TRANSPORTATION RESEARCH RECORD 891

Collection and Use of Survey Data

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1982

Transportation Research Record 891
Price $6.00
Edited for TRB by Naomi Kassabian

modes
1 highway transportation
2 public transit

subject areas
12 planning
13 forecasting

Library of Congress Cataloging in Publication Data
National Research Council. Transportation Research Board.
Collection and use of survey data.

(Transportation research record; 891)
Reports presented at the 61st annual meeting of the Transportation Research Board.
1. Traffic surveys–Congresses. I. National Research Council (U.S.). Transportation Research Board. II. Series
TE7.H5 no. 891 [HE 369] 380.5s [388.3'14'0723] 83-8062
ISBN 0-309-03503-1 ISSN 0361-1981

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Problems of Nonreported Trips in Surveys of Nonhome Activity Patterns

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The problem of nonreported trips has become the subject of substantive basic research activities. This has occurred in line with increasing concern about potential artifacts in the development of travel-behavior data attributable to the specific survey method used. In that context, three types of trips have to be distinguished, namely, (a) trips that were not reported by the respondents due to increasing lack of care in case of survey periods of several days' length, (b) trips that were not reported by the respondents because they forgot or considered them redundant, and (c) trips that the respondents did not want to report on the basis of their own deliberate decisions. It is relatively simple to check the loss of accuracy caused by type-a trips. A methodological experiment was conducted to disclose errors of type b and to gain at least a certain idea about errors of type c. The results confirm previous findings from the analysis of reporting losses for multiple-day surveys. Accordingly, in the analysis of trip volumes, a distinction has to be made first between the "nonhome share" and the "number of trips for mobile persons." Use of the (artificial) measure "trips per person" would cover up important relationships. In addition, the level of underreporting of trips measured by this means can be set between 5 and 15 percent. This underreporting is not equally distributed across all transportation modes and trip purposes, but it occurs to a disproportionately large degree for discretionary and recreation travel, especially by nonmotorized modes.

Transportation planning practice has always been dependent on reliable empirical data sets of substantial size. The expectations about the level of detail for such data have increased continuously. Whereas initially information describing the volume and direction of vehicle flows was sufficient, today information is also desired about the participants in the traffic stream. The intent is to be able to classify the travelers (e.g., according to sociodemographic criteria) as well as their type of travel participation (e.g., according to activities).

The associated switch from measuring by means of simple counting to measurement by means of surveys has quantitative as well as qualitative implications. The reason for this is that the survey techniques to be employed, regardless of their specific methodological orientation, usually prohibit their development on a massive scale due to time and budget constraints. Generally they can only be implemented in conjunction with a specific survey sampling technique.

This circumstance leads to great concern about the quality of the survey data. Consequently, extensive consideration was given to methods that could determine the magnitude of the random-sampling error. This effort usually overlooked the fact that survey techniques typically are dependent on cooperation with the prospective respondent (1). Respondents obviously are individuals subject to a variety of human weaknesses. This means that the respondent as well as the manner in which he or she is questioned will influence the survey results to a considerable degree; i.e., systematic errors, or bias, play an important role in survey responses. Since it has been demonstrated repeatedly in the literature that the importance of such systematic errors substantially exceeds that of random errors (2), the systematic investigation of these error sources is one of the most important areas of fundamental research into survey methods.

In comparison with the importance of such research, the results published to date are rather modest (3). Therefore, it will not come as a surprise that little information is available even about comparatively obvious sources of error in surveys of human subjects. It is of even greater concern that many planners, who are the users of such empirical data, often lack the awareness of these problems, and these obvious areas for investigation hardly undergo close scrutiny.

One such source of errors can be found in the fact that even in the most carefully selected survey designs, e.g., in the case of travel-behavior surveys, it cannot be avoided that the respondents do not indicate all trips they took. This phenomenon of nonreported trips is investigated more closely in this paper.

STUDY DESIGN

The acquisition of data about the accuracy of the information provided by the respondents is particularly delicate, especially due to the fact that it can only be performed with the respondents themselves, i.e., not by means of a control group. Therefore it requires a particularly carefully composed survey design.

The basis for such a design has to be a survey instrument that is as free as possible of typical error sources for such surveys and that also has been used in other, preferably large-scale travel surveys. Such a survey instrument was available for the experiment described here, namely, that used in the Continuous Travel Survey (KONTIV) of the Ministry of Transport, a survey form that has become known internationally (4).

The basic plan of this experiment was to hand to a randomly selected set of individuals a KONTIV survey form (consisting of a household survey form and a diarylike personal survey form per household member for two prespecified successive survey days, in this case work days) and to specify a time for pick-up of the forms on the day following the second survey day. During the delivery of the survey instrument, a brief interview was performed during which the respondents were presented with a number of items by which their respective attitudes were measured. By this means, it was intended to determine a potential relationship between subjective attitudes and care in filling out the survey forms.

Under the pretext that the travel-mode alternatives had been grouped incompletely and improperly due to a mistake by the survey personnel, the interviewer asked the respondent at the time of pick-up for permission to once again review with him or her the relevant entries in great detail. The interviewers had been trained to explore thoroughly all ambiguous and incomplete entries. They designated all corrections in such a fashion that they could be identified later. Also, they filled out a survey form about the interview and the interviewee, which reflected the interviewer's assessment of the reliability of the follow-up exploration.

This approach was very successful and the intended sample size of 201 respondents who undertook 1527 trips was reached with ease. The repondents rarely objected to the procedure. Their final assessment of the complete survey was mainly positive (Table 1). As was expected, they had hardly any difficulties in filling out the survey instrument, which had been tested repeatedly. This characteristic is a necessary prerequisite for an investigation of this kind. Eighty percent of the respondents had no difficulties at all in filling out the household and the personal forms. Approximately 5 percent had substantial yet surmountable difficulties. This agrees basically with the documented experience in the use of the KONTIV survey instruments.

During the data-tabulation and coding process, each data item was marked as to whether it had been provided by the respondent from the beginning (reported information) or whether it was altered due to the follow-up exploration (explored information). For the second case a distinction was made between a correction of a recognizably incorrect entry and a complementation of information that was not entered initially. An additional effort identified which of these complementary items also could have been obtained by means of a very careful coding process, e.g., nonreported return trips to the home (coded information).

Of course, even this procedure will not uncover activities that the respondent is absolutely unwilling to disclose. However, this phenomenon is not uncommon in the realm of empirical measurement techniques. No measurement technique can measure "true" reality; it can onlv come close to this reality (5). Therefore, for subsequent analyses three error sources could be distinguished:

1. Errors that could be eliminated in the coding process,
2. Errors that could only be detected by means of a follow-up exploration, and
3. Errors that could not be detected through coding or follow-up exploration.

The next sections will concentrate on errors of the second category.

TRAVEL FREQUENCY (TRIP QUANTITY)

The most commonly used mobility indicator in transportation planning is the number of trips per person. Several research studies, for example, one by Brög and Meyburg (6), show, however, that it is usually more meaningful in methodological investigations to consider the two components of mobility separately, namely, the share of nonhome activities and the mobility per mobile person (tripmaker). Such a separation shows that the reported information on mobility increases significantly in all three mobility categories (share of nonhome activities, trips per mobile person, trips per person) by means of the follow-up exploration (Table 2).

It should be pointed out that due to the sample design, which excluded so-called immobiles (persons who did not undertake activities outside their homes), the nonhome share of activities is relatively high, whereas the mobility per mobile is well within the range of comparable values. At the same time it can be recognized that approximately one-half of the additional information obtained through the follow-up exploration could have been gathered by means of a careful coding process. But since usually only the quantity and to a lesser degree the quality of such trips can be captured in the coding process and since such methods also depend strongly on the respective data-preparation process and the training and supervision of the coding personnel, this paper will not present a separate evaluation of the coded information in the course of the following discussion. This information allows the quantification of an error source, however, that is hard to avoid, especially in strongly automated data-preparation processes (7), which are used preferably in transportation planning.

A first indication of the quality of the nonreported trips (no follow-up exploration conducted) is provided through the evaluation of the quantitative measures of trip length (in kilometers) and duration (in minutes) (Table 3). There exists a clear negative correlation between trip length and the probability that a trip will not be reported. This also leads to the conclusion that a substantial number of nonreported trips are more likely attributable to carelessness rather than to conscious nondisclosure. Nevertheless, the trips detected by means of the follow-up exploration add up to a total travel distance of a magnitude that can play a role in considerations of transportation system performance: The respondents in this experiment did not report 8.8 percent of their total travel distance. In relation to the distance of all reported trips, which is the usual basis for model computations, the deficit amounts to 9.6 percent.

TRAVEL CHARACTERISTICS (TRIP QUALITY)

As is to be expected, the statistically significant correlation between the additional trips (from the follow-up exploration) and the trip length is reflected in the relevant travel-mode choice. The highest nonreported trip rate is evident for walking and bicycle trips. But underreporting for motorized travel, which is distinguished by its far higher service volume, should not be overlooked either

Table 1. Statements by respondents about filling out survey forms.

Statement by Respondent	Yes (%)	No (%)	NA (%)
Filling out form was fun	51	42	7
Expected greater difficulty	30	67	3
Can imagine that investigation will facilitate transport planning	68	28	4
Found the recording procedure for trips quite simple	84	12	4
Found it interesting to participate in a survey	63	34	3
Find filling out such survey forms an imposition	10	87	3
Can visualize the necessity for this investigation	74	22	4
May have made more accurate entries than other people	24	64	12
Recording of trips took too much time	10	89	1
Would like to participate in such a transportation study again	46	48	6
Basically it was unnecessary to review the recorded trips again in the interview	42	53	5
Anybody can fill in such survey forms	75	21	4
Found forms hard to read due to small type	3	96	1

Note: Sample size was 201 respondents.

Table 2. Nonreporting and mobility information.

Mobility Category	Reported Information	Coded Information	Reported and Explored Information	Nonreported Trip Rate[a] (%)
Nonhome share (%)	90.5	90.5	94.5	4.8
Avg no. of trips per tripmaker (mobiles)	3.60	3.90	4.02	10.4
Avg no. of trips per person	3.26	3.53	3.80	14.2

Note: Sample size was 201 respondents.

[a]Nonreported trip rate = $[T_E/(T_R + T_E)] \cdot 100$, where T_E is explored trips and T_R is reported trips.

Table 3. Nonreporting by trip length and duration.

Trip Length[a] (km)	Reported Information (%)	Explored Information (%)	Nonreported Trip Rate[b] (%)
0.0-0.4	11.0	3.9	26.3
0.5-0.9	9.4	2.9	23.4
1.0-2.9	23.9	3.8	13.9
3.0-4.9	10.7	1.2	9.9
5.0-9.9	16.6	1.4	7.8
10.0-19.9	7.1	0.6	7.7
>20.0	7.1	0.4	5.3
Total	85.8	14.2	14.2

[a] Avg trip distances: reported information, 5.7 km; explored information, 3.3 km. Avg trip duration: reported information, 20.4 min; explored information, 15.9 min. Nonreported trip rates, 8.8 and 11.4 percent, obtained as follows: [(no. of explored trips) x (avg length for explored trips)]/[(total no. of trips reported and explored) x (avg trip length)].
[b] For definition, see Table 2.

Table 4. Nonreporting by travel mode use.

Item	Reported Information (%)	Explored Information (%)	Nonreported Trip Rate[a] (%)
Predominantly used travel mode			
Walk	26.4	7.9	22.9
Bicycle	7.8	1.3	14.4
Moped, motorbicycle, motorcycle	1.2	0.4	25.0
Automobile driver	30.3	2.9	8.9
Automobile passenger	6.1	0.8	12.3
Public transit	12.6	0.9	6.7
Train	1.4	-	0.0
Total	85.8	14.2	14.2
Mode aggregation			
Nonmotorized	35.2	9.2	21.1
Motorized	37.6	4.1	9.9
Public transport	14.0	0.9	6.1

[a] For definition, see Table 2.

Table 5. Nonreporting by trip purpose and activities.

Item	Reported Information (%)	Explored Information (%)	Nonreported Trip Rate[a] (%)
Trip purpose			
Work	19.0	1.2	5.9
School (training)	6.7	0.6	8.2
Shopping	22.7	5.1	18.4
Other discretionary activities	11.8	2.0	14.5
Recreation	25.6	5.3	17.2
Total	85.8	14.2	14.2
Purpose aggregation			
Regular activities	25.7	1.8	6.4
Discretionary activities	34.5	7.1	17.1
Recreational activities	25.6	5.3	17.2

[a] For definition, see Table 2.

(Table 4). Corresponding to this fact is the particularly high level of information completeness for the trip-purpose categories that reflect regular repetitive travel (Table 5). It decreases substantially with the degree of flexibility that exists for planning the activities associated with the trips such that every sixth trip associated with recreational activities is no longer reported (for the reported information, even every fifth trip). Again, the relationship between travel modes (and associated activities) and reporting accuracy is statistically significant.

An even more accurate picture can be obtained about the relationship between the information completeness and the type of travel when the travel modes are combined with the activities for whose pursuit they were used. For this illustration the combinations already presented in Tables 4 and 5 (nonmotorized, motorized, public transit traffic, and regular occasional recreational activities) are employed to determine the matrix elements reflecting the frequency as well as the duration and length of reported and explored trips (Table 6). It becomes evident immediately that the nonreported trips for trip frequency, duration, and length are of fairly similar magnitude, but the trip frequency is somewhat more often underreported.

Throughout the matrix the particular susceptibility of nonmotorized travel to underreporting is confirmed; this effect, in line with the overall trend, increases from regular via discretionary to recreational activities. In contrast, the nonreported trip rates are particularly low for motorized travel to regular activities. They are particularly high for discretionary activities, i.e., in that area where the use of public transport reaches encouraging values. This can probably be explained on the basis that shopping trips that constitute the dominant share of discretionary trips are performed usually by persons who mainly use public transport, whereas they constitute the exception among the users of private motorized modes. It is not clear how social desirability plays a role in this connection. (At least in the German context, where these data were collected, automobile drivers might not want to admit that they also perform shopping trips for the family.) It has to be observed here that, again, nearly 10 percent of the total travel distances were not reported for motorized travel to regular and recreational activities. And it can be taken for granted that the sum of the reported and explored values still underestimates the true degree of actual travel participation.

FEASIBLE REMEDIES

The results of this methodological investigation were evaluated in greater detail than can be presented within the constraints of this paper. In-

Table 6. Nonreporting by combinations of travel modes and activities.

Activity	Nonmotorized Travel RI	Nonmotorized Travel EI	Nonmotorized Travel NRTR	Motorized Travel RI	Motorized Travel EI	Motorized Travel NRTR	Public Transit RI	Public Transit EI	Public Transit NRTR
Regular									
Trip frequency	7.6	1.0	11.5	11.0	0.4	3.4	7.1	0.4	5.3
Trip length (km)	1.4	0.7	6.1	10.7	7.4	2.4	9.0	9.2	5.4
Trip duration (min)	13.3	8.1	7.4	22.5	15.0	2.3	37.6	40.0	5.7
Discretionary									
Trip frequency	17.2	4.8	21.8	14.2	2.2	13.6	3.2	0.1	3.9
Trip length (km)	0.9	0.6	16.2	6.8	4.6	9.6	9.2	10.0	4.2
Trip duration (min)	11.6	8.3	11.7	15.6	14.5	12.6	44.6	60.0	4.0
Recreational									
Trip frequency	9.4	3.4	26.5	12.4	1.5	10.8	3.7	0.4	9.5
Trip length (km)	1.1	0.9	17.4	8.4	7.8	9.3	9.8	8.0	5.1
Trip duration (min)	15.0	20.9	32.6	24.1	25.5	11.3	41.9	33.8	8.0

Note: RI = reported information, EI = explored information, NRTR = nonreported trip rate (for definition, see Table 2).

Table 7. Differences in mobility measurements.

Mobility Category	Coded Information	Reported and Explored Information	Nonreported Trip Rate[a] (%)	KONTIV[b] Relationship of First to Second Survey Day[c]
Nonhome share of activities (%)	90.5	94.5	4.8	5.6
Avg no. of trips per tripmaker (mobiles)	3.90	4.02	3.0	2.0
Avg no. of trips per person	3.53	3.80	7.1	7.2

[a]For definition, see Table 2. However, in this case "coded information" replaces "reported information."
[b]Workdays only.
[c]Comparable with the computation of NRTR.

stead a few speculations and suggestions are put forth about the consequences that arise out of the findings that are presented here.

