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Joint Institutional Transportation Systems Management Program

WILLIAM H. DIETRICH, MICHAEL A. KENNEDY, AND JON TWICHELL

In San Francisco, as in many cities, institutions located in residential neighborhoods outside the downtown business district generate traffic and parking conditions that pose concerns for area residents and for the institutions themselves. An approach to transportation systems management (TSM) undertaken by the city of San Francisco and a consortium of 14 major institutions in response to the transportation problems of institutions in urban residential neighborhoods is described. The objectives of the joint TSM program are to reduce automobile parking and traffic impacts by means of low-capital-cost measures such as ridesharing, public and private transit services, parking management, and marketing incentives and to foster economies of operation through the institutions' cooperative efforts. The successful implementation of TSM measures at three of the participating institutions demonstrates the validity of the approach and provides a means for the early evaluation of the total program.

The San Francisco Department of City Planning and a consortium of 14 major institutions (nine hospitals, four colleges or universities, and a private insurance company) located in neighborhood districts are participating in the San Francisco Joint Institutional Transportation Systems Management (TSM) Program. The objectives of the TSM program are to reduce automobile parking and traffic impacts at each institution by means of low-capital-cost measures such as ridesharing, public and private transit services, parking management, and marketing incentives and to achieve greater impact through cooperative efforts among the participating institutions.

This joint-action TSM program, initiated and run at the institutional level, is the first of its kind in the nation and is a test case for potential application to other cities throughout the country.

PROGRAM ORGANIZATION

The overall program is organized into four phases:

1. TSM plan development,
2. Transportation broker training,
3. Program implementation, and
4. Evaluation.

Phase 1: TSM Plan Development

The first phase identified appropriate TSM actions, set working goals, and served as a reference guide during the implementation phase. Specific steps in the development of the TSM plan are to

1. Compile available transportation data and information;
2. Conduct and analyze employee travel surveys;
3. Survey existing and planned public transit to the facility, use of on-site parking, traffic conditions in the areas, and transportation programs;
4. Identify and recommend TSM measures appropriate to each institution, stressing practical actions and joint efforts; and
5. Set TSM program goals and specify implementation activities.

Phase 2: Transportation Broker Training

As a requirement of program participation, each institution designated at least one individual, a transportation broker, to assume responsibility for implementation of the TSM plan. Concurrent with the planning study, a transportation broker training course was conducted; it involved 10 classes of 3-4 h each. The course covered all aspects of TSM, including ridesharing, carpooling, vanpooling, club buses, parking management, transit, marketing, and institutional-management responsibility. Experts and managers of these various types of systems served as guest lecturers.

Phases 3 and 4: Program Implementation and Evaluation

The final two phases of the overall program are in process. The implementation phase has already begun under the direction of the transportation brokers. It will take several years to fully implement the plans and to accomplish their goals, but much of the groundwork is being laid in the first year. The fourth phase, that of evaluation and program monitoring, will be a continuing task.

EXISTING CONDITIONS

Employment

Employment varies considerably among the institutions. The largest single employer, the University of California at San Francisco (UCSF), has some 5700 faculty and staff members. Most of the other institutions employ 1000 to 2000 employees. In terms of total site population, however, the campuses of City College of San Francisco and San Francisco State College far exceed all other institutions since they have student enrollments of approximately 25 000 each.

Work Schedule

The various hospitals surveyed operate around the clock with several fixed work shifts. A smaller portion of their employees are on standard daytime work schedules than is the case with other types of employers. Similarly, daily and semester attendance patterns of college students and faculty members can be irregular and can include a significant number of nighttime travel activities.

The variation of employee work schedules has important effects on ridesharing and transit potential since it makes it more difficult to match commuting times on a regular basis and since significant travel takes place at night, when transit service is curtailed. Two institutions have adopted flexible work schedule policies designed to make it easier to share rides and to use transit service.

Means of Commuting

At all institutions except UCSF and Fireman's Fund, employees commute primarily by single-occupant automobile. Similarly, only at City College and UCSF do less than half the students drive alone. In most cases, public transit is the second most frequently reported means of commuting (typically somewhat less than one-fourth of the employees and students). In the case of City College, however, more than half of its students use public transit on a regular basis.

Carpooling exists at all institutions but only to a relatively limited extent. Buspools are operated at only two of the institutions--UCSF and Fireman's Fund--and significant numbers of vanpools operate only at UCSF.

Residence Locations

The nature of transportation services available to employees is highly dependent on residence location. Almost two-thirds of the hospital employees live within San Francisco. Fireman's Fund and campus employees have a greater tendency to live outside the city; for the most part, students tend to live in the city (indeed, virtually all City College students reside in San Francisco).

General residence is correlated with mode choice for commuting. The greatest use of single-occupant cars for commuting is by employees who live outside the city, particularly on the peninsula. This reflects the lengthy and difficult transit access from those areas.

POTENTIAL FOR TSM IMPROVEMENTS

The process for determining potential TSM improvements at each institution consisted of

1. Identification of existing transportation deficiencies,
2. Review of employee perceptions about transportation alternatives,
3. Consideration of neighborhood concerns about parking,
4. Consideration of the implications of the San Francisco Municipal Railway (Muni) five-year plan,
5. Identification of candidate TSM measures, and
6. Evaluation of TSM potential and development of the TSM program.

Existing Transportation Deficiencies

Assessment of the institutions' existing transportation services reveals the following general areas for improvement:

1. Ridesharing--Although a few of the institutions promote carpools, vanpools, and buspools, there was general need for incentives to be provided and pooling programs made visible to employees.
2. Public transit--Because the institutions are located away from the downtown focal point of local and regional transit services, they are difficult to serve well by transit. Although deficiencies are specific to each institution, in general it is observed that direct crosstown service is lacking and that in many cases access to regional transit systems requires more than one transfer or a circuitous trip.
3. Parking--At all institutions, parking is heavily used and spillover onto neighboring residential streets occurs. In many instances, parking is provided free or at low cost to employees, and no preference is given to carpoolers.
4. On-site marketing--In general, the institutions currently do little to inform employees of alternatives to the single-occupant car or to encourage their use.

Employee Perceptions About Transportation Alternatives

The travel survey asked questions about employee attitudes and interest in ridesharing and in transit. The responses reflect a general interest in any form of ridesharing, provided work schedules would be satisfied. A significant number of employees were dissatisfied with transit reliability, service frequency, directness of service, and, in certain areas of the city, safety.

Neighborhood Concerns About Parking

One of the major concerns being addressed by the TSM program is parking spillover into residential areas. Interest within San Francisco for neighborhood residential parking programs is strong and will probably continue to grow over the next few years.

Muni Five-Year Plan

Major transit service improvements are scheduled or proposed in the next five years; some of these could significantly benefit the TSM program participants. The Muni five-year plan contains recommendations for a comprehensive restructuring of Muni transit routes. The existing radial system that focuses on the downtown would be reoriented toward a grid system that would concentrate more service into north-south and east-west routes. This would greatly improve crosstown transit service and reduce service duplication to the downtown area.

EVALUATION OF TSM POTENTIAL AND DEVELOPMENT OF TSM PROGRAM

Various TSM measures were evaluated in light of the nature of each institution and its workforce, potential to resolve identified transportation deficiencies, and potential for implementation at the institution. Inappropriate measures were screened out and a comprehensive TSM program was developed that was tailored to the specific needs and constraints of the particular institution.

Candidate TSM Measures

A comprehensive range of TSM measures was considered:

1. Ridesharing--carpools, vanpools, buspools;
2. Transit--modifications to Muni five-year plan proposals (or interim route changes) to improve service to specific institutions and special shuttle services to supplement Muni;
3. Parking management--measures to favor carpool parking priority, short-term parking, parking-fee changes, bicycle-parking provisions, etc.;
4. Traffic operations--low-capital-cost measures to improve intersection operations and parking-lot access and egress;
5. Marketing--on-site transportation-information dissemination, advertising, and promotion of alternatives to the car; and
6. Administration--transportation brokers, employee transportation committees, and ongoing program evaluation.

Goals for the TSM Program

It is important to set goals for the TSM program that address the major transportation concerns at each institution and that are realistic. Two concerns are most apparent: those of parking and of traffic congestion. These concerns are shared by both the institutions and neighborhood residents, and the problem is frequently an existing one rather than one keyed to projected growth.

The primary goal of the TSM program, then, should be to reduce parking and traffic generated by the institution's population by attracting more

commuters to ridesharing and to mass transit.

Specific target levels were suggested for each institution. Essentially, the goal is for a significant reduction in the number of single-occupant automobile drivers to each institution, since the private car is the predominant means of transportation to most institutions among both employees and students.

EARLY EVALUATION

UCSF

UCSF is at the forefront in terms of its commitment to reduce impacts through TSM measures. UCSF's transportation program consists of carpool rider matching, vanpools, buspools, shuttle-bus service, marketing parking management, and other measures to promote use of these services. UCSF has committed three transportation coordinators to implement and administer the various transportation services offered. In addition, committees on parking and transportation deal with campus-related transportation issues as an ongoing activity.

The UCSF transportation program has reduced overall vehicle traffic generated by the campus by 8 percent in relation to levels that would be expected in the absence of the program. The program effected a 2 percent net reduction from 1974 traffic levels, even though campus population has grown by 5 percent since that time. The reduction in traffic generated has reduced parking space needs, vehicle miles of travel (an indicator of energy consumption and automobile-pollutant emissions), and user costs. Approximately 1200 employees and students (20 percent of the UCSF population) participate in 6 buspools, 30 vanpools, and 200 carpools, compared with some 200 persons in carpools and no buspools or vanpools in 1970. Overall, two-thirds of the daily employee, student, and visitor trips to UCSF are not made in single-occupant automobiles.

Fireman's Fund

Fireman's Fund has successful club-bus and vanpool programs that account for more than 40 percent of employee work trips. At present, 2 club buses, 3 vanpools, and 105 carpools are operating at the facility. Another 15 percent of the employees use transit. Thus, the ridesharing program is at a level equal to the goals for other institutions.

Children's Hospital

Children's Hospital has had a transportation broker implementing TSM measures for the past year. The program at Children's Hospital, assisted by neighborhood permit parking and parking-management measures in their garage, now includes 60 three-person carpools, monthly transit-pass sales of 100, a paratransit shuttle system that is in the process of being implemented, new-employee orientation, extensive marketing, and the placing of Children's Hospital employees in joint carpools, vanpools, and buspools cooperatively with at least six other participating institutions. Of about 750 day-shift employees, Children's Hospital estimates that close to half use ridesharing, transit, or other nonautomobile means to make their work trip. One unique feature at the hospital is a 15-person carpool. Since nursing and other work assignments at the institution are so variable with respect to day and time, whichever members of the pool are working that day meet at a specific staging point and take only as many vehicles as are needed to get the group to work.

CONCLUSIONS

Several unique features of the San Francisco TSM program deserve highlighting. First and foremost, this is a working program, not a planning exercise. This TSM program reduces automobile trips, makes more efficient use of present resources, promotes ridesharing and transit, improves neighborhood relations for the respective institutions, and provides a valuable employee benefit. The continuing day-to-day work of the transportation broker is the heart of the program. The enthusiasm and commitment of the broker determine the relative success of the program. The program is ongoing; continuity is maintained through a cooperative transportation brokers' association.

Second, a collective program is much more effective than focusing on a single cure-all such as carpools or express buses. Ridesharing, transit marketing, parking management, and new-employee orientation are all cumulative in their impact.

