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Using Travel Diary Data to Estimate the Emissions Impacts of Transportation Strategies: The Puget Sound Telecommuting Demonstration Project

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ABSTRACT

Transportation control measures are often implemented for their environmental benefits, but there is a need to quantify what benefits actually occur. Telecommuting has the potential to reduce the number of daily trips and miles traveled with personal vehicles and, consequently, the overall emissions resulting from vehicle activity. This search studies the emissions impacts of telecommuting for the participants of the Puget Sound Telecommuting Demonstration Project (PSTDP). The California Air Resources Board's emissions models, EMFAC7F and BURDEN7F, are used to estimate the emissions on telecommuting days and non-telecommuting days, based on travel diaries completed by program participants. This study, among the first of its kind, represents the most sophisticated application of emissions models to travel diary data.

Analysis of the travel diary data and the emissions model output supports the hypothesis that telecommuting has beneficial transportation and air quality impacts. The most important results are that telecommuting decreases the number of daily trips (by 30%), the vehicle-miles traveled (VMT) (by 63%), and the number of cold starts (by 44%), especially those taking place in early morning. These reductions are shown to have a large effect on daily emissions, with a 50% to 60% decrease in pollutants generated by a telecommuter's personal vehicle use on a telecommuting day. These net savings are almost entirely due to the elimination of commute trips, as non-commute trips increased by 0.33 trips per person-day (9% of the total trips), and the non-commute VMT increased by 2.2 miles. Overall reductions in travel and emissions of this magnitude are observed because the telecommuters in this sample are long-distance commuters, with commutes twice as long as the regional average. However, even as telecommuting adoption moves into the mainstream, its net impacts are still expected to be beneficial—a reduction in VMT and in emissions.

It is important to note that when the *level* of telecommuting is considered (that is, the percentage of work days that employees actually telecommute), the weekly savings are a much smaller proportion of total weekday travel. Also, these findings represent average per-capita reductions; the aggregate (or overall, regionwide) impacts are determined by scaling these reductions by the number of program participants. Thus, the *aggregate effectiveness* of telecommuting must take into account the number of people likely to participate as telecommuters and how often they telecommute, not just the per-capita, per-occasion impacts.

IMPLICATIONS

Telecommuting is one of many Transportation Demand Management (TDM) strategies being considered by policy makers to reduce congestion levels and improve air quality. As one of the first studies to directly measure the impacts of telecommuting on vehicle emissions levels, this research contributes to a new body of data on the air quality impacts of telecommuting. The findings support the hypothesis that telecommuting benefits both air quality and congestion. The methodology presented may be applied to other TDMs to analyze the comparative impacts of each strategy. This information will help policy makers identify the most effective congestion reduction and air quality improvement approaches.

INTRODUCTION

Transportation and energy planners became intrigued with the possibility of substituting telecommunications for travel as early as the 1960s,[1] again during the energy crisis of the 1970s,[2] and then in the 1980s as a strategy to help decrease congestion and improve air quality.[3] Today the adoption of telecommuting for the improvement of air quality is becoming increasingly widespread, making it important to study how changes in personal vehicle use due to telecommuting will influence the amount of emissions generated from that activity. Whereas a number of studies have analyzed the transportation impacts of telecommuting,[4] to date few have evaluated the direct emissions impacts which accompany those changes in travel behavior due to telecommuting. This research and a companion study of the State of California Telecommuting Pilot Project[5] constitute two of the first such analyses. To date, the methodology developed here represents the most sophisticated application of emissions models with travel diary data.

This study evaluates the emissions impacts of telecommuting using travel diary data from the Puget Sound (Washington State) Telecommuting Demonstration Project[6] (PSTDP). The emissions generated by telecommuters' personal vehicle use on telecommuting (TC) days and non-telecommuting (NTC) days are compared to each other and to the emissions of a non-telecommuting control group. To estimate the emissions for the analysis, the Puget Sound data are used as input to the

California Air Resources Board's emissions models, EMFAC7F and BURDEN7F. Modifications were made to the models to customize the analysis as much as possible to the characteristics of the Puget Sound, Washington area and of the data itself.

An emissions analysis such as this one depends on the accuracy of the models used. It is generally suspected that the EMFAC and BURDEN models underestimate the amount of emissions caused by vehicle activity, although the extent of this inaccuracy is not well known.[7,8] The current (7F) versions of the models, however, are among the most advanced mobile source emissions models available and provide the best estimates of the impacts of telecommuting on vehicle emissions at this time. Because of the potential for inaccuracy in emissions modeling, the specific emissions figures provided in this paper (in grams/person-day) should be used with caution. The percent difference in emissions between telecommuting and non-telecommuting days should be a more reliable measure of the impacts of telecommuting. These percent changes in emissions, however, are tied to percent changes in VMT and trips. Future telecommuting programs with different travel impacts should expect correspondingly different emissions reductions.

PUGET SOUND DATA

The PSTDP data used in the analysis is composed of travel diary data provided by 104 telecommuters from about 20 public and private organizations and 41 control group members, who were (for the most part) comparable, non-telecommuting employees of the same organizations. Although every telecommuter in the PSTDP was expected to participate in the evaluation, compliance with that expectation varied; 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.