First, it would be interesting to determine whether a correlation exists between nonreporting of trips and respondents' personal characteristics that would make it possible to identify those respondents who have a high probability of inaccurate reporting. Two types of personal data can be considered: sociodemographic and/or attitudinal data. For both cases there exist appropriate basic hypotheses. For example, with respect to sociodemographic variables it could be determined that age, education, and employment type especially have a statistically significant influence on the reporting accuracy for well-established and tested survey instruments. This observation is based on past experience on the basis of reported information only, i.e., without follow-up explored information (8). With respect to attitudes, it could be observed that positive interest in the subject matter of the mail-back survey constitutes a substantial determining factor for the response rate and therefore is a decisive element for evaluating nonresponse effects, which also have an influence on the survey results (9).

Both relationships were analyzed in the research presented here, but no clear answer was obtained for either case. Stratification of nonreported trips by means of respondents' sociodemographic characteristics showed that the level of nonreporting was particularly high for women, 10- to 15-year-olds, persons with poor education levels, and retired persons. These observations are plausible on the basis of theoretical considerations. These relationships were not statistically significant, however.

Similar results were obtained for the statistical evaluation of the scales that were handed to the respondent at the beginning of the follow-up interview. One of the scales dealt with interest in the survey subject matter, which contained 13 items; another scale was for reporting accuracy and care and had a total of 54 items. The evaluation of both scales resulted in weak correlations that were plausible but did not suffice for formulating statistical significance.

Neither case disproves the existence of such relationships, however. Their lack of significance could be due to special sociodemographics, to the small sample size, or to the scales, in which the items might not have been formulated so that clear separation between them was guaranteed.

Aside from the problems of explaining and therefore controlling the effect of nonreported trips due to personal characteristics, it is, of course, of special importance to find reference points by means of which the influence of this effect on the measurement results can be determined. For this objective there also exist two basic hypotheses that were tested in this research effort. Both hypotheses relate to the measured and to the unreported mobility. The third section of this paper has already referred to the first hypothesis. It states that the share of trips that can be added to the reported ones purely by means of careful coding provides an indication of how large the share of the remaining nonreported trips might be. The second hypothesis refers to the observation that reported trip frequency decreases over time for surveys that include several survey days (10); the greatest reduction often takes place after the first survey day. Furthermore, this hypothesis states that the mobility difference between the first and the second survey day can be used as a measure of the share of nonreported trips that have occurred on the first survey day (11).

The test of the first hypothesis generates several problems, irrespective of the indicated uncertainty about varying coding methods and rules. Table 2 has shown already that such a relationship is likely to exist only for the artificial measure "trips per person" (which does not make it useless, however, as an aggregate correction measure from the outset). Furthermore, opportunities for influencing such corrections are only present in certain cases, particularly for (unreported) return trips home. The relatively large share of nonreported trips that is correctible by means of the coding process is only due to the fact that the nonreported trip rates are particularly high for return trips to home (27.2 percent compared with 5.6 percent for the first trip on the first survey day). This means that the correction factors thus derived permit only a rough quantitative improvement of the data and by no means a structural one.

An examination of the second hypothesis leads to similar but slightly better results. For this test, appropriate information is required from suitable comparable surveys about the effect of the first and second survey days. The most appropriate survey for this purpose is KONTIV (12) because it is fully compatible methodologically and it is statistically sound. However, for the KONTIV survey the coding corrections have been performed already. Therefore, the comparison of the reporting differences between survey days has to be based on the difference between the coded and the explored information. As shown in Table 7, rather substantial agreement exists for the mobility measurements. Unfortunately, given the present level of knowledge, it is impossible to go beyond the formulation of a rough estimate for a mobility correction factor, because an in-depth analysis on the basis of a table structured analogous to Table 6 results in partial agreement only for the mobility measurements. Therefore, further research has to be performed in this instance also in order to gain more solid footing for formulating firm conclusions. Nevertheless, the rule of thumb holds that a decrease in mobility between the first and second survey day constitutes an acceptable indicator for the quantity of nonreported trips.

SUMMARY AND CONCLUSIONS

The methodological investigation reported in this paper discloses some disturbing facts about underreporting that typically go undetected. The effect of such information reduction can be substantial when the survey data are used uncritically for assessing mobility levels and for determining modal shares and overall travel activity levels in terms of duration and length. The paper identifies a number of methods, indicators, and relationships that permit the analyst or planner to upgrade the results of surveys by means of careful adjustments.

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Publication of this paper sponsored by Committee on Passenger Travel Demand Forecasting.

Estimation of Cross-Cordon Origin-Destination Flows from Cordon Studies

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When traffic counts obtained in a cordon study are supplemented by information about the origin and destination of a small sample of trips crossing the cordon, it is possible to obtain estimates of the prevailing origin-destination (O-D) flows. The purpose of this paper is to describe a coherent method for the identification of the maximum-likelihood estimates of vehicular O-D flows. The solution procedure proves to be relatively simple. The estimates obtained are of flows between the cordon stations, flows between the stations and the area inside the cordon, flows between traffic zones, etc. The method is illustrated by a detailed numerical example. A real-life application of the estimation method to the downtown Toronto cordon is described. It appears that it is possible to obtain much-needed O-D information at relatively little extra cost.

The pattern of tripmaking in an urban area is precisely and succinctly described by an origin-destination (O-D) flow matrix. This is why O-D matrix estimates should serve as basic information for traffic management and transport planning tasks. Unfortunately, methods for obtaining such estimates are time consuming and costly. This is why, even in major metropolitan areas, information about the prevailing pattern of tripmaking is often sketchy.

Many cities conduct cordon studies periodically. Traffic into and out of the cordon area is counted and some inferences about traffic flow patterns and trends are possible. However, a cordon study does not yield information about O-D flows. The idea explored in this paper is the possibility of attaching a small-sample O-D survey to the routine cordon counts and of using the combined information for the estimation of the prevailing O-matrix of vehicle flows crossing the boundary of the cordon at least once.

This idea is in line with other recent developments, which all rely on better utilization of the ubiquitous traffic-count information for O-D estimation. A detailed review of such models is available (1-3).

For some simple transport systems one can obtain good estimates about the O-D flows by using traffic counts only (4). In more complex systems, regularities of travel behavior have to be invoked in the form of similarity with other systems (5,6), patterns of the past, or models of the gravity form (7-12).

The estimation procedure developed in this paper departs from previous work in that travel behavior is brought into estimation by the specific information contained in small samples obtained by a survey. It is therefore not necessary to rely on elusive microstates (as in entropy models), to argue by induction and analogy, or to trust general interaction-at-distance or route-choice models. Rather, we will find the matrix of O-D flows, which is consistent with the observed traffic counts and which is most probable in view of the O-D samples obtained. Thus the task is to solve a constrained maximum-likelihood problem.

PROBLEM FORMULATION AND SOLUTION

Consider a cordon line surrounding a cordon area. There are n survey stations on the cordon line. In a conventional cordon study, vehicles entering and leaving the cordon area are counted at each survey station. Accordingly, let O_k be the number of vehicles entering the cordon area during a specified period of time at station k (k = 1, 2, ..., n) and let D_l be the number of vehicles leaving the cordon area during the specified period of time at station l (l = 1, 2, ..., n).

To allow estimation of O-D flows at each survey station, a random sample is selected from the inbound and outbound vehicles. From the drivers of the selected vehicles, additional information is obtained. For a vehicle entering the cordon area, the exit station (l) is ascertained. If the trip ends inside the cordon area, the index O is used. For a vehicle leaving the cordon area, the entry station (k) is determined. The index o will signify a trip starting inside the cordon area. Accordingly, t_{kl} will be the number of vehicles in the random sample obtained at station k from those entering the cordon area that report leaving the cordon area via station l. t_{kl}' is the corresponding number of vehicles in the random sample obtained at station l from those leaving the cordon area.

The practicalities of obtaining t_{kl} and t_{kl}' will be discussed later in the context of a real application to the downtown cordon area of metropolitan Toronto. In this section, the focus is on finding estimates of the vehicular flows T_{kl} from station k to station l by using the cordon-count data (O_k and D_l) and sample information (t_{kl} and t_{kl}'). When this problem has been solved, it will prove simple to obtain estimates of vehicular flows T_{ijkl} from zone i to zone j passing stations k and l.

Traffic engineers and transportation planners are accustomed to solving this problem in a heuristic manner. Data from roadside interviews or license plate surveys are factored to approximate traffic counts. The disadvantage of factoring is that there are many possible ways of going about the task and as many different solutions. In addition, it is difficult to make factored estimates to match all counts. In contrast, the solution derived below is unique. It has the merit of being "best" in the sense that it identifies the array of O-D flows (T_{kl}*), which maximizes the probability of observing the specific values of O_k, D_l, t_{kl}, and t_{kl}'.

Having established the notation and declared the approach to the solution, we now formulate the problem in mathematical terms.

Consider the random sample $t_{ko}, t_{ki}, \ldots, t_{kn}$ obtained at station k. This sample is drawn from the flows $T_{ko}, T_{ki}, \ldots, T_{kn}$, which are unknown. Only their sum $\Sigma_l T_{kl} = O_k$ is known.

The probability of observing this sample is approximately as follows:

$$\left[\left(\sum_l t_{kl}\right)!/\prod_l (t_{kl}!)\right] \times \prod_l (T_{kl}/O_k)^{t_{kl}} \qquad (1)$$

The symbols Σ_l and Π_l denote summation and product over l = o, 1, ..., n. (The multinomial probability model embodied in Equation 1 is only approximate because it assumes "sampling with replacement." As long as the sample is a small fraction of the population, the assumption seems proper.)

An expression analogous to Equation 1 can be written for every random sample obtained at each of the n survey stations for both inbound and outbound flows. Therefore the probability of observing all random samples is given by the following:

$$\left(\prod_{k=1}^{n}\left\{\left[\left(\sum_l t_{kl}\right)!/\prod_l (t_{kl}!)\right] \times \prod_l (T_{kl}/O_k)^{t_{kl}}\right\}\right)\left(\prod_{l=1}^{n}\left\{\left[\left(\sum_k t_{kl}'\right)!/\prod_k (t_{kl}'!)\right] \times \prod_k (T_{kl}/D_l)^{t_{kl}'}\right\}\right) \qquad (2)$$

The probability in Equation 2 is a function of the n x n array of unknown flows T_{kl}. We wish to identify that array T_{kl}* for which this probability is maximum. However, the solution must satisfy the following traffic-count constraints:

$$\sum_l T_{kl} = O_k \quad \text{for } k = 1,2,\ldots,n$$
$$\sum_k T_{kl} = D_l \quad \text{for } l = 1,2,\ldots,n \qquad (3)$$

By using the method of Lagrange multipliers, we find the following:

$$T_{ko}^* = t_{ko}/\alpha_k \quad k = 1,2,\ldots,n$$
$$T_{ol}^* = t_{ol}'/\beta_l \quad l = 1,2,\ldots,n$$
$$T_{kl}^* = (t_{kl} + t_{kl}')/(\alpha_k + \beta_l) \quad k = 1,2,\ldots,n \quad l = 1,2,\ldots,n \qquad (4)$$

The 2n unknown Lagrange multipliers α_k and β_l are determined by an iterative algorithm that uses the 2n Equations 3. The algorithm is described and illustrated by a numerical example in the section on solution procedure.

So far, the station of entry (or the cordon area) has been regarded as the origin and the station of exit (or cordon area) as the destination. However, for many purposes the traffic zone in which a trip commences is regarded as the origin and the traffic zone in which the trip terminates as the destination. In such cases, one wishes to have an estimate of the zone-to-zone O-D matrix (T_{ij}) rather than the station-to-station O-D matrix (T_{kl}).

By using the results of the above analysis, it is easy to obtain an estimate of the zone-to-zone O-D matrix if the drivers sampled from the flow provide information not only about stations of exit or entry but also about trip origin and destination.

If we generalize the previous notation, let t_{ijkl} be the number of vehicles in the random sample obtained at station k from those entering the cordon area that report zone i as the trip origin and zone j as destination and leave the cordon area by station l, t_{ijkl}' be the corresponding number of vehicles in the random sample obtained at station l from those leaving the cordon area, and T_{ijkl}* be the best estimate of the vehicular flows from zone i to zone j via stations k and l.

If we formulate the problem again as constrained

Figure 1. Cordon line with survey stations.

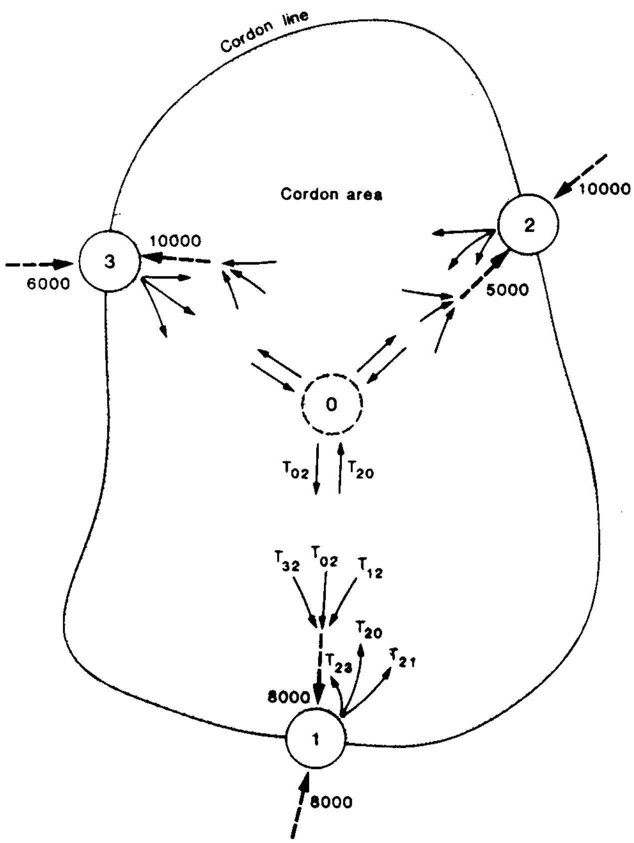


Table 1. Results of sample O-D survey.

Inbound Samples					Outbound Samples			
	To Station					To Station		
From Station	0	1	2	3	From Station	1	2	3
1	10	-	20	30	0	5	10	20
2	30	20	-	40	1	-	40	40
3	40	40	40	-	2	10	-	50
					3	40	20	-

maximization of likelihood, it can be shown that

$$T_{ijkl}{}^{*} = [(t_{ijkl} + t_{ijkl}')/(\sum_{i,j} t_{ijkl} + \sum_{i,j} t_{ijkl}')]\,T_{kl}{}^{*} \tag{5}$$

Thus the estimated flow between k and l (T_{kl}*) is apportioned to zone pairs according to their proportion in the sample passing through k and l. Of course,

$$T_{ij}{}^{*} = \sum_{k}\sum_{l} T_{ijkl}{}^{*} \tag{6}$$

The problem has been formulated and solved by assuming that O-D samples are available at all cordon stations in both the inbound and outbound directions. This may not always be the case. When only inbound or only outbound samples are missing, the solution procedure remains without change. However, when the outbound sample at, say, station 3 is missing and the inbound sample at station 7 has not been obtained, there is a gap in the information for the estimation of T_{13}, T_{03}, and T_{10}. If stations 3 and 7 are on minor roads, the analyst may combine them with neighboring stations and treat two

Table 2. Factoring up by using inbound samples and counts.

From Station	To Station 0	1	2	3	Row Sum (O)
0		(1222)	(2667)	(1 444)	
1	1667	-	3333	5 000	10 000
2	2666	1778	-	3 556	8 000
3	2000	2000	2000	-	6 000
Column sum (D)		5000	8000	10 000	

Table 3. Factoring up by using outbound samples and counts.

From Station	To Station 0	1	2	3	Row Sum (O)
0	-	454	1143	1818	
1	(1793)	-	4571	3636	10 000
2	(2546)	909	-	4545	8 000
3	(79)	3636	2285	-	6 000
Column sum (D)		5000	8000	1000	

or more stations as one. This is tantamount to assuming that the trip origins and destinations in the stations combined are similar, an often justifiable assumption. Alternatively, a two-step estimation procedure can be used. In the first step the above model is applied to stations for which sample O-D information is available; in the second, the flow not allocated in the first step is distributed by using an assumption of equally likely outcomes. The two-step process is incorporated in the computer code used for the application described in the last section.