Third, joint actions by institutions located relatively close to one another make feasible measures that, if undertaken by an individual institution, would be clearly unsupportable for want of a sufficient number of users. For instance, the requisite numbers of individuals to form a buspool or vanpool can be grouped readily from travelers to two or three institutions separated by a few city blocks. Similarly, sufficient patronage to justify express suburban transit links can be developed if the service is tailored to link groups of institutions with the corridor. Although there are substantial variations among characteristics and needs of travelers to the various institutions, joint action makes it possible to offer more types and levels of service and to make such service responsive and attractive to greater numbers of people.

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Forecasting Energy Impacts of TSM Actions: An Overview

JANIS M. GROSS

This report summarizes the findings of a recent extensive study to determine the energy savings of transportation system management (TSM) actions taken or planned in New York State for 1978-1980. For those actions planned for implementation by 1980, both the direct energy savings and the energy costs of construction and maintenance were quantified. The main determinants of an action's savings are its effects on vehicle kilometers of travel and on travel speeds. Energy costs result from the manufacture, construction, installation, operation, and/or maintenance of the facilities and equipment required for each action. The analysis found net energy savings of 86.9, 96.9, and 106.7 million equivalent L (22.9, 25.5, 28.1 million gal) of gasoline for 1978, 1979, and 1980, respectively (approximately 0.5 percent of the total annual gasoline consumption in the state). Actions that conserve the largest overall amounts of energy are traffic operational improvements, ridesharing activities, passenger amenities, computerized traffic control systems, improved transit marketing, reduced off-peak transit fares; and park-and-ride services. Certain other TSM actions, including demand-responsive transit services and express bus services, have a negative net energy impact. On the average, energy costs represent approximately 15 percent of energy savings. Energy savings occur in all urban areas of the state, but 65 percent of the savings occur in the New York City area.

Conservation of transportation energy in New York State is important for several reasons. First, since transportation consumes approximately 25 percent of all energy resources and 50 percent of all petroleum (1), conservation in this area will significantly affect total energy consumption. Second, foreign sources provide New York State with 60-70 percent of its total petroleum, compared with 50 percent for the United States as a whole (2). Thus, New York State is particularly vulnerable to cutbacks in foreign oil supplies. Conservation in the transportation sector will reduce this vulnerability.

Because of the importance of conserving transportation energy, New York State developed its State Energy Conservation Plan. This plan called for an annual transportation energy saving of 1.1 billion L of gasoline (293 million gal) by 1980. The State Energy Office and New York State Department of Transportation (NYSDOT) have entered into an agreement whereby NYSDOT will assist the State Energy Office in implementing, revising, and refining the following elements of the plan: transportation system management (TSM) plans, right turn on red, 88-km/h (55-mile/h) speed limit, and carpool-coordinator demonstration program.

The most recent estimates of savings realized by each of these activities are 106.7 million L of gasoline (28.1 million gal) for TSM plans in 1980, 29.3 million L (7.7 million gal) for right turn on red, 0.8 million L (0.2 million gal) for the carpool-coordinator demonstration project in 1979, and a net loss in 1978 compared with 1977 of 2.7 million L (0.7 million gal) for the enforcement of the speed limit. Savings for the carpool-coordinator demonstration project are small since it was only carried out among a small group of state workers in Albany, New York. The projected annual savings for this project were almost 1100 L/carpooler. The estimated loss for enforcement of the speed limit arose because of recently reduced compliance.

This paper documents findings about TSM plans. It is a summary of an extensive report (3) that describes the findings and methods in greater detail.

TSM elements of long-range transportation plans were first required in the joint Urban Mass Transportation Administration and Federal Highway Administration regulations issued on September 17, 1975. TSM actions are intended to increase the capacity and efficiency of the existing transportation system by improving traffic flow, smoothing out peak-period loads, or diverting automobile drivers to high-occupancy modes. General categories of TSM actions include (a) actions to ensure efficient use of existing road space, (b) actions to reduce vehicle use in congested areas, (c) actions to improve public transit service, and (d) actions to improve internal transit-management efficiency. These general categories of TSM actions can be broken down into 33 specific actions. A list of actions and their occurrence in eight sections of New York State are shown in Table 1.

Because of their potential to reduce travel demand and to increase transportation-system efficiency, TSM actions can conserve energy. Since TSM actions emphasize moving people rather than vehicles, vehicle kilometers of travel (VKT) are reduced and/or travel speeds are increased, which results in a reduction in energy consumption.

LITERATURE REVIEW

Several studies have examined the travel impacts of specific low-cost transportation actions. These include a review of recent experience with TSM and TSM-type actions (4-6), an examination of actions that can reduce peak-period traffic congestion (7), an analysis of activities that can improve air quality (8-10), and an analysis of actions that can be taken to reduce energy consumption (8). In general, these studies have based their analyses on a review of actual case studies in which each of the actions has been implemented.

Several of these studies have concluded that the impact of TSM-type projects on VKT and on travel speeds is small (6-8,10); these studies indicate that these actions have other benefits. In addition, several indicate that appropriate packaging of TSM actions can increase their effectiveness.

OVERVIEW OF METHODS

To estimate the energy impact of TSM actions, both the energy savings and energy costs associated with each action were determined. Generally, savings result from the travel impacts of each action in terms of changes in VKT and speeds. Energy costs are incurred in the construction, installation, operation, and maintenance of specific transportation facilities. The difference between the savings and costs is the net energy savings.

These estimates were made on an annual basis by urban area for the years 1978, 1979, and 1980. Only those projects expected to be completed by the end of 1980 were included in the analysis. The calculations can be represented as follows:

Net energy savings = energy savings - energy cost.

Energy savings = [(Δwork VKT - Δnonwork VKT) ÷ L/km] + (areawide VKT x ΔL/km).

Table 1. Status of TSM actions by metropolitan planning organizations in New York State as of 1978.

TSM Action	Tri-State (NYC)	Capital District	Utica-Rome	Syracuse	Rochester	Buffalo	Binghamton	Chemung (Elmira)
Efficient use of road space								
TOPICS, signal improvements	T,I,P,S	T,I,S	T	T,I,S	T,I,S	T,P,S	T,S	T,I,S
Computerized traffic control system	T,P,S	I			S			
Access ramp metering	S							
One-way street conversion								
Preferential lanes for HOVs	T,P,S			T	T,P	T		
Preferential treatment at toll plazas	S							
Preferential access ramps	S							
Traffic improvements for buses				S		S		
Provisions for pedestrians	S			T	T			
Provisions for bicycles	T,I,P,S	T,I,P	T	T,S	T,S	T	T,S	S
Reduced number of parking spaces	T,S	S		S				
Increased parking rates					T			
Differential parking rates	T							
Parking permit system								
Limited parking with new construction								
Transportation corridor parking	T,I,P,S	T		T				
Work-hour policies	T	T		T	T		T	
Car tolls to reduce peak-period travel	S			S				
Reduction in off-peak transit fares	T	T	T	T	T	T	T	T
Reduction of vehicle use in congested areas								
Ridesharing	T			T,S	T,I		I	S
Car-restricted zones	T,S		T	S	S	T,S		
Truck restrictions	T,I,P,S							S
Improved transit service								
Routing, scheduling, and dispatching improvement	T,P,S	T	T,S	I,S	T,S	S	T,I,P,S	T,S
Express bus service	T,S			T				
Park-and-ride service	S			T,P	T,S			
Shuttle transit services to CBD	T,P	T,P		T,S	T			
Passenger amenities	T,I,P,S	T,I	T,I,P,S	T,I,P	T,I	T,I,P	P,S	I,P
Improved fare-collection systems	T,I,P,S			T,I	T		T	T,I
Improved passenger information	T,I,P,S	T,I	T	T	T,P	T	T,P	T
Demand-responsive services	T,I,P,S	T,I,P	T,I,P	T,P,S	T,P,S	T,I,P,S	P,S	T,P
Increased transit management efficiency								
Improved maintenance	T,I,P,S	T	S	T,I,P,S	T	I,S		
Improved monitoring	T,I,P,S	T,I		T,I,S	T,P,S	T,I,S	T,S	
Improved marketing	T,I,P,S	T,I,P	T,I,P	T,I,P,S	T,I,P,S	T,I,P	T,I,P	T,I,P

Note: T = actually taken, I = in implementation, P = planned, and S = study; TOPICS = Traffic Operation Program for Increasing Capacity and Safety.

Energy costs = [capital energy cost per unit x number of units x (1/service life of project)] + (annual maintenance cost per unit x number of units).

The second term in the formula for energy savings arises from changes in consumption resulting from speed changes. For the most part, projects were analyzed individually rather than as part of packages of several projects. This was done because generally TSM actions in New York State are not implemented in a coordinated manner.

Energy Savings

No generalizations can be made concerning the methods used to estimate the VKT and speed changes required before energy savings can be calculated. These procedures included assignment-based techniques, traffic-flow approaches, and transit fare and service elasticities. The following briefly identifies the approach used for different types of TSM actions.

1. Standard approaches for measuring changes in traffic flow were used for those TSM actions that are intended to reduce travel-time delay and/or to increase travel speeds. Actions included here were traffic-operations improvements, computerized traffic-control projects, access-ramp metering, and truck restrictions.
2. Assignment-based techniques were employed for those actions whose effect on the highway network could be readily simulated. TSM actions in this category are work-hour policies and automobile-restricted zones. The analysis of automobile-restricted zones was supplemented by specific project-level data, when available.
3. Travel-time elasticities between automobile and transit were used in those instances in which the action's impact was on travel times. TSM actions evaluated in this manner were preferential lanes for high-occupancy vehicles (HOVs), preferential treatment at toll plazas for HOVs, preferential access ramps for HOVs, traffic operational improvements for buses, and bus-rerouting projects involving schedule changes. In all but the last two cases, traffic-flow techniques were then employed to determine the effects of the HOV and non-HOV lanes on speed changes.
4. Travel-cost elasticities between transit and automobiles were employed for these TSM actions that include a price change. This includes automobile tolls to reduce peak-period travel, reductions in off-peak transit fares, increased parking rates, and differential parking rates.
5. Transit-service elasticities were used for those rerouting projects that increased service to areas that already had transit, provided service to new areas, or rerouted existing bus kilometers of travel.
6. Case study approaches that applied the experiences of areas that have projects similar to

New York State's were used where other techniques were not appropriate, did not exist, or were too costly or time consuming. This includes one-way-street conversion, ridesharing, park-and-ride service, corridor parking projects, transit passenger amenities, improved transit passenger information, transit monitoring, shuttle transit services, and express bus service. For the last two actions, this technique was used only when specific project-level data were not available.

7. A review of the trip characteristics of potential users was employed for those actions for which it was felt that this was an important factor in possible diversion from driving an automobile. The specific actions studied in this manner were pedestrian facilities and bicycle facilities.

8. Project-level data were used to analyze those projects for which information was readily available. Included here are improved fare-collection projects, demand-responsive transit services, shuttle transit services, and express bus services. Data collected during the planning for similar projects in other areas were employed to analyze the effect of reductions in the number of parking spaces.

For certain types of actions, the analysis procedure cannot be generalized. This applies to improved transit maintenance, limiting parking with new construction, and parking permit systems.

In addition to the procedures identified above, it was also necessary to quantify certain factors (prior mode and use of a car left at home) when a mode change or increase in use resulted from a TSM action. Prior mode was estimated based on case studies of similar projects.

The reason for introducing a term associated with the use of a car left at home is that failure to do so would result in an overestimate of savings. Suppose a person in a one-car family that has two automobile drivers does not use a car for the work trip but instead (as a result of the implementation of a TSM action) uses bus as a mode. In this case, the actual energy saving will be less than the gasoline that the driver formerly used for the work trip. The savings are less because the car left at home is available for use by the other driver in the household for nonwork purposes. Use of a car left at home (the nonwork VKT shown in the savings formula) was estimated by comparing household VKT for households for which the mode to work is driving with that for households for which it is not. It was found that use of the car left at home resulted in a net household VKT saving of 60 percent of the VKT saved during the work trip.