Two-day travel diaries were completed by the project participants and their driving-age household members to document their travel behavior before and after telecommuting. The data were collected in three "waves," with one "before" telecommuting wave (occurring in late 1990 and early 1991) and two waves occurring about six months and one year, respectively, "after" telecommuting began. The data collected included general participant information such as the participant status (telecommuter, control group member, telecommuter household member, or control group household member), age, gender, home and work locations, locations frequently visited, transit lines used and household vehicle ownership. The travel diaries contain the trip characteristics for every trip reported by the respondents. The information for each trip includes the origin and destination, beginning and ending trip times, purpose, approximate trip length as reported by the respondent, mode used, beginning and ending odometer reading if a personal vehicle was used, and the number of passengers. In the case of personal vehicle trips, the vehicle make, model, and year are also included. Detailed discussions of the PSTDP data are reported in Quaid and Lagerberg.[6] Extensive data clean-up efforts were undertaken at the onset of the project to help ensure the accuracy of the data.[9]

A thorough review of the data revealed that the participants in the study telecommuted to varying degrees from wave to wave. The review showed that 32 of the 104 people recruited to telecommute in the study were never recorded as doing so (see Table 1). Also, 8 of the 41 control group members (supposedly non-telecommuters by design) were recorded as telecommuting over the course of the study. A "Before"/"After" analysis of the data was considered, but such an analysis should properly be performed only on the subset of "pure" telecommuters and "pure" controls for which data were available for both "Before" and "After" waves (otherwise, differences due to telecommuting are confounded with differences due to having different samples "Before" and "After"). However, this would have required the exclusion of a large number of participants and telecommuting days. To maintain the largest sample of telecommuting data, it was decided to compare travel behavior on telecommuting days and non-telecommuting days for the pure telecommuters and controls, without regard to whether a participant's day fell in the "Before" or "After" waves.

Thus, the analysis presented here involves comparing the vehicle emissions of the 72 people who were recruited to telecommute, and did, with the 33 control group members who never telecommuted. A second emissions analysis that separated all telecommuting day trips into one group and all non-telecommuting day trips into another (regardless of the participants' recruitment status) was performed with similar results.[10] Isolating the 72 telecommuters and the 33 control group members for the primary analysis and comparing the emissions of the same sample provides greater certainty in conclusions as to whether observed changes in automobile use and emissions are actually due to telecommuting. Table 2 tabulates the trips taken by these two groups. All trips are included for reference, but only the personal vehicle (drive alone) trips were analyzed in this study. Carpool and vanpool

Table 1. Distribution of project participants who telecommuted

Recruited as:	*# of people who telecommuted during diary periods*	*# of people who didn't telecommute during diary periods*	*Totals*
Telecommuting Group Members	72	32	104
Control Group Members	8	33	41
Totals	80	65	145

Table 2. Distribution of trips across comparison groups

	Telecommuters				*Controls*	
	Telecommuting Days		*Non-Telecommuting Days*			
	# Trips	*# Person-days*	*# Trips*	*# Person-days*	# Trips	# Person-days
Personal vehicle trips	279	67	948	257	648	150
All trips	334	70	1236	280	780	166
No personal vehicle trips made	—	41	—	0	—	0

trips were not included since the focus of this research is on emissions impacts. It is reasonable to assume that many, if not most, ridesharing trips would still have taken place without the telecommuter, and that telecommuting would have no emissions impacts on those trips. Also, weekend data and household member data were excluded due to infrequent and unreliable reporting. Thus, this study only addresses the personal vehicle emissions impacts of telecommuting on the work days of participants directly recruited for the project.

Of the 1227 personal vehicle trips taken by telecommuters, 279 trips took place on 67 telecommuting person-days and 948 trips took place on 257 non-telecommuting person-days. Emissions for these telecommuting day/non-telecommuting day trips are compared to the emissions produced by the 648 control group personal vehicle trips, which occurred on 150 person-days. It is noteworthy that on 41 (38%) telecommuting days no personal vehicle trips were made at all by the telecommuter, compared to only 9% (39 out of 446) of the non-telecommuting days for both telecommuters and controls. To account for different size groups, emissions data are reported in terms of grams of pollutant per person-day.

OVERVIEW OF THE MODELS

The EMFAC7F and BURDEN7F models are designed to calculate aggregate emissions inventories (in tons per day) generated from vehicle activity for air basins in California.[11] The user specifies the inventory year and the season (either summer or winter) in which vehicle activity takes place. The temperature distribution and fleet mix vary by year, and the emissions factors vary by season. Summer and winter are the two seasons for which vehicle activity patterns and atmospheric conditions combine to produce the worst air quality. The different characteristics of the seasons are associated with violations of air quality standards for different pollutants. In the summer, ozone precursors (TOG and NO_x) are of greatest concern, whereas in the winter, CO levels are most important to monitor. An emissions inventory was run for both summer and winter, although the winter inventory was of most concern to the study sponsor and, hence, is the main focus of this research. Only the winter findings are presented here; for the summer analysis see Henderson et al.[10]

Seven *pollutant types* are modeled by EMFAC7F and BURDEN7F: total organic gases (TOG), reactive organic gases (ROG), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), and lead. The SO_x and lead outputs are not reported here because the vehicle activity in this small sample did not generate measurable amounts of these pollutants. The input requirements for BURDEN7F demanded that personal vehicles be classified into *class/technology groups*. Four categories of vehicles were present in this sample: a light-duty automobile class subdivided into catalyst-equipped and non-catalyst-equipped technology groups, and a light-duty truck class with the same two subcategories. Vehicles are modeled as having seven different *emission-producing processes*: running exhaust, cold start exhaust, hot start exhaust, hot soak emissions, evaporative running losses, diurnal emissions, and evaporative resting losses. To assess the impacts of changing ambient temperatures on vehicle emissions, BURDEN7F models vehicle activity for six different *time periods* throughout the day. These time periods are: 12 midnight to 6 a.m., 6 a.m. to 9 a.m., 9 a.m. to 12 noon, 12 noon to 3 p.m., 3 p.m. to 6 p.m., and 6 p.m. to 12 midnight.