SOLUTION PROCEDURE

The flow estimates are given in Equation 4 as a function of parameters $\alpha_1, \alpha_2, \ldots, \alpha_n$; $\beta_1, \beta_2, \ldots, \beta_n$. The values of these parameters are unknown and have to be determined so that the sum of the flows at each station equals the corresponding traffic counts. The process of solving for α_i and β_j is straightforward and is best explained with reference to a simple numerical example.

Consider a cordon line with three stations (Figure 1).

The stations are numbered consecutively; a dummy station (0) represents the cordon area proper. Shown alongside the dashed arrows are the inbound and outbound flows counted at the cordon stations. Their tributary flows (T_{kl}) are schematically represented by the short solid arrows. These are the flows that are unknown and for which estimates need to be obtained.

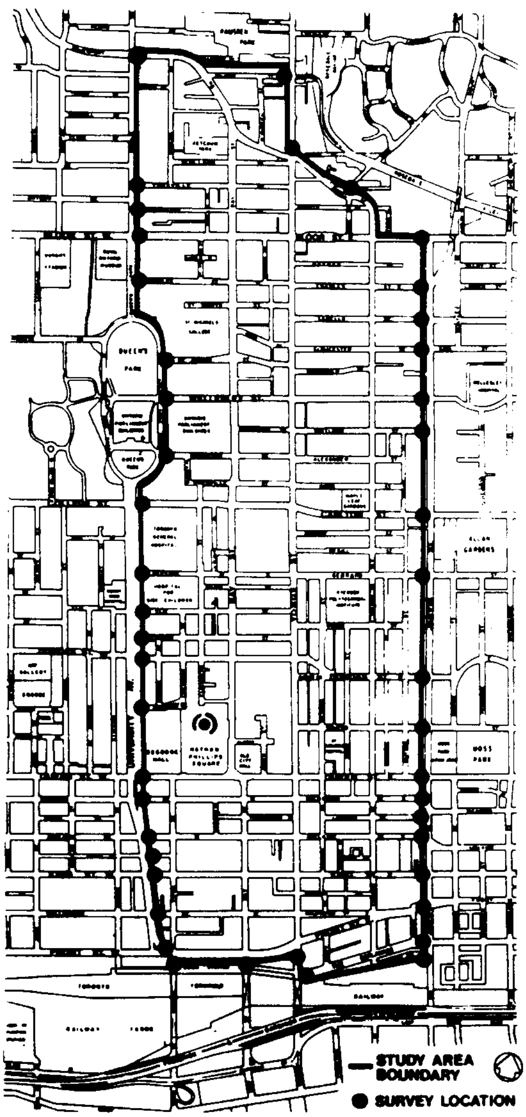
In addition to the traffic counts, a random sample of drivers is polled at each station. In this illustration we assume that entering drivers are asked only about their exit station and vice versa. The resulting information is presented in Table 1. Thus, at station 1, for example, of the 60 inbound drivers asked, 10 ended their trip inside the cordon area (station 0), 20 exited via station 2, and 30 by station 3.

Were one to use the inbound samples, in order to factor them up to the inbound traffic counts the estimates in Table 2 would be obtained. The entries in parentheses are calculated to match the column sums. Alternatively, were one to use the outbound samples and factor those up to the outbound flow, the estimates in Table 3 would be obtained.

Table 4. Estimates of station-to-station flows.

From Station	To Station 0	1	2	3	Row Sum (O)	α_k
0	–	835	1597	1 964	4 396	
1	1422	–	4513	4 065	10 000	0.007 03
2	2404	1624	–	3 971	7 999	0.012 48
3	1569	2541	1890	–	6 000	0.025 49
Column sum (D)	5395	5000	8000	10 000	28 395	
β_l		0.005 99	0.006 26	0.010 18		

Figure 2. Downtown cordon in Toronto.



Comparison of the estimates in Tables 2 and 3 highlights the difficulty inherent in heuristic factoring: Each flow can be estimated in two ways by using two different sets of field data, and the two estimates are usually different. The reconciliation of these differences by some balancing gives rise to ambiguity.

However, redundancy in data should be viewed as an opportunity to improve the quality of the estimation rather than as an embarassing nuisance. The solution obtained earlier resolves this difficulty by making good use of available information and yields unique estimates that are in some sense optimal.

The solution algorithm begins by obtaining initial estimates of $\alpha_1, \alpha_2, \ldots, \alpha_n$. In Equations 4, $\alpha_k = t_{ko}/T_{ko}^*$. The value of T_{ko}^* is at present not known. However, a reasonable starting guess may be the average of corresponding values in column 0 of Tables 2 and 3. Thus, for example, ${}^0\alpha_1 = 10/[1/2(1667 + 1793)] = 0.005\ 78$. Similarly, ${}^0\alpha_2 = 30/[1/2(2667 + 2546)] = 0.011\ 51$ and ${}^0\alpha_3 = 40/1/2(2000 + 79) = 0.038\ 48$. The left superscript is a counter of iterations. The value of α_k after, say, the seventh iteration will be denoted ${}^7\alpha_k$.

By using these tentative values for α_k, the first estimates of β_l can be obtained. Thus, for example, the sum $T_{01} + T_{21} + T_{31}$ must be 5000. Substituting for T_{0k} from Equation 4,

$$(5/{}^1\beta_1) + [(20+10)/({}^1\beta_1 + 0.011\ 51)] + [(40+40)/({}^1\beta_1 + 0.038\ 48)] = 5000 \quad (7)$$

In this equation, ${}^1\beta_1$ is the only unknown. Although it is not possible to write ${}^1\beta_1$ as a function of the constants in this equation, its value is easily determined by iterative methods. In this case, ${}^1\beta_1 = 0.004\ 14$ is the solution.

After a few iterations, the solution in Table 4 is reached.

The underlined part of Table 4 contains the flow estimates T_{ij}^*. Apart from minor discrepancies due to rounding off and termination of iterations, the estimates comply with observed traffic counts and are consistent with the information from the sample survey. The underlined cells represent trips that originate in the cordon area and have destinations outside it (4396), trips that originate outside with destinations inside the cordon area (5395), and total number of trips (28 395).

APPLICATION TO DOWNTOWN TORONTO

In most metropolitan areas, cordon counts are performed periodically in order to keep tabs on the trends in traffic and to provide a data base for transport planning and management. The Metropolitan Toronto Cordon Count Program was established in 1975. A count is conducted every second year on a web of cordons and screen lines. The downtown cordon (Figure 2) is a small yet central part of this web. During the summer of 1981, the normal count program for this cordon was supplemented by a sample O-D survey. For the Metropolitan Toronto Planning Department this was an opportunity to obtain estimates of O-D flows that are notoriously difficult to come by. For us, this was a chance to examine the estimation procedure in practice.

To obtain a sample of O-D information, a random set of license plates was recorded at each cordon station. The address of the registered owner of the vehicle was then traced and a map of the cordon area with a few questions was mailed to him. The person driving the vehicle at the time of the sighting was asked about the origin and destination of the trip as well as its trace on the map of the cordon area.

Of the 25 453 license plates recorded, 20 319 addresses were obtained and questionnaires were mailed to those. Some 6740 responses were obtained and of those, 5835 had usable answers and could be coded.

There are 22 major-flow cordon stations and 24 stations on minor streets. For a major road, an average sample of 180 was obtained; for minor streets, the average sample size is 80. These are close to the planned target. However, the planned sample size was selected without the benefit of a statistical survey design. Results of this study will serve to examine the effect of sample size on estimation accuracy. This examination is under way and it is hoped that its results will facilitate better survey design for future studies.

Random sampling is easier said than done. In the field this requires care for at least two reasons. First, the destination of a trip is not independent of the lane in which the vehicle travels. Thus, the sampling rule must ensure that there is no predisposition to record the plates of vehicles in, say, the curb lane. Otherwise the sample would contain an uncharacteristically large proportion of right-turning vehicles. Second, the origin of a trip is not independent of the place of the vehicle in the platoon. Platoon leaders might be straight-through vehicles with turning traffic forming the tail of the platoon. Thus, the sampling rule must be such that vehicles are selected at a uniform rate from all parts of the platoon. These problems can be obviated by, for example, registering the plates of all vehicles that end with some prespecified digits. It is more difficult to ensure randomness in the second stage of the sampling progress. One has no control over the correctness of the address to which the letter is sent, whether the registered owner was the driver, whether the driver recalls the trip, who decides to fill out the questionnaire and return it, etc. It is clear that this particular method of obtaining a sample of O-D trips will yield results that are not quite representative of trips by fleet vehicles, commercial vehicles, taxis, etc. Nor is this method particularly cheap. To obtain one response (field work + address search + postage + coding + keypunching), we had to invest approximately $1.60 and 10 min of work. It may be possible to simplify the process considerably (for example, by handing out questionnaires to stopped traffic). Experimentation with other workable sampling methods that do ensure randomness will be the subject of future work.

A computer code has been written (in FORTRAN) and fed the cordon-count data and the results of the sample O-D survey. Several O-D flow tables have been produced:

1. Flows between cordon stations with the cordon area as station O,
2. Same as in 1 but the cordon area disaggregated into a few zones, and
3. Flows between traffic zones for trips crossing the cordon once or more.

Many other aggregations and disaggregations are possible. A copy of the computer code listing is available on request from the Department of Civil Engineering at the University of Toronto.

SUMMARY AND DISCUSSION

When cordon counts are supplemented by information about the origin and destination of a small sample of trips crossing the cordon, it is possible to obtain estimates of the prevailing O-D flows. The problem is formulated and solved as the task of identifying the most likely flow estimates. The solution procedure is relatively simple. Estimates obtained are of flows between cordon stations, flows between the stations and the cordon area, flows between traffic zones, etc. An application of the method to the downtown cordon in Toronto is described. Thus, a method is suggested that allows estimation of much-needed O-D information at relatively little extra cost.

As formulated, the model has several flaws. The vehicular flows that are the subject of estimation here are the flows that prevailed at the time of the survey. Ordinarily, one is not interested in the flows that prevailed at some specific time. Rather, one wishes to know the underlying expected value. This distinction is usually disregarded in practice and therefore may not be important. However, personnel limitation and cost preclude the conduct of cordon counts and sample surveys at all stations of the cordon simultaneously. Therefore, one cannot pretend to estimate flows that prevail on some specific day. Yet the flow estimates are not expected values either. An added weakness in the formulation is the insistance that the sum of estimates match the traffic counts exactly. Most practitioners will find this pleasing and in line with other models in use. Nevertheless, the traffic counts are random variables just as the results of O-D samples are, and a coherent model must treat them as such [see, for example, the report by Kirby and Murchland (13)].

The formulation, solution, and illustration of the problem are all presented against the background of a cordon study. One does not ordinarily think of a bus line with its stations or a freeway with its ramps as a cordon. In an earlier paper (4), Hauer, Pagitsas, and Shin discussed the task of O-D estimation on such systems when only traffic counts are available. When in addition to traffic counts one also has small-sample O-D data, the aforementioned systems can be regarded as a cordon and the method developed in this paper applied.

ACKNOWLEDGMENT

This research was supported by the National Science and Engineering Research Council (grant A8158) and the Toronto-York Joint Program in Transportation. The application to downtown Toronto was coordinated by the Metropolitan Toronto Planning Department with the assistance of the Ministry of Transportation and Communications and Metro Roads and Traffic. Their help is gratefully acknowledged.

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Publication of this paper sponsored by Committee on Passenger Travel Demand Forecasting.

Toward Improved Collection of 24-H Travel Records

PETER R. STOPHER AND IRA M. SHESKIN

A major concern of many transportation-planning surveys is to collect data on a 24-h weekday period of travel for all members of a household who are five years of age and older. Traditionally, this has been done by asking household members to recollect their travel for the immediately preceding 24-h weekday period. A travel diary that has been developed to be used by each household member to record travel as it is undertaken is described. Although the concept of a travel diary is not new, several aspects of this diary are new and appear to be very effective in obtaining a response. The diary has been used in some recent surveys and the results of these applications are described briefly. In general, response to the instrument was found to be good when it was administered in an effective supporting survey context. It is concluded that this travel diary represents a good procedure for measuring travel and should be tested in comparable studies with conventional procedures.

Travel-behavior surveys are designed to obtain information about where, when, how, and with how many others the respondent and members of his or her household over the age of five have traveled during a 24-h period. Strictly speaking, when asked as a historical record, the information obtained is the respondent's perceptions of his or her behavior. In a travel-behavior survey, such perceptions are likely to be flawed significantly because a respondent is being asked to remember a sequence of events (and details about these events) that, to the average person, may have seemed unimportant when they occurred. The probability of the omission of trips or of the reporting of inaccurate trip details is heightened even more when (as is often necessary) one household member is asked about the travel of another. Another problem is created when lengthy travel records are collected following a lengthy home interview survey and both respondent and interviewer are tired. The possibility also exists that trips made on another day will be remembered incorrectly as having been made on the subject day. From the early metropolitan area transportation studies, such as the Detroit Metropolitan Area Transportation Study (1), to the present, most travel-behavior surveys have employed this method as part of the urban transportation planning process (2,3). A typical example of such a survey instrument may be found in books by Stopher and Meyburg (4) and by Domencich and McFadden (5).

A second method of collecting travel-behavior information is to intercept people in the process of making a trip. The roadside interview and the onboard transit survey (6) are the most common. The significant advantage of such a technique is that respondents are surveyed at the time when they are least likely to forget trip details. On the other hand, such surveys, for logistical reasons, must be kept relatively short and it is impossible to construct a 24-h trip record for the respondent and his or her household by using this method.

The third method is to use a travel diary in which respondents are asked to report their own future behavior. Such a technique is a cross between observing behavior (such as counting riders on a bus) and a participatory survey (7). The major problem such a technique is designed to circumvent is that of memory. Evidence that memory can be a significant problem in recalling behavior has been provided by Cantril (8). In his survey, only 87 percent of persons interviewed twice at a three-week interval gave the same answer both times about the person for whom they voted in the 1940 presidential election. By presenting a respondent with a document that needs to be filled out about travel for the next day, which can be filled out partly or fully while traveling or partly while traveling and partly at the end of the day, less information should be lost to memory problems. One problem not solved, of course, is that certain trips (such as trips a person may not want his or her spouse to know about) still will not be reported. Another problem is that the respondent may modify behavior by postponing trips to avoid having to spend time making entries in the diary (9). Yet another problem is that respondents, in order to impress the interviewer, may report making some trips (such as a trip to church) that actually were not made.

This paper looks briefly at some past uses of travel diaries in survey research and then reports on the development, design, costs, administration, and results from the travel diaries designed by us for several recent travel surveys.

PREVIOUS USE OF DIARY TECHNIQUE

Diary techniques have seen considerable use in television-viewing surveys and in market research (in which persons list in a diary the products they buy) (7). Some use has also been seen in sociological studies. Willcox (10) compared the morbidity data collected via a diary technique, in which respondents filled in illnesses as they occured over a period of weeks, with such data collected in a retrospective interview and, based on medical records, found the former to be more reliable.

One of the most comprehensive uses of the diary technique is a sociological study by Young and Willmott (11) of the manner in which people spend their time. A study of a respondent's time budget is similar to a study of travel behavior in that respondents are asked to record some details about a sequence of events. In addition, such studies have the same problems with defining an event as transportation planners have in defining a trip to respondents. In Young and Willmott's study, after respondents had completed the main questionnaire, those who were married and between the ages of 30 and 49 were left a time-budget diary, which they were asked to complete and mail back. They rejected holding a second interview after the diary was completed as too costly for the additional information it might generate. Because they were collecting data for Saturday, Sunday, one weekday, and five weekday evenings, it was questionable how useful probing might be after one week had elapsed. Instead, interviewers spent considerable time explaining the form when it was distributed. About 40 percent of respondents refused even to keep the diary; 48 percent returned the diaries as intended; an additional 11 percent returned theirs after either a mail or a personal follow-up. Thus, only about 60 percent of those eligible accepted and completed diaries. In addition, of those who returned diaries, about 3 percent did not complete the diary for the weekend and 31 percent omitted the four weekday evenings. The conclusion to be drawn is that the personal second interview rather than the mail-back might have been worthwhile. In fact, the response rate for the weekday evenings was considered to be so poor as to obviate any analysis. As is discussed below, a second interview can be very effective in assuring a high response rate with quality information.