Other second-order travel impacts were not considered at this time. These include switching to car travel because of reduced congestion, the impacts certain TSM actions might have on location and land use decisions, and decisions about car purchasing. These impacts are more long term in nature and would probably not manifest themselves until after 1980.

Once changes in VKT were determined, changes in fuel consumption were calculated by using the following overall average over-the-road New York State efficiencies (11): 1978 = 4.9 km/L (11.6 miles/gal), 1979 = 5.0 km/L (11.9 miles/gal), and 1980 = 5.2 km/L (12.3 miles/gal).

The data from 1971 (12), updated to the specific years analyzed, were used to determine changes in fuel consumption resulting from speed changes.

Energy Costs

The values for energy costs given in this paper refer to energy costs that arise from the manufacture and installation of equipment, the operation and maintenance of the facilities, and the energy costs arising from the construction of structures, roads, etc. Other sources of cost such as the use of the car left at home are reflected in the savings figures. Energy costs as well as savings must be determined so that a fair assessment of TSM energy impacts can be made.

The methodology used in estimating costs is very simple. There are four key steps in the process: (a) consider aspects of the action or project that result in the consumption of energy, (b) estimate the life of the project, (c) determine the appropriate energy factors, and (d) apply the basic formula. The basic formula is

Annual energy construction cost = energy cost per unit (e.g., per dollar) x number of units (e.g., dollar cost) x (1/service life of project, e.g., 10 years).

In many cases an additional annual maintenance or operating cost should be added to the result of the above calculation in order to obtain the total annual energy cost.

Published values for energy cost per unit generally reflect total energy cost. If it is deemed appropriate to amortize these costs annually, it is necessary to know the life of the project. Table 2, taken from a New York State source (13) gives service-life estimates for a range of actions. Our study simply assumed that if the life of the project is, for example, 25 years the annual energy cost associated with construction would be one-twenty-fifth of the total energy figure. Given the uncertainty in energy estimates, an amortized estimate based on interest rates would not be appropriate. The energy costs contained in this report represent annual cost.

The first step in the process to determine sources of energy consumption requires research by the analyst and, ideally, extensive knowledge of the project or action. A reasonably good estimate suitable for an environmental impact statement (EIS) can be made by using information from similar projects. It is easy to overlook certain sources of energy consumption, but such omissions made by a careful analyst should be minor ones.

Estimates of project life for this study were made by using the numbers given in Table 2 that were deemed most appropriate. The values for energy cost per unit needed for the use of the basic formula were obtained for most projects from the literature.

The most complete source of data on the energy costs of transportation actions is Energy and Transportation Systems (14). Although many numbers in that document are based on California's experience, sources that contain information for all states (15) generally show the energy costs to be similar. Thus, the use of California numbers should give acceptable results for planning purposes elsewhere.

It should be noted that numbers that reflect manufacturing energy costs will yield energy costs that truly reflect energy for New York State only when all manufacturing is done in New York. Normally, some equipment, asphalt, and so on will be manufactured outside the state. In that event the energy cost is a cost to the nation generally, though not necessarily to New York. Such possibilities, however, are not considered here.

The information provided in terms of energy cost per dollar does not generally use 1979 dollars but those of some other given year. Therefore, they were converted by using the formula

Energy per \$ (1979) = energy per \$ (given year) x (consumer price index for given year/consumer price index for 1979).

Table 2. Improvement service life (maximum).

Improvement	Service Life (years)
Right-of-way, obstacle removal	100
Major structures	30
Major geometrics (change of intersection configuration, curve flattening, etc.)	20
Concrete barrier (median or half section)	20
Minor geometrics (left-turn lanes, channelization)	15
Lighting	15
Major sign structures	15
Metal median barrier	15
Signals and flashing beacons	10
Resurfacing (2.5 in)	10
Minor signing	10
Metal guide rail	10
Armor coat (1 in)	7
Concrete pavement grooving	
<10 000 AADT/lane	7
>10 000 AADT/lane	5
Delineators and guide markers	5
Asphalt pavement grooving	
<10 000 AADT/lane	5
>10 000 AADT/lane	4
Oil and stone	4
Shoulder stabilization	4
Pavement markings	
Thermoplastic	
Minimum	3
Maximum	7
Paint	0.5

Note: AADT = annual average daily traffic.

FINDINGS

The 1978-1980 analysis of TSM actions implemented and planned in New York State found that the following energy savings, costs, and net savings in equivalent liters of gasoline (EqL) will be realized:

Year	EqL (000 000s) Savings	Costs	Net Savings
1978	101	14	87
1979	114	17	97
1980	128	21	107

A summary of these findings by TSM category and year is shown in Table 3. The net savings figures represent aproximately 0.5 percent of the total gasoline consumed annually in the state. Energy savings are distributed among all four general categories (see Table 1) of TSM actions. However, only seven actions account for more than 90 percent of the total savings. These actions that conserve a relatively large amount of energy are traffic operation improvements, ridesharing activities, passenger amenities, computerized traffic control systems, improved transit marketing, reduced off-peak transit fares, and park-and-ride services.

Few generalities can be made about the types of actions that are the most effective. One obvious observation is that they are mostly transit actions. This occurs because the majority of TSM actions taken across New York State are transit oriented. Generally, transit actions and ridesharing induce people to leave their cars without increasing nonautomobile VKT. Thus, no offsetting energy cost occurs.

Several of the actions are very successful because of the large number of projects being under-

Table 3. Estimates of gasoline savings and costs for TSM actions that will be implemented by 1980.

TSM Action	EqL (000 000s) 1978 Savings	1978 Costs	1978 Net Savings	1979 Savings	1979 Costs	1979 Net Savings	1980 Savings	1980 Costs	1980 Net Savings
TOPICS	22 504 033	2 104 885	20 399 148	28 759 882	3 116 441	25 643 441	30 276 488	3 238 546	27 037 942
Computerized traffic control systems	7 106 502	31 054	7 075 448	7 106 502	31 054	7 075 448	9 649 230	163 533	9 485 697
Preferential lanes for HOVs	1 270 408	12 833	1 257 575	1 226 830	12 833	1 213 997	2 249 729	216 072	2 033 657
Provisions for pedestrians	0	8 596	−8 596	0	8 596	−8 596	0	8 596	−8 596
Provisions for bicycles	0	126 103	−126 103	0	188 282	−188 282	0	245 598	−245 598
Reduced parking spaces	3 856 829	703	3 856 126	3 735 864	703	3 735 161	3 606 124	703	3 605 421
Increased parking rates	0	0	0	0	0	0	0	0	0
Differential parking rates	0	0	0	0	0	0	0	0	0
Work-hour policies	2 340 800	0	2 340 800	2 122 680	0	2 122 680	2 049 720	0	2 049 720
Reduced off-peak transit fares	7 531 775	0	7 531 775	7 295 217	0	7 295 217	7 041 305	0	7 041 305
Ridesharing	23 479 535	1 634	23 477 901	26 673 484	114	24 673 370	23 814 786	0	23 814 786
Automobile restricted zones	7 551	29 055	−21 504	7 315	29 055	−21 740	7 060	29 055	−21 995
Truck restrictions	0	0	0	0	0	0	0	0	0
Routing, scheduling, and dispatching improvements	2 296 716	744 933	1 551 783	2 237 961	744 933	1 493 028	2 226 876	869 079	1 357 797
Express bus service	262 679	820 070	−557 391	254 129	820 070	−565 941	246 126	820 070	−573 944
Park-and-ride service	7 007 964	1 573 056	5 434 908	8 203 448	1 609 615	6 593 833	8 929 726	1 637 089	7 292 637
Shuttle transit services	180 181	20 501	159 680	238 598	41 002	197 596	271 920	113 400	158 520
Passenger amenities	12 056 651	1 334 283	10 722 368	12 907 832	2 444 289	10 463 543	17 593 061	3 395 216	14 197 845
Improved fare collection	1 648 611	0	1 648 611	1 594 993	167 922	1 427 071	1 544 757	167 922	1 376 835
Improved passenger information	2 890 755	131 161	2 759 594	3 083 556	130 097	2 953 459	4 387 472	265 529	4 121 943
Demand-responsive services	643 906	5 113 082	−4 469 176	673 672	5 550 284	−4 876 612	891 662	7 860 213	−6 968 551
Improved maintenance	3 128 764	1 954 967	1 173 797	4 008 932	1 603 505	2 405 427	4 210 533	1 330 114	2 880 419
Improved monitoring	328 860	42 457	286 403	328 860	422 796	−93 936	328 860	861 703	−532 843
Improved marketing	2 554 736	131 746	2 422 990	5 473 562	151 027	5 322 535	8 796 529	167 724	8 628 805
Total	101 097 256	14 181 119	86 916 137	113 933 317	17 072 618	96 860 699	128 121 964	21 390 162	106 731 802

taken across the state. Individual traffic operational improvement, ridesharing, transit amenity, marketing, park-and-ride, and fare-reduction projects will each result in only small energy savings. However, if these small savings per project are multiplied by a large number of projects, a relatively large saving results.

Computerized traffic control systems are the only action that does not involve a large number of projects. Here, rather, savings occur because each project affects a large number of vehicles.

Certain actions have net energy costs. These include bicycle facilities, pedestrian facilities, automobile-restricted zones, express bus service, demand-responsive transit services, and improved transit monitoring. In part, these energy losses are a result of the special nature of these projects: Demand-responsive services are generally not implemented to conserve resources but to increase the mobility of special groups. Other actions such as bicycle and pedestrian facilities do not result in large energy savings but involve energy costs to construct and maintain the facilities. Though they may be expected to result in energy savings, express bus services actually cost energy because they generate additional buses with additional gasoline consumption but attract many of their riders from other transit services rather than from among automobile drivers.

There are eight actions for which no projects will be implemented in New York State by 1980. The absence of any energy savings associated with these actions (which were excluded from Table 3) is not meant to imply that, if implemented, these actions would not conserve energy. These actions are access-ramp metering, one-way-street conversion, preferential treatment at toll plazas for HOVs, preferential access ramps for HOVs, traffic operational improvements for buses, parking permit systems, limiting parking associated with new construction, and automobile tolls to reduce peak-period travel.

On the average, energy costs represent approximately 15 percent of energy savings. (The actual numbers are 14 percent in 1978, 15 percent in 1979, and 16.7 percent in 1980.) These costs are not evenly divided among the 33 actions. Some projects are implemented at no or relatively small costs, such as reduction in the number of parking spaces, work-hour policies, reduced off-peak transit fares, and ridesharing activities. Actions taken at relatively large energy costs per liter saved are routing, scheduling, and dispatching improvements; park-and-ride service; shuttle transit services; passenger amenities; and improved transit maintenance. This high cost occurs in part because these are actions that are required to generate additional bus kilometers (an energy cost) in order to attract new riders.

The energy saving is not evenly distributed in the eight urban areas of the state: 69.3 million L or 65 percent of the saving in 1980 is conserved in the Tri-State area, with the remainder saved in the seven upstate urban areas. Because of the extensive transit system, large transit ridership, and high VKT in the Tri-State area, the potential for conservation is greater than it is in upstate areas.

The types of projects that save energy are different in the Tri-State area than in the upstate areas. In the Tri-State area the following actions result in relatively large savings: traffic operational improvements, computerized traffic control systems, reduced off-peak transit fares, ridesharing activities, park-and-ride services, passenger amenities, improved passenger information, and improved transit marketing.