For a particular calendar year, EMFAC7F calculates an array of emissions factors for each combination of vehicle class/technology group, emissions process, and pollutant type. BURDEN7F references these emissions factors and compiles the emissions inventory for a specific set of vehicle activity data for each of the six time periods of the day. The emissions inventory is produced by weighting each measure of vehicle activity (VMT, number of cold starts, etc.) with the appropriate emissions factors and adding these emissions figures for each time period of the day. An in-depth discussion of the models is found in a CARB publication.[11]

Modifications to the Models

All major input files that make EMFAC7F and BURDEN7F California-based models were changed, using the travel diary data or Puget Sound region data. The default California temperature data files in EMFAC7F were replaced with temperature data from the Seattle-Tacoma Airport. The data included hourly temperature readings from 1988 though 1991. These data were averaged to obtain a representative daily temperature distribution for each season modeled. The Puget Sound data were tabulated to provide the necessary input for BURDEN7F's four main data files: (1) the cold start fraction of trips made by vehicles with and without catalytic converters for each of six time periods of the day; (2) the number of trips made and VMT by each vehicle class for each of the six time periods of the day; (3) VMT fractions by average speed for each of the six time periods; and (4) the average temperatures during each time period for the specific air basin in which the travel took place.

Several modifications were made to the FORTRAN code of the models. EMFAC7F and BURDEN7F were developed to model aggregate emissions for each air basin in California, and therefore use an average California vehicle fleet. However, individual-level analyses such as this study require sample-specific data, rather than aggregate data to provide meaningful comparisons across groups within the sample. To accomplish this, the average California vehicle fleet data in EMFAC7F was replaced with the actual Puget Sound vehicle representation for each group (telecommuters on telecommuting days, on non-telecommuting days, and controls). To allow the generation of accurate weighting functions, the fleet mix file subroutine was de-activated, and the output from the subroutine was generated manually to include vehicles, VMT, and trip information from the PSTDP. Also, internal changes to the BURDEN7F code were required to produce output in terms of pounds (rather than tons) of pollutant per day—a more useful unit for this individual-level analysis.

FACTORS AFFECTING THE AIR QUALITY IMPACTS OF TELECOMMUTING

Air quality may be affected in three different ways as a result of telecommuting. *Direct transportation impacts* are those first-order effects on the participants' travel patterns that are observable from the travel diary data in isolation. *Indirect transportation impacts* include higher-order changes such as effects on household travel, weekend travel, and long-term residential re-location. *Indirect non-transportation impacts* are those related to energy consumption changes due to telecommuting (e.g. lighting or heating at home that wouldn't be used otherwise). All three types of impacts should be considered in a complete analysis of the air quality impacts of telecommuting. Here, the available data permit only the direct transportation impacts of telecommuting to be studied. Even this confined analysis must be performed carefully, since many factors affect the direct air quality impacts of telecommuting, and the percent change in emissions levels is, in general, not equal to the percent change in VMT.[3] These factors include: trip length (VMT), number of trips, cold starts, trip speeds, ambient temperature for the trip, and the season in which the vehicle activity takes place.

To explain how these factors affect vehicle emissions, each must be discussed in the context of the emissions processes to which it is related. Of the seven processes modeled by EMFAC and BURDEN, the first five can be significantly influenced by telecommuting. These relationships are discussed in detail below.

Trip length (VMT). Trip length or VMT is an important factor since increased distance and time cause an increase in running emissions (including running exhaust and running evaporative losses). While evaporative emissions contribute only to TOG, running exhaust emissions contribute to every pollutant in varying degrees. For TOG and CO, running emissions are low in comparison to cold start emissions for short-to-moderate length trips (less than 20 miles). However, running emissions are the dominant contribution to NO_x, and are the only contributor to PM emissions. If telecommuting causes a reduction in number of trips as well as VMT through the elimination or reduction of commute (and possibly other) trips, reductions in overall emissions are expected. However, if shorter trips are made and overall VMT decreases, but the number of trips with cold starts increases, NO_x and PM should decrease, while TOG and CO would increase.

Number of trips. The number of trips made is important as it relates to engine start-up emissions (cold-start and hot-start) and engine shut-down emissions (hot soak). After engine shut-down at the end of each trip (whether a cold or hot start trip) a hot soak occurs. This causes evaporative TOG losses from the fuel system, resulting from hot engine temperatures. Therefore if telecommuting decreases the overall number of trips, hot soak (TOG) emissions will decrease.

Cold start emissions. Cold-start emissions are greater than hot-start emissions by an order of magnitude and thus are a major concern. As mentioned, cold starts are the dominant contributor to TOG and CO emissions for short-to-moderate length trips, as well as a major contributor to NO_x. Even with a reduction in VMT and number of trips, emissions could actually increase if telecommuting were to cause a shift in travel behavior resulting in a higher number of trips that begin with a cold-start. Since the cold-start exhaust is a major contributor to emissions, a very important measure in this study is the number of cold starts per person-day and how it changes with telecommuting.

In general, there is a U-shaped relationship between *speed* and running emissions.[12] Higher speeds mean *lower* emissions rates, up to approximately 50 mph to 60 mph, beyond which higher speeds lead to *higher* emissions rates. The impact of telecommuting on travel speeds is ambiguous: other things being equal, higher travel speeds are likely if more trips are made at off-peak (uncongested) times of the day; alternatively, lower speeds will occur if trips are shifted from the freeways to the surface streets, where vehicle travel is typically slower.[13] Emissions are also influenced by vehicle accelerations, with higher emissions occurring on trips with more accelerations and decelerations than on equally long trips with constant speeds. Acceleration/deceleration patterns are influenced by telecommuting to the extent that trips are shifted out of congested, stop-and-go traffic into more free-flowing traffic in the off-peak period. For the purposes of this study, the data do not allow accelerations and decelerations to be determined; only the average speed for the trip can be calculated from distance and time. While EMFAC7F and BURDEN7F do not model the emissions impacts due to acceleration and deceleration in detail, the Federal Test Procedures (FTPs) used to determine the baseline emissions factors used by EMFAC7F do include standardized acceleration/deceleration test cycles, so these impacts on emissions are modeled to some extent.

Ambient temperature. The ambient temperature affects vehicle emissions for each pollutant emitting process. Evaporative emissions—TOG losses related to changes in ambient temperature— increase as temperature increases. These impacts are included in the models, although their contribution to overall emissions is rather small and not expected to be affected by telecommuting. By contrast, cold-start emissions are very sensitive to ambient temperature. In general, cold-start emissions increase as ambient temperature decreases. Thus, if telecommuting causes a shift in trips to times of the day when temperatures are higher (i.e. mid-day), reductions in cold-start emissions could be significant.

