Energy-Related Emissions from Telework

ERASMIA KITOU AND ARPAD HORVATH*

Department of Civil and Environmental Engineering, University of California, 215 McLaughlin Hall #1712, Berkeley, California 94720-1712

Telework is a growing phenomenon that is thought to save energy and air emissions. This paper applies a systems model to telework and nontelework scenarios in order to quantify greenhouse gas and other air emissions from transportation, heating, cooling, lighting, and electronic and electrical equipment use both at the company and the home office. Using United States data, a WWW-based, scalable decision-support tool was created to evaluate the environmental impacts of teleworkers. For a typical case reflecting United States teleworker patterns, the analysis found that telework has the potential to reduce air emissions. However, Monte Carlo simulation employed to perform a probabilistic analysis over a set of likely parameters has revealed that telework may not affect equally the emissions of all types of pollutants. It may decrease CO_2, NO_x, SO_2, PM_{10}, and CO but not N_2O and CH_4 emissions. Therefore, the scope and goal of telework programs must be defined early in the implementation process. Work-related transportation (commuting) impacts could be reduced as a result of telework; however, home-related impacts due to an employee spending additional time at home could potentially offset these reductions. Company office-related impacts may not be reduced unless the office space is shared with other employees during telework days or eliminated entirely. In states with high telework potential (California, Georgia, Illinois, New York, Texas), telework could save emissions, but it would depend on commuting and climatic patterns and the electricity mix. Environmentally beneficial telework programs are found to depend mainly on commuting patterns, induced energy usage, and characteristics of the office and home space and equipment use.

Introduction

Telecommuting may have more than one definition, but it can be defined as working partially or entirely at home or at a specifically assigned center instead of working at a company office (*1*−*3*). Telework is a more general term that encompasses the use of telecommunications and information technology for work purposes, typically away from a company office, and includes at-home workers who may never have a commute. This paper presents a systems model of telework.

Telework Trends. Although telework frequency (hours per day or week) may vary, it has been a growing phenomenon in the United States and around the world. In Europe, estimates range from 1.2 million to 4.6 million telecommuters (*4, 5*). In Japan, the number of teleworkers is estimated at 1 million (*6*). In the United States, the number of teleworkers increased from 4 million in 1990 to 11.1 million in 1997 (*7*) and to perhaps as much as 19.6 million recently, representing 20% of the United States workforce (*8*). In California alone, 2.7 million employees, or one-third of the total, are thought to work at least partly from home during the week (*9*).

The United States Congress and governmental agencies have been increasingly promoting and encouraging telework, and a number of corresponding action plans have been established (*10*). In 1993, the Presidential Global Climate Change Action Plan promoted telework as a potential solution to some environmental problems. Subsequently, the National Teleworking Initiative was introduced, aiming to increase significantly the number of Federal teleworkers. In 2002, executive agencies were required to establish specific telework-promoting policies and increase their number of teleworking employees by 25% (*11*). Currently, 4.2% of the approximately 75 000 Federal employees in 63 agencies are considered to be teleworking (*10*).

The increase over the years in the number of teleworkers both within governmental agencies and elsewhere reflects the results of implemented telework policies aiming, among others, to reduce traffic in highly congested areas and subsequently to reduce air pollution. It also reflects the increasing growth and availability of telecommunications and information technology services. However, although cutting down on the weekly commute by teleworking is thought to be an environmentally and possibly a socially beneficial solution, management concerns (e.g., employees' performance evaluation and promotion), fairness to all employees, funding for equipment and services, confidentiality issues, technical problems, occupational health and safety concerns, and others have been some of the persisting obstacles for further growth in teleworker numbers (*10*−*12*).

Research To-Date. Research has thus far focused largely on the implementation, adoption, and growth of telecommuting programs. Models of employee and employer behavior have been devised (*1, 2, 13*−*16*), and telework's economic and environmental costs and benefits have been analyzed in a societal context with varying levels of detail. A number of studies (*2, 17, 18*) were conducted to quantify the rebound effects associated with telework such as (1) induced or nonwork related travel (accounting for non-commute vehicle miles traveled (VMT) that are generated due to the introduction of teleworking in a household, e.g., increased number of shopping trips) and (2) induced energy use (due to additional use of equipment for nonwork-related purposes, e.g., increased use of household appliances, or the demand for additional heating and lighting in a space other than that assigned as the office space, e.g., heating the whole house for more hours). Rebound effects can counteract or enhance the potential benefits from telework. More recent efforts (*2*) focused on assessing telework's public and private costs by combining economic and statistical theory. The environmental and economic effects of telework have been extended beyond transportation impacts—as it has been traditionally the case—to equipment and home and office space use (*3*).

The growth in telework numbers justifies a comprehensive and systemwide environmental and economic analysis which has led most researchers to try to identify and understand the interactions between the various elements of such

* Corresponding author phone: (510)642-7300; fax: (510)643-8919; e-mail: horvath@ce.berkeley.edu.

10.1021/es025849p CCC: $25.00 © 2003 American Chemical Society
Published on Web 06/21/2003

