cold	Hot
Day main effect	SE	SE		SE	SE		SE	
Person main effect	SE*	SE			SE		SE	
Person-day interaction effect	SE	SE					SE	

*Significant according to the *t*-test between groups, accounting for unequal variances.
Note: Empty cells denote 'no significant effect', at $p > 0.05$.

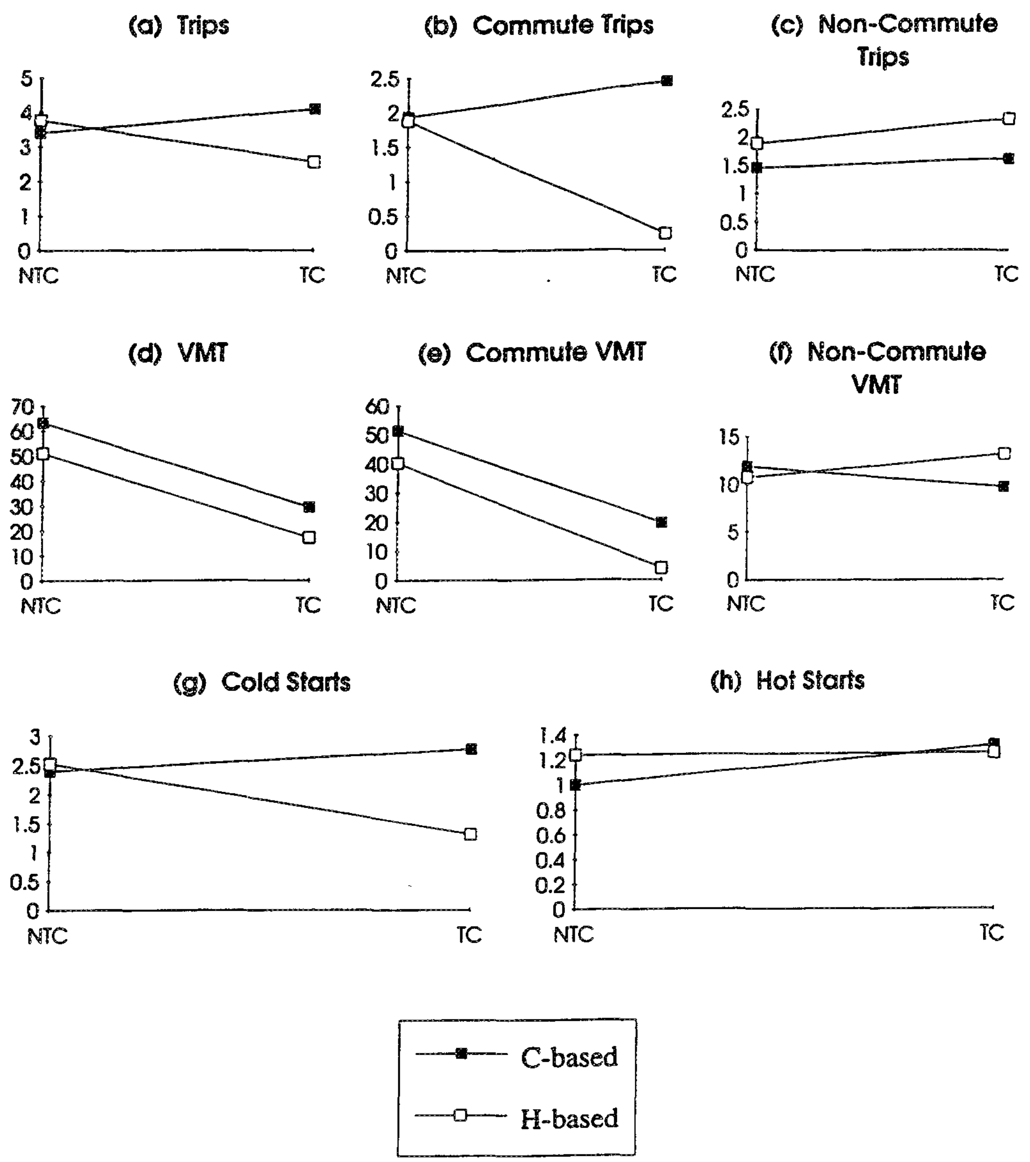

Fig. 1. ANOVA results.