Ambient temperatures are also related to *the season* for which the analysis is performed. Typically, summer temperatures are higher than winter, resulting in a decrease in cold-start emissions. However, the Reid vapor pressure (RVP) also depends on the season. In the summer, the RVP is lower, decreasing evaporative losses significantly. Because of these outside factors, the authors caution that comparing emissions across seasons may show changes in emissions levels that are unrelated to vehicle activity.

Other factors related to the climate and topography of the air basin will also affect the air quality impacts of telecommuting. For example, mountain ranges, wind patterns, or the existence of a temperature inversion layer may form barriers against the natural dispersion of pollutants. Obviously, these are beyond the scope of this analysis. Here, it is only the production of pollutants by personal vehicles that is studied. But it is important to point out that the *effects* of these emissions are a function of many other factors. The same absolute levels of personal vehicle emissions may have very different effects from one basin to the next, depending on these other factors.

EMISSIONS ANALYSIS

Presentation of the Results

Output from the models represents emissions for all vehicle activity in the sample (in units of pounds). These numbers are then divided by the number of person-days represented by the sample and converted by the appropriate factor to yield an emissions output in terms of grams of pollutant per person-day. Similarly, the travel indicators are based on the sum of all activity for the sample, divided by the number of person-days. The travel activity totals, however, are simply tabulated from the travel diary data, independent of the emissions models. In this context, a person-day is defined as a day on which a participant in the study kept a record of his or her trips. This study focuses on the impact of telecommuting on personal vehicle travel and emissions. Thus, trips involving travel by other modes (such as mass transit or walking) have been excluded from the analysis. Emissions for these modes are either absolutely zero (e.g., for walking) or zero at the margin (e.g., for mass transit, assuming the bus will be traveling with or without the telecommuter on board). Consequently, person-days involving *only* trips by modes other than personal vehicles have been excluded from the denominator of the ratio of grams of pollutant to person-days.

However, the 41 telecommuting days on which no personal vehicle trips were recorded *are* included in the denominator, as the reduction of personal vehicle travel due to telecommuting is precisely one of the impacts we are attempting to measure. To the extent that a given telecommuter would virtually never travel by personal vehicle (e.g., the telecommuter doesn't own a car and takes mass transit or walks everywhere), we are slightly overstating the impacts of telecommuting 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.

Table 3. Travel and emissions comparison of telecommuters and controls (per person-day).

	Telecommuters NTC Days # people=71 # person-days=257	*Controls # of people=33 # person-days=150*	*% Difference* between *Controls and NTC Days*
# of personal vehicle trips	3.69	4.33**	-14.78
VMT (personal vehicles)	52.00	33.11**	57.05
# of cold starts	2.50	2.75***	-9.09
# of hot starts	1.19	1.57***	-24.20
Average mph (weighted by VMT)	32.47	27.42**	18.42
Total Organic Gas*	54.75	61.02	-10.28
Carbon Monoxide*	437.25	462.99	-5.55
Oxides of Nitrogen*	46.09	37.83	21.83
Particulate Matter*	11.00	6.96	58.05

*Measured in gm/person-day. Statistical tests could not be performed on these measures, because the model does not produce emissions by individual and therefore standard deviations could not be computed.

**Statistically different from telecommuters on NTC days at $\alpha \leq 0.005$

***Statistically different from telecommuters on NTC days at $\alpha \leq 0.050$

Findings

Before assessing the changes in emissions due to telecommuting, it is important to check the

Table 4. Travel and Emissions Comparison of TC Days and NTC Days (per person-day).

	Telecommuters TC Days # people = 72 # person-days = 108	NTC Days # people = 71 # person-days = 257	% Difference between NTC Days and TC Days
# of personal vehicle trips	2.58**	3.69	-30.08
VMT (personal vehicles)	19 22**	52.00	-63.04
# of cold starts	1 41**	2.50	-43 60
# of hot starts	1.18	1.19	-0.84
Average mph (weighted by VMT)	27.74**	32.47	-14.57
Total Organic Gas*	28 79	54.75	-47.42
Carbon Monoxide*	233.10	437.25	-46.69
Oxides of Nitrogen*	18.77	46.09	-59.28
Particulate Matter*	4.08	11.00	-62.91

*Measured in gm/person-day. Statistical tests could not be performed on these measures, because the model does not produce emissions by individual and therefore standard deviations could not be computed.
**Statistically different from Telecommuters on NTC days at $\alpha \leq 0.005$.

Table 5. Number and percent of cold starts per person-day, by time of day.

	Telecommuters TC Days	Telecommuters NTC Days	Controls
12 midnight - 6 a m.	0.01 (1 0%)	0.14 (5.6%)	0.01 (0.4%)
6 a.m. - 9 a.m.	0.28 (19.9%)	0.84 (33.5%)	0.96 (34.9%)
9 a.m. - 12 noon	0.20 (14.2%)	0.14 (5.6%)	0.28 (10.2%)
12 noon - 3 p.m.	0.25 (17.7%)	0.16 (6.4%)	0.23 (8.4%)
3 p.m. - 6 p.m.	0.44 (31.2%)	0.86 (34.3%)	0.92 (33.4%)
6 p.m. - 12 midnight	0 23 (16.3%)	0.37 (14.7%)	0.35 (12.7%)
Total # Cold Starts	1.41 (100%)	2.50 (100%)	2.75 (100%)

extent to which the telecommuters and controls are comparable, independent of telecommuting. Comparing telecommuters on NTC days with the control group reveals two critical differences (see Table 3). First, telecommuters make 15% *fewer* trips than controls (3.69 versus 4.33 per person per day). This translates into 9% fewer cold starts and 24% fewer hot starts. Second, telecommuters have a 57% *higher* daily VMT (52.00 versus 33.11 miles per person-day). Both differences are statistically significant at a less than 0.005% level. The higher VMT for telecommuters on NTC days is due to the fact that, on average, their commute length is 2.5 times longer than the controls.[10] As for the smaller number of trips, it may be that because telecommuters spend considerably more time on a single trip—the commute—they have less time to spend on other discretionary trips than do the controls.