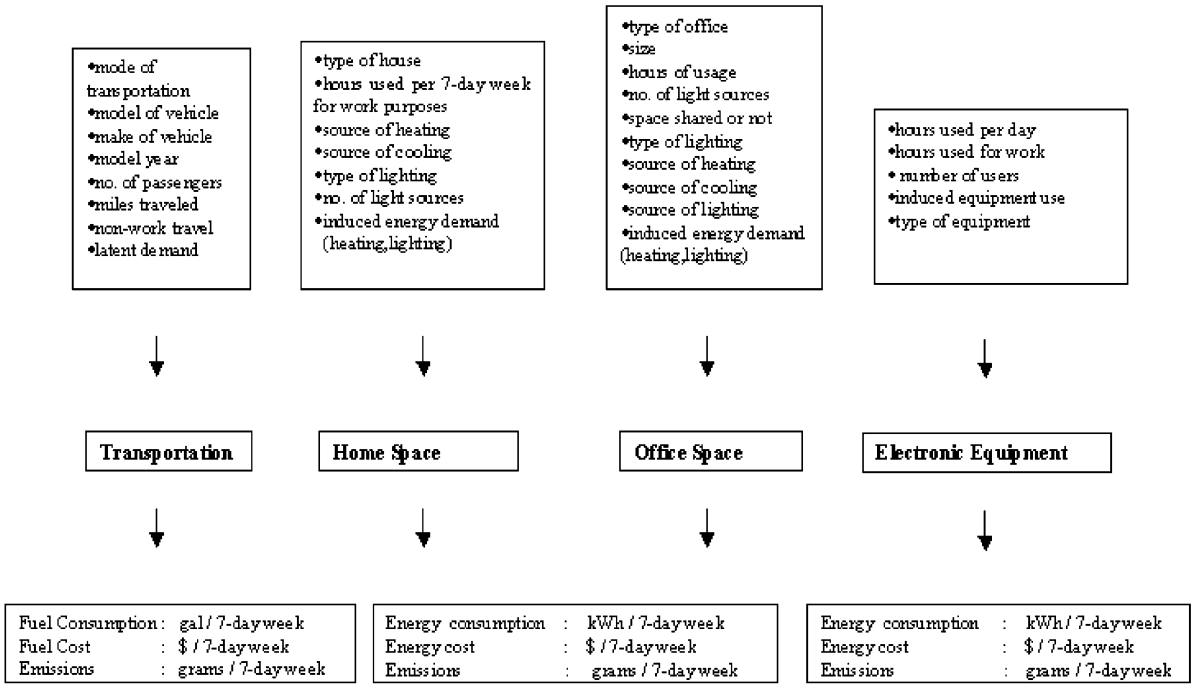

FIGURE 1. Systems model of telework.

programs. If telework, which is currently one of the most prevalent teleservices (i.e., services enabled by information technology and telecommunications) proves not to be a beneficial alternative to traditional practices in terms of substituting travel and decreasing transportation-related impacts, it is possible that other teleactivities such as teleshopping may not prove to be effective either (*19*).

To enable more informed decision-making, this paper presents the further development and applications of a comprehensive environmental model of telework including not just transportation but other components of the affected systems: electronic and electrical equipment use, heating, cooling, and lighting in the company and the home office (*20*).

Systems Model of Telework

A comprehensive telework model should be disaggregated into a commute and a noncommute part to observe how environmental impacts differ as employees change behavior (*21, 22*). The environmental impacts of a teleworking or noncommuting (EI_{TW}) and a nonteleworking or commuting (EI_{NTW}) employee have the same main components (*3*): transportation (EI_{TR}), use of electronic and electrical equipment (EI_{EE}), and heating, cooling, and lighting in the company office (EI_{OS}) and in the home office (EI_{HS}):

$$EI_{TW\ or\ NTW} = EI_{TR} + EI_{EE} + EI_{OS} + EI_{HS} \quad (1)$$

Therefore, the net environmental impacts (NEI_{TW}) associated with telework are

$$NEI_{TW} = EI_{TW} - EI_{NTW} \quad (2)$$

Equation 1 accounts for the fact that employees' choices and daily habits may— to an extent—be dictated or induced by their work even when they are not teleworking. The systemwide framework of the telework model is presented in Figure 1.

The unit of analysis chosen for the model is a 7-day week, acknowledging that some employees may go to the office on more than just the "working days" of the week. Additionally, the 7-day week unit is preferable since telework could potentially induce noncommute travel and additional energy use on any given day of the week, including Saturday and Sunday.

This systems model is implemented in a Web-based tool that supports deterministic analyses (*23*) and an MS Excel-based tool that enables probabilistic analyses (*20*). Table SI-1 (Supporting Information) summarizes the types and sources of emissions included. Currently, the tools utilize United States data. The model is scalable: it can be applied to a single individual (even to those who are not teleworkers but would like to find out the environmental effects of their commute and office use patterns) or to a group participating in a telecommuting program.

(1) Transportation. Telework has been considered an efficient way of reducing commute-related environmental impacts since it is believed to reduce commute VMT. However, the actual savings are largely determined by the mode of transportation and the number of miles that are ultimately avoided. The final results are influenced by the side (rebound) effects of telework such as induced (or nonwork-related) travel and latent demand. Induced travel is for leisure, social, and other purposes that would not have occurred if it were not for employee telecommuting and for a possibility to avoid the daily commute to work. The concept of induced travel does not include travel between the workplace and home or travel for the fulfillment of the objectives of an organization (such as business travel). Latent demand is introduced to account for the additional VMT due to an increase in available roadway capacity because of telework. Latent demand is only applicable when performing a large-scale assessment of telework. Both of these variables are important to managers and regulators since they could potentially counteract the expected transportation-related benefits. The following modes of transportation are included in the model: passenger vehicle (various models and years), carpool, vanpool, commuter express bus, urban transit bus, commuter rail, light rail, Amtrak (diesel-electric), ferry (diesel), ferry (natural gas), and airplane (various sizes and engines).

To specifically calculate emissions from passenger vehicles, the values of the following parameters need to be determined (*24, 25*): model year, make, model, emissions

certifications, and number of passengers (for carpool/vanpool option).

(2) Home and Office Equipment. This part of the model accounts for the environmental impacts of the electronic equipment used in the company office and the electronic and electrical equipment (Supporting Information: Table SI-9) used at home. The objective is to determine the electricity consumption of these devices as they relate to work. The equipment included in this model is as follows: desktop, laptop, copier, inkjet printer, laser printer, wired phone, answering device, cordless phone, and cordless phone and answering device.

Additional information required by the model: the amount of time that the equipment is in *active*, *low-power*, and *off* mode per day, the amount of time that the equipment is used for work purposes per day, and the number of people the equipment is shared with in the company office.

It remains a challenge to determine the extent to which working from home creates additional energy needs that are not directly related to work (e.g., someone who is teleworking may use the radio or the dishwasher more often). To account for these rebound effects, the induced equipment use parameter is introduced. The employee is asked to estimate the electricity consumption increase (or decrease) in the house after starting to participate in a telework program.