The use of the diary technique in transportation research is somewhat limited and includes studies that have asked respondents to record their travel for a 24-h period as well as studies that query travel behavior for extended periods.

McGrath and Guinn (12) report a technique that is a variation of the historical-record method for collecting information for a 24-h period. Questionnaires were mailed to 100 000 households in the New Haven area in 1962. An advertising campaign was designed to encourage potential respondents to watch a television show about how to fill out the survey. Only a 10 percent response rate was achieved. It was also impossible to discern the percentage of respondents who had watched the television program. Significant income bias was found in the results. In addition, the survey was biased against those without televisions. It is not clear from the instructions provided whether the travel cards were to be completed for a day in the past or for a future date. In either case, the low response rate tends to suggest why this technique has not seen further use.

Memmott (3) suggests that evidence exists to indicate that home interview surveys result in a 10 percent underreporting of trips. He suggests three possible modifications to the traditional methodology. The first is to have the interviewer question all persons in the household directly and not rely on one person to describe the travel of all in the household. This obviously increases costs due to the need to make one or more additional calls back if given household members are not at home. A second modification is to leave the respondent a telephone number to call in case he or she realizes after the interviewer has departed that he or she forgot to report a given trip.

The third modification is simply a travel diary technique similar in administration to that described below in which diaries are left with the household and are picked up and checked in a second interview. Memmott cites three studies that experimented with the travel diary technique in the 1950s. The basic question posed back in 1962 by Memmott (and still unanswered today) is, Would the improvement in trip reporting more than compensate for the additional interviewer time and cost involved in using this procedure? Data from a New Orleans travel diary show no conclusive results. Results from experiments with diaries in Pittsburgh were promising, which indicates superiority of the diary. Evidence from an experimental use of diaries in the Penn-Jersey Transportation Study indicated that the diary yields no basic improvement over the historical-record method.

For the Niagara Frontier Transportation Study reported by Memmott, interviews were conducted by using three methods. The first involved the traditional historical-record method. The second developed trip records historically, but interviewers were required to interview everyone individually (called "intensive interviewing"). Travel diaries were used with a third group. The conclusion is drawn that the intensive-interviewing method is effective at improving response, but that the travel diary technique is not.

Some studies have used travel diaries that were kept by selected households for extended time periods. Marble, Hanson, and Hanson (13) administered a travel diary to 1179 households in Uppsala, Sweden. Diaries were kept for a five-week period by all household members older than 16 (14). A copy of the diary form may be found in a paper by Burnett (15). The diary collected information on trip time, whether the respondent planned to make the stop before leaving the house, mode, vehicle occupancy, address at destination, and activities performed at each destination.

A monetary incentive was offered to encourage cooperation. The drop-out rate was only 15 percent, probably because much attention was given to assuring understanding during an initial interview. Also, interviewers called respondents on a regular basis to see whether they had questions and respondents were given a telephone number to call if questions arose. A 17-page set of instructions with examples was given to each household.

Kuzmyak and Prensky (16) discuss the problems of measuring changes in travel mobility for the elderly population. Memory problems in a historical-record type of survey may be more significant for this group. Also, because travel may vary a great deal for the elderly from one week to the next, long-term data are needed (17). Thus, they suggest the use of a travel diary and report the planning and implementation of a before-and-after survey that incorporated diary techniques as part of the evaluation of a user-side-subsidy demonstration project in Lawrence, Massachusetts. In recognition of the need for a significant incentive, each respondent was given a \$5 beginning payment and a \$15 completion bonus. Once-a-week visits were made to each household. Information collected was kept to a minimum: origin, destination, mode, purpose, and start time. The final cost was \$77 per usable diary; 285 completed one-month diaries were returned.

Kuzmyak and Prensky (16) also report the results of a disaggregate data set pilot test by the State University of New York at Buffalo. Presumably because of the lack of incentive and the absence of surveillance, the survey suffered from a low level of success. A survey performed in London, the London Transport Survey (LTS) (18), used travel diaries to collect information on transit trips. Perhaps because of the public spirit of transit riders in England and the brevity of the instrument, 98 percent accepted the diaries and 81.5 percent completed the survey. A 1966 Skokie survey (19) tested various travel diary procedures, including the effects of different instrument formats, incentive plans, and levels of surveillance. Incentives varied from \$3.50 to \$11.50. Surveillance levels varied from one to three visits per week. About 56 percent of those contacted agreed to participate; about half eventually completed the survey.

Two travel surveys by Schimpeler-Corradino Associates also have used a travel diary. One done in Washtenaw County, Michigan (1980), was part of a mail-out/mail-back survey that followed a telephone survey (20,21), but little analysis of the results has occurred to date. The second was a similar effort, in Broward County, Florida, by using a forerunner of the travel diary reported below (22). The poor response rate to the travel diary section of this survey (about 20 percent) suggests the difficulty of convincing an entire household to undertake such an arduous task in a mail survey. Finally, a travel diary on which the one described below is based has been used successfully in Germany, according to W. Brög, Socialdata GmbH, Munich.

A number of conclusions may be drawn. First, convincing respondents to participate in a travel diary survey implies the need for a reasonably significant incentive. Second, surveillance, either in the form of an appointment to pick up the travel diary (for a 24-h diary) or repeated visits (for a long-term diary), seems essential. Third, the diary must be kept as simple as possible and explicit instructions must be provided. Finally, although all agree that the historical-record method leads to underreporting of trips, the evidence that travel diaries are superior is mixed.

TRAVEL DIARY IN THIS SURVEY

Survey

The subject survey was designed to collect data from a stratified random sample of the population in seven southeast Michigan counties (23). The principal purposes of the survey were to provide the following:

1. The means to update trip-generation rates and modal-split models,
2. Attitudes of the population toward transportation and energy,
3. Attitudes toward possible changes in the transit system, and
4. Preferred methods of obtaining information on carpooling.

The trip-generation and modal-split models to be updated use certain demographic characteristics and income as input variables, so these characteristics must be measured to permit updating to be accomplished. Also, the survey coincided with a period of high unemployment in the southeast Michigan region (mainly connected to a low cycle in the automotive industry). Because of the potential effects of this on tripmaking, detailed information was required on employment status.

Survey Mechanism Pretest

The selected survey mechanism was the home-interview survey. Two instruments were used. The first was an attitudinal, demographic survey asked of a randomly selected adult household member. The second was a travel diary distributed to each household member 5 years old and older and designed to obtain trip information for a 24-h weekday period.

Since it had been recognized that convincing respondents to participate in the travel diary section of the survey might be difficult, two possibilities were pretested as part of the pilot survey:

Procedure 1: Distribute the travel diaries, make an appointment to pick up the travel diaries, and then do the attitude survey when picking up the diaries (travel diary first, interview later).

Procedure 2: Do the attitude survey, distribute the travel diaries, and then make an appointment to pick up the travel diaries (interview first, travel diaries later).

Procedure 1 had the following advantages. Because the attitude survey was of limited utility unless the travel diaries had been completed, and a high percentage of refusals to complete the travel diaries was expected, time would not be spent on the attitude survey unless the travel diaries were complete. Also, it would permit the interviewer to probe more easily for completion and correct interpretation of the travel diaries. A disadvantage of procedure 2 is that a respondent might feel as if he or she had done his or her duty by being interviewed and might use this as an excuse not to accept the travel diaries. Procedure 2, on the other hand, would permit some rapport between the interviewer and the interviewee to develop during the course of the interview. It might then be expected to be easier to convince the household to take and complete the travel diaries.

Both procedures were pretested in the pilot study in which 138 households were contacted. There were 41 nonresponses, including 17 outright refusals, 1 termination, and 23 "no answers." Of the remaining 97 households, half were given travel diaries first (procedure 1); half, interviews first (procedure 2). Procedure 2 was clearly superior. When presented with the travel diaries first, 53 percent of respondents refused to take them compared with a 4 percent refusal rate when the interview was held first. Evidently, it is necessary to build up rapport prior to asking respondents to participate in something that, on the surface, appears to be a difficult task. Also, in both procedures, once respondents had complied with whatever form was presented first, very low refusal rates (4 and 5 percent) were experienced for the other form.

Administering the Survey

The procedure used in the main survey was as follows. The interviewer made an initial contact with a randomly selected household and used respondent selection grids similar to those described by Backstrom and Hursh (24) to select a household member to interview for the attitude survey. The interview then proceeded and lasted about 45 min. At the conclusion of the interview, the interviewer informed the respondent that the first part of the survey was now complete and the second part involved all in the household 5 years old or older. As many members of the household that were at home then were gathered to listen to the instructions. These oral instructions were designed to emphasize the written instructions and to make certain that all understood the task. (The design features to encourage understanding and response are described below.) The following materials were then given to the household:

1. One travel diary for each household member 5 years old or older [three exceptions were made: (a) if a person was incapable of travel, perhaps due to illness or injury, no travel diary was left; (b) if respondents indicated that they were likely to make more than 10 trips, two travel diaries were left; and (c) out-of-town guests, although not strictly members of the household, were given travel diaries];
2. A travel diary envelope, which contained some instructions on the outside and was designed to be used by the respondents to put their diaries in when complete so that they were all together when the interviewer arived to pick them up; and
3. Two "Travel-Logging Day" signs.

The travel-logging day was assigned as the weekday after the interview; those interviewed on Friday were assigned Monday as the travel-logging day. Also, if the interview was on Saturday and the interviewee was male, diaries were to be used on Monday; if female, on Tuesday. If the interview was on Sunday and the interviewee was male, Thursday became the travel-logging day; if female, Wednesday. This procedure was designed so that, as far as possible, a uniform number of travel diaries would be completed for each weekday. The signs indicated the proper weekday and had a peel-off label that permitted them to be hung on the front door and refrigerator to remind respondents to take their travel diaries with them on the correct day. In addition, if the travel-logging day was not the next day, interviewers were instructed to call the respondent the night before as a reminder.

Because respondents were being asked to perform what might at first seem to be an arduous task, an incentive was offered consisting of free tickets for round trips on the bus. One free ticket was provided for each returned travel diary, given that all travel diaries were returned. In addition, each household was provided informational brochures and bus-route and road maps of the area. These incentives improved the interviewer's morale by providing an additional tool to encourage response on the travel diaries. Interviewers were paid for an interview only if all travel diaries were obtained. The incentive was effective also in building good public relations for the survey.

Once all materials had been distributed and explained, an appointment was established for the interviewer to return and collect the completed travel diaries. At first, the same interviewer returned to collect the diaries, because this person had already established a rapport with the household. Although this is certainly the preferred procedure, to accelerate the process, specially trained personnel were developed to pick up the diaries. In either case, the appointment was set to be within four days of the travel-logging day. When picking up the travel diaries, the interviewer checked them for completeness, particularly for trips back home during the day and at the end of the day, because pilot testing had shown such journeys to be omitted most often. Also, the need to enter each leg of a round trip often was omitted. If a respondent only showed trips to and from work, he or she was quizzed about where lunch was eaten and what was done in the evening.

If a household forgot to complete one or more travel diaries, the interviewer was instructed to attempt to reconstruct the information. If the household completed the diaries for the wrong day, this was judged as acceptable and not worth the cost or bad feelings from asking the household to repeat the procedure.

DESIGN FEATURES TO ENCOURAGE RESPONSE

Of the 2706 attitude surveys that were completed (which represents an 85 percent response rate), 2502 complete sets of travel diaries (6453 diaries) were received (93 percent of those handed out). Because the travel diary was not introduced until after the interview had been completed, the 15 percent initial refusal had nothing to do with the travel diary. The effective refusal of the travel diary was 7 percent of the interviewed households. We believe that this relatively high rate of response to this seemingly difficult task was due to a combination of small devices employed to give the impression that the information was important, that the task was not difficult, and that it might even be fun.

Some of these devices have been referred to above: The use of the travel diary envelope gave the respondent a place to put completed diaries. The obvious expense of this tricolored envelope acted to emphasize the importance of the survey. The travel-logging signs acted as an important reminder to fill out the forms. The incentive was of sufficient value (as much as $5.00 for some respondents) to act to encourage response significantly. It is also probably true that merely the idea that there is some payoff to the respondent encourages response (26).

Travel Diaries

The travel diary was the subject of an extensive design process aimed at encouraging understanding and response. The effect of each individual design element is not known; however, the overall combination of these elements was effective in producing quality responses from 93 percent of the households asked to complete travel diaries.

The diary was designed as a booklet measuring 7 in by 5 in, so that it would be relatively easy to put in a pocket or purse and be carried around by the respondent on the designated travel-logging day. The outside front cover provided various pieces of identification: of the study, the household, the person (by number and name), and the travel-logging day. Two brief instructions were also included in a color-highlighted box. The entire travel diary was set up in three basic colors--white, orange, and yellow. In addition to being pleasing and effective in guiding responses, the colors are also those used in the logo on the vehicles of the sponsoring agency, thereby providing an additional subtle tie to that agency and implicitly reemphasizing the seriousness of the survey activity.

The inside front cover of the booklet is marked out for 10 trips, each one of which has space pro-

Table 1. Trips per person from travel diary.

No. of Trips	No. of Respondents	Percent	Cumulative Percent
0	1289	19.98	19.98
1	30	0.46	20.44
2	2360	36.57	57.01
3	476	7.38	64.39
4	972	15.06	79.45
5	361	5.59	85.04
6	403	6.25	91.29
7	172	2.67	93.96
8	162	2.51	96.47
9	93	1.44	97.91
10	101	1.57	99.48
11	18	0.28	99.76
12	8	0.12	99.88
13	4	0.06	99.94
14	1	0.01	99.95
15	1	0.01	99.96
16	1	0.01	99.97
25	1	0.01	99.98
	6453		

vided across one line. An eleventh trip is included as an example before trip 1. The lines for the trips are colored alternatively white and orange. The remainder of the travel diary is stapled on the top edge to the back cover. The topmost page is an instruction page on yellow stock (to distinguish it from all other pages) that uses both boldface type and two screen boxes to emphasize and highlight the most important instructions. Beneath this are 11 pages, one for each line on the inside front cover. These pages are colored to match their corresponding line on the cover, and have indent cuts on the left side, so that each is cut in from the bottom to its line level. The line (trip) number is printed on the tab and corresponds to a number printed at the left end of the line on the inside front cover. Arrows are used to direct the respondents' attention to the corresponding page for each line. The yellow page was cut to a narrower width than the underlying pages, so that this matching was immediately apparent when the booklet was opened.

The diary is designed to be used in the following manner. The front cover (the Travel Record page) can be folded over and the diary carried displaying the inside front cover throughout the travel-logging day. The remainder of the log provides a thick-enough base to permit easy use of the front cover. The respondent is asked to fill in each line as he or she makes each trip during the day. The information requested (in order) is the start time, the destination, and arrival time for each trip. This is designed basically as a memory prompt to identify each trip made and to provide enough information to the respondent to allow him or her to provide more detailed information later. This more detailed information is requested on the individual pages on the right of the diary (the Trip Detail pages) and consists of trip purpose, main mode of travel, access mode (if any), destination address, and automobile occupancy and parking cost, if automobile was used. Color highlighting, screening, and arrows are used to help the respondent through conditional-question sequences. Each successive page, as noted previously, is colored either orange or white and uses the other color for color highlighting. The first line of the inside front cover and the page immediately below the instruction sheet are used for an example; possible information is filled out in blue and appears as a handwritten record. Finally, the back of the back cover was laid out as a space for comments.

The extent to which respondents actually did fill in the Travel Record page during the day and the Trip Detail pages at night is unknown. Chances are that a significant number of persons completed the entire form at night. Nevertheless, it is contended that superior information is obtained, even from those not following instructions, than would be obtained from a historical record. Just knowing that it would be necessary to record information about one's travel for the day should cause the respondent to pay attention to, and thus remember, trip details.

