

# A SYNTHETIC APPROACH TO ESTIMATING THE IMPACTS OF TELECOMMUTING ON TRAVEL

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## ABSTRACT

A multiplicative model is proposed as a framework for examining the current state of knowledge in forecasting the demand for telecommuting and the resulting transportation impacts. A running illustrative example (containing a base and a future case) is developed, using plausible values for each factor in the model. The base case suggests that 6.1% of the workforce may be currently telecommuting (at least in California), 1.2 days a week on average, with the result that 1.5% of the workforce may be telecommuting on any given day. It is estimated that the vehicle-miles eliminated by this level of telecommuting constitute at most 1.1% of total household vehicle travel. When the limited knowledge about potential stimulation effects of telecommuting is incorporated, it is estimated that the net reduction falls to at most 0.6% of household travel. Reductions in the future could be smaller as commute distances of telecommuters fall closer to the average and as the stimulation effect grows. In any event it is likely that, due to counteracting forces, the aggregate travel impacts will remain relatively flat well into the future, even if the amount of telecommuting increases considerably.

## 1. INTRODUCTION

The potential of telecommunications to mitigate urban traffic congestion and improve air quality through reducing the need to travel has in recent years captured the attention of public planners and policy-makers. The application of telecommuting offers particular appeal since it addresses a number of other policy issues such as the "family friendly" workplace (Gordon, 1996a) and employment opportunities for mobility-limited sectors of the labor force (Hesse, 1995). Mokhtarian (1991b) lists examples of policy statements supporting telecommuting from the state governments of California, Washington, Florida, and Virginia as well as the Federal Government (Bush Administration). Since that time, similar laws, resolutions, and proclamations have been adopted by the states of Arizona (Gordon, 1996b), New Jersey (Gordon, 1992), Georgia (Gordon, 1993), and Minnesota (proclamation by Governor Carlson declaring the week of May 13, 1991 to be "Telecommuting Week"), among other activities at local, state, and federal levels. At the federal level, the Clinton Administration recently released the *President's Management Council National Telecommuting Initiative Action Plan* (November, 1995), which calls for an increase in the number of Federal government telecommuters from about 4000 to 60,000 by the end of fiscal year 1998 (about 3% of the civilian federal workforce).

A number of regional planning agencies are considering what the likely impacts of telecommunications on future travel might be and how to incorporate those impacts into the conventional transportation demand forecasting process. Occasionally some agencies must overtly confront the question of whether those impacts will be of such a magnitude as to affect (reduce) the need for new infrastructure capacity. The following comment by a planner with the Austin, Texas, metropolitan planning organization is not atypical:

“Is it possible to forecast how telecommuting will affect transportation by the year 2020? We have members of the Austin community who insist that the light rail line which is in the planning process and roadway expansions are not necessary due to the significant future levels of telecommuting. While we believe that the technology will continue to advance at a rapid pace, human acceptance of this technology as an alternative to physical travel is questionable. Any light you can shed on this subject... would be most appreciated. It is difficult to plan a transportation system which takes into account the use of telecommuting when future levels of diffusion are difficult to assess” (e-mail communication from David Mann to Gil Gordon, October 6, 1995).

One government study (US DOE, 1994) estimates that telecommuting in the 339 largest US cities (accounting for two-thirds of its population) could eliminate the need for 7,300 - 11,200 lane-miles of freeways and major arterials by the year 2010, for an (undiscounted) cost savings of \$13 - 20 billion. Another study (US DOT, 1993) estimates that nationwide, telecommuting could result in 408 - 815 lives saved and 58,850 - 117,700 accidents avoided by the year 2002 due to reducing travel. The same study estimates travel time savings by telecommuters at 826 million to 1.7 billion hours in 2002. Yet another study, by a respected consulting firm, calculated the nationwide benefits of an expected 10-20% substitution of travel by telecommunications to include 1100 lives saved, 1.6 million accidents avoided (saving \$3.9 billion), 3.1 billion hours of time saved, and about \$600 million in infrastructure maintenance cost savings (Boghani, *et al.*, 1991; Boghani, 1992).

Are these expectations realistic? With numbers such as these under serious discussion, reliable information on the travel impacts of telecommunications would appear to be highly valuable to agencies at all levels of government.

Over at least the past decade, a number of overviews of the impacts of telecommunications on travel have appeared, both conceptual (Salomon, 1985; Mokhtarian, 1990) and empirical (Nilles, 1988; Mokhtarian, 1991b; Mokhtarian, *et al.*, 1995). Most of the empirical research has focused on telecommuting, probably because (1) it has been feasible for longer than most other "tele-applications" (such as videoconferencing or on-line shopping), (2) it has the appealing side benefits alluded to above, and (3) the prospect of eliminating or reducing the peak-period commute trip is especially attractive. Although its share of total trips (but not miles) is declining, commuting still accounts for more trips (26% in 1990) and miles traveled (32%) than any other single purpose (Hu and Young, 1992). Also, it may well be the case that a higher proportion of commute trips than other types of trips will be amenable to substitution through telecommunications. Both factors combined mean that telecommuting probably has

the highest potential for travel reduction of any of the tele-applications, which undoubtedly justifies a continued interest in the study of its adoption and impacts.

Even though the most recent review of the impacts of telecommuting on travel was published in just 1995, considerable empirical research has occurred since the time that paper was written (1992-3), much of which is only recently published, still in press, or still in progress. This body of research offers extensive insight into the impacts of telecommuting on travel, and it would be productive to bring together and place in context many of those individual findings. The present paper attempts to assemble the substantive findings to date under a unified framework. The framework is a simple multiplicative model, the factors of which represent various elements critical to forecasting the transportation impacts of telecommuting. Each factor is itself the subject of separate research efforts.

The *New American Webster Dictionary* defines "synthetic" as (1) "pertaining to or based on synthesis", i.e. on "the combination of separate elements into a complex whole", or (2) "artificial". I refer to the framework presented in this paper as a "synthetic approach to estimating the impacts of telecommuting on travel" in both senses of the word. Certainly it represents a complex combination of separate elements, but that combination will of necessity be somewhat artificial, precisely because of the complexity of the relationships involved. At the same time, the approach offers a basis for getting to the "bottom line" that is both readily understood by practitioners and based on the best research to date. It further makes very clear the areas in which additional research is needed and to some extent implicitly suggests the specific form that such research might take. In any application of the model, each factor can be updated as better information becomes available. Depending on the context, "better" may mean more broadly representative or more locally specialized.

The following section focuses on the portion of the framework relating to estimating the amount of telecommuting that occurs on any given day. Section 3 continues the framework to account for the impact that a given level of telecommuting will have on travel. Section 4 summarizes the preceding discussion and examines fruitful directions for future research.

## **2. FACTORS IN ESTIMATING THE AMOUNT OF TELECOMMUTING**

### **2.1 A "Simple" Model of Telecommuting Levels**

The amount of telecommuting that occurs on any given day, independent of its transportation impacts, will itself be of interest to a number of parties besides transportation planners – for example, to providers of telecommunications services to the home. That amount is literally the product of a series of factors. Who *can* do it? Of those who can, how many *want* to do it? Of those who can and want to, how many *will* do it? Of those, *how often* will they telecommute, and for *how long*? Specifically, let

- E = an average number of people employed within a certain time frame,
- A = the proportion of workers who are able to telecommute,
- W = the proportion of those able to telecommute who want to,
- C = the proportion of those able and wanting to telecommute who choose to, and

F = the average frequency of telecommuting, expressed as a fraction of a five-day work week (for example, telecommuting two days a week means doing so 40% of the time, or a frequency of 0.4).

Then the expected number of people who are in a period of active telecommuting at any given time can be estimated by

$$T = E \times A \times W \times C.$$

The average number of people telecommuting on any given day, that is the expected number of telecommuting occasions, is estimated by

$$O = E \times A \times W \times C \times F = T \times F.$$

The numbers T and O illustrate the difference between the concepts of telecommuting *penetration* and *levels*, respectively, discussed in Handy and Mokhtarian (1995). Obviously E can be omitted from both equations if the focus is on the proportion of the workforce rather than on the actual number telecommuting, but for some applications (notably, in assessing the facility-specific impacts of telecommuting, whether on communications or transportation networks, since network capacities are absolute rather than relative quantities) knowing the actual number is critical.

The most important thing to realize about the above definitions is that each one represents the expected value of a random variable. The true expected number of people telecommuting on any given day is the expected value of the product of those underlying random variables. Now, if all the random variables implied by the above definitions were independent, then the expected value of the product would equal the product of the expected values, and the expressions given for T and O would be exact equations. To the extent that the various factors are correlated, however, that equality does not hold, and the expressions given for T and O are only approximations of the true expected values. It cannot be emphasized strongly enough that a failure to properly account for interactions among the various factors can result in estimates of telecommuting that could be wildly inaccurate *in either direction*. Some of the important likely interactions and their impacts on the model will be examined in further detail below, and the concluding section of the paper discusses refining the simple model presented here to more formally account for correlations among variables.