Due to these important differences, the control group will not serve as a very useful comparison to the telecommuters. When measures such as number of trips are already lower on NTC days than for controls, they will be even lower on TC days. But (as shown by comparing Tables 3 and 4) even measures that are higher on NTC days than for the controls (VMT, NO_x, and PM) are much lower on TC days than for the controls. This provides additional qualitative support for the effectiveness of telecommuting.

We turn now to the comparison of telecommuters' TC days and NTC days. This analysis reveals several important transportation-and emissions-related findings. Table 4 shows that VMT, number of trips, and daily emissions have dramatically decreased as a result of telecommuting. Telecommuters made significantly fewer (30%) trips on TC days than on NTC days. Average VMT per person-day decreased by 63% on TC days, from 52.00 miles per day to 19.22 miles per day. Emissions-related findings include reductions in the number of cold starts by 44% (significant at $\alpha \leq 0.005$) and hot starts by 1% (not significant). Each pollutant of major concern was considerably reduced on TC days. Figures 1 through 4 show that total organic gas and carbon monoxide decreased by approximately 47%, while oxides of nitrogen decreased by 59%. The decrease in particulate matter emissions was exactly proportional to the reduction in VMT (63%).

The following discussion of results (referencing Table 4) relates these decreases in emissions levels to the changes in travel behavior due to telecommuting. The first area of interest is VMT. The savings of 63% in VMT for this particular sample of telecommuters is larger than would be expected from a more representative sample, since their 50-mile round-trip commute was observed to be twice as long as the regional average.[14] Over time, as telecommuting becomes more widespread, commute lengths of telecommuters are expected to fall closer to the regional average and the VMT reductions are expected to decrease. Nonetheless, from an emissions standpoint, the sharp decrease in VMT for this sample led to substantially reduced running emissions, especially running exhaust (see Figures 1 through 4). Emissions of PM and NO_x, which are primarily running-exhaust related, decreased in parallel to the VMT reductions. CO and TOG emissions are less directly related to running emissions and, consequently, were only slightly affected by the change in VMT.

The next area of interest is the 30% decrease in the number of vehicle trips due to telecommuting. Cold-start trips, which decreased by 44%, are one of the largest contributors to emissions and are discussed in detail below. Hot-start trips remained statistically equivalent between TC and NTC days. Thus, there was a higher *proportion* of hot starts on TC days,

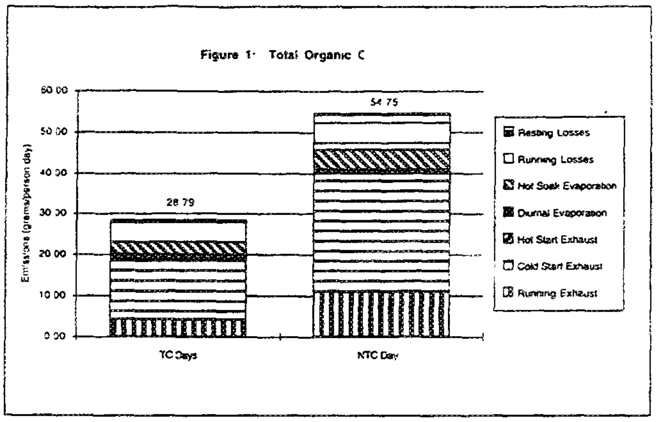

Figure 1. Total organic gas.

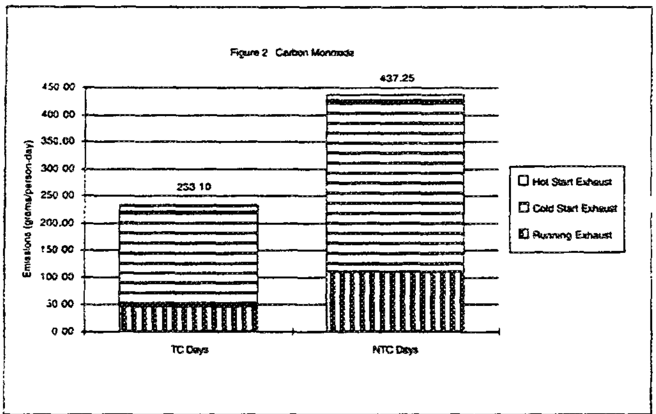

Figure 2. Carbon monoxide.

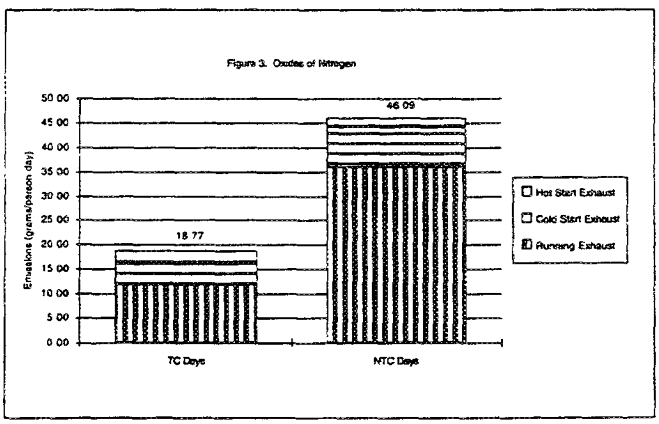

Figure 3. Oxides of nitrogen.