Various other items were used to assist the respondent. A box was provided to be checked on the inside front cover if the respondent did not leave home on the travel-logging day. Different type faces were used to distinguish between questions and instructions, and whenever possible, multiple answers were provided by means of boxes to check. Considerable care was taken in choosing wording to try to ensure nonambiguity, clarity, and simplicity and also to be nonthreatening, e.g., the use of "What to Do" in place of "Instructions." Although it was not overdone, "please" and "thank you" were used whenever appropriate.

Respondents were asked to continue on a blank page if more than 10 journeys were made. (If a respondent indicated that he or she would make more than 10 journeys at the time the diaries were distributed, two diaries were provided.) It was felt that most respondents would make less than 10 journeys [in fact, only 0.5 percent, or 34 respondents, reported making more than 10 (Table 1)] and that producing extra pages would not be worth the additional cost and bulk. On the other hand, the sudden drop in the number of respondents between 10 and 11 trips shown in Table 1 suggests that had more pages been provided, some respondents might have reported more trips.

The design described is the result of a developmental application in one locality (including pretests) and subsequent pretests in a second locality.

Travel Diary Envelopes

The need for the travel diary envelope was seen as a result of the in-field pilot survey. Interviewers would arrive to pick up the travel diaries and some member of the household would need to walk around the house to find the diaries. Even worse, diaries for given household members could not be found and interviewers had to return for one or more diaries. In addition, interviewers were having trouble keeping the interview forms and travel diaries together for the household. This same problem was experienced by supervisors and other personnel checking to make certain that travel diary sets were complete. These problems were solved by the envelope, which was a standard legal size so that both the travel diary sets and the 8.5-by-11-in interview form could be placed inside. This filing system also proved invaluable through the geocoding, keypunching, data-cleaning, and data-analysis stages of the project.

As with the travel diaries, the envelopes were designed to be eyecatching. Bands of orange and yellow were printed as background to certain instructions whose importance was emphasized by their placement on the envelope. An important feature of the envelope was the presentation of a "toll-free hotline" number. Respondents could call this number to ask any questions about completing the diaries. It was manned by a supervisor in the office of one of the firms conducting the survey. A telephone-answering machine was used during off hours to provide round-the-clock service. In fact, use of the hotline by respondents (as expected) was minimal. Nevertheless, the hotlines served an important function in emphasizing that completing the travel diaries accurately was a very important task.

One change that should be made to the travel diary envelope deriving from its use in the main survey is that a box needs to be added (marked "For Office Use Only") to be used to keep track of the contents of the envelope and the varying clerical tasks that must be performed to computerize the results.

Thus, much care was given to the design of both the diary and the envelope. The overall positive effect is demonstrated by the overwhelmingly positive response by the public to this rather difficult task.

COSTS OF TRAVEL DIARY PROCEDURE

One input to any decision about the value of an effort is cost. Unfortunately, as with many multifaceted expensive projects, it is often difficult to assign costs to individual elements. The final estimated cost for the entire survey described here was $310 000, including data collection, verification of 15 percent of interviews, coding, keypunching, editing, and preliminary analysis. The survey effort resulted in 2706 complete home-interview attitude surveys and 2502 complete surveys with travel diaries. This implies a per-interview cost of $115/completed attitude survey and $124/attitude survey with complete travel diaries. The travel diaries added costs to three aspects of the survey: printing, administration, and data analysis.

The printing costs added a reasonably significant amount. Because of the enormous economies of scale in printing, it is obviously superior to make one large print run than several small ones. It was estimated that obtaining the original goal of 2605 surveys might mean contacting 3000 households, because some households would take diaries and then fail to complete them. Also, figuring an average household size of four who were more than 5 years old (it turned out to be 2.638) implies the need for 12 000 travel diaries. The average cost of these was about $1 each in 1980 dollars (subsequently it was found to be possible to produce the travel diaries for as little as $0.65-0.69 each). The total cost, then, was about $12 000 or about 4 percent of the cost of the completed interview. Because of this expense, some cost-cutting procedures were examined but rejected: the color (orange) added only 6 percent to the cost of each diary; the blue for the answers on the sample page, only 2.5 percent of the diary cost; and the screening to produce the grey areas, less than 0.1 percent of the cost. Most of the cost derived from the need to collate nonstandard paper sizes. From the average cost per household must be subtracted some small cost for the additional printing that would have been necessary if a historical travel record section had been included on the interview survey. The 4000 travel diary envelopes ordered cost $665 or $0.166 each.

The chief administrative cost introduced was the need to conduct a second interview when the travel diaries were to be picked up and checked over. Although returning to the household was not very far out of the way for the interviewer in some cases (because of the multistage sampling process in which traffic-analysis zones were sampled randomly, then blocks, and then households), interviewers often found themselves needing to make special trips to pick up travel diaries. On the other hand, the time spent in the home to check that the information was complete was considerably less than would have been needed to ask all the questions as a historical record. There is no question that this procedure complicated the interviewer's task considerably and that the survey was slowed down because new interviews could not be conducted while the interviewers were busy picking up travel diaries. As mentioned above, special personnel were developed to collect travel diaries in order to speed up the survey.

Some additional costs were incurred during the data-preparation stages as well. The existence of separate forms for each person and the need to turn each page to keypunch each trip led to increased keypunching charges. The geocoding process also was hampered slightly by the need to turn pages. Costs were added by the need to sort the interview surveys into the travel diary envelopes after they had been keypunched. Computer analysis was complicated by the need to match identification numbers between the travel diaries and the attitude surveys in order to add demographic information to the trip-record file and trip information to the home-interview file.

Thus, some significant costs are added to the survey. It is impossible to calculate an exact amount over what the cost would have been had the information been collected historically. Obviously, the additional costs must be weighed against the results obtained. Certainly, obtaining seemingly logical and complete diaries from 93 percent of those interviewed speaks positively for the procedure. The next section reports the results (trip rates) from the travel diaries.

RESULTS FROM TRAVEL DIARIES

The question that one would want to answer is whether the results obtained are more accurate than would have been obtained from recording trips via the historical-record method. As revealed by the literature review, no definitive answer to this question exists and, unfortunately, this case study does not provide one either. Had, for example, half of the respondents been asked about their travel historically and half by using the diaries, a comparison of trip rates could be made. Even this would not reveal anything about the quality of information obtained by either procedure. Obviously, a major regional travel survey is not the place for each experimentation.

The comparisons in trip rates that can be made include both temporal and spatial dimensions. That is, the trip rates for this survey can be compared with earlier rates found in this region as well as with rates found in other cities. The question, then, is: Were more trips reported by respondents via the diary method than is usual for surveys that use the historical-record method? Unfortunately, the results reported below can be viewed only as instructive rather then definitive, because factors that affect trip rates (such as energy prices, unemployment rates, and the number of households in various income and automobile-ownership groups) are not static either spatially or temporally.

The discussion that follows reports trip rates for 1980 and for 1965 for the region of the case study. Both sets of trip rates are based on a sample of households. Optimally, the procedure that should be used is to test for significant differences between average trip rates in 1965 and 1980. Unfortunately, the appropriate statistical test (the difference-of-means t-test) requires knowledge of the standard deviations of the trip rates for both years. These statistics are unavailable for 1965, which precludes the use of statistical tests.

In this instance, however, this problem is not critical. The 1965 survey was a 4 percent sample of households; the resulting sampling error is very small. The 1980 survey, although only a 0.15 percent sample (N = 2502), was designed for and obtained a sampling error of no more than ±5 percent at the 90 percent confidence level. With such large sample sizes and such small sampling errors, it is highly unlikely that any of the differences in trip rates between 1965 and 1980 are not significantly different (with the probable exception of person trips for personal business in Table 4, discussed below).

Trip rates by purpose for both households and individuals are shown in Table 2. The motorized person trip rate of 2.797 consists chiefly of work (0.672), school (0.380), shop (0.302), and non-home-based trips (0.691). This rate compares favorably both temporally and spatially with trip rates measured in other cities with study area populations more than 1 million [Table 3 (25,26)]. Detroit's 1980 rate is considerably higher than the rates shown for all but two of the other cities in Table 3. Also, this rate represents a 14 percent increase over the 1965 data from the Detroit Regional Transportation and Land Use Study (TALUS).

Table 4 compares the 1965 and 1980 person trip rates for Detroit by purpose. Although both household and person trip rates are shown, the household trip rates are difficult to compare over time because average household size has decreased by 24 percent from 3.48 to 2.64 in the 15-year period. It is thus not surprising that with the exception of school trips, all trip purposes show decreasing household rates, with an overall drop of 14 percent in household tripmaking.

An examination of the person trip rates reveals some interesting, but not unexpected, trends. Work trips have increased by 27 percent, which probably reflects increased labor-force participation, particularly among women. School trips have increased by an astounding 88 percent, perhaps due to an increase in persons attending evening classes. The 17 percent decrease in home-based shopping trips may be due to increased trip chaining, which results in an increase in non-home-based trips; note the 28 percent increase in the "non-home-based all" category. The three discretionary trip categories--shop, personal business, and social or recreation--all show decreases, although the decrease in personal business trips is not significant. The 28 percent increase in non-home-based trips is clearly due to an increase in trip chaining as a result of energy costs. Overall, a 14 percent increase in person trips is shown.

The question not answered is whether the changes in trip rates are due to the methodology change from the historical-method record or to actual changes in behavior. Is the increase in school trips due to greater participation in educational activities or to a higher level of reporting of, say, the child's trip home for lunch during the school day? Is the increase in non-home-based trips due to increased trip chaining as a response to the energy crisis or to the fact that the diary is a better method to

Table 2. Travel diary trip rates by purpose.

Trip Type[a]	Household Trip Rate: All Trips	Household Trip Rate: Motorized Trips[b]	Person Trip Rate: All Trips	Person Trip Rate: Motorized Trips[b]
Home-based				
Work	1.775	1.775	0.672	0.672
Shop	0.962	0.796	0.364	0.302
School	1.459	1.002	0.553	0.380
Restaurant	0.253	0.237	0.096	0.090
Serve passenger	0.388	0.375	0.147	0.142
Personal business	0.522	0.470	0.198	0.178
Visit friend or relative	0.508	0.394	0.192	0.149
Health care	0.155	0.145	0.059	0.055
Recreation	0.341	0.277	0.129	0.031
Other	0.117	0.088	0.044	0.033
All	6.566	5.559	2.483	2.106
Non-home-based all	2.043	1.825	0.774	0.691
All trips	8.609	7.384	3.261	2.797

[a]Average number of trips for a 24-h period.
[b]Excludes walk only and bicycle trips, except work trips.

Table 3. Comparison of motorized person trip rates with rates from earlier studies.

City	Study Year	Person Trip Rate
Dallas	1964	2.89
Denver	1971	2.83
Detroit	1953[a]	2.15
Detroit	1965[b]	2.46[c]
Detroit	1980	2.80[c]
Minneapolis-St. Paul	1970	2.72
San Diego	1966	2.67
Chicago	1970	2.45
Cleveland	1963	2.34
Los Angeles	1967	2.28
San Francisco	1965	2.25
Boston	1963	2.23
Washington, D.C.	1968	2.17
Cincinnati	1965	2.17
Miami	1964	2.16
Houston	1960	2.12
Milwaukee	1963	2.07
Buffalo	1962	2.04
Philadelphia	1960	2.03
St. Louis	1957	1.94
New York (Tri-State)	1963	1.81
Seattle	1961	1.76
Pittsburgh	1967	1.72
Baltimore	1962	1.66

[a]Detroit Metropolitan Area Transportation Study.
[b]Detroit Regional Transportation and Land Use Study (TALUS).
[c]14 percent increase.

Table 4. Comparison of motorized trip rates by purpose with 1965 TALUS survey in Detroit.

Trip Type	Trip Rate, 1980: Household	Trip Rate, 1980: Person	Trip Rate, 1965: Household	Trip Rate, 1965: Person	Increase or Decrease, Household: Trip Rate	Increase or Decrease, Household: Percent	Increase or Decrease, Person: Trip Rate	Increase or Decrease, Person: Percent
Home-based								
Work	1.775	0.672	1.852	0.531	-0.077	-4	0.141	27
Shop	0.796	0.302	1.284	0.364	-0.488	-38	-0.062	-17
School	1.002	0.380	0.711	0.204	0.291	41	0.176	88
Personal business[a]	1.078	0.408	1.435	0.411	-0.357	-25	-0.003	-1
Social or recreation[b]	0.908	0.270	1.393	0.408	-0.485	-35	-0.138	-34
Non-home-based all	1.825	0.691	1.885	0.538	-0.060	-3	0.153	28
Total	7.384	2.797	8.558	2.460	-1.174	-14	0.337	14
Avg household size	2.64		3.48					

Note: Data for 1965 are from TALUS report (25); for 1980, from Stopher and Sheskin.
[a]For 1980, this category includes personal business, health care, serve passenger, and other.
[b]For 1980, this category includes recreation, eat meal, and visit friend or relative.

emphasize remembering and reporting such journeys?

CONCLUSIONS

This paper has suggested that the traditional method for obtaining travel-behavior information may be flawed. That is, logic, and some evidence, seems to suggest that when people are asked about their behavior in a retrospective manner, as a historical record, they tend to forget trips, particularly trips made irregularly.

One possible alternative is to use a travel diary in which respondents are asked to record various details about their travel for some future date. Previous use of such a technique to collect information has seen only limited use in transportation research. The travel diary developed by us is the first use of this technique for a major metropolitan areawide travel study.

This paper has discussed the development, design, administration, and costs of the diary technique. A number of conclusions may be drawn. First, the household must be presented with the diaries after a home interview rather than before. This allows the development of rapport and commitment prior to asking respondents to participate in a seemingly difficult task. Second, every detail of the diary and supporting materials must be examined carefully for their possible impact on the response rate and the quality of response. Third, a second interview is needed during which the travel diaries are checked for logic and completeness. Fourth, a significant cost is added to the survey both in terms of dollars and time. Finally, although logic would seem to suggest that at least some of the increase in trip rates shown between Detroit and other cities and within Detroit over time is due to the use of the diary technique, the results presented above cannot prove this contention. Further research is needed in which the diary method and the historical-record method are used in the same survey.

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Publication of this paper sponsored by Committee on Passenger Travel Demand Forecasting.

Assessing Day-to-Day Variability in Complex Travel Patterns

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Recent questioning of assumptions underlying current theory and practice in studies of urban travel behavior is continued. The focus here is on the assumption that the individual's day-to-day travel is habitual and that therefore a one-day record of behavior constitutes a sufficient data base for theory and for model building. A rationale for examining the day-to-day variation in an individual's travel is established; then some of the field procedures that can contribute to making longitudinal data suitable for studying this issue are discussed and, by using the Uppsala Household Travel Survey data as an example, the efficacy of these procedures is tested. Next several techniques are described for measuring travel patterns so that day-to-day variability can be detected, and an approach to the measurement problem is outlined with illustrative examples from the Uppsala data, which consist of travel diaries collected over 35 consecutive days. The results of the empirical analysis are preliminary, but they indicate that (a) the quality of longitudinal travel-diary data need not deteriorate over the survey period, (b) both employed men and nonworking women exhibit a great deal of repetition in their daily travel-activity patterns, so that (c) days with similar travel patterns can be identified and grouped.

This paper continues recent questioning of assumptions underlying current theory and practice in studies of urban travel behavior (1-3). Here we focus on the assumption that the individual's day-to-day travel is extremely stereotyped or habitual and that therefore a one-day record of behavior constitutes a sufficient data base for theory and model building. In this paper we first establish a rationale for examining the day-to-day variation in an individual's travel; we then discuss some of the field procedures that can contribute to making longitudinal data suitable for studying this issue, and, by using the Uppsala Household Travel Survey data as an example, we test the efficacy of these procedures. Next we describe several techniques for measuring travel patterns so that day-to-day variability can be detected, and we outline our own approach to the measurement problem by using illustrative examples from the Uppsala data set, which includes travel diaries collected over 35 consecutive days.

The assumption of habitual travel behavior is implicit in most travel research but has been made explicit by some researchers [for example, Brög and Erl (4)]. Given that most people are satisficers rather than optimizers (5) and given that routine behavior is a stress-minimizing, satisficing strategy because it eliminates the need for constant decisionmaking, there are certainly grounds for expecting that most people establish habitual behavior patterns. Yet there are also grounds for believing that travel behavior is cyclical, with cycles that are daily, weekly, monthly, and yearly, but perhaps also of two to three days' length. Evidence from time-budget studies indicates that one-day data can present serious problems of inference and that the level of error is a function of the cycle over which an activity recurs (6, pp. 79-80). The assumption of habitual behavior has been questioned by few in the field of transportation, but Goodwin (7) is one who, in the context of mode-choice models, has warned of the limits of the one-day-data base and who has urged that more attention be paid to temporal variability in travel behavior.