Thus, the apparent "simplicity" of the equation for O is (not surprisingly) somewhat illusory: first because of the interactions mentioned above, and second because each factor in the equation can be thought of as the outcome of a separate complex model – with uncertainties of measurement and forecasting – in its own right.

Nevertheless, this model is conceptually similar to the "demand decomposition" approach commonly taken by marketers and adopted by Gautschi and Sabavala (1995) to analyze the demand for automobiles and telephones in the early years of their introduction. Gautschi and Sabavala use the simple equation  $S = N \times T \times R$ , where S is sales volume, N is the size of the potential market, T is the

fraction of potential customers who actually buy, and  $R$  is the average number of transactions per person. Their  $S$  roughly corresponds to our  $O$  (number of telecommuting occasions), their  $N$  to our  $E \times A$  (number of people able to telecommute), their  $T$  to our  $W \times C$ , and their  $R$  to our  $F$  (intensity of telecommuting by those who do so). Salomon (1994) also used a similar approach to forecast the amount of telecommuting (and consequent trip reduction) for the Tel-Aviv metropolitan area in the year 2020. The current approach is not specifically based on Salomon's, and it is operationalized with empirical data not available at that time, but the two studies inevitably have some conceptual congruence.

The next four subsections of this paper respectively discuss what is known about the factors  $A$ ,  $W$ ,  $C$ , and  $F$ . For the purposes of illustration, plausible values for each quantity are suggested based on the discussion, and combined to compute hypothetical values of  $T$  and  $O$ . Table 1 contains each variable defined throughout the paper, and the illustrative values for each. A value of one million is used for  $E$ , as a convenient unit which can be scaled up or down for a specific metropolitan area. The astute reader will have noticed that the question, "How long?", at the beginning of this subsection was not matched by a factor in the equations for  $T$  and  $O$ . The reason for this is explained in Section 2.6. The final subsection discusses the combined outcome of all the factors presented in this section.

## 2.2 Who Can?

A starting point for calculating the size of the universe of potential telecommuters is sometimes taken to be the number of information workers in the workforce, with the proportion of such workers in the U.S. estimated to be somewhere above 50% now and as high as 70% in the future. This approach, which essentially equates information worker status with job suitability for telecommuting, errs in being both too broad, and not broad enough. It is not broad enough because many jobs which would not be considered information work contain a sufficient number of information-based tasks to make them telecommutable to some extent (Mokhtarian, 1991a, b). Hence, based on the evidence of actual telecommuting, the universe of potential telecommuters should include occupations such as restaurant inspectors, probation officers, and home health care workers.

On the other hand, taking the universe of potential telecommuters to be information workers is in another sense too broad, for two reasons. First, not all information worker jobs are amenable to telecommuting. A number of studies recognize this, but the estimates of the proportion of jobs for which this is true have been largely judgmental. For example, Nilles (1988) assumed that 20% of information jobs would not be telecommutable. Salomon (1994), on the other hand, estimated that proportion to be around 49%. There are at least two empirical pieces of evidence. One study of 628 employees, 95% of whom were information workers (and Salomon, 1996a). In a sample of 686, similarly dominated by information workers, Mahmassani, *et al.* (1993) found that 38% believed their job was not suitable for working from

**TABLE 1**  
**SUMMARY OF KEY FACTORS**

| <b>Vari-<br/>able</b> | <b>Definition</b>   | <b>Illustrative Assumption<br/>or Computed Result</b> |
|-----------------------|---|---|
| E                     | number of people employed   | 1 million   |
| A                     | proportion of employees able to telecommute<br>(current base case, hypothetical future case)  | 0.16 - 0.30   |
| W                     | proportion of those able to telecommute who want to   | 0.50  |
| C                     | proportion of those able and wanting to who choose to telecommute   | 0.76  |
| T                     | = $E \times A \times W \times C$ , the (estimated) expected number who are in an active period of telecommuting                             | 60,800 - 114,000                                      |
| F                     | average frequency of telecommuting (fraction)   | 0.24  |
| O                     | = $E \times A \times W \times C \times F = T \times F$ , the (estimated) expected no. of telecommuting occasions on any one day             | 14,592 - 27,360                                       |
| D                     | average round-trip drive-alone commute distance<br>(base case, future)  | 47 - 27   |
| a                     | proportion of telecommuting occasions eliminating a vehicle commute trip  | 0.72  |
| V                     | = $O \times a \times D$ , the total (commute) vehicle-miles eliminated on a given weekday<br>(low O $\times$ high D, high O $\times$ low D) | 493,793 - 531,878                                     |
|                       | $aD / M_1$ , the proportion reduction in VMT for a telecommuter on a telecommuting day<br>(base case, future)                               | 0.65 - 0.53   |
|                       | $aD \times F / M_1$ , the proportion reduction in VMT for a telecommuter over a five-day workweek<br>(base case, future)                    | 0.16 - 0.13   |
| $M_2$                 | average total drive-alone VMT by any worker on an   | 30 - 33   |

|                            |  |                                     |
|----------------------------|--|-------------------------------------|
|                            | ordinary weekday   |                                     |
| <b>TABLE 1 (continued)</b> |  |                                     |
| P                          | population of licensed drivers (1.22×E)  | 1.22 million                        |
| M <sub>3</sub>             | average total (drive-alone and rideshare) VMT per driver in a calendar week  | 189 - 208                           |
| X                          | = $O \times aD \times 5 / P \times M_3$ , average proportion reduction in total household VMT                        | 0.011 - 0.010                       |
| N                          | increase in VMT due to non-work travel generation, expressed as a fraction of V                                      | 0 - 0.073                           |
| R                          | increase in VMT due to residential relocation, expressed as a fraction of V  | 0                                   |
| L                          | increase in VMT due to latent demand, expressed as a fraction of V   | 0.50                                |
| I                          | increase in VMT due to induced demand, expressed as a fraction of V  | ???                                 |
|                            | 1 - (N+R+L+I), the proportion of V representing the net reduction in travel, taking stimulation effects into account | 0.50 - 0.43<br>(taking I = 0)       |
| Z                          | = $V - (N+R+L+I) \times V$ , the net change in VMT for a given weekday   | 246,897 - 228,708<br>(taking I = 0) |
|                            | $Z \times 5 / P \times M_3$ , the net change in VMT as a proportion of total travel                                  | 0.0054 - 0.0045                     |

home several days a week. In one additional study (Brewer and Hensher, 1996), job unsuitability was given as the reason for not telecommuting by 74% of the sample, but that sample of commuters in six Australia capitals probably has a lower proportion of information workers than in the other two cases cited.

One difference between these high numbers and Nilles's lower number is that Nilles assumed that a number of jobs which would not be suitable for home-based telecommuting, would be appropriate for center-based telecommuting. This certainly seems plausible in principle, but (1) it is not clear that centers would remove the job suitability constraint for about half of those whose jobs do not permit telecommuting from home (as would need to be the case to reconcile his assumed value with the two

empirically-derived values of 44% and 38%), and (2) the little empirical evidence available to date suggests that workers perceive their job suitability to be *higher* for home-based than for center-based telecommuting (Mokhtarian, *et al.*, 1996b). Although this may appear to be counterintuitive, and may in fact be partially an artifact of the novelty of the telecenter concept, several workers who were interviewed specifically about this apparent discrepancy were able to give rational explanations for their answers based on the characteristics of their specific jobs. Preference for home-based telecommuting also appears to be stronger than for the center-based form at this point (Mokhtarian, *et al.*, 1996b; Bernardino and Ben-Akiva, 1996).

The second reason that equating information workers with the universe of potential telecommuters is too broad is that job suitability is only one of several constraints which preclude an individual from telecommuting. Mokhtarian and Salomon (1994) identify a number of potential constraints on the ability to telecommute: external constraints that can be related either to awareness, to the organization, or to the job, and internal psychosocial constraints. The internal constraints may be viewed as affecting the *desire* and the actual *choice* to telecommute but not, in general, the *ability* to do so. This distinction is not absolute, however: some constraints classified as psychosocial (such as household distractions) may in fact pose real external barriers to telecommuting.

Three key external constraints are lack of awareness, manager unwillingness, and job unsuitability. In the same sample of 628 described above, lack of awareness was active for 4% of the respondents, job unsuitability for 44%, and manager unwillingness for 51%. At least one of these three constraints was active for 68% of the sample, meaning that telecommuting was possible for no more than 32%. In view of the characteristics of the sample (predominantly information employees of an organization with an active, visible, and long-term telecommuting program supported by upper management), the prevalence of these constraints is certainly *underrepresentative* of the situation for the workforce as a whole. Mokhtarian and Salomon (1996b) estimated that, taking these three key constraints as well as other external constraints into account, telecommuting would have been feasible for 14-16% of the workforce in 1992, the year their data were collected.