The number of non-commute trips per person-day [Fig. 1(c)] shows insignificant main and interaction effects. This is an important observation because of the concern that telecommuting may increase levels of non-commute-related travel [see, for example, Salomon (1985)].

The daily VMT measure showed an insignificant person and interaction effect, but a significant day effect [Fig. 1(d)]. This means that telecommuting significantly reduced the VMT similarly for the two groups. For a more detailed analysis, the daily VMT was disaggregated into commute-related VMT [Fig. 1(e)] and non-commute-related VMT [Fig. 1(f)]. The person and day status main effects are both significant for commute VMT, but the interaction effect is not. Neither the main nor the interaction effects are significant for the non-commute VMT as the non-commute-related VMT remained almost constant for both groups on NTC and TC days. This shows that the impacts of telecommuting on daily VMT are due to changes in commute, rather than non-commute, VMT providing further support against the hypothesis that telecommuting may stimulate non-commute travel.

The final two indicators are the number of cold engine starts [Fig. 1(g)] and the number of hot engine starts per person-day [Fig. 1(h)]. For cold starts, both main effects and the interaction effect are significant, with cold starts declining significantly on home-based TC days and increasing negligibly on center-based TC days. For hot starts, neither the main effects nor the interaction effect were significant. This result is related to the finding for the number of trips since each trip must begin with either a cold or a hot start. The analysis shows that telecommuting did not impact the number of hot starts, rather, significant differences in the number of trips represented changes in cold start trips.

Temporal distribution effects of cold and hot starts

This differential impact on cold starts and hot starts and between groups can be explored further. Each sequence of trips that starts at home and ends at work (or starts at work and ends at home) typically begins with a cold start. The center-based group *increased* the number of commute trips made on their TC days compared to their NTC days (primarily due to an increase in trips home for lunch) accounting for the increase in cold starts. For this group, the number of commute trips increased by 0.53 trips per person-day (2.46 on TC days compared to 1.93 on NTC days), and the number of cold starts increased by 0.38 (2.77 on TC days compared to 2.39 on NTC days). It is plausible that some return-to-work segments of a lunch time commute would be hot starts, as a trip is classified as a 'hot start' if it begins within an hour of the end of the preceding trip made by the same vehicle (assuming a vehicle is equipped with a catalytic converter as is the case for the majority of this sample).

The home-based group must be analyzed in a slightly different manner since their commute trips were, for the most part, eliminated on TC days. The home-based group *decreased* their number of commute trips on TC days by 1.63 trips, but their number of cold starts only decreased by 1.21. This is likely to be the case because the typical afternoon chain of trips would begin with a cold start whether that chain contained a commute trip or not. Thus, the reduction in cold starts for the home-based group comprises primarily the reduction in early morning commute trip cold starts combined with the elimination of the afternoon chain of trips for those participants who did not travel at all on their TC days.

Emissions resulting from a cold engine start increase as ambient temperature decreases. Thus, it follows that if the number of cold starts decreases, larger savings are realized if the decrease takes place in the early morning (when ambient temperatures are lower) than in the afternoon. The temporal distribution of cold starts is illustrated in Fig. 2. Chi-squared tests were performed to determine whether differences in the distributions of each group were statistically significant. The tests showed no significant differences ($p > 0.5$) among the three groups on NTC days, but a significant difference ($p \approx 0.000$) between the center- and home-based telecommuting groups on TC days. Further, analysis of Fig. 2 shows that a disproportionate change in the distribution of cold starts by the time of day (statistically significant at $p \approx 0.000$) is precisely what occurred for the home-based telecommuting group when comparing their NTC day behavior to TC days. Because a larger proportion of early morning cold starts was eliminated for that group, larger emissions savings were realized than if the cold start reduction had taken place uniformly. However, the *absolute decrease* in the number of cold starts is the largest contributor to the savings in cold start emissions.