(3) Home and Office Space. Energy consumption at the company office and at home has not yet been comprehensively assessed and quantified in the context of telework. Initial research projects that monitored teleworkers have indicated that the increased use of household energy may represent 11−25% of the net travel savings (*26*). These projects also acknowledged that the increase in energy consumption in the home might be counteracted by a simultaneous decrease of energy use in the company office. The model presented herein is performing a parallel analysis of the two and is focusing on energy use related to heating, cooling, and lighting to explore if implementing telework programs could induce energy savings. The telework model is constructed in a way that lighting and heating- and cooling-related energy use in the company office does not count against a teleworker when another employee occupies that office space.

Telework Scenarios

Telework has emerged as a growing phenomenon. Can it save energy and air emissions? The following illustrates how the model presented above can be utilized to assess the environmental effects of telework through a deterministic and a probabilistic scenario.

The National Telework Survey revealed that "telework has evolved in the U.S. primarily on an informal basis, rather than through creation of large, formally structured programs" (*27*). Thus, the total hours and the time of the day that an employee is working at home tend to vary and extend into, before, and after normal business hours, making it challenging to determine the amount of time that an employee spends in the office versus at home. For the purposes of this scenario, on telework days the total hours accounted for are those spent working at home less the hours the employee would anyway spend working at home on a "normal," nontelework day.

The scenarios used estimates of telework patterns from the United States based on literature, surveys, and personal interviews as well as emissions from the energy use of vehicles, electronic and electrical equipment, and heating, cooling, and lighting of company and home offices. California's average electricity mix (consisting of 50% natural gas, 16% nuclear, 12% eligible renewables, 11% coal, 10% large hydroelectric, and 1% other sources) (*28*) was used for the emissions calculations. The values for induced usage were estimated by the authors. In assessing the environmental impacts of the various components of the model, it is important to identify the parameters that are most likely to counteract anticipated telework-related benefits. Hence, although the induced usage values could be considered high, they are appropriate to assess the potential of the expected benefits to be counteracted. In the final assessment of the results no more than two significant digits were taken into account respecting the uncertainties associated with the underlying data.

Analysis of a Deterministic Scenario of Telework

The analysis first explores how telework frequency affects the net impacts ($EI_{TW} - EI_{NTW}$) by comparing the effects of a nonteleworking employee with the same employee teleworking 1, 3, or 5 days per week. Differences in net impacts due to the use of either heating or cooling as well as when rebound effects are not accounted for are explored. Since some 27% of telecommuters report that their workspace at their employer's location has been reduced in size or shifted to a shared space (*8*), the assumption for the 3- and 5-day telework cases is that the company office is shared with a co-worker.

As each state uses a different electricity mix, the deterministic analysis is also used to estimate how the geographic location of a teleworking employee impacts the final results. The differences are highlighted by applying the model to the states with the highest and lowest electricity emission factors for CO_2, NO_x, and SO_2. The analysis also extends to states with potentially large telework populations in major metropolitan areas.

Parameter Estimation for a Typical Teleworking Employee. *Transportation.* Transportation surveys indicate that the passenger vehicle is the preferred mode of transportation in commuting to work in the United States (*27, 29*). It is also the mode of choice for this analysis. The average occupancy of automobiles for commute purposes is 1, while the average vehicle occupancy for trips other than commuting is approximately 2 (*29*). This difference in occupancy rates is accounted for when estimating the VMT for the telework scenario. The assumed passenger vehicle is a Honda Accord, a typical midsize sedan in the United States that has an "environmental friendliness" rating by EPA of 6/10 (*30*), an average rating for its class. The EPA's rating is based on the emissions and fuel economy of each car. Since the average age of passenger vehicles is 9 years in the United States (*29*), the passenger vehicle is assumed to be a 1994 model. One-way commute distance to work is 12 miles (*29*), and the corresponding emissions are normalized by the number of passengers.

While one of the major benefits anticipated when implementing a telecommuting program is reducing transportation-related environmental impacts by eliminating travel on telework days, past research has expressed a concern that a number of parameters could counteract these benefits (*15, 31, 32*). Due to a lack of consistent information about the nonwork-related number of miles traveled as a result of telework, and in an effort to combine the results of various surveys (*27, 29*), the assumed average induced distance traveled on a telework day is 6 miles (Supporting Information: Table SI-2).

Electronic and Electrical Equipment Use. Copiers, printers, and fax machines in the company office are assumed to be shared among a number of employees, while each employee is typically provided with a desktop computer and a phone. The equipment is powered up for most part of the day, and surveys (*33, 34*) have indicated that it is often left on even after hours (Supporting Information: Table SI-3).

The estimation of the impacts associated with the home office is based on the information that 45% of teleworkers

TABLE 1: Results of an Example Deterministic Telework Scenario (in Grams per 7-Day Week)