Constraints can be mitigated over time; useful questions for further research are how rapidly and to what ultimate degree. For the hypothetical example of this paper, we will take  $A=0.16$  as a base case, and set  $A=0.30$  for some unspecified point in the future. By contrast, another study, focusing only on the job suitability factor, proposed 40% as a "current" (1988) floor (which was also assumed to rise over time) on the proportion of the workforce that could potentially telecommute (Nilles, 1988).

### **2.3 Who Wants to?**

Not everyone who is able to telecommute will want to. Mokhtarian and Salomon (1994) point out that the absence of binding constraints is a necessary but not sufficient condition for telecommuting to occur. One or more drives or motivations to telecommute must also be present. Five such types of drives are identified: work, family, leisure or independence, commuting, and ideology (specifically a pro-environment orientation).

Thus, there are two reasons why not everyone who can telecommute (in terms of external constraints) will want to: a drive to do so may not be present, or, the drive(s) may be outweighed by the

intensity of internal constraints such as risk aversion, interpersonal interaction needs, or the perceived benefit of the commute.

Some estimates of the proportion of workers who want to telecommute that have appeared in the literature include 88% (Mahmassani, *et al.*, 1993, sample proportion), and 50-80% (Salomon, 1994, judgmental range). In this context, however, given the structure of the proposed model it is important to condition the desire to telecommute on the ability to do so. There is evidence that those two factors are not entirely independent: in the sample of 628 workers mentioned earlier, Mokhtarian and Salomon (1996a) found that 87% of those for whom telecommuting was not possible (based only on the three key external constraints described in Section 2.2) wanted to telecommute, compared to 91% of those for whom it was possible. They also found job suitability to be the strongest and most significant out of nine explanatory variables in a model of telecommuting preference (Mokhtarian and Salomon, 1997). Hence, not unnaturally, one is less likely to want to telecommute if it is not possible to do so. However, those specific numbers are heavily influenced by the selection bias of the sample (as is the 88% figure cited above). That is, people who do not want to or cannot telecommute are less likely than others to return the survey, and hence the numbers given are overrepresentative of the population as a whole. Correcting for that bias, Mokhtarian and Salomon (1996a, 1996b) estimate that telecommuting may be "desired by as few as 46% of those for whom it is possible."

Since desire (once external constraints are controlled for) is primarily a function of psychological characteristics, there is little reason to expect large changes over time in the value of  $W$ . Hence, for the illustrative example developed here, we take  $W=0.5$  for both the base and the future cases.

At this point, several studies have modeled the preference to telecommute (including both home- and center-based forms), and it may be of interest to review characteristics found to be significant to the desire to telecommute. Such a review is beyond the scope of the present paper, but the interested reader is referred to Mokhtarian and Salomon (1997), Bagley and Mokhtarian (forthcoming), Stanek and Mokhtarian (1997), Bernardino and Ben-Akiva (1996), and Sullivan, *et al.* (1993, a stated preference model of telecommuting frequency).

## 2.4 Who Will?

It was pointed out in Section 2.3 that even when no external constraints are binding and a drive to telecommute is present, internal constraints may be strong enough to cause telecommuting to be perceived as undesirable. In other situations, those constraints may not be powerful enough to overcome a preference to telecommute, but they may be sufficiently strong to prevent choice. For example, it is quite possible for someone to express a desire to telecommute based on one or more drives, but to choose not to out of a fear that it would negatively impact her promotion potential (see, e.g., Bagley, *et al.*, 1996). Thus, not everyone who can and wants to telecommute will do so. Based on Mokhtarian and Salomon (1996b) we can estimate that of the portion of the workforce for which telecommuting is both possible and preferred, about 76% will choose it. With no other known empirical evidence, we take for our example  $C=0.76$ .

Again, there are several studies modeling the choice to telecommute, which identify explanatory variables significant to choice. The interested reader is referred to Mokhtarian and Salomon (1996b) and Mannering and Mokhtarian (1995, the choice of telecommuting frequency).

## 2.5 How Often?

Whereas early treatments of telecommuting often considered it as occurring full-time or not at all, conventional wisdom holds that most telecommuting today is part time—“one or two days a week”. Conventional wisdom is supported by the empirical evidence. In a review of eight home-based telecommuting studies (taking place in the late 1980s and early 1990s), Handy and Mokhtarian (1995) found an average telecommuting frequency of 1.2 days a week, or 24%. Brewer and Hensher (1996) present a distribution of telecommuting frequencies for their 1994 sample; estimating each category by its midpoint and assuming a 21-workday month yields an estimated average frequency of 22%. A recent study of center-based telecommuting (Varma, *et al.*, 1996) found frequencies of 17-25% (based on data collected from 1992 to 1995).

These various estimates appear to show a fair amount of spatial and temporal stability. As Handy and Mokhtarian (1996a) point out, there are plausible arguments in either direction for the way in which the average frequency of telecommuting may change over time. On the one hand, the early adopters of telecommuting being measured in most of these studies may be more motivated, and hence telecommute more often, than the later adopters will as telecommuting spreads. On the other hand, improvements in technology and in the comfort of both employers and employees with telecommuting may lead to greater frequencies over time. In the absence of any compelling evidence for a trend upward or downward, we suggest that average frequencies will remain stable and take  $F=0.24$ .

One further observation which can be made is that actual telecommuting frequency is typically less than the expected and desired frequency (Mokhtarian, *et al.*, 1996b). One sample of 27 telecenter users (Mokhtarian, *et al.*, 1996a) reported before beginning to telecommute that they wanted to use the center 59% of the time (about three days a week) and expected to do so 50% of the time. About six months (on average) after beginning to telecommute, their actual reported frequency was 39% (two days a week). Hence, it would be unreliable to base an estimate of future telecommuting frequency on prospective self-reports without applying some kind of correction factor.

## 2.6 How Long?

The nature of temporal patterns of telecommuting is an important research and practical question that has received little attention to date. Once people begin to telecommute, how long do they continue to do so? Do they telecommute for a while then quit altogether, do they cycle in and out of it at various points in their career? Why do they quit, why re-start? How often do they “exit” telecommuting to take up a home-based business, as opposed to returning to a conventional work arrangement or to some other alternative? What is the average duration of telecommuting periods, or spells, and what distribution do these periods exhibit?

Varma, *et al.* (1996) review the limited empirical data available on telecommuting duration from three two-year home-based telecommuting programs, and present preliminary findings from a telecenter program. Across the three home-based programs, they report that 32-60% of those originally selected to telecommute were still doing so at the conclusion of the two-year pilot (not all of those will have telecommuted the full two years, as recruitment sometimes spread over six months or more). Of those originally selected (meaning that they volunteered and completed an initial questionnaire, that their managers approved, and sometimes that they completed a training session), 17-53% never even telecommuted at all. The key finding on duration from the telecenter program was that 50% of its telecommuters quit within nine months after starting.

Thus, the study of the adoption of telecommuting is unlike the case for a simple technology improvement such as a microwave oven or video cassette recorder, which is most often “permanently” acquired. In those situations, new adopters are added to a base of existing adopters, and penetration steadily rises. In the case of telecommuting, penetration may fluctuate somewhat over time due to attrition among previous adopters. For example, the market research firm Find/SVP, which conducts an annual survey of home-based work, estimated that the number of telecommuting employees in the US fell (for the first time in the ten years during which the surveys had been taken) from 9.1 million in 1994 to 8.2 million in 1995, lower than the 8.5 million estimated for 1993 (Miller, 1995, also reported in Mokhtarian and Henderson, 1996).

Even if the measured drop in penetration is only a temporary dip in a generally rising trendline (and Find/SVP is projecting an increase to 8.7 telecommuters in 1996), the message seems to be that attrition among telecommuters will limit the growth in penetration to be lower —perhaps considerably lower—than would be expected if attrition were not accounted for.

Why do people quit? Different category labels across the studies reviewed by Varma, *et al.* (1996) inhibit comparability, but the most common reason (offered in 30-63% of the cases) appears to be job changes, whether to a different job altogether or to different emphases, responsibilities, or circumstances within the same job. (Corporate downsizing and outsourcing were also cited by Miller (1995) as some of the likely reasons for the national decline in telecommuting). The next most common reason is apparently manager concerns (offered by about a quarter of the participants in two of the reviewed studies). Dissatisfaction with telecommuting was mentioned rather infrequently as a reason for quitting, and most former telecommuters interviewed in one study expressed a desire to return to telecommuting when possible.

Hence, attrition seems to be due primarily (although not exclusively) to external constraints rather than to a disillusionment with the delivery of benefits promised by telecommuting. As discussed in Section 2.2, these types of constraints can be mitigated to some degree over time. The lesson here, however, appears to be (congruent with the path of telecommuting penetration itself) that although mitigation of these constraints may follow a generally upward path in the aggregate, there is likely to be considerable turnover at disaggregate levels. That is, for an individual, constraints will be removed and reimposed at various points in time, although over time the constraints will be less often applicable to more and more people. The net result, however, is again that the growth of telecommuting may not be as rapid as expected under the view that constraints would be permanently removed for an ever-

widening circle of people. In the current framework, the practical question is whether and how fast the hypothetical value of  $A=0.30$  proposed in Section 2.2 could in fact be reached.