In the upstate areas, the list is more limited. Two actions--traffic operational improvements and ridesharing activities--account for 90 percent of the saving there. There is much less emphasis on transit-related actions, since transit ridership is low in upstate areas. Those actions intended to produce a systemwide ridership increase (such as amenities and information) have a smaller potential for impact. The large saving attributed to traffic operational improvements is in part the result of the large number of projects being undertaken throughout the state.

CONCLUSIONS

As previously stated, TSM actions implemented and planned by New York State by 1980 will conserve an estimated 106.7 million EqL of gasoline (28.1 million gal). This figure represents 0.5 percent of estimated 1980 gasoline consumption in the state.

These findings indicate that implementation of planned TSM actions will not be a major factor in realizing the goal of the State Energy Conservation Plan, which calls for a saving of 1.1 billion L (293 million gal) in the transportation sector by 1980. The estimated saving attributed to TSM plans is, in fact, only 9.6 percent of this goal. Even if the eight urban areas in New York State could be encouraged to double their effort in the TSM area, less than 20 percent of the needed saving would be achieved. It is unlikely that this doubling of effort could be achieved, especially in the short term.

New York State will obviously have to pursue additional transportation actions if 5 percent of this sector's overall energy is to be conserved. It has been estimated at NYSDOT that full compliance with the 88-km/h (55-mile/h) speed limit could save approximately 1.8 percent of the state's annual gasoline consumption, or about 414 million L (108 million gal). NYSDOT has also made estimates of the potential effect of trip combining or chaining. Studies indicate that this group of actions can potentially save between 1.6 and 13.1 percent of upstate New York's estimated 1980 gasoline consumption (16). Though the upper range may be unrealistic, the lower range is reasonable and would make this an action worth encouraging. Extensive programs to encourage ridesharing can also be effective. A 10 percent increase in automobile occupancy for work and for shopping trips can reduce New York State's estimated 1980 gasoline consumption by 1.7 percent. A 25 percent increase would result in a 3 percent saving (16).

A large potential saving also lies in the purchase of fuel-efficient vehicles. The increase in average automobile efficiencies between 1977 and 1978 resulted in a saving of 545 million L (143.4 million gal) of gasoline (2.4 percent of gasoline used in the state) compared with expected consumption if fleet efficiencies had not increased, according to a 1979 NYSDOT estimate.

The above discussion is not meant to imply that TSM actions should not be pursued. Other reasons exist for implementing such actions, e.g., effect on mobility, air quality, safety, and conservation of resources. It is left to each area to trade off and weigh the attainment of these various goals and objectives (including energy) against each other in order to develop a comprehensive TSM program. As a result of this process, projects that save considerable amounts of energy may be rejected whereas those that have small or no energy savings may be accepted.

The development of coordinated packages of TSM projects may increase the savings that can be

realized from TSM actions. This has not been done in the past in New York State. Rather, TSM planning has been an inventory activity. It appears, however, that the urban areas in the state are beginning to view TSM as a planning process and to develop a coordinated and comprehensive TSM element of their transportation plans.

One additional point concerning energy conservation in New York State is important to note. New York State is the most energy-efficient state in the nation; it consumes 33 percent less gasoline per capita than the national average. Much of this is a result of the existing extensive use of transit in the downstate area, where the rate of use of public transportation is considerably higher than the national average rate. Because of the high transit ridership, it becomes difficult to effect additional mode shifts from automobile. That is why the prior mode of many of the new patrons of new services is other transit and not automobile.

In spite of these findings, it is important to consider project impacts on energy use in evaluating TSM actions. This has not always been done in the past. The magnitude of the impact on energy use of this category of projects is probably in the same range as their impact on other things such as air quality, safety, and traffic congestion. When included in the evaluation process, energy savings will generally be another factor in these projects' favor.

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Abridgment

Evaluation of Transportation System Management Strategies

PETER M. LIMA

The construction of a transportation system management evaluation framework that can be easily integrated into the current urban transportation planning process and that can be adapted to previously established institutional arrangements within medium-sized metropolitan areas is discussed. The scope of this project was two-fold. On the one hand, the study involved the development of a general evaluation framework that could be adapted to specific metropolitan areas. On the other hand, the project encompassed the testing of a framework that could be adapted to specific metropolitan areas. For this testing, the evaluation framework was partially applied within one case-study area: the Omaha-Council Bluffs metropolitan area, which encompasses portions of Nebraska and Iowa. Based on the general investigation and the specific case study, a program was then developed to implement the evaluation framework within a metropolitan planning organization.

This study sought to improve the evaluation phase of transportation system management (TSM) planning by applying a systems-analytic approach to the construction of a TSM evaluation framework (1). Other researchers have also applied this concept to TSM strategies (2-4).

FRAMEWORK

The basic components of this framework are (a) goals and objectives, (b) measures of effectiveness, (c) strategies, (d) a decision model to evaluate strategy performance, and (e) techniques to monitor strategy performance. Since each metropolitan area is unique in character and institutional arrangements, the individual agencies responsible for strategy implementation and regional transportation planning must identify the specific components for that metropolitan area. The following conclusions were drawn from this study with respect to how these agencies should identify the basic components:

1. Statements of TSM objectives should be constructed that clearly identify the objectives and the measures of effectiveness that will be used to measure the degree of attainment of an objective by a given strategy.
2. Initially all the identified TSM strategies should be screened against the objectives to develop a set of potential strategies for that metropolitan area.
3. The potential strategies should then be grouped into alternative TSM packages. For example, the single strategies of a carpool program, transit management program, and a staggered work-hours program might constitute one TSM package.
4. The set of alternative TSM packages should be evaluated and monitored according to a geographical stratification of the transportation system, i.e., corridor, subarea, or link.

Once these basic components are identified for a given metropolitan area, the next step is to compare each TSM package with the other packages. Three techniques (5-7) that have been applied to evaluate various types of transportation facilities (the traditional cost-benefit analysis, cost-effectiveness analysis, and utility-based analysis) were analyzed. This analysis led to the recommendation that an additive-utilities model be used as a TSM decision model for several reasons: (a) The model is based on expected consumer-behavior theory, (b) the model can incorporate TSM measures of effectiveness that are both economic and noneconomic in nature, and (c) in general, the model is relatively easy to apply. The mathematical form of the model is

$$U(x_1, \ldots, x_n) = \sum_{i=1}^{n} w(x_i)\, u(x_i) \quad (1)$$

where

- $U(x_1,\ldots,x_n)$ = the total utility of a TSM package with regard to all the TSM attributes x_n,
- $w(x_i)$ = the weight or utility of attribute x_i,
- $u(x_i)$ = the utility function defined at the attribute value of x_i, and
- n = the total number of attributes.

The recommended steps to apply this technique are (a) determine the TSM objectives and measures of effectiveness; (b) assign weights, $w(x_i)$, to the TSM attributes; (c) develop alternative TSM packages; (d) estimate the values of each measure of effectiveness for each package; (e) determine the shape of the utility functions, $u(x_i)$, for each measure; (f) compute the utility of each package from the above equation, subject to any predetermined constraints; and (g) select the package that yields the highest total utility, subject to a budget constraint.

Since the specification of the weights and the utility functions are based on subjective judgments, it is recommended that the model be used only as a tool to narrow the range of the TSM packages. Ultimately the final selection of a "best" TSM package will be accomplished through negotiation among implementing agencies, planning agencies, and citizens.

Of course, the adequacy of the overall evaluation process clearly depends on the detail of available information on the measures of effectiveness. Thus, it is important that each implementing agency, or any other agency concerned with a particular measure of effectiveness, monitor the transportation system with respect to the stated TSM measures of effectiveness. Examples of monitoring techniques are (a) machine and manual traffic counts, (b) travel time and delay studies, (c) accident studies, (d) noise and air quality monitoring, and (e) energy monitoring. The following conclusions were made about monitoring:

1. A monitoring technique must be tied to a particular TSM objective and measure of effectiveness.
2. The monitoring of TSM strategies should be carried out according to geographical component, i.e., corridor or link.
3. The monitoring of TSM strategies should be conducted on a periodic basis. In general, it will be necessary to establish a base condition and time period for each measure of effectiveness.
4. The monitoring of the various types of strategies must be coordinated on a regional level to ensure consistency in measurement.

CASE STUDY IN EVALUATION

The above framework was used to evaluate TSM strategies within the Omaha-Council Bluffs metropolitan area, a major midwestern region centrally located within the United States. Although the downtown business districts of Omaha and Council Bluffs constitute the traditional urban core, the metropolitan region has undergone intensive decentralization over the last decade. In general, urban development has sprawled outward, resulting in a low-density pattern serviced by lineal commercial development. This fairly rapid suburbanization resulted in the following transport inefficiencies: (a) Highway capacity is unevenly distributed throughout the region, (b) automobile occupancy rates are low, (c) alternative modes to the automobile are severely limited, and (d) noise pollution, air pollution, and energy waste are by-products of sprawling development (8). As this study determined, these inefficiencies can be linked to the way in which transportation projects are evaluated. If TSM strategies are to be successful in coping with these inefficiencies, then the proposed evaluation framework must be carried out within metropolitan areas.

After an extensive literature search was conducted in order to identify objectives and measures of effectiveness that might be appropriate for the Omaha-Council Bluffs metropolitan area, 13 TSM-objective statements were constructed. Two examples are (a) to improve the quality of transportation service within the metropolitan area by reducing the average point-to-point travel time during the peak hour and (b) to improve the safety of traveling on the transportation system by reducing the total number of accidents per year.

Since the state of the art of forecasting the outcomes of TSM strategies is in a relatively early stage, the study team simulated the values for the 13 TSM measures of effectiveness. Five abstract TSM packages were simulated for testing the additive-utilities model. To illustrate, consider the following example. The simulated values of travel time for packages 1 and 5 are, respectively, 3.4 and 2.6 min/mile. Here, 3.4 represents the worst travel time and 2.6 represents the best travel time among the five packages. Similarly, the simulated value of the total number of accidents was 15 732 and 16 073 for packages 1 and 5, respectively. Thus, values were simulated for each of the 13 TSM measures of effectiveness in order to define the five abstract TSM packages.

The TSM objectives, measures of effectiveness, and five abstract packages were given to five "judges" (four transportation planners on the Omaha-Council Bluffs Metropolitan Area Planning Agency staff and one study-team member), who were asked to assign ratings to the 13 TSM measures on a scale of 0 to 10 on which 0 indicates that the attribute is of no value and 10 indicates that the attribute is of extreme importance. After the judges had rated each attribute, the means and standard deviations of the ratings were computed, and then each judge was asked to reconsider his or her response for an attribute if his or her rating varied ± 2 points from the mean rating. Once this second round was completed, a set of normalized weights, $w(x_i)$, was computed so that the sum of the weights is equal to 1. In general, such quality and efficiency attributes as travel time and travel costs were rated as highly important by all the judges. The weights placed on travel time and costs were 0.111 and 0.127, respectively. In contrast, safety was rated as moderately important and was given a weight of 0.065.

The next step in the quantification of the additive-utilities model involved the specification by the five judges of each utility function, $u(x_i)$, for the 13 TSM measures of effectiveness. Given the range of values of the measures among the five packages, the boundary conditions for each utility function were determined as u(best x) = 1 and u(worst x) = 0, where best x is the most-preferred value for a measure x among the five packages and worst x is the least-preferred value. For example, $596.7 million/year (package 3) is the most-preferred value for cost, whereas $634.2 million/year (package 1) is the least-preferred value. Each judge was then asked to assign values to each measure at corresponding utilities of 0.25, 0.50, and 0.75. Subsequently, the mean value for each measure of effectiveness was computed, and one composite utility function was determined for each attribute.