Analysis of the center-based distribution of cold start trips by time of day shows very little change (statistically insignificant at $p > 0.1$) between NTC and TC days. Small decreases are observed in the 9 a.m.–12 p.m. time period. An increase in cold starts during the 12 p.m.–3 p.m. time period occurs, presumably reflecting, at least in part, the additional travel generated by trips home for lunch. It is unlikely that the ambient temperatures will fluctuate enough across these time periods to cause a measurable emissions impact. The lack of change in the distribution provides further evidence that the center-based group is not impacted by telecommuting in terms of either the number of daily trips or the times of the day when they occur.

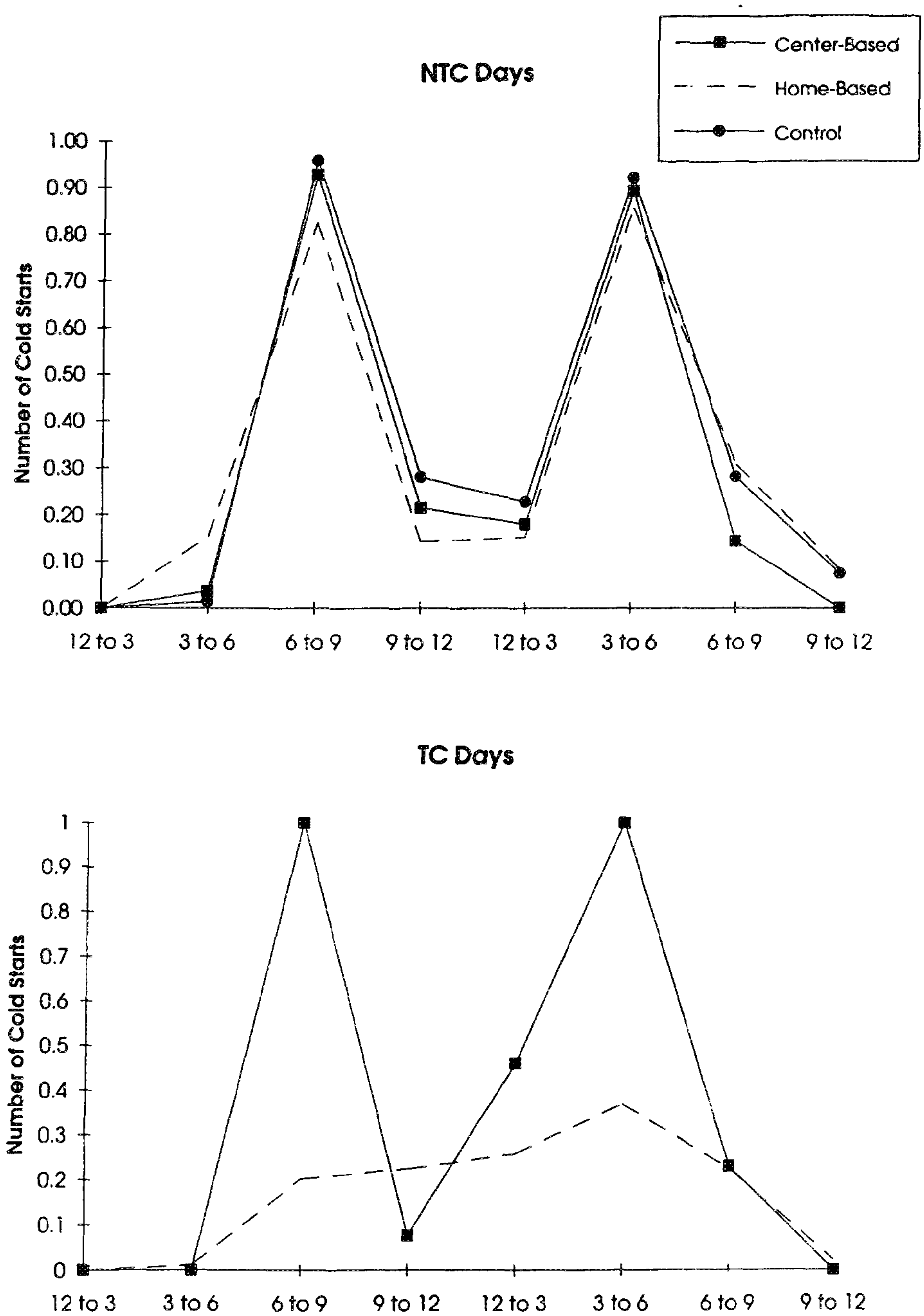

Fig. 2. Distribution of cold starts (per person-day) by time of day.

Discussion

The overall result is that telecommuting impacts both center-based and home-based telecommuters in some important, but different ways. In terms of the number of trips made, home-based telecommuting significantly reduces the number of daily trips by eliminating the commute, while only slightly (but not significantly) increasing non-commute-related trips. These reductions lead to significant decreases in the number of cold starts (especially in the early morning) without significantly affecting the number of hot starts. Center-based telecommuters are essentially unaffected in terms of trips, commute trips, non-commute trips, and subsequently, cold starts and hot starts. VMT, on the other hand, is significantly reduced for both groups. The reductions are primarily due to the elimination of the commute trip for the home-based group and to the much shorter commute distance for the center-based group. For both groups, the overall reductions in daily VMT comprise significant reductions in commute-related VMT with insignificant changes in non-commute-related VMT.

The fact that home-based telecommuters reduce both trips and VMT, whereas center-based telecommuters only reduce VMT, leads to the obvious conclusion that home-based telecommuting has larger per-occasion emissions benefits, all else being equal. While it is true that home-based telecommuting has the potential to reduce emissions at higher levels, the fact that center-based telecommuting may be more appropriate for a large percentage of the work force motivates an emissions analysis to determine whether overall emissions benefits are realized for this form. After qualitatively assessing the emissions impacts through analysis of the *D/C* ratio in the following section, the percentage changes in each pollutant are quantitatively modeled.