How should attrition among telecommuters be incorporated into the multiplicative model which constitutes the framework of this paper? In essence, it is incorporated automatically and implicitly. When people stop telecommuting, it is either because they are no longer motivated or driven to do so, or because some constraint (whether internal or external) prevents them either from being able to telecommute, from desiring to telecommute, or from choosing to do so. The effects of all of these possibilities are embedded within the factors of  $A$ ,  $W$ , and  $C$  (and  $F$ , for that matter); to incorporate an additional duration factor would be to double-count these effects. Thus, to the extent that  $A$ ,  $W$ ,  $C$ , and  $F$  are accurately forecast, no further adjustment for duration should be needed.

Nevertheless, the study of temporal patterns of telecommuting remains critical precisely to *improve* our ability to forecast changes in these other factors over time, as well as more generally to improve our understanding of the dynamic element in the adoption of a strategy such as telecommuting. See Kitamura (1990) for a persuasive discussion of the importance of longitudinal (panel) data in the analysis of dynamic behavior patterns.

## 2.7 Combined Outcome

The entries for  $T$  and  $O$  in Table 1 show the results of the assumptions made about each variable so far. The base case assumption that 16% of the workforce can telecommute leads to the estimate ( $T$ ) that for every million workers, 60,800 of them will be in a period of active telecommuting—in other words, that 6.1% of the workforce is telecommuting. The same assumption leads further to the estimate ( $O$ ) that about 14,600 or 1.5% of the workforce will be telecommuting on any given day. These numbers (illustrated in Figure 1) essentially replicate estimates of the penetration and level of telecommuting in the California workforce in 1991 (Handy and Mokhtarian, 1995). Although the relationship between  $T$  and  $O$  is based on the same assumed value for  $F$  in both cases, the similarity of  $T$  here to Handy and Mokhtarian's estimate is an independent outcome (noted by Mokhtarian and Salomon, 1996a).

The assumption that at some point in the future, 30% of the workforce will be able to telecommute, leads to estimates for  $T$  and  $O$  equivalent to 11.4% and 2.7% of the workforce, respectively. Thus, a sizable (and highly speculative) increase in the ability of workers to telecommute still results in relatively low levels of activity on any given day. It should also be pointed out that since the factors in the model were "calibrated" primarily with California data, they reflect California conditions. In view of the higher than average share of workers in "telecommuting-conducive occupations" in California (Handy and Mokhtarian, 1996a), and the





extent of its congestion problems (perhaps motivating individuals to telecommute), values for A and W in particular may be lower in many other parts of the country, both now and in the future.

### 3. FACTORS IN ESTIMATING THE TRANSPORTATION IMPACTS

#### 3.1 Key Factors and Relationships

Having examined the variables relevant to estimating the amount of telecommuting occurring on any single day, we turn now to those factors necessary for estimating the transportation impacts of telecommuting. The average transportation impacts for any one occasion can be multiplied by the expected number of occasions (O) to obtain the (estimated) aggregate impacts, which can be expressed either on a per-weekday basis, or as a proportion of total travel. Here, we focus on vehicle-miles traveled (VMT) as a key travel indicator of interest, but a similar approach may be taken with other indicators such as number of trips, peak period trips or VMT, person-miles traveled, and so on. To analyze the travel impacts for a single occasion, the key questions are: how far does the average telecommuter commute? How much of that is actually eliminated due to telecommuting? What proportion of total travel does that represent? And what about increases in travel that might occur, due to changes in residential location, increases in non-work travel, mode shifts, latent demand, and induced demand?

Specifically, let

- D = the average round-trip commute distance in drive-alone vehicle-miles of those telecommuting on a given day,
- a = the proportion of telecommuting occasions that eliminate a vehicle commute trip,
- M<sub>1</sub> = the average total drive-alone VMT by a telecommuter on an ordinary (non-telecommuting) weekday,
- M<sub>2</sub> = the average total drive-alone VMT by any worker on an ordinary weekday,
- M<sub>3</sub> = the average total (drive-alone and rideshare) VMT per licensed driver in a calendar week, and
- P = the population of licensed drivers.

Then  $aD$  is the average number of vehicle-miles eliminated per telecommuting occasion, and it is useful to define the key quantity

$V = O \times aD$ , the total expected number of vehicle-miles eliminated on any given weekday.

As mentioned earlier, for some applications it is the absolute reduction  $aD$  or  $V$  that is important. It is also valuable, however, to express the reduction in terms of proportions of some total amount of travel. Three such totals are of interest, defined as  $M_1$ ,  $M_2$ , and  $M_3$  above. The first measure allows us to express  $aD$  as a proportion of telecommuters' own total travel, and the latter two allow us to express  $V$  as a proportion of travel by everyone. Specifically, we can compute:

$aD / M_1 =$  the average proportion reduction in VMT for a telecommuter on a telecommuting day,

$aD \times 5 \times F =$  the average number of vehicle-miles eliminated per telecommuter in a five-day workweek,

$aD \times 5 \times F / 5 \times M_1 = aD \times F / M_1$

$=$  the average proportion reduction in VMT for a telecommuter over a workweek,

$O \times aD / E \times M_2 =$  the average proportion reduction in workers' total weekday VMT,

$O \times aD \times 5 = V \times 5 =$  the average total vehicle-miles eliminated in a five-day workweek, and

$X = O \times aD \times 5 / P \times M_3 =$  the average proportion reduction in total household VMT.

To account for hypothesized increases in travel, let

$N, R$

$=$  the expected increases in travel due to non-work trip generation and longer commute distances due to residential relocation, respectively, expressed in terms of fractions of the reduction in VMT ( $V$ ), and

$L, I$

$=$  the expected increases in travel due to the additional effects of latent demand and induced demand, respectively, expressed as fractions of the reduction in VMT.

Then the net change in VMT will be equal to

$V - (N+R+L+I) \times V.$

If  $N+R+L+I$  exceeds one, then the cumulative generation effects exceed the substitution effects and the net result will be increased travel.

As with the adoption of telecommuting, what is known about each of the factors listed above is discussed in the remaining subsections of this section. We continue the running example by proposing an illustrative value for each factor and discussing the combined outcome in the final subsection.

### 3.2 How Far?

In this subsection we estimate the reduction in VMT due to the elimination of the commute trip by telecommuting. We focus on drive-alone vehicle-miles rather than on person-miles since that is the critical measure as far as congestion and air quality are concerned. Eliminating a person-trip taken by bus or walking (or even a carpool trip if the carpool vehicle still makes the commute) does not by itself affect either congestion or air quality.

As a simplification, we assume that when the conventional commute trip is not made, the full round-trip distance (in drive-alone vehicle-miles) between the telecommuting location and the regular workplace is not traveled. This will slightly overstate the reduction, since in some cases trips that were chained to the commute will still take place. However, this can be compensated for by adjusting the factor  $N$  appropriately (see Section 3.4.1).

### 3.2.1 *The Value of a*

On the other hand, we do *not* adopt the simplification, as is often done in a “quick-and-dirty” estimate of travel reduction due to telecommuting, that every telecommute occasion eliminates a conventional commute trip (corresponding to  $a=1$ ). Mokhtarian (1997) points out that in one sample of 34 telecommuters, close inspection of the circumstances revealed that for five (15%) of those people, commute trips were not being eliminated. “For three of those participants – maternity and temporary disability cases – the alternative to working from home was not working at all. For a fourth, the alternative was continuing to work part-time (three days a week only, all in the main office, instead of three days in the office and the other two at home). The fifth respondent telecommuted partial days, which shifted commute travel out of the peak but did not eliminate it.”

At least three other studies examined this issue. In analyzing a sample of 3,646 center-based telecommuting occasions, Mokhtarian, *et al.* (1996a) found that trips to the regular workplace were made on 8% of those occasions. For home-based telecommuting, Henderson, *et al.* (1996) reported that 10 (14%) out of 71 home-based telecommuters in their sample made drive-alone commute trips on telecommuting days. Koenig, *et al.* (1996) reported that three (7.5%) out of 40 telecommuters in their sample did the same, although this only accounted for 6% of the telecommuting person-days in the sample. Both of these latter sources also pointed out that not every *conventional* workday involved a drive-alone commute. Nationwide, for example, 73.2% of commute trips in 1990 were drive-alone (Ball, 1994). Drive-alone mode shares for telecommuters in these two studies were higher, in the 81-83% range.