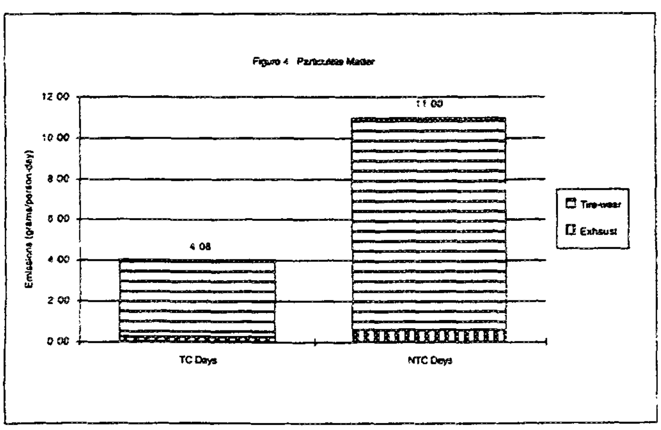

Figure 4. Particulate matter.

even though the *number* of hot starts did not increase. On NTC days, the proportion was 32% hot starts to 68% cold starts, whereas on TC days the proportion was 46% hot starts to 54% cold starts. If the total number of trips remained constant, but telecommuting shifted some of those trips from cold starts to hot starts, emissions would still be reduced, since hot starts generate far lower emissions than cold starts. In this sample, however, the decrease in emissions is entirely due to the decrease in number of trips (predominantly cold starts), not to the increase in the proportion of hot starts. Hot-soak emissions—the evaporative TOG emissions which occur when a vehicle is parked after a period of hot running—decreased by 38%. However, hot-soak emissions contribute to only about 10% of all TOG emissions and, consequently, were a relatively minor part of the TOG savings due to telecommuting.

An analysis of the pollutant emitting processes reveals that one of the primary indicators of how emissions are impacted by telecommuting is how cold starts are affected. Of particular importance are the difference in the number of cold starts and the times of the day when they occur. Table 5 shows the distribution of cold starts throughout the day. The total at the bottom of each column represents the total number of cold starts per person-day for that particular group. Analysis of the table reveals two important findings. First, on TC days, the absolute number of cold starts per person-day is lower for four out of the six time periods, compared to NTC days. The overall 44% decrease in the number of cold starts is one of the primary reasons telecommuters produced much lower emissions on TC days than NTC days. TOG and CO emissions were most affected, as cold starts contribute to well over half of the emissions for both pollutants.

The second important finding is that telecommuting was proportionately more effective at reducing cold starts in the morning than in the afternoon. That is, while cold-start trips were reduced for four out of the six time periods, the largest reductions were in the morning (between 6 and 9 a.m.). The benefit of this disproportionate reduction in cold starts is greater than if the reduction had been equal in each time period. It is more desirable to eliminate cold starts in the morning than in the afternoon because cold starts at lower ambient temperatures cause higher emissions. To quantify the benefits of the disproportionate decrease, another emissions inventory was performed to isolate the time-of-day (TOD) effects of telecommuting on cold-start reductions. This was accomplished by imposing the TOD distribution for NTC days on the TC day cold start totals and rerunning the emissions inventories. The new emissions totals represent purely the effect of having a smaller number of cold-starts on a TC day, holding time-of-day distribution constant. The difference between the old and the new totals represents the TOD impacts on cold start emissions. Table 6 shows the savings in grams per person-day resulting from TOD impacts. For TOG and CO, these savings represent 10% to 12% of the total grams saved as a result of telecommuting. For NO_x, TOD shifts represent 2.2% of the savings. For TOG and CO, this is a significant contribution to reducing emissions levels and shows the sensitivity of cold-start emissions to TOD effects. However, the *absolute decrease* in the number of cold starts is the largest contributor to the savings in cold start emissions.

Speeds do not seem to be greatly affected by telecommuting in this case. The average daily speed for telecommuting days is 27.74 mph, compared to 32.47 mph on non-telecommuting days. This is probably due to the fact that primarily commute trips are being eliminated, and commute trips tend to be longer, faster trips on average than non-commute trips. An analysis similar to the one done for the TOD distribution was performed to assess the extent of these impacts, which in this instance would be negative (since slower speeds generally result in higher emissions rates). The NTC day speed distribution was imposed on the TC day travel activity and the emissions model was rerun. The findings from the model runs show that the impacts of the slower speeds are negligible (less than 5% of the overall emissions levels).

Impacts on Non-Commute Travel

It is important to note (as shown in Table 4) that the number of trips was reduced by only 1.1, when it was expected that two commute trips would be eliminated. Further, a comparison of the VMT figures shows that telecommuting caused a 32.8-mile average reduction, whereas the average round trip commute distance for the 57 telecommuters (80% of the sample) for whom it could be unequivocally computed was 50 miles. Thus, at first glance it appeared as though increases in non-commute travel may have occurred on TC days. As this has been an important hypothesized negative impact of telecommuting (see, e.g., Salomon),[15] an investigation was conducted to determine why the number of trips was not reduced by two and why the VMT was not reduced by the average commute length.

The issue was complicated by the fact that it was not possible to disaggregate the total average daily VMT into commute-related and non-commute-related with complete precision. For 20% (14) of the telecommuters, no direct home-to-work or work-to-home trips were recorded during the diary period.When, say, the trip to work was linked with a non-commute activity, it could not be determined how much of the "home-other-work" distance was attributable to the commute and how much to the non-commute activity.Thus, the average commute length for the entire sample of 71 telecommuters may be less than or greater than 50 miles by an unknown amount. Further, it should be noted that 50 miles is the average commute length counting the 57 applicable telecommuters only once each. The number of diary days and commute trips reported by each respondent varied somewhat, however, and to ascertain the proportion of total sample VMT that is due to commuting, a commute trip should be counted as often as it appears in the sample, not just once per respondent.