The total utility of any given TSM package was then computed from the additive model. To illustrate the operation of this model, consider the TSM package 2 and the TSM attribute of travel time. The simulated value of travel time is 3.1 min/mile for package 2, and the weight, $w(x_1)$, placed on travel time is 0.111. The utility of 3.1 min/mile, u(3.1), determined by the judges is approximately 0.60. Thus the contribution of the weight and utility of travel time to the total utility of package 2 is

$$w(3.1)\ u(3.1) = (0.111)(0.60) = 0.067$$

The contributions of all the 13 attributes were computed in the same manner and summed to give a total utility for package 2 of 0.34. For packages 1 through 5, the total utilities were computed to be 0.23, 0.34, 0.57, 0.56, and 0.54, respectively. Thus, according to the highest-utility criterion, the packages are ordered according to decreasing utility as 3, 4, 5, 2, 1. The "best" package among the five packages is number 3.

The following observations were made with regard to the application of the evaluation framework:

1. The overall procedure is relatively straightforward and simple to apply to evaluate TSM strategies.
2. The process of assigning weights and specifying utility functions encouraged the participants to give a hard look at their preferences with regard to evaluation criteria.
3. The outcome of the additive model may be sensitive to the specific weights and utility functions. Therefore, it is desirable to use a diverse group of individuals to quantify the model. In general, the assignment of the weights should not pose any difficulties to the layperson. On the other hand, the specification of the utility functions probably will pose difficulties; thus, it will be necessary to carefully guide the individual through this specification.
4. The additive-utilities model was successful in distinguishing between different packages and indicating similar packages.
5. Grouping the TSM strategies into packages appears to be the best way of analyzing the strategies. When strategies are grouped into packages, the synergistic effects of one strategy on another can be accounted for in both modeling and monitoring.
6. As noted earlier, since the outcome of the additive model is based on the subjective attitudes of various individuals, the models should be used only as a tool to guide the decision makers in their negotiation process for developing the TSM element.

TSM INFORMATION SYSTEM

The successful implementation of an evaluation framework requires the interaction between the agencies involved in the TSM process and the specific evaluation components. This interaction can be accomplished by a TSM information system that provides a clear flow of information from the stating of objectives through all the evaluation functions. This study recommended an information system that includes specific functions, agency roles, and information products. This information system includes the following functions:

1. Setting objectives and measures of effectiveness,
2. Identifying potential TSM strategies,
3. Grouping the strategies into alternative TSM packages,
4. Forecasting the consequences of the TSM packages,
5. Developing a priority list for the packages based on the additive-utilities model,
6. Implementing the packages,
7. Monitoring the packages,
8. Processing the TSM data, and
9. Retrieving the data.

Six specific examples of functions (or roles) and products are given below.

1. a. Function: The metropolitan planning organization (MPO) takes the lead role in setting TSM objectives and in determining measures of effectiveness to ensure consistency among the various implementing agencies. In addition, the MPO divides the transportation system into geographical components to establish a consistent geographical basis for evaluation and monitoring. Furthermore, the MPO takes the lead role, assisted by the implementing agencies, in developing the format to be followed in data collection.

   b. The products are a statement of TSM goals and objectives, a list of TSM measures of effectiveness, a geographical stratification of the transportation system, and a specific data format.

2. a. Function: Each implementing agency, supported by the MPO, identifies the potential TSM strategies within its jurisdiction. Each agency then groups these strategies into alternative TSM packages according to its area of responsibility (such as a traffic operations package or a transit management package).

   b. The product is a set of TSM packages delineated according to implementing agency.

3. a. Function: The MPO groups the individual TSM packages into more comprehensive packages that include all types of TSM strategies and encompass all the implementing agencies. Moreover, the MPO constructs these packages according to geographical components previously defined.

   b. The product is a set of alternative TSM packages that will be tested on a systemwide basis.

4. a. Function: The MPO predicts the consequences of the alternative TSM packages with respect to the TSM measures of effectiveness. The prediction of the consequences should be made according to geographical component.

   b. The product is the estimated values for the TSM measures of effectiveness by geographical component for all the alternative TSM packages.

5. a. Function: Each implementing agency then develops a priority listing of the alternative TSM packages according to a utility-based decision rule. The weights and utility functions used in the model will reflect the preferences of the decision makers and constituency of that agency.

   b. The product is a priority listing of TSM packages with regard to a regional perspective.

6. a. Function: The MPO negotiates with the implementing agencies in order to develop a final priority listing of packages. The "best" package is then selected according to a total budget constraint, and a schedule is set for the implementation of each strategy.

   b. The product is a "best" TSM package to be implemented according to a proposed schedule.

All of the evaluation functions were detailed in a similar manner in order to construct a program that can be implemented within an MPO.

CONCLUSION

Clearly, in order to increase the effectiveness of TSM strategies to improve transport efficiency, MPOs and implementing agencies must evaluate potential strategies in a systematic manner. To improve this evaluation process, this paper recommended that these organizations apply a framework consisting of the following steps: (a) defining goals and objectives, (b) determining measures of effectiveness, (c) identifying potential strategies, (d) using a decision model to evaluate strategy performance, and (e) monitoring strategy performance. This paper also recommended a TSM information system to be used to collect and store TSM data, retrieve TSM information, and transmit the information to decision makers. The implementation of this system by MPOs will help to improve not only TSM evaluation but also the entire TSM planning process.

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Measuring the Effectiveness of Priority Schemes for High-Occupancy Vehicles

YACOV ZAHAVI AND GABRIEL ROTH

In order to measure the effectiveness of high-occupancy-vehicle priority measures or any similar plan to improve transport systems, it is necessary to provide operational definitions of the output of the system and the mobility of its users. Based on theoretical and empirical studies, it is suggested that a useful measurement of system output would be the total distance traveled on the system per day by all travelers (including pedestrians), and a useful measurement of mobility would be the product of daily distance traveled and speed per household and per traveler. These criteria combine the effect of interactions among many travel components such as trip rate, distance, time, and speed that are evaluated separately by the conventional procedures. They can, and often should, be applied to total travel in the area affected, and not only to the direct, local effects of the improvements. The suggested measurements were applied to assess the results of the Singapore Area Licensing Scheme, the first road-pricing measure to be introduced in a complete city center. Data obtained from tabulations prepared in the World Bank from the results of before-and-after household surveys carried out in Singapore in conjunction with the introduction of the Area Licensing Scheme in June 1975 are presented. The results indicate that the introduction of this plan was associated with a significant reduction in both the output of the road system and the mobility of car-owning households and with an insignificant change in the mobility of carless households.

Priority measures for high-occupancy vehicles (HOVs) generally have a number of objectives. The basic ones are likely to be

1. To increase the useful output of the road network and the mobility of the people who use it and
2. To reduce travel costs, with consideration of time, fuel and other vehicle operating costs, accidents, atmospheric pollution, and noise pollution.

It is rarely possible for all objectives to be achieved, and trade-offs have to be accepted; for example, savings in travel costs can be associated with the loss of mobility, and savings in time can be associated with increased accidents. However, many of the concepts routinely used by traffic engineers can be used to assess the achievement of each objective separately. The task of assessing all these effects on the basis of one measuring rod (for example, money) is beyond the scope of this paper, which is concerned with quantitative measurements of transport output and mobility.

LOCAL AND GENERAL EFFECTS

The introduction of HOV-priority measures may be expected to have immediate impacts on traffic along the routes directly affected. For example, the Shirley Highway Express-Bus-on-Freeway Demonstration Project had an immediate effect on bus users when it was introduced and on carpool users when carpools were allowed on the busway. These effects can be assessed with the aid of standard traffic-engineering measurements of vehicle counts, speed, and vehicle occupancy. But the immediate effects can result in significant secondary ones--the encouragement of carpools on the Shirley Highway route can result in a decline in vehicle ownership as travelers who switch to carpools find they need fewer cars in their households. Alternatively, the effect might be that automobiles not used for journeys to work are used by other members of the household, with important consequences to local activities such as shopping. To measure effects of this kind, it is often necessary to consider the total travel habits of a population affected by HOV-priority measures.

Many HOV-priority programs will result in gains to some travelers and in losses to others. It is important that losses as well as gains be considered. In some circumstances it may be desirable to split the travelers affected, e.g., by income group, by mode, by period of travel (peak or off-peak), or by residential zones. Thus, results might show that a program results in gains to bus users and losses to car users, or in gains to city-center dwellers and losses to suburbanites. The appropriate grouping of the affected users will vary from one situation to another. An example that shows gains and losses of mobility in Singapore is given in this paper. The fact that higher-income groups tend to travel more than lower-income groups suggests that mobility is valued at all income levels and that a reduction in mobility is regarded by most as a loss rather than a benefit.

MEASUREMENTS OF TRANSPORT OUTPUT AND MOBILITY

The output of a road network may be expressed in terms of vehicle kilometers (or miles) per unit of time, the vehicles varying in size and shape from the individual pedestrian to the truck or bus. Mobility is a measurement of the movement of the population using the road system. It can be measured in terms of average person trips per day, average person miles per day, or (for each traveler) daily travel distance times speed. More than 30 such definitions exist, ranging from single and simple measures of flow and speed to complex ratings of kinetic energy and various congestion and demand ratios (1).

However, it is suggested that a useful measurement of output, from the users' point of view, is the travelers' daily travel distance, measured in passenger kilometers. This measurement is based on theoretical and empirical considerations, conforms to conventional definitions, and can be derived directly from a home-interview survey without the need to calibrate a model. More specifically, the required data are the observed travel distance per household and per traveler, stratified by mode and by the households' socioeconomic characteristics.

In addition, this paper suggests a quantitative definition of mobility, also based on theoretical considerations and empirical evidence, that is the product of the daily travel distance and the mean speed. Such a measurement follows previous definitions, especially that of travel kinetic energy developed for describing road network levels of service (2), but is extended to encompass the total travel generated per household.

The suggestions presented are exploratory in nature. They need more research, testing, and interaction among professionals and policymakers before the few simple criteria that would meet the varied evaluation requirements of a wide range of travel measures aimed at improving travel conditions can be made final.

MEASUREMENTS OF TRAVEL

Travel Demand

Travel demand is conventionally expressed by many isolated travel components, such as trip rate by purpose, trip distance, and trip time. One major problem in dealing with trip rates is that they depend on the definitions by which trips are linked in the early stages of the analyses. Thus, trip rates may differ not only between one city and another but also within the same city, depending on how they are linked. Furthermore, any change in such trip rates will also change their trip distance and trip time. The total daily travel distance and travel time per traveler and per household, on the other hand, are independent of definition of trip linkage. Moreover, total travel distance is directly related to the amounts that travelers pay in total travel time and total travel money.

The use of total distance traveled simplifies the measurement of travel demand since it is expressed by one unit: daily distance per traveler and per household. Furthermore, the output of a transport system is also measured by passenger and vehicle kilometers of travel, so that the use of this measurement enables demand and supply of passenger transport to have the same common denominator, daily travel distance. Defining travel demand by daily travel distance also facilitates the derivation of a quantitative measurement of mobility described below.

Mobility

Measurements of accessibility usually refer to a locality and express the amount of effort required to reach it. Measurements of mobility, on the other hand, usually refer to households and their travelers, and they should express the amounts of accessibility that travelers can obtain with their resources of trip time and money. In general, a household at a high income level can allow its travelers to achieve a higher level of mobility than can a low-income household. A car-owning household may be expected to have a higher mobility than a carless household, even when both generate the same number of daily trips, since travelers of the former household are able to travel at higher speeds than travelers of the latter.

An operational definition of mobility should express the combined effects of trip rates, distances, and speed; it should also express the potential area that can be reached within a given period of, say, a day. For example, travelers from a car-owning household will generally be able to reach more destinations than travelers from a carless household. The question is, What should the functional form of mobility be?