Thus, unless the proportion of telecommuting occasions is discounted by the share of those occasions which would not have involved a drive-alone commute and the share on which the commute is actually made, the effects of telecommuting on traffic and air quality will be exaggerated. To see the combined impact of these two possibilities, consider 100 telecommuting occasions. On only 82 (say) of them would the telecommuter have commuted by driving alone, so at most 82 commute round trips would be eliminated. But on perhaps 10 of those 100 occasions (taking the midpoint of the 6-14% range found in the literature), the telecommuter actually makes a drive-alone commute after all, meaning

that only 72 round trips are eliminated. Thus, we take 0.72 as our illustrative value of  $\alpha$ . That is, we estimate that telecommuting actually eliminates a commute vehicle-trip only 72% of the time.

### 3.2.2 The Value of $D$

The second factor in assessing the quantity of vehicle-miles eliminated due to telecommuting is the average round-trip (drive alone) commute distance,  $D$ . For our

**TABLE 2**  
**SUMMARY OF TRANSPORTATION FINDINGS FROM PREVIOUS STUDIES <sup>1</sup>**

|   | Puget Sound <sup>2</sup> | State of California <sup>3</sup> | Puget Sound Telecenter <sup>4</sup> | Neighborhood Telecenters <sup>5</sup> |
|---|--------------------------|----------------------------------|-------------------------------------|---------------------------------------|
| <b>Dates of Study</b>                               | 1990-91                  | 1988-90                          | 1990-91                             | 1993-95                               |
| <b>Type of Telecommuting</b>                        | home+center              | home                             | center                              | center                                |
| <b>Sample Size (Telecommuters)</b>                  | 72                       | 40                               | 8                                   | 24                                    |
| <b>Sample Person-Days</b>                           |                          |                                  |                                     |                                       |
| Non-t'cing (NTC) Day                                | 251                      | 114                              | 28                                  | 39                                    |
| Telecommuting (TC) Day                              | 108                      | 52                               | 13                                  | 30                                    |
| <b>Sample Total Trips</b>                           |                          |                                  |                                     |                                       |
| NTC Day   | 948                      | 429                              | 95                                  | 88                                    |
| TC Day  | 279                      | 142                              | 53                                  | 96                                    |
| <b>Per Person-Day Averages (Drive -Alone Mode):</b> |                          |                                  |                                     |                                       |
| <b>Vehicle-Miles</b>                                |                          |                                  |                                     |                                       |
| NTC Day   | 52                       | 45                               | 63                                  | 59                                    |
| TC Day  | 19                       | 10                               | 29                                  | 21                                    |
| Difference (TC - NTC)                               | -33                      | -35                              | -34                                 | -38                                   |
| Percent Change                                      | -63%                     | -77%                             | -54%                                | -65%                                  |
| <b>Vehicle-Trips</b>                                |                          |                                  |                                     |                                       |
| NTC Day   | 3.7                      | 3.8                              | 3.4                                 | 2.3                                   |
| TC Day  | 2.6                      | 2.7                              | 4.1                                 | 3.2                                   |
| Difference (TC - NTC)                               | -1.1                     | -1.0                             | +0.7                                | +0.9                                  |
| Percent Change                                      | -30%                     | -27%                             | +20%                                | +42%                                  |

|                                    |      |      |      |            |
|------------------------------------|------|------|------|------------|
| <b>Change in Commute VMT</b>       | -35  | -29  | -32  | -41        |
| <b>Change in Non-Commute VMT</b>   | +2   | -5   | -2   | +3         |
| <b>Change in Commute Trips</b>     | -1.4 | -1.5 | +0.5 | not avail. |
| <b>Change in Non-Commute Trips</b> | +0.3 | +0.5 | +0.2 | not avail. |

hypothetical example, we offer a high estimate of D representing current conditions, and a low estimate of D representing hypothetical future conditions. The high estimate of D is based on average distances observed for telecommuters to date. For example, Mokhtarian, *et al.* (1995) take the weighted average of drive-alone commute distances for telecommuters in five studies and obtain a 26.3-mile round-trip distance. In the four more recent studies summarized in Table 2, average commute VMT savings ranging from 29 to 41 miles were found, with a weighted average of 34 miles per telecommuting occasion.

**Notes to Table 2:**

- <sup>1</sup> All four studies are based on travel diary data collected before and after telecommuting began.
- <sup>2</sup> Source: Henderson, *et al.* (1996).
- <sup>3</sup> Source: Koenig, *et al.* (1996).
- <sup>4</sup> Source: Henderson and Mokhtarian (1996).
- <sup>5</sup> Sources: Balepur, *et al.* (1996) or Mokhtarian, *et al.* (1996a).

In the former group of studies, each telecommuter was given equal weight. In the latter group of studies, the actual savings for a specific person was weighted by the number of telecommuting occasions for that person. It is plausible for there to be a relationship between commute distance and telecommuting frequency (the longer the commute distance, the greater the motivation to telecommute more often), although several previous studies have notably failed to find such a correlation (Olszewski and Mokhtarian, 1994; Mannering and Mokhtarian, 1995; Mokhtarian, 1997). Sullivan, *et al.* 1993, however, did find commute time significant in the preference for full-time telecommuting. Nevertheless, if such a relationship does exist, the latter estimate of commute VMT savings per telecommuting occasion is preferable because it accounts for that interaction (the commute reduction for more frequent telecommuters is counted more

often in the average). However, it is important to realize that the number 34 represents not just D but aD, since it is averaging out distances traveled over all person-days in the sample (thus taking into account regular days on which commuting did not occur and telecommuting days on which commuting did occur). Dividing 34 by a=0.72 would give an estimate of D=47 vehicle-miles reduction on a telecommuting occasion.

On the other hand, it is clear from the above discussion, as has been noted before (Mokhtarian, *et al.*, 1995), that the early adopters of telecommuting measured in all of these studies tend to have longer-than-average commutes. It does seem to be the case that longer-distance commuters are more motivated to adopt telecommuting: commute characteristics generally turn up significant in models of telecommuting preference and choice (Mokhtarian and Salomon, 1997, 1996b; Bernardino and Ben-Akiva, 1996; Bagley and Mokhtarian, forthcoming), even though as noted above they do not always

seem to affect choice of telecommuting frequency. However, the same models identify numerous other variables significant to the adoption of telecommuting, and hence it would be expected (and is in fact observed) that people even with relatively short commutes find telecommuting attractive for other reasons. The observed commute length averages for these telecommuters may be due in part to a bias in the programs studied toward telecommuting as a transportation mitigation strategy. In some cases a long commute was actually an explicit selection criterion for participants.

Hence, it is reasonable to believe that in terms of commute length, the relatively small proportion of telecommuters measured in these several studies are not even representative of all current telecommuters, let alone of telecommuters in the future. Nevertheless, to illustrate an extreme, we will take  $D=47$  as our high (current) estimate.

Over time we should expect the commute lengths of telecommuters to decrease, and perhaps to approach the average for all workers, although the average for telecommuters will probably remain somewhat higher (Mokhtarian, *et al.*, 1995). Hence, the low (future) estimate of  $D$  is based on average population commute lengths. According to the Nationwide Personal Transportation Survey (NPTS) (Hu and Young, 1992), the average (one-way) commute length in 1990 was 11.0 vehicle-miles. Arbitrarily supposing that length to rise to 15 miles (at least for telecommuters) by some future date, and dividing that by an average vehicle occupancy of 1.1 gives an average of 13.6 drive-alone miles. We take  $D=27$  as our low estimate of round-trip vehicle-miles reduced on a telecommuting occasion.

As a side note, we have not in this paper dwelled on the distinction between home-based and center-based telecommuting. Table 2 illustrates that even though center-based telecommuters tend to travel farther on telecommuting days than their home-based counterparts (primarily due to making the commute trip to the telecenter), they also tend to travel about the same amount farther on their non-telecommuting days, with the net reduction in vehicle-miles being approximately equal for both groups. However, differences in adoption and impacts between home- and center-based telecommuting are important areas for future research.

### 3.2.3 *The Value of V*

As indicated earlier, the total number of vehicle-miles eliminated due to telecommuting on a single workday ( $V$ ) is equal to the number of telecommuting occasions on that day ( $O$ ) times the average number of miles saved per occasion ( $aD$ ). The current base case estimate of  $V$  is given by using the low value for  $O$  and the high value for  $D$ ; that is,

$V = O \times aD = 14,592 \times 0.72 \times 47 = 493,793$  miles per weekday, or (dividing by  $E$ ) about 1/2-mile per worker per weekday.

To estimate the value of  $V$  in the future, we should use the high value for  $O$  and the low value for  $D$ . That is, in the future, more workers are likely to be able to telecommute, but their average commute lengths are likely to be shorter and hence the per-capita reductions due to telecommuting likely to be lower. Multiplying the illustrative values out gives

$V = 27,360 \times 0.72 \times 27 = 531,878$  miles per weekday.

Note that  $V$  increased by only 8% even though  $O$ , the number of telecommuting occasions, increased by 88%. While there is obviously a certain degree of arbitrariness in the choices for the high values of  $A$  and the low values of  $D$ , the point is not the specific number arrived at here for a future value of  $V$ , but rather to illustrate that counteracting forces may well result in the travel impacts of telecommuting increasing much more slowly than the adoption of telecommuting itself. In fact in the short term it is possible for the travel impacts of telecommuting actually to decrease in the aggregate.