Because there are many questions of both a substantive and a methodological nature that at present remain unanswered, there are many reasons for assessing empirically the level of variability in daily travel behavior. Is there such a thing as a "typical," "usual," or "habitual" pattern of behavior around which minor deviations swirl? If there is, and if the habitual pattern of behavior is built around a day rather than around a longer slice of time, then it does make sense to ask a subject what he or she usually does, for example, on a weekday. But how much variability exists in a habitual pattern of behavior? What kind of systematic, cyclical, temporal variability in behavior does the one-day window on an individual's travel ignore? Is it reasonable to rely on a one-day sample of an individual's behavior in travel models? Does the interpersonal variability in travel behavior present in a large sample adequately replicate the intrapersonal variability in an individual's behavior over time? If it does not, then what are the implications for present and future models of travel? Do certain identifiable groups of individuals exhibit certain levels of variability (say, from purely repetitive to purely random)? How much intergroup variation is there in degree of repetition? What are the sources of systematic variability?

For the purposes of transportation planning and even of understanding travel behavior, we may consider much of the variability, and therefore the sources of that variability, to be simply random events; there are, however, likely to be patterns of variability that are systematic rather than random and that can be explained, therefore, by nonrandom factors. Several geographers have looked at variability in destination selection and have posited different possible reasons for this particular type of variation in travel. Smith cites the individual's desire to spread risks over a number of different destinations (8); Hay and Johnston propose that variability in destination selection reflects the need for an on-going search in the face of changes in the attributes of the choice set (9); and Hanson has shown that the causal mechanism may lie in the complexity of travel as embodied in the multiple-purpose trip (10).

The ability to answer these questions hinges on the availability of high-quality longitudinal data and on the capacity to measure day-to-day variation in an individual's complex travel-activity patterns. Although it is easy to conceptualize a routine or habitual pattern of behavior as having a high level of repetition in choice of modes, destinations, times, and purposes of travel, any measurement procedure runs into the problem of how to define "habitual." Hypothetically, we may consider behavior as ranging from completely repetitive to completely random, but to define what is routine behavior, the analyst must determine the limits within which variations will be considered part of a habitual pattern. The level of repetition observed empirically and the way in which habitual behavior is defined both depend, therefore, on the length of time over which behavior is observed. It also depends on the ways in which modes, activities, locations, and travel times are classified.

LONGITUDINAL DATA: MAINTAINING QUALITY OVER TIME

Perhaps the main reason for the lack of empirical

Figure 1. Number of stops and journeys per day by day of study, individual ID 16031.

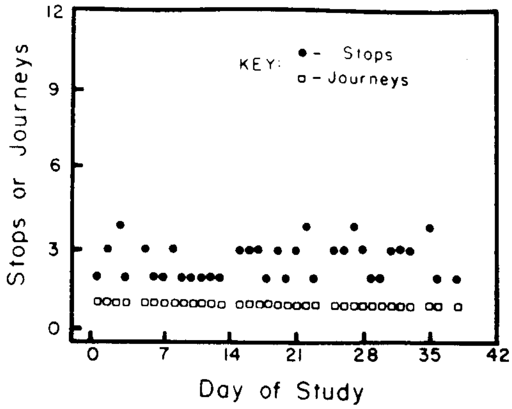
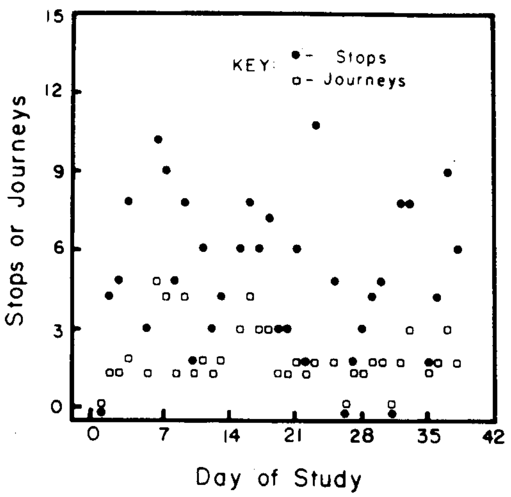


Figure 2. Number of stops and journeys per day by day of study, individual ID 36082.



attention to the daily variability in travel is the dearth of longitudinal data on individuals' travel-activity patterns. Longitudinal travel-diary data are expensive to collect and moreover may be vulnerable to bias because respondents do not record their behavior with consistent precision over a prolonged period of time (11, p. 38). For example, in the Canadian National Driving Survey, in which respondents recorded all automobile trips (but only automobile trips) made over a seven-day period, there was a slight reduction in the number of trips recorded per day toward the end of the recording period; moreover, respondents tended to report fewer short trips as the study wore on (12). Therefore, the first question to address to a longitudinal data set before attempting to measure day-to-day variability is the degree to which trip recording remains stable over time. Have panel members indeed become lax and irresponsible as the novelty of participating in the study wears off?

Data-collection procedures used in the field obviously can affect the degree to which respondents cooperate in generating a reliable, unbiased data set. Three factors that are particularly important in maintaining panel participation in a longitudinal study are (a) offering an incentive for completing the diary, (b) clarifying from the outset the diary-keeping procedures to be followed, and (c) maintaining frequent contact with the household to answer questions, check diaries, deliver new forms, and so on.

All of these methods were used in the Uppsala study to encourage faithful diary recording. In a pilot study in Skokie, Illinois, Garrison and Worrall found that the offer of incentives increased the willingness of households to participate in a four-week travel diary and also helped to reduce the dropout rate during the longitudinal study (13). As an incentive to solicit and to maintain the household's interest in the Uppsala project, each household successfully completing the survey was eligible for a chance in a small lottery that was held shortly after the end of the survey period.

Field operations were designed to allow for adequate time with each household to explain the diary procedures. To even out the field staff's workload, particularly during the initial and terminal household-contact periods, the sample was divided into five streams with the households in each stream to begin recording in their travel diaries on each of five successive days. Once a household had agreed to participate in the study, a field-staff member held a briefing session with the household to go over the diary recording procedure in great detail. During this session, which took about an hour, the interviewer went through an instruction manual (which was then left with the household) and helped each household member fill out diary sheets for the preceding day's trips as a sample of what the person was to do.

During the five weeks of the study, the field-staff members maintained briefer personal contact with each household once a week and made telephone contact midway between visits. The first visit to each household took place not later than two days after the household began recording. This high level of contact was necessary to ensure that any questions would be answered as soon as possible; in addition, each household was given a number to call for answering of questions that might not have been covered during the prearranged personal and telephone contacts. When field-staff members visited the households, they carefully checked the completed diary forms and collected them. This permitted a reasonable check on the reliability of the filled-in diaries and enabled a rapid return to a central facility for on-going sorting, cataloging, coding, and further checks for blatant errors and omissions--all while households were still participating in the study.

To see if these field measures were successful in keeping the Uppsala panel members faithful to their travel diaries, we have examined the number of journeys per day (where a journey is a home-to-home circuit) and the number of stops per day by day of the study for each individual. The question addressed here is whether or not overall tripmaking was relatively stable or whether it declined during the 35-day period. For each individual the number of journeys per day and the number of stops per day were arrayed by the day of the study (from 1 to 35); this was done for all 35 days of the study and then for weekdays only (where the days are numbered from 1 to 25). Figures 1 and 2 show examples of these scatterplots for two different individuals. A regression was then run on each of the resulting four scatterplots for each of 149 individuals (belonging to 94 households), who make up a representative sample of Uppsala's population. If indeed tripmaking is relatively stable, then we would expect that the regression coefficients would not differ significantly from zero.

The regression results (given in Table 1) show that for more than 90 percent of the persons in the sample, travel (or at least travel as recorded in

Table 1. Analysis of stability of travel over surveillance period, Uppsala Household Travel Survey, March 29-May 6, 1971.

Independent Variable	Regression Coefficient (N = 149)		Standard Error (N = 149)		Regression Coefficient Significant[a]		
	Mean	SD	Mean	SD	Positive Coefficient	Negative Coefficient	Total
No. of journeys per day[b]	0.001	0.024	0.750	0.282	6	8	14
No. of stops per day[b]	0.008	0.064	2.165	0.815	8	6	14
No. of journeys per day[c]	0.006	0.033	0.705	0.280	7	6	13
No. of stops per day[c]	0.025	0.086	2.045	0.803	8	3	11

Note: Results from regression of independent variables against day of the study for 149 individuals.
[a]P < 0.01 levels. [b]All 35 days. [c]On 25 weekdays only.

the diaries) is stable over the surveillance period. For each of the four independent variables examined (number of journeys made per day for all 35 days, number of stops made per day for all 35 days, number of journeys made per day on the 25 weekdays, and number of stops made per day on the 25 weekdays), the mean of the 149 regression coefficients is close to zero.

Because we had thought that weekday travel was likely to be more habitual than travel over all days, we had hypothesized that the standard errors of the estimate would be lower for the variables relating to travel only on the weekdays. But as Table 1 shows, there is little difference in the means of the standard errors for weekdays compared with those for all days. There is, however, a noticeable difference between the standard errors associated with the regressions for journeys and those for stops; the number of stops an individual makes per day is a great deal more variable than is the number of journeys made per day. Figures 1 and 2 also clearly illustrate this point.

Not only were the means of the regression coefficients near zero but also in every set of regressions less than 10 percent of the sample individuals had regression coefficients that were significant at the level of $P < 0.01$; moreover, the significant regression coefficients were not consistently negative. We can conclude, therefore, that only for a tiny proportion of the sample (2-5 percent, depending on the independent variable in question) did trip recording decline over time. Because we do not know what proportion of actual trips was recorded, we of course have no way of knowing whether or not the proportion of recorded-to-actual trips changed over time.

MEASURING TRAVEL-ACTIVITY PATTERNS

In order to assess day-to-day variability in travel, one must devise measures of travel-activity patterns that are sensitive enough to permit meaningful comparison between any two days' travel. A number of different approaches to this problem have recently been developed and given the current importance accorded this problem (9), it seems worthwhile, for purposes of comparison, to describe briefly each of the various approaches before outlining our own.

Perhaps the simplest approach is to create, for each day's travel pattern, a vector of descriptive attributes such as the number of journeys, the number of stops, activities pursued, modes used, distances traveled, time spent outside home, and centrographic measures on the spatial distribution of destination sites. This approach has never been used to compare travel patterns between single days, but it is essentially the same method that has been used to describe an individual's travel-activity pattern over an extended period of time (14). Such a procedure would be adequate for determining the similarity between two days' travel in fairly general terms, but this method does not retain detail at the level of the stop.

Pas has pursued a stop-based measurement approach in an effort to classify travel-activity patterns (15). For each daily pattern, Pas develops a descriptor that basically counts the number of ways in which two stops are similar and then sums over the number of stops in the pattern. Pas's descriptive measures distinguish between the primary and the secondary attributes of stops; a primary attribute measures whether or not a stop was made, and a secondary attribute measures a characteristic of a particular stop, for example, the mode used. Two travel patterns are compared on the basis of, first, whether or not a stop was made (if yes, then there is a match; if no, then there is a mismatch) and, second, on the basis of the number of matching stop characteristics. Pas's measure of similarity between two patterns is based on Gower's work (16) and is a weighted average of the similarity between the two patterns on each attribute. In Pas's application of the technique, each pattern to be measured represents a different individual because the method was developed to compare the one-day travel patterns of a sample of individuals. Nevertheless, the method could be extended to compare different days' travel patterns for a single individual.

A third approach is based on the now familiar two-dimensional representation of a day's travel-activity pattern as a time-space path (2,17,18). Recker and Schuler have recently developed a way to classify such time-space paths by using pattern-recognition techniques (19). Transformations are used first to simplify the space-time path, and then similar paths are clustered on the basis of selected characteristics of the paths. This method emphasizes the location of the individual in space and time throughout a given day, but it does not permit information such as mode use or activity participation to be considered simultaneously with the space-time coordinates. Attributes of the space-time path such as activity participation and mode use can be handled by establishing separate paths that show, for example, type of activity being pursued at any time during the day.

Here we propose yet another way of measuring travel-activity patterns and of comparing patterns from different days. The basis for measurement and for comparison of travel pattern i with travel pattern j is the ordered set of trip links (t_{iN}) that constitute the Nth daily travel pattern T_N (in the Uppsala case, N = 1, ..., 35). Each stop made is assigned to an equivalence class (X_j) where the equivalence relation is defined on the basis of selected trip-link characteristics. The degree of similarity between two travel patterns can then be measured in terms of the number, order, and type of trip links (as described by their equivalence class) common to both daily travel patterns.

Each trip link (or stop) is assumed to have the following properties: trip purpose or activity (a), mode of travel (m), time interval of arrival (t), distance from last stop (d), and location of destination (l) defined by x-y coordinates corresponding to street addresses. Trip-link equivalence classes can be defined in terms of one or more of the five trip-link properties, and the method therefore permits comparison of daily travel patterns on the basis of a different number of stop characteristics. Comparisons based on only one stop dimension would require equivalence classes such as $(X_i|m)$, the set of all stops by mode i, or $(X_j|a)$, the set of all stops for activity j. Comparisons based on two stop characteristics would use equivalence classes such as $(X_k|m,l)$, the set of all trip links that have a given mode and a given destination location in common. Similarly, comparisons can use equivalence classes defined in terms of three, four, and five dimensions of trip links. Daily travel patterns can therefore be compared in terms ranging from the simple, involving one stop characteristic, to the complex, involving all five stop characteristics.

When the stops have been partitioned into equivalence classes, it is possible to classify or group daily travel patterns on the basis of trip links common to patterns in the class. We begin by defining, for each person, an N x N commonality matrix $C = c_{ij}$ where N is the number of days in the longitudinal record and c_{ij} is the set of trip links, as defined by their respective equivalence classes, which are common to travel patterns T_i and T_j. Travel patterns can then be grouped sequentially into increasingly general travel classes on the basis of the number of trip links or stops common to the travel patterns. The linkage algorithm simply searches for the largest number of commonly held trip links and groups the two patterns or sets of patterns containing these links. The algorithm need not generate disjoint equivalence classes at each level of aggregation because disjointness appears to be neither a necessary nor a desirable property of a travel-pattern classification scheme.

We illustrate this procedure with an empirical example by using two dimensions of trip links and two small samples drawn from the Uppsala survey. The samples were chosen to be internally homogeneous with respect to sociodemographics and consist of (a) nine married women (aged 18 to 39) who do not work outside the home and who have at least one preschool child at home and (b) their husbands, all of whom are employed full time. In addition, all of these individuals have lived in Uppsala for more than four years and therefore should no longer be in the early stages of learning about the city. We would expect repetitive patterns of behavior to be well established by those who have lived in a city for this length of time.

The first step is to determine the appropriate equivalence classes for each individual. Because we expect behavior to be repetitive, setting up equivalence classes for every possible mode, activity, destination, etc., is unnecessarily unwieldy; moreover, the tractability of the measurement procedure is enhanced if stops are concentrated at a few destinations, activities, modes, and so on. We examine the degree to which any two stop characteristics (e.g., mode and activity) occur together repetitively by examining a series of contingency tables for each person. If behavior is indeed habitual, we would expect an individual's stops to be concentrated in a very few cells within each contingency table. Complete repetition would mean of course that all stops would fall in one cell of any given contingency table, and if behavior were completely random, the individual's stops would be evenly distributed throughout the cells of any given table. Analysis of contingency tables therefore indicates the degree to which behavior is habitual as well as the nature of the equivalence classes that should be defined for each person.

For each person we constructed 10 contingency tables and for each table we examined the level of repetition via three measures: (a) the number of cells in the table with more than 10 percent of the stops, (b) the number of cells in the table with more than one stop, and (c) the percentage of stops occurring in the largest cell of the table (see Tables 2 and 3). Ten percent was chosen arbitrarily as representing a significant percentage of stops; counting cells with more than one stop gives a measure of the distribution of stops throughout the cells, and focusing on the value in the largest cell gives a measure of stop concentration in the table. Routinized behavior would yield small values for the

Table 2. Some measures of repetition based on two stop characteristics for 35-day travel patterns: nonworking married women with preschool children (N = 9).