With this background, then, the more detailed investigation of trip and VMT reductions revealed several interesting findings. First, even though only weekdays (Monday through Friday) were analyzed, *NTC days did not always involve a personal vehicle (PV) commute.* In fact, PV commute trips (i.e., at least one leg of a trip sequence which had home as the origin and work as the destination) were reported for only 94% of NTC person-days. This has two implications. First, the average NTC day VMT of 52.00 miles is smaller than it would have been if PV commute trips had been made on 100% of the person-days, meaning that the difference between NTC and TC day VMT is also smaller than would have been expected with full commuting. Second, the average number of PV commute trips on NTC days is not exactly equal to two, as expected, but is rather equal to 1.92 (counting the number of home-to-work sequences in the sample, whether or not there are any intervening trips, multiplying by two, and dividing by 257, the number of NTC person-days).

This suggests that telecommuting might be expected to eliminate 1.92 trips rather than two. However, the second noteworthy observation drawn from closer inspection of the data is that *TC days did not always eliminate the commute.* On 21% of TC person-days (23 days), at least one commute trip involving a PV was reported. Of the 71 telecommuters in the sample, eight were found to be telecommuting from a center and ten were apparently telecommuting partial days and still making the trip to the regular office. This finding also has two implications, complementary to the first finding. The first implication is that the TC day average VMT is larger than it would have been if no PV commute trips had been made on TC days, which further contributed to the difference between NTC and TC day VMT being smaller than expected. The second implication is that the average number of PV commute trips on TC days is not zero as expected, but rather 0.48.

Table 6. Time of day impacts on emissions.

	TC Days (1)	NTC Days (2)	TC Days with NTC TOD distribution (3)	TOD savings (3) - (1) (4)	% Total savings due to TOD effects (100%) x (4) / [(2)-(1)]
TOG*	28.79	54 75	31.35	2.56	9.6%
CO*	233.10	437.25	256.46	23 86	11.7%
NOx*	18 77	46.09	19.36	0 59	2.2%

* gm/person-day

Table 7. Impacts of telecommuting on commute versus non-commute VMT.

	Telecommuters *NTC day*	**Telecommuters** *TC day*	**Difference**
Total VMT	52.0	19.2	32.8
Commute VMT (method I)	41.8	6.8	35.0
Non-Commute VMT (method I)	10 2	12.4	-2.2
Commute VMT (method II)	41 5	6.5	35.0
Non-Commute VMT (method II)	10.5	12.7	-2.2

Taken together, these two findings mean that if non-commute trips did not change, we would expect to find a reduction of 1.44 trips on TC days. Since we instead find a reduction of 1.11 trips, we conclude that non-commute trips increased by 0.33 trips on average. Hence, the 30.08% reduction in trips reported in Table 4 may be viewed as the net of a 39.02% decrease in total trips due to eliminating the commute and a 8.94% increase in total trips due to non-commute travel generation.

Determining the impact of telecommuting on non-commute VMT is, as mentioned earlier, more problematic. The following procedure was used. For the majority of participants with a known commute length, each time a sequence of trips was made that started at home and ended at work, their known one-way commute length was counted as the commute portion of that trip sequence. These commute lengths were added together to give a subtotal of one-way commute VMT. For the remaining commute trip sequences, involving participants for whom their commute length was not known, one-way commute distances were estimated using two different methods to provide an upper and lower limit on the true value.

In the first method, the lengths of all trip sequences starting at home and ending at work (including all intermediate trips to non-work destinations) were added to the subtotal. Focusing on the home-to-work chain was based on the assumptions that more non-work activities chained to the commute trip (e.g., eating or shopping) occur in the afternoon than in the morning, that morning non-work destinations such as day care or school are likely to be closer to home on average than the more diverse afternoon destinations, and therefore that the morning commute is likely to provide a more accurate estimate of the one-way commute length than the afternoon commute. The total one-way commute distance for the entire group was then doubled (to approximate the round-trip commute distance) and divided by the number of person-days in the group to obtain a per-person-day average. This will overestimate the actual commute travel for the minority of participants with an unknown commute length, except in the unlikely event that all stops on the way to work occur on the direct route between home and work.

In the second method, for each trip chain starting at home and ending at work, only the length of the last trip—the one ending at work—was counted and added to the subtotal. This total for the entire group was doubled to provide the lower limit of the total commute VMT and then divided by the number of person-days in that group. This method will underestimate the actual commute travel for the same minority of participants, except in the unlikely event that the distance from an intermediate destination to work is on average longer than a direct home-to-work trip. Morning commutes were the focus here for the same reasons as before. Analysis confirmed that using both the morning and afternoon commutes in this second approach, instead of just the morning commute, underestimated actual commute travel even further.

Table 7 presents the estimated values of average commute and non-commute VMT for NTC and TC days, respectively, under each of the two methods described above. For both methods, non-commute VMT was calculated as the difference between total and commute VMT. The table shows exactly the same final result for both methods indicating that each group (NTC day and TC day) was affected in the same way by the difference between the two methods. Analysis of the table shows that the 32.8-mile reduction in VMT on TC days comprises a decrease of 35.0 commute miles and an increase of 2.2 non-commute miles. Therefore, the 63.04% reduction in overall VMT reported in Table 4 may be viewed as a 67.31% decrease in commute VMT and a 4.27% increase in non-commute VMT. The final result is that telecommuting caused a small increase in both the number of trips and VMT for non-commute-related travel.

Distance/Cold Start Ratio

As demonstrated in the preceding discussion, the relative efficiency of a particular transportation demand management (TDM) strategy compared to others can be assessed by examining the percent reductions in emissions for each pollutant of concern. To decrease vehicle emissions, TDMs typically focus on reducing either the distance traveled (VMT) or the number of (cold-start) trips, or both. Distance (VMT) is a surrogate for running emissions, which is the major contributor to PM and NO_x, and the number of cold starts is a surrogate for 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 TDMs, without requiring the extensive effort of air quality modeling. A ratio may be defined to help facilitate this type of investigation. We define the Distance/Cold-start ratio, or "D/C ratio" as:

$$D / C \text{ Ratio} = \frac{\text{\% reduction in VMT}}{\text{\% reduction in number of cold starts}}$$

It is useful to analyze both the fraction form of the D/C ratio and the single number resulting from the quotient. This allows more information to be obtained from the ratio, as it provides a comparison measure to be used across various TDMs, as well as insight into the relative savings of each pollutant. Provided that the implementation of a TDM results in a reduction of both VMT and number of cold starts, a benefit to air quality should be realized. This will likely be the case for many TDMs. Some TDMs, however, including telecommuting and compressed work schedules, have been hypothesized to increase the number of cold-start trips. Thus, it is possible for the ratio to be negative, indicating that a decrease in one measure is obtained at the expense of an increase in the other. In analyzing these cases, we found that the most useful expression of the measure is in fraction form, as it allows the numerator and denominator to be examined independently.