There are now three independent approaches to research, all of which converge to the following quantitative definition: Mobility equals the product of travel distance and speed during a unit of time (say an hour or a day). This definition is attractive for several reasons. It includes the measurement of travel demand (travel distance, the product of trip rate and trip distance) and is also consistent with measurement of system supply. Therefore, improvements in system supply can be related directly to potential improvements in mobility. This is a simple measurement that can be derived from a few observations available from a home-interview survey. The following is a brief discussion of the three independent approaches.

1. Kinetic energy of traffic flow (2): The level of service of a road network can be measured by

$$L = Cv^2 \quad (1)$$

where

L = level of service of the road network,
C = vehicle concentration (number of vehicles per unit of distance), and
v = observed speed at the given concentration.

This expression is analogous to kinetic energy, namely $(m/2)v^2$, where m is mass. Since traffic flow (q) equals the product of concentration and speed, it follows that Equation 1 can also be expressed as

$$L = qv \quad (2)$$

namely, the product of flow and speed. Thus, the total kinetic energy of all sections of a road network is the sum of the products of travel distance and speed.

2. The alpha relationship (3): Empirical analyses of the interactions between traffic intensity, road density, and speed of various road networks suggested the following relationship:

$$I = \alpha(D/v)^m \quad (3)$$

where

I = traffic intensity (vehicle-km/km^2);
D = road density (lane-km/km^2);
v = space-mean speed (km/h);
m = exponent, found empirically to be 1.0; and
α = coefficient, specific to a road category.

An example of such a relationship is shown in Figure 1 (4). A reordering of Equation 3 results in

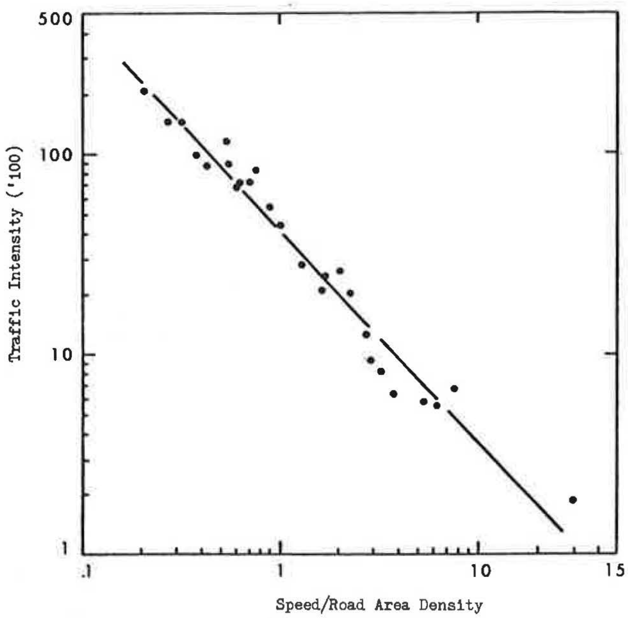
$$\alpha = Iv/D = [(\text{vehicle-km/area}) \div (\text{road length/area})] \text{ speed} = qv \quad (4)$$

This relationship was called the alpha relationship and was found to equal the observed kinetic energy of the traffic flow, as in Equation 2. Furthermore, the total kinetic energy capacity of the complete road network is the sum of the products of travel distance and speed.

3. Mobility measurements of urban transit systems (5): A mobility measurement for urban transit systems from the users' point of view (based on theoretical considerations of consistency among five basic requirements) was developed for the Urban Mass Transportation Administration in 1972 (5). It resulted in the following expression:

$$M = Pdv \quad (5)$$

Figure 1. Alpha relationship for arterial roads (per 1-m width) in Hagen, Germany.



where

- M = mobility measurement,
- P = number of trips,
- d = average trip distance, and
- v = space-mean speed.

Since the product of P and d equals passenger travel distance, mobility equals the product of travel distance and speed, as in the two previous results.

Measuring Changes in Travel Behavior

Because urban travel is a reflection of activities, it is dynamic in nature and changes daily and hourly. Trying to identify long-term trends of travel behavior from the kaleidoscope of cross-sectional one-day travel patterns is a lengthy and expensive undertaking usually based on a comprehensive home-interview survey. The problem of expense becomes even more acute when the effects of a local change in the transportation system, such as a reserved lane for HOVs, must be assessed, since a comprehensive survey cannot be justified on economic grounds. In such cases, therefore, the surveys are mostly limited to before-and-after counts of vehicles and passengers and measurements of travel time and speed at several key points of the system. The results of such localized observations, however, may not tell the full story of travel behavior, not even of those households directly affected by the change. Consider the case where before-and-after traffic counts of a new HOV-reserved lane show a considerable shift of automobile drivers to carpools and buses. These results could suggest that the measure, as such, was successful: It reduced the cost of travel for the affected automobile drivers. So far, so good. However, a visit to the households in the area may disclose additional effects not directly observable by the localized before-and-after counts, for example: (a) cars remaining at home were used by other household members, thus not necessarily saving gasoline and even increasing traffic flows at other locations; (b) reduced traffic flows and higher speeds along the corridor reduced costs and encouraged carless households to purchase cars and/or encouraged travel from other parts of the system to divert to the improved corridor; or (c) the affected households displayed significantly reduced mobility. Such effects, whether considered good or bad, are integral parts of the same HOV-priority measure and should not be ignored.

The following section details some of the results of a home-interview survey conducted in Singapore before and after the introduction of a major HOV program in the city's central business district (CBD). This example is presented because we were unable to find comprehensive before-and-after data for a major HOV-priority improvement program in the United States.

It should be emphasized that no attempt is made to attribute any results to the HOV program nor to assess whether they are favorable or unfavorable; our purpose is only to suggest that localized traffic counts, or analyses of selected trips, may not convey the whole story. It is also suggested that the analysis and evaluation of HOV-priority programs, especially experimental ones, should encompass all possible effects, so as to reveal those that may be unexpected and unsuspected.

SINGAPORE BEFORE-AND-AFTER STUDY

Background

Following is a summary of travel data collected before and after the introduction of the Area License Scheme (ALS) in Singapore's CBD in June 1975. This measure imposed a fee on each car carrying fewer than four persons that entered a restricted central zone during the morning peak period. The data were derived from conventional before-and-after home-interview surveys, and the household sample was augmented by a sample of car-owning households. The same households were interviewed twice, before and after the introduction of ALS, in order to identify and quantify possible effects on the households' travel behavior.

The first analyses, carried out in the World Bank, were concerned mainly with the direct effects of ALS (6). The present paper reports on the total travel characteristics in the whole area of Singapore, as derived from the before-and-after home-interview surveys.

Four sets of tables were prepared in the World Bank during 1978 and 1979. Travel characteristics per traveler and per household before and after the introduction of ALS and the principal results by household income are summarized in Table 1. Because the original sample was augmented by a survey of car-owning households, it is not representative of the total population and, hence, the tables in this paper are also stratified by car-owning and carless households. Car-owning households are defined as those having the use of a motor vehicle (car or motorcycle) that is based at the household even if it is owned by a firm. Table 2 summarizes the principal travel components, averaged for the whole area.

Trip Rates

The trip rates of car-owning households and of their travelers decreased appreciably, by about 10.5 percent and 5.3 percent, respectively. The difference between the two proportions is the result of a concurrent decrease in the number of travelers per household, as presented in Table 2. The trip rates of carless households and of their travelers, on the other hand, remained practically unchanged.

The trip rates per traveler of car-owning and carless households appear to be very low, just over the minimum of two daily trips per traveler. These low trip rates suggest an underreporting of trips in the home-interview surveys, a recurring problem in such surveys usually corrected by adjustment factors based on screen-line comparisons. No such corrections were made in the Singapore surveys and, therefore, the emphasis in the following analyses is on the relative changes in the travel characteristics, rather than on their absolute values.

Figure 2 shows the relationship between the trip rate per household and per traveler versus household income level for car-owning and carless households. Of special interest is the consistent decrease of the trip rate per household in car-owning households at all income levels, with only a mild decrease in the case of carless households. The trip rate per traveler, on the other hand, remained relatively stable. Thus, most of the variation in the trip rate per household was caused by changes in the number of travelers per household: a decrease of 6.5 percent in car-owning households and an increase of 2.3 percent in carless households.

One possible explanation of the increased number of travelers in carless households is a growth of household incomes, as can be seen in Table 1. Indeed, the average income of carless households increased during the period from S$680 to S$728 (an increase of 7.1 percent), although the average income of car-owning households remained practically the same (S$1380 versus S$1383). As the number of travelers per household tends to increase with income and to decrease with increasing travel costs, it appears that the changes in income levels, coupled with increased car travel costs (because of ALS and a rise in gasoline and parking prices during 1975), resulted in conflicting trends in the number

Table 1. Travel characteristics per traveler and per household.

		Vehicle-Owning Households								Non-Vehicle-Owning Households							
		Household Monthly Income (S$00s)								Household Monthly Income (S$00s)							
Characteristic	Time Period	2-4	4-7	7-10	10-15	15-20	20-25	25+	All	0-2	2-4	4-7	7-10	10-15	15-20	20-25	All
Households	B	57	201	169	236	139	100	172	1074	16	106	171	89	49	20	4	455
	A	55	149	192	259	188	85	146	1074	17	86	159	113	66	14	8	463
Travelers	B	136	612	630	1036	618	473	838	4343	36	257	581	324	232	97	20	1565
	A	129	403	669	971	812	392	678	4054	38	184	521	463	312	64	49	1635
Travelers per household[a]	B	2.39	3.05	3.72	4.34	4.49	4.74	4.86	4.13	2.25	2.38	3.40	3.85	4.74	4.85	5.00	3.44
	A	2.31	2.71	3.50	3.75	4.33	4.61	4.66	3.86	2.23	2.14	3.26	4.10	4.72	4.57	6.12	3.52
Distance per household (km)	B	28.64	42.13	55.47	69.91	76.96	80.10	96.11	66.31	17.17	22.72	38.07	45.07	67.87	70.51	77.83	40.29
	A	22.77	34.15	47.93	59.51	73.19	72.89	79.54	58.22	17.14	19.06	34.70	47.49	67.00	66.51	81.95	40.65
Distance per traveler (km)	B	12.00	13.80	14.91	16.12	17.14	16.90	19.78	16.07	7.63	9.53	11.20	11.71	14.33	14.54	15.57	11.31
	A	9.85	12.62	13.71	15.88	16.92	15.80	17.07	15.07	7.67	8.90	10.65	11.59	14.19	14.55	13.38	11.11
Trip rate per household[a]	B	5.14	6.53	8.11	9.46	10.46	11.28	11.62	9.33	4.50	5.05	7.07	8.05	10.10	10.62	11.75	7.16
	A	4.74	5.77	7.39	7.95	9.27	10.00	10.30	8.26	4.28	4.30	6.62	8.36	9.63	9.28	12.00	7.15
Trip rate per traveler	B	2.15	2.14	2.18	2.18	2.33	2.38	2.39	2.26	2.00	2.12	2.08	2.09	2.13	2.19	2.35	2.08
	A	2.05	2.13	2.11	2.12	2.14	2.17	2.21	2.14	1.92	2.01	2.03	2.04	2.04	2.03	1.96	2.03
Travel time per household (h)	B	2.79	3.81	4.89	5.57	5.63	5.80	6.17	5.25	2.91	3.34	4.41	5.81	7.04	6.88	8.27	4.75
	A	2.70	3.38	4.69	4.83	5.40	5.53	5.27	4.83	2.50	2.57	4.08	5.56	6.36	6.71	9.57	4.61
Travel time per traveler (min)	B	70.07	75.01	78.89	76.95	75.22	73.47	76.15	75.96	77.51	84.13	77.85	90.60	89.11	85.08	99.25	83.01
	A	70.18	74.94	80.39	77.22	74.78	72.19	67.87	74.75	67.30	72.14	75.17	81.38	80.90	88.08	93.78	78.57
Speed[a] (km/h)	B	10.28	11.04	11.34	12.57	13.67	13.80	15.59	12.65	5.91	6.80	8.63	7.75	9.65	10.25	9.41	8.20
	A	8.42	10.10	10.23	12.34	13.58	13.13	15.09	12.06	6.84	7.40	8.50	8.55	10.52	9.91	8.56	8.48
Trip distance[a] (km)	B	5.58	6.45	6.84	7.39	7.36	7.10	8.28	7.11	3.82	4.50	5.38	5.60	6.73	6.64	6.63	5.44
	A	4.80	5.92	6.50	7.49	7.91	7.28	7.72	7.04	3.99	4.43	5.25	5.68	6.96	7.17	6.83	5.47
Trip time[a] (min)	B	32.6	35.1	36.2	35.3	32.3	30.9	31.9	33.6	38.8	39.7	37.4	43.4	41.8	38.9	42.2	39.9
	A	34.2	35.2	38.1	36.4	34.9	33.3	30.7	34.9	35.1	35.9	37.0	39.9	39.7	43.4	47.9	38.7