EMISSIONS ANALYSIS

Analysis of the D/C ratio

An approximation of the emissions impacts of telecommuting can be determined by analyzing reductions in travel measures using the *D/C* ratio (Henderson *et al.*, 1996). Distance (VMT) is primarily associated with running emissions, which is the major contributor to PM and NO_x, and the number of cold starts is related to cold start emissions, which is the major contributor to TOG and CO. Using these surrogates permits a rough assessment of the emissions impacts of various TCMs without requiring the extensive effort of applying analytic emissions modeling tools. The distance/cold start ratio, or '*D/C* ratio' is defined as:

$$D/C \text{ ratio} = \frac{\text{Percentage reduction in VMT}}{\text{Percentage reduction in number of cold starts}}.$$

To determine the relative impacts on the groups analyzed here, the *D/C* ratio has the following values. For the center-based group, the value is 54/(−16), and for the home-based group, the value is 66/48. The center-based group value indicates that the VMT was reduced by 54%, whereas the number of cold starts increased by 16%. This increase in cold starts will increase the TOG and CO emissions for that process. However, it should be noted that, although the reduction in VMT primarily affects PM and NO_x pollutants, TOG and CO are also reduced, which will help to offset the increased cold start emissions. Because the 16% increase in cold starts is relatively small in comparison to the 54% decrease in VMT, the overall impact on TOG and CO is unclear, and should be investigated in more detail using emissions modeling tools. It can be stated with certainty, however, that center-based telecommuting resulted in significant decreases of PM and NO_x emissions due to reduced VMT on telecommuting days.

The *D/C* ratio for the home-based group indicates that VMT was reduced by 66%, and the number of cold starts was decreased by 48%. Thus, home-based telecommuting is a very effective tool for decreasing TOG and CO emissions (the pollutants associated with the cold start process), and is *even more* effective for decreasing PM and NO_x emissions (the pollutants associated with VMT). As implied earlier, it is superior to center-based telecommuting for both VMT and cold start measures on a per-occasion basis.