	No. of Cells with >10 Percent of Stops		No. of Cells with >1 Stop		Value of Largest Cell (%)	
Contingency Table[a]	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
Activity[b] x mode[c] (20)	3.2	0.4	9.0	2.4	34.2	9.7
Time[d] x mode (16)	2.7	0.7	6.5	1.9	52.7	16.6
Distance[e] x mode (20)	2.8	1.2	8.2	2.5	44.4	10.7
Activity x time (20)	2.9	0.8	8.5	2.2	41.8	11.1
Distance x time (20)	2.5	1.1	9.2	2.2	42.7	14.8
Activity x distance (25)	2.6	0.7	10.6	3.2	30.6	9.3
Location[f] x distance ( )[g]	1.1	0.8	10.9	4.0	23.0	12.3
Location x time ( )	1.4	0.7	12.7	4.6	22.8	12.9
Location x activity ( )[g]	1.4	0.9	9.4	3.2	21.4	11.3
Location x mode ( )[g]	1.3	0.5	11.7	4.0	23.3	10.3

Note: Data are from Uppsala Household Travel Survey, Uppsala, Sweden, 1971.
[a]Numbers in parentheses indicate number of cells in table.
[b]Activities were coded as follows: 1 = social, 2 = personal business, 3 = shop, 4 = work, 5 = recreation, 6 = home.
[c]Modes were coded as follows: 1 = walk, 2 = bicycle, 3 = bus, 4 = automobile, 5 = other (moped, taxi, horse, elevator, etc.).
[d]Time of arrival at destination was coded as follows: 1 = midnight to 8:59 a.m., 2 = 9:00 a.m. to 3:59 p.m., 3 = 4:00 p.m. to 6:59 p.m., 4 = 7 p.m. to midnight.
[e]Distance traveled to stop destination (on that trip link) was coded as follows: 1 = 0 to 0.49 km, 2 = 0.5 to 0.99 km, 3 = 1.0 to 1.99 km, 4 = 2.0 to 2.99 km, 5 = ≥ 3.0 km.
[f]Unique locations were identified by street address.
[g]Number of unique locations (and therefore the number of cells in tables using location) differs by individual; average number of unique locations visited by women was 30.9 with a standard deviation of 8.2 and by men was 26.0 with a standard deviation of 13.4.

Table 3. Some measures of repetition based on two stop characteristics for 35-day travel patterns: full-time employed married men with nonworking wives and preschool children (N = 9).

	No. of Cells with >10 Percent of Stops		No. of Cells with >1 Stop		Value of Largest Cell (%)	
Contingency Table[a]	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
Activity[b] x mode[c] (20)	3.0	0.8	10.1	4.0	34.3	10.7
Time[d] x mode (16)	3.9	1.2	7.8	3.0	36.3	16.8
Distance[e] x mode (20)	2.5	0.9	7.4	3.8	41.2	16.9
Activity x time (20)	3.1	1.2	10.7	4.9	29.0	13.7
Distance x time (20)	2.7	1.6	10.5	4.5	32.2	15.6
Activity x distance (25)	1.9	0.9	13.0	6.1	36.3	13.0
Location[f] x distance ( )[g]	1.7	0.7	12.3	6.3	26.7	9.7
Location x time ( )[g]	1.4	1.0	14.1	9.0	21.9	13.2
Location x activity ( )[g]	1.7	0.8	11.8	7.8	28.7	11.4
Location x mode ( )[g]	1.7	1.0	12.8	6.6	24.5	7.9

Note: Data are from Uppsala Household Travel Survey, Uppsala, Sweden, 1971.
[a]Numbers in parentheses indicate number of cells in table.
[b]Activities were coded as follows: 1 = social, 2 = personal business, 3 = shop, 4 = work, 5 = recreation, 6 = home.
[c]Modes were coded as follows: 1 = walk, 2 = bicycle, 3 = bus, 4 = automobile, 5 = other (moped, taxi, horse, elevator, etc.).
[d]Time of arrival at destination was coded as follows: 1 = midnight to 8:59 a.m., 2 = 9:00 a.m. to 3:59 p.m., 3 = 4:00 p.m. to 6:59 p.m., 4 = 7 p.m. to midnight.
[e]Distance traveled to stop destination (on that trip link) was coded as follows: 1 = 0 to 0.49 km, 2 = 0.5 to 0.99 km, 3 = 1.0 to 1.99 km, 4 = 2.0 to 2.99 km, 5 = ≥ 3.0 km.
[f]Unique locations were identified by street address.
[g]Number of unique locations (and therefore number of cells in tables using location) differs by individual; average number of unique locations visited by women was 30.9 with a standard deviation of 8.2 and by men was 26.0 with a standard deviation of 13.4.

first two measures and a large value for the third measure.

The results are given in Tables 2 and 3 and support Marble and Bowlby's finding that travel is highly repetitive (20). Yet the behavior patterns are not completely stereotyped. On the average, a small number of cells contain more than 10 percent of the stops in a table, whereas up to half of the cells in a table have more than one stop. Also, depending on the table in question, the average proportion of an individual's stops that falls in the largest cell ranges from roughly one-fifth to one-half. Clearly, the equivalence classes for a person need to be chosen carefully, for with a relatively small number of such classes (small by comparison with the total number of possible equivalence classes) the analyst can capture the lion's share of a person's daily travel behavior.

We had selected the two samples expecting to find sizeable differences between them in the degree to which behavior was habitual. Because the men had full-time jobs and because none of the women worked outside the home, we thought that the men's stops would be more heavily concentrated in a few cells of the contingency tables. Yet the evidence in Tables 2 and 3 does not support this hypothesis; the men's stops are not consistently more concentrated in a few cells. To test for statistically significant differences between the men and the women, we used the two-tailed Student's t-test to compare the means in Table 2 with those in Table 3. In only one instance (the number of cells with more than 10 percent of stops in the time-x-mode table) was the difference between means significant at the $P < 0.05$ level. This very preliminary evidence suggests that, despite clear differences in employment status, individuals' travel patterns do not differ drastically in terms of level of routine or repetition. Clearly, this is one research area that needs further attention.

We illustrate the remainder of the procedure with the travel records of one individual taken from the sample of men. Table 4 gives the equivalence classes defined for this person and used in drawing up the commonality matrices. A portion of the mode-distance commonality matrix is shown in Figure 3. The commonality matrix shows the trip-link characteristics (in this case the mode and distance characteristics) that any two days' travel patterns have in common, and the number of times these common equivalence classes occur is given in parentheses. Of course, in the full-scale analysis each cell of the commonality matrix would hold all equivalence classes common to the two days in question. The similarity between any two days' travel patterns can then be determined by the number and type of equivalence classes common to both days. In Figure 4 the similarities among the travel patterns shown in Figure 3 have been diagrammed to show the nature of the commonalities at different levels of generalization. Figure 4 is an example of a linkage tree, in which similar days are grouped on the basis of the number of common trip-link characteristics; days 1 and 2, for example, have six M_1D_1 (walk, < 0.5 km) stops in common, and days 5, 1, 2, and 3 have at least two such stops in common. Figure 5 shows the way in which similar days may be grouped on the basis of commonly held time and activity stop characteristics.

SUMMARY AND RESEARCH NEEDS

This paper provides some empirical understanding of the day-to-day variability in individuals' complex travel-activity patterns. Analysis of the Uppsala diary data has shown that the overall level of trip-making did not decline over the study period; the argument that longitudinal data are not worth analyzing longitudinally (because trip recording falls off over the surveillance period) is therefore not supported in this instance. The primary purpose of the analysis described in this paper has been to illustrate a methodology for measuring the day-to-day variation in travel patterns, but a number of interesting points have emerged from this preliminary work. The analysis has shown that although there is a great deal of repetition in individuals' daily travel patterns, and although even unemployed people display a high level of this repetition in their travel, there is still a noticeable amount of variability in travel even on weekdays for a full-time employed person. This means that more extensive analysis of the systematic variability in daily travel patterns is likely to yield interesting insights.

In the method described here, a person's trip links are classified in terms of one or more characteristics, and then travel pattern i is compared with travel pattern j on the basis of these trip-link equivalence classes. We have shown how the method may be used to identify days with similar travel patterns, but there are additional results that can be obtained. Summary statistics on the distribution of waiting times between trip links in the same equivalence class can provide insight into the cyclical nature of travel at the trip-link level. Also, the most frequent trip-link combinations can be analyzed to determine archetype travel patterns that persist across time for one individual or across different individuals; these archetypes should describe typical travel patterns to which other, less frequent or nonrepetitive trips are linked. If, for example, $c_{ij}*$ is the number of trip links common to T_i and T_j, then a simple measure of travel-pattern similarity is $s_{ij} = c_{ij}*/c_{ii}*$. In addition, comparing longitudinal travel patterns across individuals as well as within individuals would permit us to separate the observed variance about the mean for any measure into two components: variance due to aggregation over nonidentical individuals and variance internal to each individual's longitudinal record.

Current travel-demand models focus almost exclusively on the prediction of single trip links in the daily travel pattern. They often fail to recognize or consider possible interdependencies existing between trips contained in a home-to-home circuit and invariably ignore the possibility that trip sequences recur in some systematic fashion over time. From a policy standpoint, the estimates of travel-demand elasticities (as derived from the coefficients in the travel-demand model) are likely to be in error if the trip links in the daily travel pattern are not independent and if the daily travel pattern for an individual varies systematically from one day to the next. The methodology described here will enable analysts to identify spatial and temporal regularities and interdependencies existing between trip links and between daily travel-activity patterns. In particular, it should allow us to distinguish between variation intrinsic to the individual and variation arising from differences among individuals and to assess the implications for travel-demand models of ignoring the day-to-day variability in individual travel patterns.

ACKNOWLEDGMENT

This research was funded in part by National Science Foundation grant SES 81-05845. We would also like to thank our research assistants, Kimberly Churchill-Jones and Anna Shaw, and our typist, Sandra Snow.

Table 4. Equivalence classes defined for individual ID 26081.

Contingency Table	Notation Used	Description of Equivalence Class
Activity x mode	A_4,M_2	Work, bike
	A_3,M_1	Shop, walk
	A_3,M_4	Shop, car
Time x mode	T_1,M_2	< 9 a.m., bike
	T_2,M_2	9 a.m. - 4 p.m., bike
	T_2,M_1	9 a.m. - 4 p.m., walk
	T_2,M_4	9 a.m. - 4 p.m., car
Distance x mode	D_1,M_1	< 0.5 km, walk
	D_2,M_2	0.5 to 1 km, bike
Time x activity	T_1,A_4	< 9 a.m., work
	T_2,A_2	9 a.m. - 4 p.m., personal business
	T_2,A_3	9 a.m. - 4 p.m., shop
	T_2,A_4	9 a.m. - 4 p.m., work
	T_2,A_6	9 a.m. - 4 p.m., home
	T_3,A_3	4 p.m. - 7 p.m., shop
	T_3,A_6	4 p.m. - 7 p.m., home
Distance x time	D_1,T_2	0.5 km, 9 a.m. - 4 p.m.
	D_2,T_2	0.5 - 1 km, 9 a.m. - 4 p.m.
	D_2,T_1	0.5 - 1 km, < 9 a.m.
	D_3,T_2	1 - 2 km, 9 a.m. - 4 p.m.
Activity x distance	A_3,D_1	Shop, < 0.5 km
	A_4,D_2	Work, 0.5 - 1 km
Location x distance	L_8,T_2	Location 8, 0.5 - 1 km
Location x time	L_8,T_1	Location 8, < 9 a.m.
	L_8,T_2	Location 8, 9 a.m. - 4 p.m.
Location x activity	L_8,A_4	Location 8, work
	L_{26},A_4	Location 26, work
Location x mode	L_8,M_2	Location 8, bike

Figure 3. Portion of mode-distance commonality matrix for trip links, individual ID 26081.

DAY	1	2	3	4	5	6	7
1	M_1D_1 (7), M_1D_2, M_1D_3 M_4D_3 (2)	M_1D_1(6)	M_1D_1(2)	0	M_1D_1(4)	M_4D_3(2)	0
2	M_1D_1(6)	M_1D_1(6)	M_1D_1(2)	0	M_1D_1(4)	0	0
3			M_1D_1(2), M_2D_2(4), M_4D_4(2)	M_2D_2(3)	M_1D_1(2)	0	M_2D_2(4)
4				M_1D_5, M_2D_2(3), M_2D_5	0	0	M D (3)
5					M_1D_1(4)	0	0
6						M_4D_3(2)	0
7							M_2D_2(4), M_2D_3(2)

Figure 4. Linkage diagram for mode-distance characteristics of travel patterns of days 1-7, individual ID 26081.

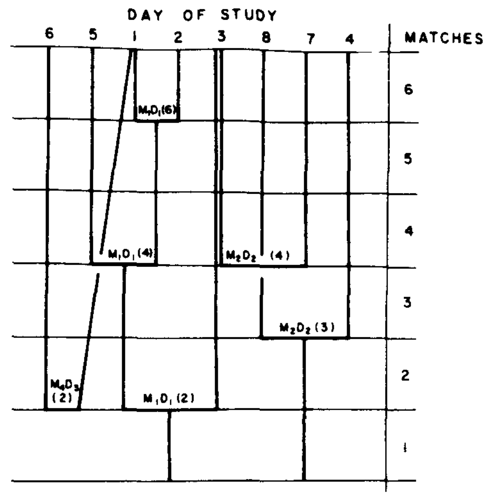
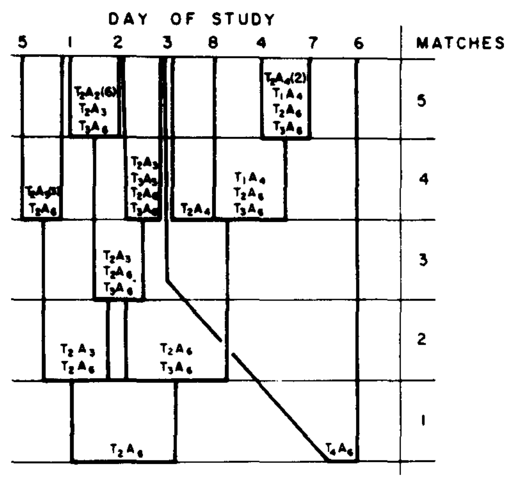


Figure 5. Linkage diagram for time-activity characteristics of travel patterns of days 1-7, individual ID 26081.



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Publication of this paper sponsored by Committee on Passenger Travel Demand Forecasting.

Monitoring and Evaluation of State Highway Systems

DOUGLASS B. LEE

During the three immediately preceding decades, the U.S. highway system has been characterized by steady growth in total travel, increased system mileage and capacity, and net investment in both pavement strength and surface quality. The pattern for the coming decades is already becoming apparent, and it will be characterized by approximately stable overall traffic levels, maintenance and reconstruction of existing mileage, and probably some net disinvestment in the system as a whole. The data and the methods that highway planners have used to guide decisions during the previous phase of development of the highway system are unsuited to the problems of the coming decades, and state-level monitoring and evaluation functions will require a major reorientation in data collection and analytic tools.

Evaluation means estimating the incremental benefits and costs of alternative projects and programs, whereas monitoring means collecting the data that will support the evaluations. Instead of simply prioritizing projects within an exogenous budget constraint, highway planners must be able to distinguish those improvements that are worthwhile from those that are not, no matter how big or small the budget. Analysis capable of making this distinction attains a much higher level of technical and political credibility than analysis that is not so capable. Several states have taken steps in this direction (1,2) and the Federal Highway Administration (FHWA) supports an analytic package (3), but the pace of implementation needs to be accelerated.

EXISTING SYSTEM

The familiar distributions of highway mileage and vehicle miles of travel (VMT) by functional system are arrayed in Table 1. The vast bulk of the mileage is not included in the federal-aid system, and most of this excluded mileage is in rural county roads. A large share of these roads lack an all-weather surface. In contrast, travel is heavily concentrated in urban areas and on Interstates. Even at this level, then, the existence of a large extent of relatively low-volume roads is suggested.