It is important to note that the numerator and denominator of the ratio represent average per-capita reductions and that the aggregate (or overall, regionwide) impacts are determined by scaling these reductions up by the number of program participants. Thus, a comparison of the aggregate effectiveness of two TDM measures must take into account the number of people likely to be affected by each measure, not just the per capita impacts.

A study of the ratio expressed as the quotient (a single number) provides information internal to the TDM itself, i.e. which processes and pollutants achieved proportionately greater reductions. A ratio with a quotient of one indicates that the percent savings in VMT and number of cold starts are equal and that each pollutant is reduced at comparable levels. A value less than one indicates proportionately higher reductions in cold starts with therefore, the highest emissions reductions observed for TOG and CO. A value greater than one indicates proportionately higher reductions in VMT, resulting in higher reductions for PM and No_x. Thus, a higher value of the quotient is not necessarily "better"; it only indicates the relative emphasis between the two processes for a particular TDM. Similarly, no tradeoff is necessary for shifting the D/C ratio higher or lower. The ratio can be increased by increasing the percent reduction in VMT while holding percent reduction in cold starts constant, thus increasing PM and NO_x savings without sacrificing TOG and CO savings. The ratio can be lowered in a similar fashion by holding the reduction in VMT constant and increasing the percent reduction in number of cold starts.

A study of the numerator and denominator of the ratio expressed as a fraction provides a useful measure across TDMs. For example, a ratio of 75/50 would show that the reduction of VMT was 75%, while the reduction in the number of cold starts was 50%. This hypothetical TDM can be compared to a second TDM whose D/C ratio is, say, 25/25. The quotients of the two TDMs are 1.5 and 1, respectively. If TOG is the pollutant of concern, an analysis of the quotient would show that the latter TDM had a better *relative* reduction in TOG (since it had a *lower* quotient). However, looking at the fraction it is obvious that the first TDM would be more effective, since it caused higher percent reductions in both VMT (numerator) and the number of cold starts (denominator). It is important to distinguish these two different expressions of the D/C ratio since each conveys useful information when interpreted correctly.

In this current study the D/C ratio has a value of 63/44 = 1.43, meaning that the percent reduction in VMT is equal to 1.43 times the percent reduction in the number of cold starts. While this indicates a significant (44%) decrease in the number of cold starts (CO and TOG), the ratio also shows that telecommuting was even *more* effective (63% decrease) at reducing VMT (NO_x and PM). The numerator and denominator values obtained here will be useful in future studies of telecommuting and other TDMs to investigate the effectiveness of various programs.

CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

Cold-start activity and VMT are important factors in determining levels of personal vehicle emissions. The results of this analysis indicate that telecommuting has beneficial transportation and air quality impacts for both of those indicators. The most important results are that telecommuting decreases the number of daily trips (by 30%), the VMT (by 63%), and the number of cold starts (by 44%), especially those taking place before 9:00 a.m. These reductions are shown to have a large effect on daily emissions, with a 50% to 60% decrease in pollutants generated by the telecommuter's personal vehicle use on telecommuting days. These findings are supported by those from the State of California Telecommuting Pilot Project analysis.[5] The percent savings in daily emissions are comparable between the two studies, as are the reductions in number of trips and VMT. Disaggregating the observed travel into commute and non-commute trips and VMT showed that the net savings in travel and emissions are almost entirely due to the elimination of commute trips, as the non-commute trips were found to increase by 0.33 trips per person-day (9% of the total trips), and the non-commute VMT increased by 2.2 miles.

It is important to realize that reductions of this magnitude are observed because the telecommuters in this sample are long-distance commuters. With commutes twice as long as the regional average, a disproportionate amount of their daily travel is spent commuting. As telecommuting becomes more widely adopted, and the average commute length for telecommuters becomes more representative of the average for the region as a whole, the per capita impacts on travel and emissions reported here will decrease.[4] However, the net impacts are still expected to be beneficial—a reduction in VMT and emissions.

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. Also, these findings represent average per capita reductions; the aggregate (or overall, regionwide) impacts are determined by scaling these reductions by the number of program participants.Thus, the *aggregate effectiveness* of telecommuting must take into account the number of people likely to participate as telecommuters and how often they telecommute, not just the per capita, per occasion impacts.

Future research on the emissions impacts of telecommuting will benefit from improvements to the EMFAC/BURDEN models. It is expected that the upcoming (7G) versions of the models will increase predicted emissions levels to be more consistent with field-measured pollutant concentrations.[16] These advances will improve the estimates of emissions levels, allowing for more accurate comparisons of the emissions benefits of telecommuting and other TDMs.

Finally, a number of interesting research questions remain regarding the transportation-related impacts of telecommuting. One of particular relevance to the subject of this paper is the transportation and emissions impacts of telecommuting from a center compared to telecommuting from home. Center-based telecommuting by definition requires a commute of some kind (albeit shorter than the trip to the conventional workplace) and, therefore may involve a cold start.

Policy makers are reluctant to fully support telecommuting centers as a TDM until more is known empirically about their effectiveness in reducing emissions. Multiple projects are currently underway to evaluate center-based telecommuting by comparing VMT, number of trips, commute mode choices, and trip-linking characteristics of telecenter users with those of home-based telecommuters and non-telecommuters of the same organization. These and other studies will continue to provide useful new insights into the travel and air quality-related impacts of telecommuting.

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