Emissions impacts estimated with the EMFAC7F and BURDEN7F models

The California EMFAC7F and BURDEN7F models used in this study (CARB, 1993) are among the most advanced mobile source emissions models available and represent the current state of the art. However, several researchers (e.g. Pierson *et al.*, 1990; Pollack *et al.*, 1992) have found that the emissions estimates from models (such as EMFAC/BURDEN and the federal EPA model, MOBILE) are lower than field-measured pollutant concentrations. These studies have raised concerns about the accuracy and usefulness of the models. While we are cognizant of the shortcomings of current emissions models, we maintain

Table 7. Comparison of emissions across groups (grams per person-day)

	Center-based		Home-based		
	NTC day 1	TC day 2	NTC day 3	TC day 4	Control 5
TOG	37.45	35.97	56.70	29.59	61.05
CO	328.50	328.63	456.83	232.05	462.96
NO_x	38.91	19.91	47.37	19.03	37.83
PM	13.30	6.29	10.77	3.62	6.96

that, with the appropriate input data, they can be very useful tools for providing a relative comparison of emissions levels among groups. Because of the potential for modeling inaccuracy, however, the specific emissions figures provided in this report (in grams/day) should be used with caution. The percentage differences among groups should be more reliable measures, and they are the primary basis for comparison presented here.

The methodology for modeling the emissions of sample-specific travel diary data is developed in detail in Henderson *et al.* (1994). The modifications for this study involve replacing every default data file containing aggregate California data with the actual data tabulations derived from the travel diaries of the Puget Sound Project participants. These data include the travel activity in terms of trips, VMT, average trip speeds and population of vehicles for each class (light duty trucks and light duty autos), and by each time period of the day. Six time periods are modeled: 12 a.m.–6 a.m., 6 a.m.–9 a.m., 9 a.m.–12 p.m., 12 p.m.–3 p.m., 3 p.m.–6 p.m., and 6 p.m.–12 a.m. The fraction of cold engine starts made by vehicles with and without catalytic converters is another important input. Finally, the vehicle fleet itself is replaced with the participants' vehicle information, including the proportions of miles and trips made by each model year vehicle represented in the sample. Because the previous analysis of the same data assumed that all travel took place in winter (the season of greatest interest to the sponsor of that study), the same assumption was made here. Therefore, the winter emissions inventory (when levels of carbon monoxide, CO, are of greatest concern) was specified for the model runs.

Four pollutants are modeled: total organic gases (TOG), carbon monoxide (CO), oxides of nitrogen (NO_x) and particulate matter (PM). The estimated levels of emissions for each pollutant for each group are presented in Table 7. A comparison of the center-based NTC days with the TC days shows that TOG was reduced by 4%, CO was essentially unaffected, NO_x was reduced by 49% and PM decreased by 53%. Thus, as expected from the travel behavior analysis, the two pollutants that are most directly dependent on VMT (NO_x and PM) decreased substantially, roughly in proportion to the VMT reduction of 54%. On the other hand, the two pollutants primarily associated with cold engine starts (TOG and CO) remained relatively constant, even though cold starts increased by 16%. As noted earlier, the VMT reduction also affects these two pollutants, in this case enough to just counteract the increases in each due to the rise in cold starts.