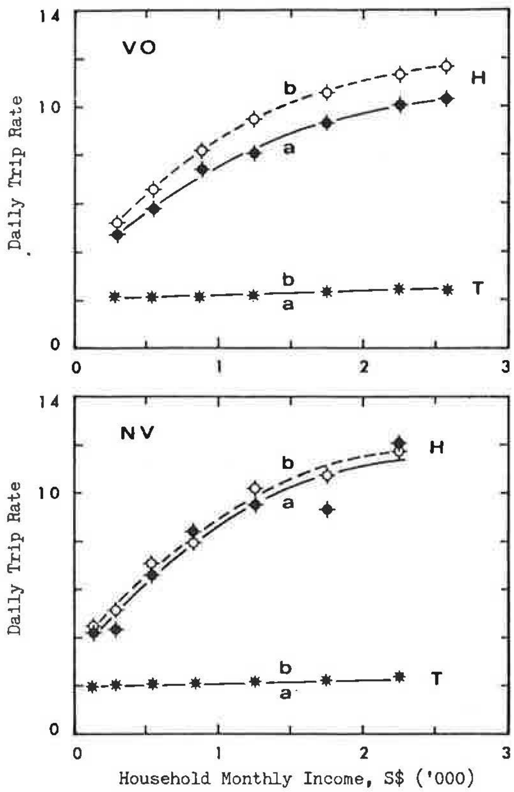
Note: B = before; A = after.

[a]Derived values are weighted by households.

Table 2. Summary of travel characteristics per traveler and per household.

	Vehicle-Owning				Non-Vehicle-Owning			
	Travelers		Households		Travelers		Households	
Characteristic	Before	After	Before	After	Before	After	Before	After
Monthly income (S$)	–	–	1380	1383	–	–	680	728
Travelers per household	–	–	4.13	3.86	–	–	3.44	3.52
Trip rate	2.26	2.14	9.33	8.26	2.08	2.03	7.16	7.15
Travel distance (km)	16.07	15.07	66.31	58.22	11.31	11.11	40.29	40.65
Travel time (h)	1.27	1.25	5.25	4.83	1.38	1.31	4.75	4.61
Speed (km/h)	12.7	12.1	12.7	12.1	8.2	8.5	8.2	8.5
Trip distance (km)	7.11	7.04	7.11	7.04	5.44	5.47	5.44	5.47
Trip time (min)	33.6	34.9	33.6	34.9	39.9	38.7	39.9	38.7
Mobility	209	186	861	720	96	102	336	359

Figure 2. Daily trip rate per traveler and per household by car ownership.



Note: VO = vehicle-owning households; NV = non-vehicle-owning households; H = household; T = traveler; b = before; a = after.

of travelers per household of car-owning and carless households.

Daily Travel Distance

The changes in the daily travel distance per household that took place before and after the introduction of ALS are shown in Figure 3, stratified by household income. The relationships can be expressed by a logarithmic function for car-owning households before:

$$\text{Distance per household} = -141.21 + 29.38\ \ln(\text{income}) \quad (6)$$

and after:

$$\text{Distance per household} = -134.47 + 27.20\ \ln(\text{income}) \quad (7)$$

and for carless households before:

$$\text{Distance per household} = -109.97 + 24.06\ \ln(\text{income}) \quad (8)$$

and after:

$$\text{Distance per household} = -116.78 + 24.98\ \ln(\text{income}) \quad (9)$$

where the daily travel distance per household is expressed in kilometers. The striking result is a significant drop in travel distance per household of car-owning households at all income levels, whereas travel distance remained practically unchanged for carless households.

Table 3 presents the breakdown of the daily travel distance per household by mode used. It shows changes in mode choice within each household group before and after the introduction of ALS. Results of this table can be summarized as follows:

1. The sharp drop in daily travel distance per car-owning household, 12.0 percent, is mainly the result of a decrease in travel by car and motorcycle and, contrary to conventional expectations, no consistent shift to bus travel is noted. Travel distance by walking and bicycle is negligible and is discussed later.
2. Daily travel distance per carless household increased slightly (by only 1.9 percent) and seems to have been the result of a small shift to car and motorcycle travel (probably as passengers), whereas the travel distance by bus decreased.

An assessment of these results indicates that the expectation that ALS would shift travelers from car to transit and raise travel speeds for road users paying the ALS fee was not realized in the observed travel behavior derived from the home-interview surveys. Unfortunately, no transit passenger counts were carried out concurrently with the home-interview surveys to serve as a check on the sampled results.

Trip Distance

An indirect way of checking the above results is to assess changes in trip distance. Table 2 shows that the average trip distance of car-owning households decreased appreciably (from 16.1 km to 15.1 km), whereas the decrease in trip distance of carless households was quite small (from 11.3 km to 11.1 km). This tends to support the assumption that the loss of travel by car-owning households was real.

Another way of checking the above results is shown in Table 4, in which the daily travel distance per traveler is stratified by major trip purposes. It appears that travel distance home by carless drivers remained unchanged and that travel distance to work and business increased slightly. Travel distance of travelers from car-owning households, on the other hand, tended to decrease in the cases of all major trip purposes, thus suggesting once again that the loss of travel distance by such households was real.

Trip Time

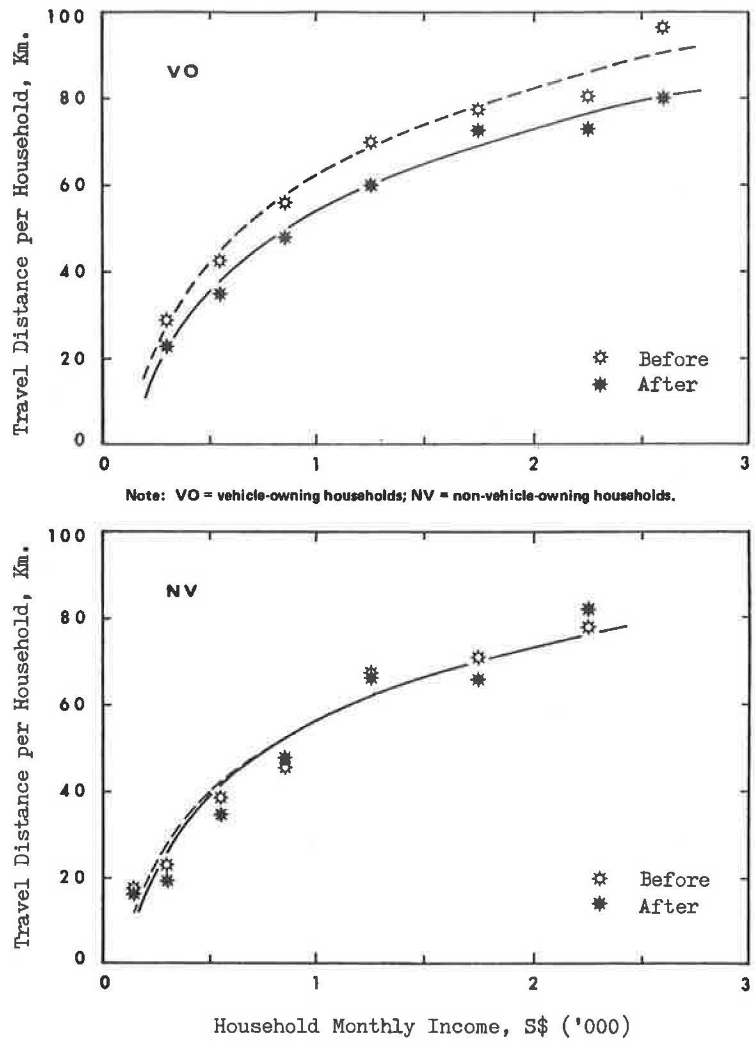
All travel times are door-to-door times, as reported by the respondents in the home-interview surveys. Tables 1 and 2 show that the trip time of car-owning households increased. As the proportion of car travel by car-owning households decreased and the proportion of transit travel increased, the proportion of longer trip times by transit should be expected to increase the average trip time. For carless households (whose total travel remained unchanged) the trip time should not have increased. Indeed, it slightly decreased.

Modal Changes

It is often wrongly assumed that trips can be shifted between modes with no change and that, therefore, such shifts can be expressed as percentages or normalized as probabilities. But Table 3 tells another story, summarized below:

Time Period	Mode	Distance (km)	Share (%)
Before	Car	32.45	49.6
	Motorcycle	6.12	9.3
	Bus	26.93	41.1
	Total	65.50	100.0
After	Car	26.17	45.4
	Motorcycle	4.96	8.6
	Bus	26.49	46.0
	Total	57.62	100.0

Figure 3. Daily travel distance per household by vehicle ownership.



Note: VO = vehicle-owning households; NV = non-vehicle-owning households.

Table 3. Daily travel distance per household by motorized mode.

Time Period	Mode	Distance (km) Household Income (S$00s) 0-2	2-4	4-7	7-10	10-15	15-20	20-25	25+	Avg
Vehicle-Owning Households										
Before	Car	–	4.36	11.21	18.14	29.69	43.33	47.72	66.76	32.45
	Motorcycle	–	11.32	8.66	7.60	5.80	5.12	4.42	2.18	6.12
	Bus	–	12.56	21.08	28.70	33.40	27.86	27.53	26.81	26.93
	Total		28.24	40.95	54.44	68.89	76.31	79.67	95.75	65.50
After	Car	–	2.35	9.33	12.60	25.22	36.32	38.53	51.57	26.17
	Motorcycle	–	8.35	6.43	4.86	5.91	4.59	3.67	1.86	4.96
	Bus	–	11.75	17.80	29.34	27.66	31.94	30.25	25.89	26.49
	Total		22.45	33.56	46.80	58.79	72.85	72.45	79.32	57.62
Non-Vehicle-Owning Households										
Before	Car	–	0.28	2.11	1.48	1.25	11.18	15.64	–	1.91
	Motorcycle	–	0.08	0.27	–	–	–	–	–	0.12
	Bus	14.47	20.37	34.43	41.45	65.40	58.04	59.19	–	36.42
	Total	14.47	20.73	36.81	42.93	66.65	69.22	74.83		38.45
After	Car	0.28	0.45	1.54	5.36	6.49	9.71	2.85	–	3.20
	Motorcycle	–	–	1.09	0.10	1.36	–	–	–	0.59
	Bus	16.15	17.20	30.63	39.80	58.35	56.23	78.43	–	35.39
	Total	16.43	17.65	33.26	45.26	66.20	65.94	81.28		39.18

When modal shares are based on travel distance (as the product of trip rate and trip distance), it becomes obvious that, although the modal share of transit increased from 41.1 percent to 46.0 percent, or an increase of about 12 percent units, the actual travel distance by transit decreased slightly. The reason for this is that, after the introduction of ALS, transit received an increased share of a smaller amount of travel. Furthermore, transit travel distance by carless households decreased in absolute and relative terms.