		CO_2	SO_2	NO_x	N_2O	CH_4	CO	PM_{10}
transportation	NTW	46 000	N/A	160	N/A	N/A	1700	14
	1-day	38 000	N/A	130	N/A	N/A	1400	11
	3-day	22 000	N/A	73	N/A	N/A	800	6.4
	5-day	5100	N/A	17	N/A	N/A	180	1.5
	no rebound (5-day)	0	N/A	0	N/A	N/A	0	0
office electronic and electrical equipment	NTW	1800	1.2	1.4	0.003	0.003	N/A	N/A
	1-day	1600	1.1	1.2	0.002	0.003	N/A	N/A
	3-day	1100	0.7	0.8	0.002	0.002	N/A	N/A
	5-day	0	0	0	0	0	N/A	N/A
	no rebound (5-day)	0	0	0	0	0	N/A	N/A
home electronic and electrical equipment	NTW	310	0.2	0.2	0.0004	0.001	0	0
	1-day	1800	0.5	1.6	0.04	0.04	0.7	0.1
	3-day	7100	2	6.2	0.2	0.2	2.9	0.5
	5-day	11 000	3	9.3	0.2	0.3	4.3	0.8
	no rebound (5-day)	1600	1.1	1.2	0	0	0	0
office lighting	NTW	1800	1.3	1.4	0.003	0.003	N/A	N/A
	1-day	1800	1.3	1.4	0.003	0.003	N/A	N/A
	3-day	880	0.6	0.7	0.001	0.002	N/A	N/A
	5-day	0	0	0	0	0	N/A	N/A
	no rebound (5-day)	0	0	0	0	0	N/A	N/A
home lighting	NTW	50	0.04	0.0	0.0001	0.0001	N/A	N/A
	1-day	180	0.1	0.1	0	0	N/A	N/A
	3-day	550	0.4	0.4	0	0	N/A	N/A
	5-day	910	0.6	0.7	0	0.001	N/A	N/A
	no rebound (5-day)	470	0.3	0.4	0	0	N/A	N/A
office heating	NTW	3000	0.03	2.8	0.05	0.06	1	0.2
	1-day	3000	0.03	2.8	0.05	0.06	1	0.2
	3-day	1400	0.01	1.3	0.02	0.03	0.5	0.1
	5-day	0	0	0	0	0	0	0
	no rebound (5-day)	0	0	0	0	0	0	0
office cooling	NTW	9800	6.8	7.7	0.01	0.02	N/A	N/A
	1-day	9800	6.8	7.7	0.01	0.02	N/A	N/A
	3-day	4600	3.2	3.6	0	0.01	N/A	N/A
	5-day	0	0	0	0	0	N/A	N/A
	no rebound (5-day)	0	0	0	0	0	N/A	N/A
home heating	NTW	0	0	0	0	0	0	0
	1-day	5300	0.04	5	0.1	0.1	1.8	0.3
	3-day	16 000	0.1	15	0.3	0.3	5.3	1
	5-day	27 000	0.2	25	0.5	0.5	9	1.7
	no rebound (5-day)	27 000	0.2	25	0.5	0.5	9	1.7
home cooling	NTW	0	0	0	0	0	N/A	N/A
	1-day	1600	1.1	1.2	0.002	0.003	N/A	N/A
	3-day	4800	3.3	3.7	0.01	0.01	N/A	N/A
	5-day	8000	5.5	6.2	0.01	0.02	N/A	N/A
	no rebound (5-day)	8000	5.5	6.2	0.01	0.02	N/A	N/A
total for heating days	NTW	53 000	2.8	170	0.007	0.007	1700	14
	1-day	52 000	3.1	140	0.2	0.2	1400	12
	3-day	49 000	3.8	97	0.5	0.5	800	8
	5-day	44 000	3.8	52	0.7	0.8	190	4
	no rebound (5-day)	29 000	1.6	27	0.5	0.5	9	2
total for cooling days	NTW	60 000	9.5	170	0.02	0.03	1700	14
	1-day	55 000	11	140	0.06	0.07	1400	11
	3-day	41 000	10	88	0.2	0.2	800	7
	5-day	25 000	9.1	33	0.2	0.3	180	2
	no rebound (5-day)	10 000	6.9	7.8	0.01	0.02	0	0

have a separate home office (*35*), while the rest typically share a family space for work purposes. Most households own a desktop (*36*) and increasingly a laser printer as well (Supporting Information: Table SI-4). Work-related usage of electronic equipment at home is difficult to measure, so the numbers used were based on typical usage patterns in the company office. Induced usage of appliances such as the TV, stereo system, gas range and oven, dishwasher, washing machine, and dryer is assessed as a teleworker might use these more often due to spending more time at home (Supporting Information: Table SI-5).

Heating, Cooling, and Lighting. For heating and cooling, natural gas air furnace and central air conditioning are the preferred choices for both the company and the home office (*36*) (Supporting Information: Table SI-6). At home lighting is typically provided by incandescent bulbs (*36*) (Supporting Information: Table SI-7). For the company office usage is estimated based on the floor area (ft^2) since in a typical case a central unit determines usage levels, independent of the employee (Supporting Information: Table SI-6 and Table SI-8).

Discussion of Results. Table 1 shows that for the assumed scenario increased teleworking frequency decreases CO_2 emissions by 2−80% (rounded), NO_x by 20−100%, PM_{10} by 10−100%, and CO by 20−100%, while SO_2 emissions increase or decrease by 40%, depending on heating or cooling days and the presence of rebound effects. Even though N_2O and CH_4 emissions are found to increase 10−100-fold, their absolute values are negligible compared to the other greenhouse gas, CO_2. Transportation is the major contributor but tends to diminish in relative significance as telework days increase. However, even if an employee telecommuted 5 days

TABLE 2: Environmental Effects of Telework in States with High Telework Potential Estimated Based on an Example Deterministic Telework Scenario (in Grams per 7-Day Week)

	CO_2	NO_x	SO_2	CH_4	CO	N_2O	PM_{10}	HC	Hg
Heating Season									
Nontelework									
California	54 000	170	3	0.1	1720	0.1	14	110	6.E-06
Georgia	62 000	190	110	0.1	1660	0.3	13	110	2.E-04
Illinois	65 000	200	120	0.2	1690	0.3	14	110	4.E-04
New York	49 000	140	44	0.1	1350	0.1	11	86	8.E-05
Texas	65 000	190	39	0.1	1770	0.2	14	110	3.E-04
Telework (3-Day Scenario)									
California	49 000	95	4	0.4	810	0.4	8	52	5.E-05
Georgia	60 000	130	140	0.5	780	0.7	8	50	3.E-04
Illinois	74 000	150	150	0.8	800	0.9	9	51	5.E-04
New York	64 000	110	54	0.7	660	0.7	7	42	2.E-04
Texas	62 000	130	48	0.5	830	0.6	8	53	4.E-04
Cooling Season									
Nontelework									
California	61 000	170	10	0.0	1720	0.0	14	110	0.E+00
Georgia	83 000	250	300	0.3	1660	0.6	13	110	6.E-04
Illinois	80 000	260	300	0.2	1690	0.4	14	110	9.E-04
New York	58 000	160	100	0.1	1350	0.2	11	86	2.E-04
Texas	88 000	240	110	0.2	1770	0.5	14	110	7.E-04
Telework (3-Day Scenario)									
California	41 000	89	11	0.1	800	0.1	7	52	9.E-06
Georgia	68 000	180	340	0.4	780	0.8	6	50	7.E-04
Illinois	57 000	170	270	0.3	790	0.5	7	51	9.E-04
New York	42 000	95	94	0.2	650	0.2	5	42	2.E-04
Texas	72 000	160	120	0.3	820	0.6	7	53	8.E-04

a week, transportation impacts would still contribute 10−90% to the total (depending on the pollutant and heating or cooling days) on the account of the induced miles traveled. Electronic and electrical equipment usage impacts generally increase with telework frequency reflecting the assumption that when an employee is working at home, one may be more likely to use various electronic and electrical equipment for more hours than when not teleworking. When rebound effects are not included in the 5-day telework scenario (where these effects are prominent), a major emission reduction is observed for home electronic and electrical equipment use and transportation but not for home heating, cooling, or lighting (Table 1). Eliminating rebound effects is found to be important in this scenario since it avoided, e.g., 15 kg of CO_2 emissions, or 30−60% of the total for the 5-day scenario (44 kg vs 29 kg on heating days and 25 kg vs 10 kg on cooling days), and nearly all of PM_{10} and CO emissions.