Comparison of the home-based telecommuting NTC days with the TC days shows reductions for each pollutant: 48% for TOG, 49% for CO, 60% for NO_x and 66% for PM. Of course these reductions are greater than the reductions observed for the center-based telecommuting group because many of the home-based telecommuters eliminated both their VMT and trips associated with the commute to the regular work place.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The impacts of center-based telecommuting on transportation and emissions have been quantified and compared to the impacts of home-based telecommuting. As expected based on previous results, home-based telecommuting was found to reduce travel and emissions primarily due to the elimination of commute trips. Comparing NTC days to TC days for the home-based group showed reductions in VMT and in the number of daily trips of 66.5% and 31.9%, respectively. The decrease in the number of trips led to a 48.0% reduction in the number of cold engine starts for the group. Because the center-based group is still required to make a commute trip of somewhat shorter length, the VMT was significantly reduced for them, but the trips and number of cold starts were not. VMT decreased for the center-based group on its TC days by 53.7%, a statistically significant difference at $p \leq 0.002$. The number of daily trips increased by 20.4%, and the number of cold engine starts per person-day increased by 15.9%, both statistically insignificant differences.

Home-based telecommuting reduces each pollutant of concern because of its ability to impact each pollutant producing process. Specifically, reductions in VMT lead to reductions in NO_x and PM. Reductions in cold starts lead to reductions in TOG and CO. Thus, 48–66% reductions are realized for each pollutant as a result of home-based telecommuting. The situation differs for center-based telecommuting. Since specific pollutants are primarily associated with specific vehicle activity processes, the emissions analysis showed that only the VMT-related pollutants, NO_x and PM, are substantially reduced for the telecenter users. TOG emissions show a small (4%) saving, and CO levels remain virtually constant. A critical observation to make is that, for center-based telecommuting, there were no statistically significant increases in either the levels of any travel indicators or the levels of any pollutants. Thus, although savings were only realized for specific pollutants, there was no 'cost' involved, that is, one pollutant did not decrease at the expense of increasing another.

The final result is that center-based telecommuting has both transportation and air quality benefits. Although the reductions in travel and emissions are lower than for home-based telecommuting, it appears that, if a large percentage of employees are able to utilize telecommuting centers, their contributions to aggregate, region-wide savings may be substantial. The reader is reminded that the reported impacts represent percent reductions in weekday travel and emissions for the telecommuters themselves, not for the population as a whole. Thus, these findings represent average per-capita weekday impacts for early adopters of center-based telecommuting; the aggregate (or overall, region-wide) impacts are determined by scaling these reductions by the proportion of telecommuters in the workforce and accounting for the frequency at which telecommuting takes place.

Many questions about the efficacy of telecenters remain to be answered. Perhaps most importantly, what *is* the relative demand for home- and center-based telecommuting? In particular, despite their hypothesized advantages, is there in fact a market niche for telecommuting centers? From the employee perspective, early studies (Bagley, 1995; Stanek, 1995) have been unable to identify a substantial segment of the workforce which exclusively prefers center-based telecommuting. From the employer's perspective, the economic and institutional viability of the concept remains unproven, potentially involving the spatial and organizational restructuring of the main workplace in order to succeed. However, if home will do as well or nearly as well for an alternative work location, the demand for a more complex and costly center-based arrangement may be minimal.

Another question relates to the frequency of telecommuting under each form. As indicated earlier, telecommuting centers may offer better equipment than is available at home, and may also offer less isolation from other co-workers. Employers may feel more comfortable allowing an employee to work from a center than from home. Will these and other advantages cause center-based telecommuters to telecommute more frequently than their home-based counterparts? If so, then even though the per-occasion transportation and air quality benefits may be higher for home-based telecommuting, the center-based form may overall be more beneficial in these respects. Evidence to date suggests that telecommuting frequencies are about the same for the two forms, but it may be too early to consider this a definitive conclusion.

Finally, there is a need to analyze the transportation and air quality impacts of center-based telecommuting on a larger sample. This will provide more robust results that can confirm or counter the preliminary conclusions presented here. Work is currently underway, at the direction of the second author, to conduct such an analysis. Under the

Residential Area-Based Offices Project funded by the Federal Highway Administration and the State of California Department of Transportation, before and after travel diary data are being collected from users of 15 telecommuting centers in California, plus home-based telecommuting and non-telecommuting comparison groups. Analyzing these data will provide additional insights into the transportation-related impacts of center-based telecommuting. Other parts of the same project will be examining the other questions discussed above.

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