A parallel set of numbers is constructed in Table 2 (4) as an attempt to portray the total value of the capital stock. Applying the average per-mile replacement cost estimates (including right-of-way) to the mileages in Table 1 yields total replacement costs for each functional system. This distribution of the value of the capital stock by functional class is much closer to the VMT distribution than is the mileage distribution; rural collectors and area service roads show a lower VMT per dollar of capital value. Figure 1 shows how the three distributions compare.

As a rough indicator of cost, the total replacement value can be converted to an annual figure by means of a capital recovery factor (CRF), i.e.,

Equivalent annual cost = CRF x total replacement value,

where the CRF includes both a lifetime and a discount rate. Using a CRF of 0.10 yields an annual capital cost of $174 billion annually, on the assumption that all highways are maintained and replaced as they wear out and both the land and other resources used could earn a market rate of return if put to other purposes. This is an estimate of the value of the resources that will be foregone by society in order to maintain the highway system as is in perpetuity. Nothing is implied about the benefits of doing so.

Actual expenditure on highways is a measure of cost that, under present financing arrangements, does not include any component for opportunity costs (e.g., the interest foregone on funds expended in highway construction). If the interest cost is removed from the replacement cost estimate above, the residual will represent expenditures for maintenance and reconstruction needed to offset the physical depreciation of the highway system. If we assume that 70 percent of the investment in a typical highway depreciates over a lifetime of 15 years, the total replacement value translates into an expenditure level of $81 billion that is required to be spent each year so as to keep the entire system in stable condition. Current expenditures for capital and maintenance by all levels of government are about $30 billion. These contrasts are illustrated in Figure 2.

Some of the information from the previous tables has been recombined in Table 3, which shows average daily traffic (ADT) and economic cost (including interest costs) per vehicle mile. Average volumes are substantial on some systems and meager on others, and the averages conceal an additional dimension of variation within the categories. Cost per vehicle mile (no administrative or externality costs are in-

Table 1. Total road and street mileage and VMT by functional system.

	Rural		Urban		Total		Rural		Urban		Total	
System	Miles	Percent	Miles	Percent	Miles	Percent	VMT	Percent	VMT	Percent	VMT	Percent
Interstate	31 334	0.8	9 114	0.2	40 448	1.0	133 597	8.7	159 452	10.4	293 049	19.2
Arterial	235 492	6.0	115 956	3.0	351 448	9.0	274 110	17.9	474 274	31.0	248 384	48.9
Collector	727 216	18.7	63 537	1.6	790 753	20.3	177 258	11.6	75 159	4.9	252 417	16.5
Local	2 284 756	58.7	427 727	11.0	2 712 483	69.6	85 114	5.6	150 169	9.8	235 283	15.4
Total	3 278 798	84.2	616 334	15.8	3 895 132		670 079	43.8	859 054	56.2	1 529 133	

Table 2. Average replacement cost per mile and total replacement cost by functional class.

	Replacement Cost/Mile (1978 $)					
	Rural		Urban		Total	
System	Amount	Percent	Amount	Percent	Amount	Percent
Interstate	77 614	4.5	109 131	6.3	186 745	10.7
Arterial	288 949	16.6	427 182	24.6	716 130	41.2
Collector	314 885	18.1	121 038	7.0	435 922	25.1
Local	228 476	13.1	171 091	9.8	399 566	23.0
Total	909 923	52.3	828 441	47.7	1 738 365	

Figure 1. Comparison of shares of mileage, VMT, and capital replacement value by functional system.

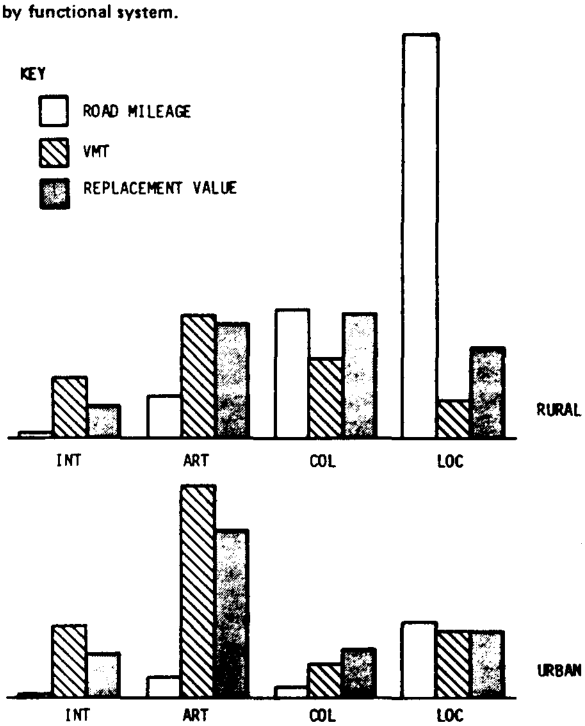


Figure 2. Comparison of current user charges, expenditures, and capital replacement for highways.

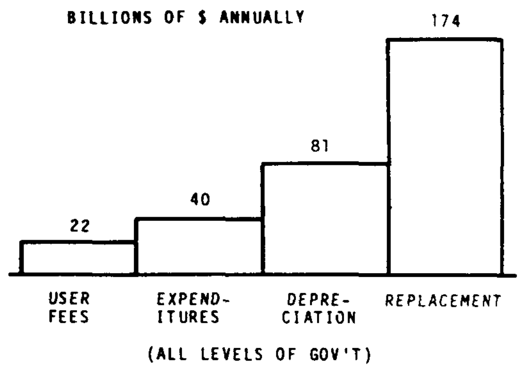
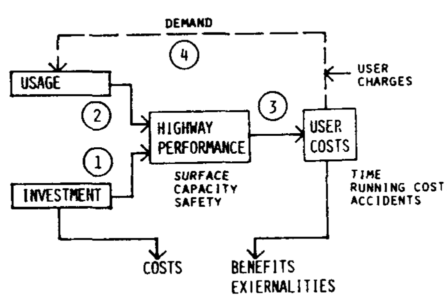


Table 3. ADT and average capital replacement cost per vehicle mile by functional system.

	Rural		Urban	
System	ADT	Dollars/ VMT	ADT	Dollars/ VMT
Interstate	11 681	0.06	47 932	0.07
Arterial	3 189	0.10	11 206	0.09
Collector	668	0.18	3 241	0.16
Local	102	0.27	962	0.11

Figure 3. Functional relationships between highway costs and benefits.



cluded) varies less than ADT but also suppresses some variation. Thus there are probably some urban Interstate segments the average depreciation costs of which exceed 27 cents/vehicle mile and some rural locals the costs of which are less than 6 cents/vehicle mile. No private operating or travel time costs are included in these figures; they are solely for the capital cost of the facilities.

With current user charges running about 1.5 cents/vehicle mile overall, users are not being asked to demonstrate a willingness to pay the long-run costs. The benefits to the users may exceed the costs incurred, but the evidence must come from sources other than, or in addition to, user charges. For the relatively low-volume rural roads, it seems unlikely that users would undertake nearly as much travel as they now do if user fees averaged 27 cents/vehicle mile. Although state and local taxpayers might be willing to carry some portion of the total cost, there is reason to doubt that they would tolerate general tax increases of the magnitude that would apparently be required.

Another dimension of the existing system is who uses it. The breakdown by VMT for 1977 (5), shown below, indicates that perhaps as much as 90 percent is passenger travel if pickups and vans are used primarily for that purpose. At the other end, about 5 percent of the travel is by heavy trucks. As a rough generalization, congestion is caused by passenger vehicles and pavement wear is caused by heavy trucks.

Vehicle Class	VMT (%)
Primarily passenger	
Motorcycle	0.8
Small automobile	15.4
Standard automobile	59.3
Pickup and van	17.6
Bus	0.4
	93.5
Freight vehicle	
Single-unit truck	1.9
Combination < 70 000 lb	2.7
Combination > 70 000 lb	1.9
	6.5

The VMT distribution by vehicle class is not the same across functional systems, so heavy vehicles are more likely to be concentrated on heavy-duty Interstates and primary roads. Under certain conditions, however, a very small amount of heavy-truck VMT on light roads can result in very heavy damage.

Thus the highway system overall is characterized by extremely skewed distributions. High VMT and high construction costs are concentrated in a small area of road mileage; heavy weight and high VMT are concentrated in a few vehicle classes. Small errors in measuring the parameters of these distributions at critical points may lead to large errors in investment programming and pricing, whereas large errors at other points may make very little difference.

CRITICAL INFORMATION NEEDS

Improved understanding of four types of relationships will be essential for sound management of the highway system in the coming decades. The four kinds of relationships, illustrated in Figure 3, are as follows:

1. Effects of improvements (surfacing, widening, strengthening, etc.) on highway performance characteristics (capacity, surface quality, safety);
2. Effects of use (freight and passenger vehicle travel) on highway characteristics;
3. Effects of highway performance characteristics on user costs (time, running costs, accidents); and
4. Effects of user costs and user charges on highway use.

In addition, information that will allow the impacts of improvements, user costs, and externalities to be stated in common units (such as dollars) is also needed.

Improvements and Highway Performance

On one side are expenditures for overlays, bridges, lanes, shoulders, medians, grading, tunneling, land acquisition, signing, signals, pavement markings, maintenance, repair, landscaping, and other construction and operating activities. On the other side are capacity, surface quality, strength, design speed, directness of route, safety, and other qualities associated with the service being provided. Relationships between the two sides include estimation of the expected life of pavements and geometric design.

Of the four kinds of relationships, effects of improvements on performance are the best understood. There is still much that is missing or could be improved, however, such as matching the incremental costs of different types of improvements in alternative combinations with the resulting performance changes.

Use and Highway Performance

The two primary variables here are congestion and pavement wear. Although both have been the subject of much attention, the basic empirical information is still weak. Consumption of capacity is measured in passenger car equivalents (PCEs), and the contribution of a given vehicle varies with the size and performance characteristics of the vehicle, the grade and other geometrics of the highway, and the mix of vehicles in the traffic stream. Each of these general sets of variables includes many specific measures, and the interrelationships between the sets are often important. For example, a vehicle that has a low power-to-weight ratio in mountainous terrain possesses a much different PCE on a two-lane road than on a four-lane road.

Pavement wear is thought to increase with the fourth power of the weight on the axle, a relationship that implies a high sensitivity at the heavy end. Aggregate evidence that Interstate highways are wearing out faster than expected suggests the importance of a better understanding of the usage-damage relationship. Weather and soil conditions are known to affect the vulnerability of pavement to axle-load applications, but the statistical experiments needed to verify and extend the relationships have not been undertaken.

Highway Performance and User Costs

Time has value to travelers as productive working time lost or foregone leisure and to goods movement as inventory costs. Pavement quality affects speed, wear, fuel consumption, and accidents. Geometric design and traffic volumes affect accidents as well as time and running costs. The relationships among these variables are, as with many of the other important relationships, highly nonlinear. Congestion reduces fatalities over at least some ranges, and poor pavement quality may have no effect on speeds for some geometrics. Many of these relationships are poorly understood, yet they are basic to the evaluation of investment in highway improvements.

User Costs and Demand

An essential relationship that has been almost completely overlooked is the demand for highway travel as a function of highway user fees and the performance characteristics of the highway system. Reduced pavement quality increases travel time and running costs, and this undoubtedly has a price effect on use, but the elasticities have been only roughly approximated.

Data Collection

Better information about these relationships will be acquired only by monitoring highway performance and travel over a substantial period of time, and these data-collection activities should be regarded as part of a continuous effort. Expenditures need to be tabulated by functional improvement and location so they can be linked to other data on segment-specific characteristics of use. Weigh-in-motion capabilities have improved to the point where no disruption of the traffic flow is necessary (for example, by using bridges). Measurement, recording, storage, and analysis of data can be heavily automated at unit costs that are steadily declining. Many kinds of data are available simply by tapping into an already existing data flow. These can be supplemented with case studies and specific highly focused sampling experiments and other low-cost studies. The most critical deficiency at present is the lack of an experimental design framework that will allow the data that are collected to be used for improving understanding of the key relationships.

ANALYSIS NEEDS

The data and empirical relationships described above are useful for many aspects of highway system management, but only three will be selected for further discussion.

Improvement Programming

Evaluation of the trade-offs among different types of improvements and different locations needs to be done in a way that allows the benefits of an improvement to be related to its costs. Current practice avoids this question by assuming that the budget to be spent is determined exogenously, and the only analytic problem is to prioritize improvements among the set of those available. The possibility that the budget might be sufficient to include some projects that are not worthwhile is not admitted, and the methods for prioritizing do not illuminate the trade-offs among types of improvements and locations.

A benefit-cost framework is clearly the suitable model for improvement programming, and using even the data that are currently available would produce better results than typical practice, with less effort. Without better information on performance characteristics and user costs, however, there is no method that will efficiently allocate resources to incremental highway improvements.

User Charges

The notion that users should pay something for the use of the highways has been accepted for a long time, but the concept that users should pay the economic costs of their use has not yet been established as clearly in the highway sector as it has in such areas as telephone service and utility rate structures. Deriving the maximum benefit from the highway system requires implementing user charges that more closely approximate the costs of use. If future investment in highways is to be concentrated in the most productive links and kinds of improvements, information on user benefits as derived from evidence of willingness to pay will be a necessary ingredient. Moreover, well-designed user charges will provide signals to users about how they can best economize (such as by spreading heavy loads onto more axles) on scarce highway resources. Financing the highway system calls for determining which vehicle classes to get the revenues from and which segments can only be supported if nonusers pay for them.

Design Standards

In the debate over the completion of the Interstate system, it has been recognized that design standards are not immutable and inviolable truths. In fact, many design standards are not cost-effective in many of the situations to which they ostensibly apply, and either the standards have been compromised in practice or overdesigned facilities have been constructed. While standards have many benefits, including the savings from not having to calculate the optimal design from scratch in each situation, they are only approximations to good solutions at best. At worst, they force expenditures for design characteristics that do not justify their costs.

Design standards can be evaluated from the benefit-cost perspective, drawing on the same body of information that improvement programming and user charge design do. With major expansion of the highway system no longer a likely future scenario, the costs of overdesign may be just as great as the costs of underdesign.

WHAT CURRENT PRACTICE CAN BE DELETED?

Most of the monitoring and evaluation activities that have been described above could be carried on with little or no additional cost if some of the less productive activities currently undertaken were reduced or dropped. State highway planning varies greatly from state to state, but several kinds of analysis are typical of many state agencies and are representative of the practice that could be improved.

Sufficiency Ratings

A messy and awkward analytic process, the construction of sufficiency ratings, is based on such weak and ad hoc information that the results contain very little of value. The same amount of analytic effort could be used with much of the same or substitutable data to produce more useful evaluations of the incremental benefits and costs of alternative improvement projects and programs.

Long-Range Plans

Major multiyear long-term capital planning never reached a very high level of development in most states, and the need for such planning has fairly obviously declined. The method lingers on, however, because many planners believe that not having a plan is professionally irresponsible. Streamlined versions are available for those who still need to make plans, and other programming techniques can be used by those less constrained.

Cost-Allocation Studies

There is often a political need for some document that will justify raising fuel taxes by a few cents, and budget-allocation studies have generally served this purpose. Highway user-charge design is, as already stated, a very important function for state highway planners, but elaborate cost-allocation studies are not the technically sound route to this end. If budget-allocation studies are inescapable, they can still be done with an eye toward minimizing their costs.

Indirect-Impact Studies

Studies of land use around interchanges and the multiplier effects of highway construction employment on local communities have little relevance to highway investment decisions, and they are generally unnecessary for other purposes as well.

CONCLUSIONS

The success with which states finance their highway programs in the next decade will depend on two analytic capabilities: the design and implementation of efficient user-charge instruments and the selection of links and subsystems in which to invest.

User-charge design requires knowledge of the economic costs created by each vehicle class on each type of road under relevant conditions; investment programming requires knowledge of how improvement costs translate into benefits. For these kinds of tasks, information is needed on four kinds of relationships: improvements and highway performance, use and performance, performance and user costs, and user costs and use. Both the structural knowledge of these relationships and their empirical calibration have been insufficiently developed to support current analysis needs, and the bulk of the job of creating this information base is likely to fall to the states.

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Publication of this paper sponsored by Committee on Statewide Multimodal Transportation Planning.