Can the benefits from reducing transportation impacts be counteracted by the nontransportation components of the model? For CO_2, as Table 1 reveals, the expected transportation benefits (a decrease by 24 and 41 kg for the 3-day and 5-day scenarios, respectively) are nearly counteracted on heating days. In the cooling season, a teleworker's impacts are reduced by one-third in a 3-day scenario and by 60% in a 5-day scenario primarily due to transportation savings.

In addition, although company office impacts decrease as teleworking frequency increases (since the office is shared with a co-worker in the 3- and 5-day cases), home impacts increase significantly since the employee is now spending more time at home (assuming no one else is at home during the work hours). As a result, home impacts counteract the benefits of reduced company office impacts in the case of heating and electronic equipment, while in the case of lighting and cooling an appreciable change in total impacts is observed. The energy use associated with heating and cooling is, of course, influenced by local climate.

Would Telework's Air Emissions Differ by State?

In the previous analysis the emissions were assessed based on California's electricity mix. What if the same telework scenario was introduced in other states with high telework potential: New York, Texas, Georgia, and Illinois? Table 2 shows a 3-day telework scenario where the daily commute distances (*37*), heating and cooling loads (*36*), and electricity generation mixes (*38*) vary by state. The resulting PM_{10}, CO, and hydrocarbon (HC) emissions are comparable between the states, but the other emissions exhibit more of a variation. For example, in the nontelework scenario the observed difference between the lowest and highest CO_2 emissions is 30% in the heating season and approximately 50% in the

TABLE 3: Environmental Effects of Telework in the States with the Highest and Lowest CO_2, SO_2, and NO_x Emissions Based on an Example Deterministic Telework Scenario (in Grams per 7-Day Week)

	CO_2	NO_x	SO_2	CH_4	CO	N_2O	PM_{10}	HC	Hg
Heating Season									
Nontelework									
Idaho	45 000	140	0.0	0.1	1520	0.1	12	100	6.E-06
North Dakota	72 000	210	130	0.3	1520	0.4	13	100	8.E-04
Ohio	60 000	200	190	0.2	1320	0.4	11	86	5.E-04
Rhode Island	54 000	150	0.0	0.1	1520	0.1	12	100	7.E-06
Telework (3-Day Scenario)									
Idaho	54 000	93	1	0.7	730	0.6	8	47	7.E-05
North Dakota	86 000	180	160	0.9	730	1.1	8	47	1.E-03
Ohio	76 000	170	240	0.8	650	1.0	7	41	7.E-04
Rhode Island	66 000	97	0.0	0.7	730	0.7	8	47	7.E-05
Cooling Season									
Nontelework									
Idaho	42 000	140	1	0.0	1520	0.0	12	100	0.E+00
North Dakota	104 000	310	330	0.4	1520	0.8	12	100	2.E-03
Ohio	83 000	300	480	0.3	1320	0.7	11	86	1.E-03
Rhode Island	63 000	150	0.0	0.1	1520	0.0	12	100	0.E+00
Telework (3-Day Scenario)									
Idaho	25 000	70	1	0.1	720	0.1	6	47	9.E-06
North Dakota	81 000	220	300	0.4	720	0.8	6	47	2.E-03
Ohio	64 000	220	430	0.4	640	0.7	5	41	1.E-03
Rhode Island	45 000	76	0.0	0.1	720	0.1	6	47	9.E-06

TABLE 4: Critical Parameters Identified in a Monte Carlo Simulation that Influence the Environmental Effects of a Telework Program

	nontelework part	telework part
transportation	average no. of passengers telecommuting distance vehicle emissions	average no. of passengers telecommuting frequency no. of roundtrips telecommuting distance
electronic and electrical equipment	desktop PC energy consumption electricity emissions copier energy consumption	no. of hours (e.g., TV set) no. of loads (e.g., dishwater) telecommuting frequency electricity emissions
lighting	office space size type of office electricity emissions	office space size type of office electricity emissions
heating and cooling	office space size % of the time office used (shared?) natural gas emissions	office space size natural gas consumption natural gas emissions

cooling season, while for the 3-day telework scenario the differences are 50% and 80%, respectively.

The net impacts ($EI_{TW} - EI_{NTW}$) of telework programs differ by pollutant, state, and heating/cooling season. For example, 3-day telework programs may decrease CO_2 emissions by 10% in some states but increase them by 30% in others in the heating season or decrease them in all states by 20−30% in the cooling season. The net decrease observed in CO_2 emissions in the cooling season is important since nontelework CO_2 emissions are higher then.

In addition, variations in heating and cooling loads may influence the annual net benefits of telework programs. For example, CO_2 savings of telework programs in California may be 10% in the heating and 30% in the cooling season, while in Illinois CO_2 emissions decrease by 30% in the cooling season but increase by more than 10% in the heating season. Overall, under the assumed scenario, more NO_x, CO, PM_{10}, and HC emissions would be generated by nonteleworkers than by teleworkers in either season.

Table 3 summarizes the results when applying the same scenario to the states with the lowest and highest CO_2, NO_x, and SO_2 emission factors per kWh of electricity generated. Idaho had the lowest and North Dakota the highest CO_2 and NO_x, while Rhode Island the lowest and Ohio the highest SO_2 emission factors. Table 3 indicates that low electricity emission factors contributed to relatively low total emissions and high emission factors to high overall emissions from nontelework as well as telework programs.