### 3.3 Out of How Much?

Is a daily reduction of half a mile per worker a lot or a little? To put the absolute reductions  $aD$  and  $V$  in context, we would like to know what proportion of total travel they constitute. As defined in Section 3.1, we examine three measures of total travel,  $M_1$ ,  $M_2$ , and  $M_3$ , to calculate four proportions.

#### 3.3.1 *The Value of $M_1$*

For a base case estimate of  $M_1$ , the total VMT per telecommuter on a non-telecommuting weekday, we take an average (weighted by the number of telecommuters in each study) of the “Vehicle-Miles, NTC Day” figures in Table 2 and obtain  $M_1=52$ . Since, as has been noted before, the telecommuters in these studies are long-distance commuters, their total weekday drive-alone VMT is likely to be higher than the current population average, and higher than the average for future telecommuters. For a future estimate of  $M_1$ , we take the future value of  $M_2$  (the population average weekday drive-alone VMT, estimated in Section 3.3.2 to be 33 miles), judgmentally increase that figure slightly to account for still-slightly-longer-than-average commute lengths of future telecommuters, and choose  $M_1$  (future) = 37.

Using these two measures of  $M_1$ , we compute  $aD / M_1$ , the average proportion reduction in VMT for a telecommuter on a telecommuting day, to be 0.65 for the base case and 0.53 in the future. This illustrates that the savings in commute travel due to telecommuting is likely to be a declining share of telecommuters’ total weekday travel, as their commute distances approach the population average.

The measure  $aD / M_1$  is commonly reported in studies of the impacts of telecommuting on travel (note the “Vehicle-Miles, Percent Change” row of Table 2, with reductions ranging from 54-77% and a weighted average of 67%; these numbers are consistent with the 66% reduction in car travel found in an Australian study: RTA, 1995), because it is readily available and requires no data external to the study. Although valid on its own terms, it can be easily misinterpreted as suggesting highly exaggerated effects of telecommuting (Mokhtarian, 1996). One deficiency of this measure is that it does not indicate the frequency with which such a reduction in VMT occurs. That deficiency is addressed by the second measure, which averages out the reduction on any one telecommuting day across the entire workweek based on the frequency with which telecommuting occurs.

Specifically, we compute  $\Delta D \times F / M_1$ , the average proportion reduction in VMT for a telecommuter over a workweek. Taking  $F=0.24$  as a constant, we obtain 0.16 for the base case and 0.13 in the future. That is, taking the frequency of telecommuting into account, the VMT reduction due to telecommuting is currently perhaps 16% of a telecommuter's total weekday travel (Balepur, *et al.* 1996), in process, found the reduction in their telecenter study to be 17%, using the more accurate method of weighting *each individual's* VMT by the frequency of telecommuting for that individual, compared to a reduction of 12% obtained by multiplying averages in the aggregate as we have done here. Thus, the reminder is again in order that failing to account for interactions among variables may alter the results appreciably. In this case, it appears that there *is* in fact an interaction between telecommuting frequency and VMT).

### 3.3.2 The Value of $M_2$

These relative measures of reduction as a proportion of telecommuters' own travel are useful, but from a system standpoint it is more important to place the reduction in a broader context. Two measures for doing that are introduced: the first looking at workers' total weekday drive-alone travel and the second looking at all household vehicle travel. The first measure is useful from the perspective of the impact of telecommuting on weekday congestion (although from that perspective it is incomplete—it should really include all weekday vehicle travel for the entire population, but values for that are less readily available), and the second is useful from the perspective of its impact on total fuel consumption for personal travel.

First, then, we estimate  $M_2$ , the average total weekday drive-alone miles per worker. For the base case, one way to do that is to take the weighted average for the non-telecommuting control group workers reported by the studies cited in Table 2, which is 33 miles (the averages for each study are not shown in the table, but are either 32 or 33 miles in each case). However, these studies suggest that even the control group members have commutes and VMT that are longer-than-average although not as long as the telecommuters'. This is plausible since in many cases control group members are "telecommuter wanna-bes" who hope to join a later cohort of telecommuters (JALA, 1990). One clear lower bound for  $M_2$  is the value for  $M_3/7$ , which is below taken to be 27 for the base case. Hence, for the base case here, we judgmentally take  $M_2=30$ . For a future case we will arbitrarily consider a 10% increase in total weekday drive-alone VMT, and take  $M_2=33$ .

Then we have  $\Delta D / E \times M_2 = 0.493793 / 30 = 0.016$  for the base case, and  $0.531878 / 33 = 0.016$  for the future case. That is, the reduction in VMT due to telecommuting represents 1.6% of workers' total weekday drive-alone VMT under both cases, with future increases in the number of telecommuting occasions being counterbalanced by decreases in average (absolute) reductions per occasion and slightly higher background amounts of travel.

### 3.3.3 The Values of $M_3$ and $P$

Finally, it is in some contexts most germane to examine the reduction in VMT as a proportion of total household personal vehicle travel, including travel by non-workers and weekend travel. Thus, we take a seven-day week as the unit, with  $\Delta D \times 5 = V \times 5$  being the average total vehicle-miles

eliminated in a week (assuming that telecommuting eliminates commuting only during the five-day workweek). We need values for P, the population of licensed drivers (expressed in terms of E), and  $M_3$ , the average total household VMT per driver in a week.

For P, we estimate the number of licensed drivers in the US in 1990 at 143,312,000 based on the NPTS (Hu and Young, 1992), take the number of (civilian) workers in the same year to be 117,914,000 from *The Statistical Abstract of the United States*, and computing the ratio of those two numbers to be 1.22, use  $P=1.22 \times E$  (that is, 1.22 licensed drivers per worker).

For the base case for  $M_3$ , we estimate the number of licensed drivers per household in the US in 1990 to be 1.54 based on the NPTS, find the average annual VMT per household to be 15,100 miles from the same source, and from those two numbers compute 9,805 annual miles or 27 daily miles per driver, for a weekly total of  $M_3 = 7 \times 27 = 189$ . For the future case, we again assume a 10% increase in total household personal vehicle VMT, giving  $M_3$  (future) = 208.

From these assumptions it can be calculated that X, the average proportion reduction in total is equal to 0.011 for the base case and 0.010 for the future case. That is, as shown in Figure 2 for the base case, direct reductions in VMT currently constitute about 1.1% of total household vehicle travel

(at most – recall that base case estimates of A, perhaps W, and particularly D are considered to be on the high side), and are likely to stay in that range for some time to come. These values fall in the range (0.7 - 1.4%) projected by a US Department of Transportation study for the year 2002 (US DOT, 1993), although those results were based on different assumptions notably, a lower proportion of telecommuters, saving fewer miles on average per occasion, but telecommuting far more frequently).

### 3.4 What about Increases in Travel?

There has been speculation for some time (e.g. Albertson, 1977; Salomon, 1985; Mokhtarian, 1990) about the extent to which the savings in travel due to the elimination (or reduction) of the commute might be counteracted by increases in travel. Travel could be stimulated in several ways, representing N, R, L, and I, respectively:

- The time saved by telecommuting may partially be spent in out-of-home activities generating new travel.
- The ability to commute less often might prompt some to move farther away from work — potentially far enough that total commute VMT even on a smaller number of commuting days exceeds previous levels.
- Any transportation capacity freed up by large numbers of people telecommuting will be partially or completely filled by the realization of latent demand on the part of others. Hence, travel saved by telecommuters may be compensated for through travel increases by non-telecommuters.
- Telecommunications may directly stimulate new travel (for telecommuters and non-telecommuters alike) through increasing both contacts with other people and information about activities of interest.

Note that new non-work travel may also be viewed as a form of induced demand, but in the present context we conceptually distinguish N from I by the characteristic that new non-work travel is a direct consequence of the time saved by telecommuting itself (and hence applies only to telecommuters and perhaps their household members), whereas "I" here refers to travel generated by other telecommunications applications, which can occur for non-telecommuters as well. In practice, however, it can be difficult to distinguish these two effects, at least for telecommuters.

Another way in which telecommuting has been hypothesized to increase travel is through shifts away from shared modes of transportation in favor of driving alone, resulting in relative increases in VMT even if person-miles traveled remain constant or decline (see, e.g., Mokhtarian, 1991b). These effects, however, will be automatically captured through measured differences in  $a$  and  $N$ , which account for daily differences in vehicle-miles for commute and non-commute trips due to telecommuting.

The four potential effects listed above are discussed in turn. Particularly the last three types of effects are longer-term and indirect, and hence they have been much less studied than the other factors analyzed so far. For R, L, and I, then, the numbers chosen for the illustrative example become somewhat more speculative.