Probabilistic Analysis of a 3-Day Telework Scenario

The uncertainty involved in modeling telework's environmental performance based on a limited pool of empirical data has hindered past evaluations. Thus, after having explored an example deterministic scenario and demonstrated the functionality of the Web-based tool developed in this research (*23*), the effects of the various components and parameters of the telework model on the final results were assessed using the MS Excel version of that same tool which utilizes Monte Carlo simulation. The uncertainty associated with assigning a single value to each critical variable was quantified since the variables are allowed to vary over a specified range (estimated based on literature and experience). The goal was to identify the critical parameters that may influence the likelihood that the environmental impacts of a telework program would be less than the impacts associated with nontelework.

Framework for Sensitivity Analysis and Monte Carlo Simulation. The probabilistic analysis is based on the same basic set of parameters as the deterministic scenario for a 3-day telecommuter. The assumed mode of transportation is a typical passenger vehicle, and the selected source of heating for both the home and the office space is natural gas. Telework and nontelework impacts are assessed in both the company and the home space, and rebound effects are accounted for (Supporting Information: Table SI-9). However, the probabilistic scenario includes all the variables associated with induced usage. Monte Carlo simulation is used to estimate the average total emissions for the teleworking and nonteleworking scenarios based on prespecified ranges of the variables.

TABLE 5: Results of Monte Carlo Simulation of an Example Probabilistic Telework Scenario (in Grams per 7-Day Week)[a]

		CO_2	SO_2	NO_x	N_2O	CH_4	CO	PM_{10}
TW−NTW	mean	−3600	−4	−36	0.1	0.1	−120	−1.5
	st.dev	7800	12	33	0.1	0.1	100	1.5
TW_{total}	mean	23 000	27	94	0.2	0.1	240	3.7
	st.dev	10 000	22	51	0.1	0.1	160	2.3
NTW_{total}	mean	27 000	30	130	0.1	0.1	360	5.2
	st.dev	11 000	23	70	0.06	0.03	220	3.2
TW_{TR}	mean	12 000	N/A	75	N/A	N/A	240	N/A
	st.dev	7900	N/A	50	N/A	N/A	160	N/A
NTW_{TR}	mean	18 000	N/A	110	N/A	N/A	360	N/A
	st.dev	11 000	N/A	69	N/A	N/A	220	N/A
TW_{EE}	mean	7800	16	12	0.1	0.1	1.1	0.2
	st.dev	6000	15	9	0.1	0.1	1.5	0.3
NTW_{EE}	mean	3600	16	9	0.1	0.02	N/A	N/A
	st.dev	1800	12	5	0.03	0.01	N/A	N/A
TW_L	mean	2500	11	6	0.03	0.02	N/A	N/A
	st.dev	1400	9	4	0.02	0.01	N/A	N/A
NTW_L	mean	3300	15	8	0.04	0.02	N/A	N/A
	st.dev	2100	13	6	0.03	0.01	N/A	N/A
TW_{HC}	mean	1900	0	2	0.03	0.04	0.6	0.1
	st.dev	800	0	1	0.02	0.02	0.3	0.1
NTW_{HC}	mean	2000	0	2	0.04	0.04	0.7	0.1
	st.dev	1000	0	1	0.02	0.02	0.3	0.1

[a] Note: TR = transportation, EE = electronic and electrical equipment, L = lighting, HC = heating or cooling, and N/A = not available.

Discussion of Results. Table 4 shows the critical parameters that influence the environmental impacts of a telework program. However, when some of the parameters get excluded based on the assumptions of the analyst, the results should be expected to be slightly different. Transportation impacts vary with the number of passengers while telecommuting distance in the nontelework part and telecommuting frequency for telework are also important. The heating, cooling, and lighting-related portions of the analysis are primarily influenced by the size of the company office. Electronic and electrical equipment-related impacts in the nontelework part are mostly affected by the amount of energy consumed by the various pieces of equipment, while in the telework part rebound effects and telecommuting frequency prevail as most important. Table 4 suggests that carsharing,

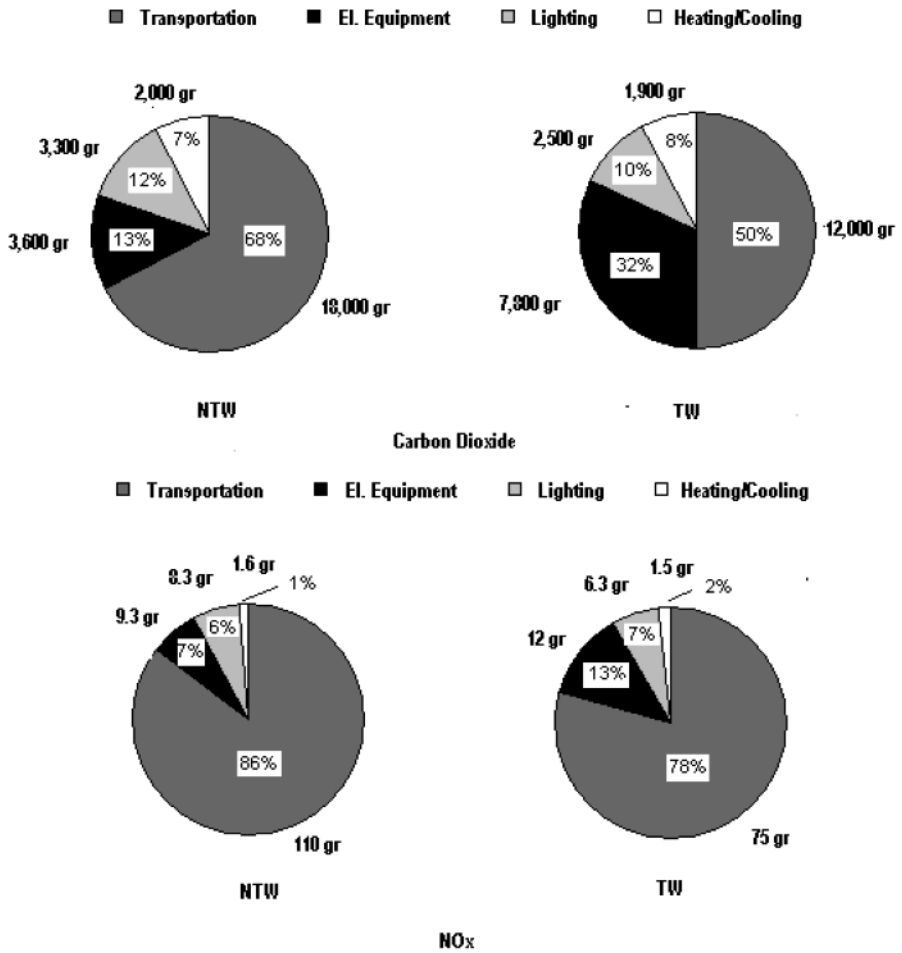

FIGURE 2. Contribution of various components of an example probabilistic telework scenario to CO_2 and NO_x emissions (per 7-day week).

i.e., increasing vehicle occupancy, as well as minimizing the amount of space and equipment used by teleworking employees are the key to a successful implementation of telework programs.