#### 3.4.1 *Non-work Travel*

The studies summarized in Table 2 partition the total VMT on telecommuting and non-telecommuting days into commute and non-commute, so that it is possible to examine separately the changes in each type of travel. From Table 2 it can be seen that (as expected) commute VMT decreased in every study. Non-commute VMT, on the other hand, decreased slightly in two of the studies and increased slightly in the other two. For at least the studies in the last two columns of the table, the changes in non-commute VMT were not significant; statistical tests were not reported for the first two studies. Hence, it might be interpreted that the observed changes simply constitute random fluctuations around a base of essentially no change. In fact the weighted average change in non-commute VMT across all four studies is precisely 0, and thus for the base case we take  $N=0$ .

This is a plausible result: telecommuters are, presumably, working at least their normal hours (and thus not making new trips during that time), and there is anecdotal evidence that many of them work through most or all of what would otherwise be their commuting time as well. New trips that are made during those times may be walk or bike trips. Mokhtarian, *et al.* (1995) present several other explanations for the observed result. In particular, they point out that since these tend to be long-distance commuters, they may already be traveling more than they would like on their regular commuting days, and be more than happy to curtail their travel when telecommuting makes it possible. In the Puget Sound study, for example (Henderson, *et al.*, 1996), no drive-alone trips at all were made on 38% of all telecommuting days, compared to 9% of all non-telecommuting days (for both telecommuters and controls).

This suggests, however, that as average commute distances for telecommuters become shorter over time, this result may change, and the hypothesized desire for mobility (Salomon, 1985) may lead to a discernible increase in non-commute travel on telecommuting days. To adopt a reasonable but conservative future value of  $N$  (and in keeping with the adage that “the future is already here; it's just not evenly distributed yet”), we use the highest proportionate increase in non-commute VMT observed to date, namely the 3 miles found in the Neighborhood Telecenters study (compared to a commute decrease of 41 miles), and take  $N(\text{future}) = 3/41 = 0.073$ . That is, in the future, increases in non-commute travel might counteract 7% of the decrease in commute travel.

### 3.4.2 Residential Relocation

Researchers have speculated for some time about the decentralizing effects on urban form of telecommuting and other telecommunications applications, but scant empirical evidence is available to date. The meager direct evidence that is available (Nilles, 1991) shows little or no impact on residential relocation, but those findings are based on self-reports from short-term experience with telecommuting, during which time frame large numbers of relocation decisions could not be expected to occur.

At least one theoretical model of residential relocation due to telecommuting has been advanced from which it is possible to estimate tentative values for  $R$  (Stough and Paelinck, 1996, also model the impact of telecommunications on residential choice, but since their choice alternatives are location categories—central city, suburb, edge city—it is not straightforward to express the changes forecast by their model in terms of changes in VMT). Lund and Mokhtarian (1994) propose a simple location

model for a monocentric metropolis. Briefly, to roughly estimate the impact of residential relocation on the travel saved by telecommuting, we insert representative values from the example developed here into their equations. In their notation, we take for the base case  $T_0 = 470$ ,  $T_1 = 357$ ,  $k = 0.2$ , and  $d_0^* = aD/2 = 17$ , where  $T_0$  and  $T_1$  are the number of one-way commute trips per year before and after the onset of telecommuting (so that  $T_1 / T_0 = 1 - F$  in our notation),  $k$  is the decay constant of land prices (smaller values of  $k$  indicating a shallow decline in prices as one moves away from the city center), and  $d_0^*$  is the one-way number of vehicle-miles traveled on each commute.

With these values, we find the number of miles saved annually by telecommuting *in the absence of residential relocation* to be  $d_0^* \times (T_1 - T_0) = 1921$ , the change in  $d_0^*$  *with residential relocation* to be  $\ln(T_0 / T_1) / k = 1.37$  (translating to a change in one-way commute length of  $1.37 / a = 1.85$ ), and the increase in miles traveled due to relocation to be  $1.37 \times T_1 = 490$ . Then the ratio  $490/1921 = 0.26$  represents the proportion of miles saved that are offset by residential relocation, and may be taken as an estimate of  $R$ . Similar calculations for the future case, in which the only change is  $d_0^* = 10.0$ , leads to  $R$  (future) = 0.43.

That is, under classical location theory, telecommuting at 24% frequency prompts an individual to move 1.85 miles farther from work, resulting in  $1.37 \times 2$  additional vehicle-miles being traveled on each of the 76% of workdays on which a conventional commute is made, resulting in an increase in travel which constitutes 26% of the savings in the base case, and 43% in the future (for which the same absolute increase in travel is divided by a lower savings due to the assumption that average commute distances for telecommuters decline over time in the aggregate).

Several comments are in order. First, interrelationships among variables should again be emphasized. In particular, in Lund and Mokhtarian's model the assumed increase in commute distance due to residential relocation is very much a (non-linear) function of telecommuting frequency: the more often one telecommutes, the farther away is the optimal residential location *but* the less often that greater distance is traveled. The outcome is that the more frequently telecommuting occurs, the closer the net travel impact (taking residential relocation into account) is to the direct impact in the absence of relocation, i.e. the smaller  $R$  is. This may be the reason why another study (US DOE, 1994) estimated the increase in travel due to "increased urban sprawl" at roughly 16% of the savings in travel (that study focused on fuel consumption rather than VMT) – it assumed average telecommuting frequencies around 60%.

At another level, however, we must question how accurately such a simple relocation model will reflect actual behavior, especially in view of the widespread recognition of the limitations of such models (see, e.g., Giuliano, 1989). Even aside from the question of the extent to which commuting costs any longer influence location decisions, a change of 1.85 miles in the theoretically optimum location is not necessarily likely to prompt a move in view of the transaction costs of such an action. Further, the question of the duration of telecommuting, as discussed in Section 2.6, should be taken into account: a telecommuting spell of only one or two years is also not likely to prompt a move.

In summary, then, this author finds it difficult to believe that the part-time, short-term telecommuting that seems to be the norm in most cases is *itself* going to stimulate a great deal of residential relocation (decentralization is likely to continue to occur for a number of other reasons, but that is not the subject here). These observations are somewhat corroborated by the aggregate empirical evidence offered by Kumar (1990), in which he shows using NPTS data that commute distances are in fact *decreasing* over time for information workers, and *increasing* for blue-collar workers. This is happening even while commute frequencies decline for information workers (a fact which Kumar attributes to a combination of telecommuting and "flexible work arrangements" without being able to distinguish the relative proportions of each).

Hence, the calculated values of R (0.26 now and 0.43 in the future) do not appear to be realistic, and on the basis of the available empirical evidence, there does not appear to be any justification for choosing any particular value of  $R > 0$ . Accordingly, we take  $R=0$  until new evidence presents itself. However, this effect should be monitored empirically, as it may be the case that future adopters who have shorter commutes when they begin telecommuting than do today's adopters, may be more likely to relocate.

### 3.4.3 Latent Demand

The ability of new transportation capacity to attract new trips has been recognized (see, e.g., Shunk, 1991; Transportation Research Board, 1996) but the behavioral mechanisms involved are poorly understood. The process is a complex one, in which realized latent demand on a capacity-improved link may reflect some combination of:

- *development* traffic due to land use changes;
- natural *growth* due to demographic changes;
- traffic *diverted* from other routes;
- traffic *transferred* from other modes;
- traffic *shifted* to new destinations; and
- new trips *induced* by the newly-available capacity

(Zimmerman, *et al.*, 1974, cited in Kitamura, 1991). At a systemwide level, some of these effects result in only a redistribution of, rather than an increase in, total travel.

Apparently only one study (US DOE, 1994) has attempted to quantify the effect of the realization of latent demand on filling up the system capacity freed by telecommuting. That study estimated that latent demand would offset 50% of the direct savings in travel. The assumptions made there differ from ours in ways similar to those for the US DOT study cited above, but, as above, those differences counteract each other to result in similar projected savings in travel. Hence, there is no apparent reason for modifying the DOE result, and again until further evidence is developed we take  $L = 0.50$ . However, that study also notes that the latent demand effect is unlikely to occur in areas in which congestion is not a problem. There may also be a threshold effect; that is, very small (and unpublicized) increases in effective capacity may not be sufficient to bring out latent demand. In that

case, the systemwide levels of travel reduction due to telecommuting seen today (and even into the future if the analysis presented in this paper is to be believed) may not be sufficient to trigger this effect.

#### 3.4.4 *Induced Demand*

If little is known about the impacts of latent demand, even less is known about the demand for travel induced by telecommunications capabilities themselves. One report (Niles, 1994) provides a thoughtful extended discussion of ways in which this phenomenon might occur, including:

- an increased awareness of activities of interest;
- stimulation of economic growth, which stimulates travel;
- an expanding network of personal and business relationships;
- geographic decentralization (partially represented here as the "R" effect);
- an increased customization and rapid-response capability;
- reducing the disutility of travel by making travel time more productive; and
- improving the efficiency of the transportation system.

However, the report stops short of quantifying the impacts of all these processes, and in fact no one has attempted to do so to this author's knowledge. Not wishing to rush in where angels fear to tread, this author will refrain from doing so as well.

It can be pointed out, however, that all of the travel generation effects discussed in Section 3.4 collectively manifest themselves in increased total VMT on non-telecommuting days (for telecommuters and non-telecommuters alike). So one (artificial) way of accounting for all these effects simultaneously is simply to adjust an assumed growth rate in VMT to represent various future scenarios of increased travel. Time-series or other models can be calibrated to forecast increases in VMT, and refined over time as more information on the causal processes involved becomes available.

It should also be pointed out that if a model of induced demand does become available, care should be taken when fitting it into the current framework that N, R, and L effects are not double-counted.

### 3.5 **Combined Outcome**

The final two rows of Table 1 present the "bottom line" impacts of telecommuting using the illustrative case discussed here (and taking  $I = 0$ ).  $N+R+L+I = 0.50$  for the base case and  $0.57$  for the future case, meaning that the net reduction in travel is only at most about 50% and 43%, respectively, of what would be assumed if stimulation effects were not taken into account (a non-zero assumption for  $I$  would reduce those numbers still more). These two values have the intriguing result that the net absolute reduction in VMT is higher for the base case (nearly 247,000 miles) than for the future case (about 229,000 miles) – in either case, about 0.2 miles per worker. As can be seen, the outcomes of the two cases are so close that small changes in the assumptions either way can alter the relative ordering of the results. For example, had we assumed  $N$  to be equal for both the base and future cases, the ordering

of the two outcomes would have been reversed. Nevertheless, it is not unreasonable to expect the trip generation effects of telecommuting to increase over time to the extent that the net reduction in travel shrinks. In fact, had we taken  $R=0.43$  in the future case as the Lund and Mokhtarian model suggested, then  $N+R+L+I$  would exceed one (the more so to the extent that  $I > 0$ ), meaning that in the future, the travel stimulation effect of telecommuting would equal or exceed its travel reduction effect.

#### **4. IMPLICATIONS AND DIRECTIONS FOR FUTURE RESEARCH**

This paper has attempted to synthesize (combine) what is known about the adoption and travel impacts of telecommuting into a synthetic (artificial) multiplicative model containing the key relevant factors. Plausible assumptions (based on the best available empirical evidence) about the value of each factor result in estimates of relatively modest transportation savings—probably currently no more than 0.6% of total household travel, as shown in the last row of Table 1. Even more importantly, it appears to be likely that, due to counteracting forces, the aggregate travel impacts will remain relatively flat well into the future (potentially even declining), even if the amount of telecommuting increases considerably. Since it was asserted in the introduction to this paper that telecommuting probably has the highest potential for travel reduction of any of the tele-applications, the outlook for telecommunications as a major solution to urban congestion is not promising.

Thus, in response to the potential concerns of regional planning agencies, it appears quite unlikely that telecommuting will reduce travel to the extent of obviating the need for new infrastructure capacity (whether that capacity should be provided, and the particular modal form it should take, however, are separate questions to which the current paper does not speak). On the other hand, the potential reductions in travel due to telecommuting are of an order of magnitude comparable to the estimated impacts of other transportation demand management (TDM) strategies. A bundle of such TDM measures that includes telecommuting may collectively have a noticeable impact on congestion. For that reason, it continues to be desirable to promote telecommuting as a TDM strategy (with appropriate expectations as to its effectiveness), and to learn more about its impacts on travel.

A great deal of uncertainty remains, both in the likely future values of the key factors studied here and in the way those factors will combine to give an aggregate result—enough uncertainty to warrant further refinement of our knowledge in this area. For example, until recently, most telecommuting was voluntary—chosen by the employee with the concurrence of management. Now, thousands of employees (so far, typically sales workers) in firms including Ernst and Young, IBM, AT&T, Xerox are being involuntarily shifted to “non-territorial office” arrangements as a cost-saving strategy on the part of the organization (see, e.g., Shellenbarger, 1994). Trends in the adoption of this form of telecommuting should be monitored and its travel impacts assessed.

The results presented here may differ somewhat if a transportation indicator other than VMT is chosen as the focus. For example, adoption of partial-day telecommuting may be increasing faster than full-day telecommuting. That is, it may be increasingly common for professional workers to work at home an hour or two in the morning to avoid rush-hour traffic, so that if peak-period trips were the measure of interest, the impacts of telecommuting may be somewhat more substantial. However, it is

also likely that many of those workers would not apply the label “telecommuting” to what they are doing, which highlights the need for careful question wording in any attempts to survey the extent of such practices.

Discussion of each factor and relationships among them has identified a number of areas needing further research. For example, it would be valuable to gather data on A, W, and C (those who can, want to, and do telecommute) from a larger and representative sample (and on an ongoing, say annual, basis), to analyze the interactions among those dimensions and trends in their values. It is important to further develop causal models of telecommuting frequency. The longitudinal study of temporal patterns and duration of telecommuting is a critical missing link to date, with duration of telecommuting potentially affecting downstream factors such as residential relocation decisions. Little is known so far about the adoption of center-based telecommuting and potential differences in travel impacts from the home-based form. And, of course, the entire set of processes by which travel can be stimulated through telecommunications deserves careful analysis.

These studies would improve our ability to forecast each factor of the simple multiplicative model presented here. Additional work could be done to further refine the model itself. Rather than using only an aggregate expected value for each factor as has been done here, distributions for each factor can be developed. In some cases these can be joint distributions among two or more variables to account for key correlations; in some cases (as has been done by Mokhtarian and Salomon and others for the variables W and C) a variable can be represented through a disaggregate probabilistic submodel as a function of other explanatory variables. Then a population outcome can be estimated through a Monte Carlo simulation, in which for each simulated individual, values from the assumed distributions or submodels are generated and combined in the model at a disaggregate level, with the results summed across individuals. The model could eventually incorporate a dynamic element, to account for changes over time in ability to telecommute, desire to telecommute, frequency of telecommuting, commute length, total VMT, and so on. Such a dynamic, disaggregate simulation model seems to fit well with the current approach to improving travel demand forecasting models in general (e.g. RDC, Inc., 1995), and could probably be relatively easily integrated with that approach.

The illustrative future case numbers presented in Table 1 can be viewed as a plausible future scenario “letting nature take its course”. Planners and policy-makers may wish to consider how those numbers might change in the presence of policies that aggressively support telecommuting. For example, allowing congestion to reach far worse levels than are experienced today, or introducing serious congestion pricing mechanisms, would increase the salience of commute reduction as a personal motivation to telecommute. This would presumably increase W (the proportion of those able to telecommute who want to), C (the proportion of those who can and want to who do), and F (the frequency of telecommuting) which in the present formulation are assumed to remain constant over time. Regulatory mechanisms could diminish the organizational constraints on telecommuting and hence increase A (the proportion of the workforce that is able to telecommute) more rapidly than would be the case otherwise.

Further research is therefore needed to understand the likely impacts of such policy measures. Existing behavioral models of telecommuting preference and choice (containing policy-sensitive variables) can be used as a starting point in evaluating such “what if” scenarios. New stated preference models can be developed in the context of policy evaluations, and calibrated against the revealed preference or manifest behavior shown by current workers (see, e.g., Morikawa, 1994). When such policies are initially introduced on a limited basis, experiments and pilot studies should be conducted as early as possible and used to identify the actual impacts on telecommuting. In short, empirical information on the impacts of such policies should be gathered early and often, and the expectations for such policies should be revised as new information becomes available.

Finally, two additional important phenomena falling under the broader rubric of “teleworking” which have not been emphasized here but whose transportation impacts need further study are the increase in home-based businesses and in the number of mobile workers in the workforce (Handy and Mokhtarian, 1996b; US Congress Office of Technology Assessment, 1995). Mokhtarian and Henderson (1996) found that home-based business workers have higher daily total, work-related, and drive-alone trip rates than other workers, but have lower total travel time. Trip departure times for home-based workers were unimodally rather than bimodally distributed across the day, and considerable variations were found across workers in different industries. These results illustrate that the travel patterns of home-based business workers differ substantially from conventional workers', and current regional travel forecasting models are not well-equipped to treat these patterns. Further, it is an interesting research question to explore how operating a home-based business affects the choice of residential location (central city, suburban, exurban, satellite town, out of the region of employment altogether) and characteristics of the dwelling unit.

Similarly, the travel and communication patterns of mobile workers are likely to exhibit considerable variation, both within subcategories of mobile workers, and between them and non-mobile workers. For both mobile and home-based workers (which are not mutually-exclusive categories), the predominant effect of telecommunications is probably not to reduce travel, but to increase the flexibility of travel. Total travel may in fact be higher for these workers than for others, but shifted to off-peak periods where possible. When peak-period travel is necessary, telecommunications (the cellular phone) can reduce the cost of congestion for these workers. Additional research is needed to further understand the travel and communications patterns of teleworkers of all types.

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