Table 5 shows that the emissions associated with nontelework are higher, except for N_2O and CH_4, but their absolute values are negligible compared to CO_2. However, the relatively large standard deviations suggest that the choice and value of the variables may change the final ratio between telework and nontelework impacts.

Figure 2 shows the absolute and relative contributions of each component of the model to CO_2 and NO_x emissions. Transportation impacts are responsible for the majority of CO_2 emissions from regular commuting. However, in a telework scenario, the CO_2 emissions associated with the nontransportation parameters are practically equal to the transportation emissions, revealing the importance of assessing the effects of space and equipment use when estimating telework-related air pollution. This analysis suggests that there is a shift of pollution to where the electricity generation for cooling, lighting, and electronic and electrical equipment use is located, i.e., the electric power plants.

Figure 2 also shows that although the relative contribution of transportation NO_x emissions may decrease with telework, the impacts associated with the other components of the model remain approximately the same. Impacts from electronic and electrical equipment use and lighting appear the most significant after transportation, while heating/cooling impacts are not as important. The relative contribution of each component of the telework model is different for the two types of pollutants, demonstrating that telework's effects may vary from one pollutant to another. Such differences should be taken into consideration when defining the scope or implementing a telework program since they determine the ultimate environmental benefits.

The results of the probabilistic scenario support the findings from the deterministic scenario, except that for the deterministic scenario heating is associated with larger impacts than electronic and electrical equipment use while in the probabilistic scenario the electronic and electrical equipment-related impacts are larger. This difference is due to the probabilistic scenario including more variables related to induced usage (allowed to vary over a specific range) than the deterministic scenario. The results of the probabilistic scenario reveal the significance and impact that the choice of induced usage variables could have on the final results.

Discussion

Telework may not have the same effect on all types of pollutants. However, based on Monte Carlo simulation, it appears to decrease CO_2, NO_x, SO_2, PM_{10}, and CO emissions under the assumed conditions. Thus the scope of a telework program needs to be defined early in the implementation process. Transportation-related impacts could be reduced as a result of telework; however, home-related impacts due to an employee spending additional time at home could offset these reductions. A corresponding shift of pollution to the source of energy generation would be expected. Company office-related impacts may not be reduced unless the office space is shared with other employees during teleworking days, or eliminated entirely. Rebound effects can significantly affect not only the transportation but also the company and home office-related effects. The success of a telework program

appears to depend mainly on commuting patterns, induced energy usage, and characteristics of office and home space use.

The systems model of telework presented in this paper is applicable worldwide. The parameters are universal, but the values of the parameters may be different from one country or region to the other. The scenarios analyzed in this paper are based on United States emissions data and national average values for typical United States teleworkers obtained from literature, surveys, and personal interviews. Commuting and work patterns may be different in other countries. For example, while the majority of commuters in North America get to their destinations in a passenger vehicle or a light-duty truck (with average occupancy of one), public transportation has a higher share in Japan and Europe. There may be differences worldwide in commute mode and distance, rebound effects, efficiency of heating and cooling of company and home offices, emission factors from energy use and electricity generation, and other factors.

Future Research Needs. Telework calls for careful quantification of private and social costs and benefits. The results presented in Table 5 suggest that there are significant uncertainties associated with the data and the model. Quantifying the magnitude and researching the significance of rebound effects such as nonwork-related travel and induced energy demand and extending the model to account for additional environmental and economic effects from land use, urban sprawl, life-cycle of buildings, transportation, heating and cooling, and electronic and electrical equipment (e.g., embedded energy of manufacturing and end-of-life effects) would provide an even more comprehensive tool for the assessment of the systemwide implications of telework. Moreover, employing a more comprehensive transportation model that accounts for the effects of the different driving conditions (e.g., hot and cold starts) on vehicle fuel efficiency could improve the accuracy of the transportation-related impacts. Monitoring and surveying telework programs implemented in industry and government could provide a wealth of information that could help draw a more accurate picture of the uncertainties associated with the current model and data and could ensure that telework programs are successfully incorporated into private and social decision-making concerning improved quality of life. Exploring in greater detail the differences of telework's impacts on the various types of emissions and extending the database that supports the model to reflect country-specific commute, work, and environmental conditions would also increase the usefulness and applicability of the model.

Acknowledgments

E. Kitou acknowledges the support of the University of California Toxic Substances Research & Training Program in 2000−2002. A. Horvath is an AT&T Foundation Industrial Ecology Faculty Fellow. Both authors are grateful for the support of AT&T. The views expressed in this paper are solely those of the authors and do not necessarily reflect the views of the supporting organizations.

Supporting Information Available

Summary of emissions included in the telework model (Table SI-1); inputs for the transportation, office equipment, and home equipment components of the deterministic scenario (Tables SI-2−4); inputs for the induced energy use part of the home electronics component (Table SI-5); inputs for the home and office heating and cooling component and the home and office lighting components of the deterministic scenario (Tables SI-6−8); and inputs for the probabilistic scenario (Table SI-9). This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Niles, S. J. *Beyond Telecommuting: A New Paradigm for the Effect of Telecommunications on Travel;* Technical Report; Global Telematics: 1994.
(2) Shafizadeh, R. K.; Mokhtarian, P. L.; Niemeier, D. A.; Salomon, I. *The Costs and Benefits of Home-Based Telecommuting;* Technical Report; University of California: Davis, CA, 2000.
(3) Arnfalk, P. Licensiate Thesis, Lund University, Sweden, 1999.
(4) Korte, W. B.; Kordey, N.; Robinson, S. *Telework Penetration, Potential and Practice in Europe;* Report for TELDET Project 1994; European Commission: 1995.
(5) *Telework Data Report (Population Survey) − Ten Countries in Comparison;* European Union: Bonn, Germany, 2000. http://www.empirica.com/ecatt/index.html (accessed October 10, 2002).
(6) *The Research for Teleworking Population in Japan 1996;* Satellite Office Association of Japan: Tokyo, Japan. http://www.soajhome.ab.psiweb.com/english/twp96-e.htm (accessed October 10, 2002).
(7) *The Facts and Figures of Teleworking;* The Teleworkers Web Site. http://members.aol.com/telwebsite/twfacts.htm (accessed April 2, 2002).
(8) *Telework Facts, Appendix II;* International Telework Association and Council. http://www.telecommute.org/resources/facts.shtm (accessed April 2, 2002).
(9) Bay Area Telework Association. http://www.baytelework.org/ (accessed April 1, 2002).
(10) *The Status of Telework in the Federal Management;* U.S. Office of Personnel Management: Washington, DC. http://www.opm.gov/telework/ (accessed April 1, 2002).
(11) *Telework Program;* U.S. General Services Administration. http://www.gsa.gov/Portal/content/offerings_content.jsp?contentOID=115208&contentType=1004 (accessed February 10, 2003).
(12) Kunkle, R. *Perspectives on Successful Telework Initiatives;* Technical Report; WSU Cooperative Extension Energy Program: 2000.
(13) Nilles, M. J. *Making Telecommuting Happen − A Guide for Telemanagers and Telecommuters;* Van Nostrand Reinhold: New York, 1994.
(14) Handy, S. L.; Mokhtarian, P. L. *Transportation* **1996**, *23*(2), 163−189.
(15) Mokhtarian, P. L. *Urban Studies* **1998**, *35*(2), 215−242.
(16) Viswanathan, K.; Goulias, K. *Travel Behavior Implications of Information and Communications Technology in the Puget Sound Region;* 80th Annual Meeting of the Transportation Research Board, Washington, DC; Transportation Research Board: Washington, DC, 2001.
(17) *Transportation Implications of Telecommuting;* Technical Report; U.S. Department of Transportation: Washington, DC, 1993.
(18) *Energy, Emissions, and Social Consequences of Telecommuting;* U.S. Department of Energy, Office of the Secretary; U.S. Government Printing Office: Washington, DC, 1994.
(19) Mokhtarian, P. L. *Sci. Am.* **1997**, 93.
(20) Kitou, E. Ph.D. Dissertation, University of California, Berkeley, 2002.
(21) Balepur, N. P.; Varma, K. V.; Mokhtarian, P. L. *Transportation* **1998**, *25*(3), 287−305
(22) Mokhtarian, P. L.; Varma, K. V. *Transportation Res. D* **1998**, *3*(6), 419−428.
(23) Kitou, E.; Horvath, A. *Telework Impact Estimation Tool;* Consortium on Green Design and Manufacturing, University of California, Berkeley. http://greenmfg.me.berkeley.edu/green/SoftwareTools/Telework/ (accessed January 28, 2003).
(24) *Tailpipe Tally − How Much Does Your Vehicle Pollute?* Online Calculator; Environmental Defense. http://www.ed.org (accessed April 2, 2002).
(25) *Fuel Economy Guide;* Online Calculator/Database; U.S. Department of Energy/U.S. Environmental Protection Agency. http://www.fueleconomy.gov (accessed April 2, 2002).
(26) Handy, S. L.; Mokhtarian, P. L. *Transportation Res. A* **1995**, *29A*(4), 283−302.
(27) Pratt, J. H. *Costs/Benefits of Teleworking to Manage Work/Life Responsibilities;* American National Telework Survey, International Telework Association and Council: 1999.
(28) *California's Power Content Label;* California Energy Commission. http://www.energy.ca.gov/consumer/power_content_label.html (accessed March 20, 2003).
(29) *National Transportation Statistics 2000;* U.S. Department of Transportation, Bureau of Transportation Statistics. http://www.bts.gov/btsprod/nts/ (accessed April 2002).

(30) *Federal and California Exhaust and Evaporative Emission Standards for Light-duty Vehicles and Light-Duty Trucks 2001;* U.S. Environmental Protection Agency, Office of Transportation and Air Quality. http://www.epa.gov/otaq/stds-id.htm (accessed April 3, 2002).
(31) Mokhtarian, P. L. In *Understanding Travel Behavior in an Era of Change*; Stopher, P. R., Lee-Gosselin, M., Eds.; Pergamon Press: Oxford, 1997; pp 91−106.
(32) Mokhtarian, P. L. *J. Ind. Ecol.* **2002**, *6*(2), 43.
(33) Nordman, B.; Piette, M. A.; Pon, B.; Kinney, K. *It's Midnight... Is Your Copier On? Energy Star Copier Performance;* LBNL-41332 UC-1600; Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory: Berkeley, CA, 1998.
(34) *Energy Star Purchasing Initiative;* Online Calculator/Database; U.S. Environmental Protection Agency/U.S. Department of Energy, and Lawrence Berkeley National Laboratory, Energy Star Program. http://www.epa.gov/appdstar/purchasing/calculators (accessed April 2, 2002).
(35) *Telework and the Environment;* White Paper Sponsored by National Environmental Policy Institute; National Environmental Policy Institute/International Telework Association and Council: Washington, DC, 1999.
(36) *A Look at Residential Energy Consumption in 1997;* DOE/EIA-0632; U.S. Department of Energy, Energy Information Administration, Office of Energy Markets and End Use, 1997 Residential Energy Consumption Survey; 1999.
(37) *National Household Travel Survey 2001;* U.S. Department of Transportation: Washington, DC, 2003.
(38) *The Emissions & Generation Resource Integrated Database;* U.S. Environmental Protection Agency. http://www.epa.gov/airmarkets/egrid/ (accessed April 2, 2002).

Received for review June 6, 2002. Revised manuscript received May 8, 2003. Accepted May 13, 2003.

ES025849P