Daily Travel Time per Traveler

Table 2 indicates that the daily travel time per traveler of car-owning households was virtually unaffected--1.27 h before as opposed to 1.25 h after. One example of the breakdown of daily travel time by mode and by household income level for the before case is shown in Figure 4. It can be seen that, whereas the proportions of time allocated to the different modes varied significantly by household income, the total daily travel time per traveler remained similar at all income levels. This similarity remained also in the after case, although a higher proportion of time was allocated to transit travel.

Trends of daily travel time per traveler of carless households were that

1. Daily travel time decreased slightly, from 1.38 h to 1.31 h;
2. There was more variation between different income groups, probably because of smaller sample size than in the case of car-owning households, although the stable trend is still evident;
3. Proportions of time allocated by mode were different from those of car-owning households, with more of the time allocated to bus travel; and
4. Proportion of time allocated to car travel increased with income even for travelers from carless households.

These trends remain unchanged in the after case.

The results also indicate that time allocated to walking and cycling was a small proportion of total daily travel time per traveler and was similar at all income levels of car-owning and of carless households. The same applied to travel distance by these modes.

Stability and Variation of Daily Travel Time

The stability and similarity of daily travel time per traveler, even after major changes in travel distance by car-owning households, follow trends

Table 4. Daily travel distance per traveler by trip purpose.

Trip Purpose	Vehicle-Owning Households Distance Before (km)	Vehicle-Owning Households Distance After (km)	Non-Vehicle-Owning Households Distance Before (km)	Non-Vehicle-Owning Households Distance After (km)
Home	7.65	7.22	5.42	5.40
Work and business	5.56	5.35	3.47	3.75
School	1.68	1.76	1.64	1.48
Personal and social	1.00	0.62	0.61	0.39
Shopping	0.18	0.12	0.17	0.09
Total	16.07	15.07	11.31	11.11

Figure 4. Daily travel time per traveler by vehicle ownership.

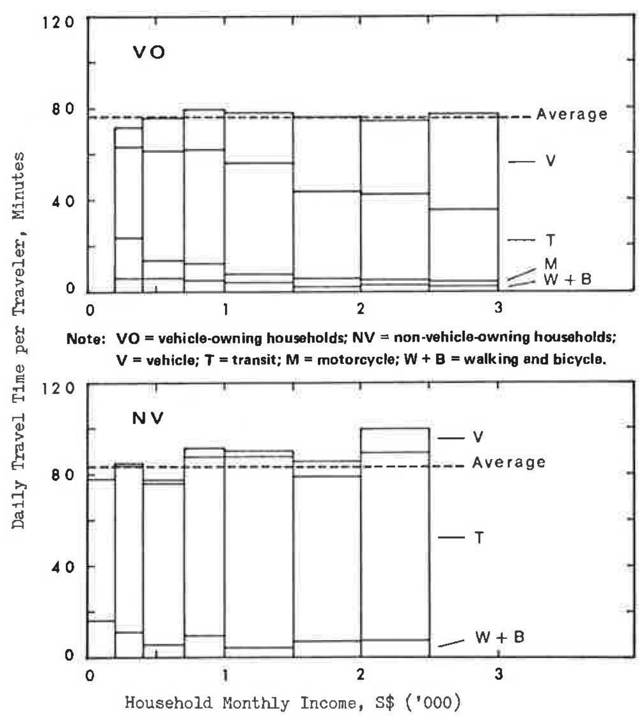


Table 5. Daily travel time per traveler and coefficient of variation by income and vehicle ownership.

Household Monthly Income (S$)	Before: Vehicle-Owning Households No.	TT (h)	C	Before: Non-Vehicle-Owning Households No.	TT (h)	C	After: Vehicle-Owning Households No.	TT (h)	C	After: Non-Vehicle-Owning Households No.	TT (h)	C
Up to 200	9	1.06	0.39	36	1.29	0.40	4	0.54	0.46	38	1.12	0.40
200-400	136	1.17	0.52	257	1.40	0.78	129	1.17	0.50	184	1.21	0.49
400-700	612	1.25	0.58	581	1.30	0.51	403	1.25	0.62	521	1.25	0.52
700-1000	630	1.31	0.74	342	1.51	0.88	669	1.34	0.56	463	1.36	0.54
1000-1500	1036	1.28	0.54	232	1.49	0.73	971	1.29	0.59	312	1.35	0.48
1500-2000	618	1.25	0.54	97	1.42	0.51	812	1.25	0.51	64	1.47	0.48
2000-2500	473	1.23	0.55	20	1.65	0.43	392	1.20	0.51	49	1.56	0.41
2500+	838	1.27	0.64	8	1.26	0.40	678	1.14	0.48	4	2.50	–
Total	4352			1573			4058			1635		
Average		1.27	0.60		1.40	0.70		1.25	0.56		1.31	0.51

Note: TT = daily travel time per traveler; C = coefficent of variation.

already noted in other cities (7,8). Even the higher daily travel time per traveler of carless households versus car-owning households is in line with the previous results in other cities. It may, therefore, be inferred that when travelers are faced with changing travel conditions (e.g., travel costs or speeds) they tend to adjust and fit their choices into a relatively narrow range of average daily travel times.

Stability of daily travel time per traveler does not mean that each and every traveler travels the same amount of time each day. Variations of individual travelers from the mean value can be expressed by the coefficient of variation (standard deviation over the mean). Table 5 summarizes this measurement for the daily travel time per traveler, and it can be seen that it tends to be similar for all segments that have at least 25 travelers. The same range of coefficients was also noted in other cities (4), suggesting that the daily mean travel time per traveler and the variations around it may be a behavioral phenomenon.

Speed

If daily travel time per traveler displays predictable regularities, then the daily travel distance is directly related to travel speed. Although the door-to-door speed in the case of Singapore is a derived value (distance over time), it is still an important indicator for the before and after changes in travel conditions. Table 2 shows that the door-to-door speed of car-owning households decreased slightly, from 12.7 km/h to 12.1 km/h, whereas the speed of carless households increased slightly, from 8.2 km/h to 8.5 km/h.

Two conclusions may be inferred from these results: First, the door-to-door speed of car-owning households is about 50 percent higher than the door-to-door speed of carless households; thus, travelers from carless households have to spend more travel time for less travel distance than do travelers from car-owning households. Second, the before-and-after surveys suggest that a slight deterioration in travel speeds occurred for car-owning households and a parallel improvement of travel speed occurred for carless households. These changes are not necessarily attributable to changes in road-network speeds; the reduction in the door-to-door speed of car-owning households results mainly from a decrease in travel by car and, hence, an increasing proportion of travel by the slower transit mode. Similarly, a shift of travel from transit to car travel may explain the slight increase in speed of carless households. Unfortunately, there were no reported before-and-after speed measurements in Singapore as an independent check on the changes in network speeds.

Mobility

Based on the discussion of mobility above, it is now possible to evaluate the before and after levels of mobility in the Singapore area. A distinction should be made between the mobility per traveler and per household, since the mobility per household may increase as a result of an increase in the number of travelers per household, even if mobility per traveler does not increase.

From Table 6 it can be seen that the mobility of travelers and of households among car-owning households decreased appreciably--by 11 percent and 16 percent, respectively. This can be regarded as a significant loss of mobility. On the other hand, mobility of travelers and of households among carless households increased slightly, by 6 percent and 7 percent, respectively.

It is difficult to assess the effect of these changes on the total population in Singapore directly from the survey results because the sample of car-owning households was augmented and was not representative. An exploratory test based on the proportions of car-owning and carless households at each income level is presented in Table 7. The results suggest that except for the lowest income group, which constitutes about 5.5 percent of all households, the households in each income group experienced a net decrease in mobility, with a total weighted loss of about 12 percent.

Table 6. Mobility per traveler and per household.

Household Income (S$)	Mobility (km^2/h): Vehicle-Owning Households, Traveler B	A	Household B	A	Non-Vehicle-Owning Households, Traveler B	A	Household B	A
0-200	–	–	–	–	50	50	100	120
200-400	120	80	290	190	60	70	150	140
400-700	150	130	470	340	100	90	330	290
700-1000	170	140	630	490	90	100	350	410
1000-1500	200	200	880	730	140	150	650	700
1500-2000	230	230	1050	990	150	140	720	660
2000-2500	230	210	1110	960	150	110	730	700
2500+	260	310	1500	1200	–	–	–	–
Average	209	186	861	720	96	102	336	359

Note: B = before; A = after.

Table 7. Total weighted mobility.

Household Income (S$)	Percentage of All Households	Percentage by Vehicle Ownership: VO	NV	Mobility (km^2/h): VO B	VO A	NV B	NV A	Weighted Average B	Weighted Average A
0-200	5.5	6	94	–	–	100	120	5.5	6.6
200-400	24.5	17	83	290	190	150	140	42.6	36.4
400-700	32.0	33	67	470	340	330	290	120.4	98.1
700-1000	16.0	42	58	630	490	350	410	74.8	71.0
1000-1500	11.0	64	36	880	730	650	700	60.6	56.6
1500-2000	5.5	75	25	1050	990	720	660	53.2	49.9
2000-2500	3.0	87	13	1100	960	730	700	31.6	27.8
2500+	2.5	91	9	1500	1200	–	–	34.1	27.3
Average								422.8	373.7

Note: VO = vehicle-owning households; NV = non-vehicle-owning households; B = before; A = after.

It should be emphasized that all the above results are for the whole Singapore area. Furthermore, the observed changes cannot--and should not--be attributed solely to ALS. Other factors, such as the economic slowdown during 1975, may have caused the observed changes. The point to note, however, is that any anticipated effects of a major change in system supply or policy measures should be analyzed and evaluated within the context of total travel, since the effects may spread to other, possibly unforeseen, parts of travel behavior. To name just one example: The principal justification for improving a road network is the economic benefits of saved travel time by its users. However, since the saved times are often traded off for more travel, forecasts of future travel are found to be underestimates. Thus, analysis of the possible effects of a change in travel conditions should also cover their possible propagation through the whole travel system.

The measurements relating to total daily travel, which are required to monitor travel behavior, either once a year or before and after a major change in travel conditions, can be restricted to a small sample. For instance, travel patterns of one-day cross-sectional data appear to stabilize for groups of travelers numbering 25 or more. Thus, depending on the number of desired stratifications, a sample of several hundred households may often be large enough to provide all required data. In the case of minor changes in travel conditions, measurements of travel behavior could be limited to the households of the travelers directly affected by the program.

It is recommended, therefore, that more attention be given to such small--but continuous--home-interview surveys that, coupled with the standard periodic traffic counts, can provide a reliable basis for the evaluation of such changes in travel behavior as those that result from the introduction of HOV-priority programs.

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Traffic Conflicts Techniques for Use at Intersections

WILLIAM D. GLAUZ AND D. J. MIGLETZ

Field studies and analyses of observation of traffic conflicts at intersections are described. The field studies covered more than 24 sites and used 17 trained observers who applied a number of alternative operational definitions of traffic conflicts. The definitions that provide the best reliability, repeatability, and practicality are recommended. Initial estimates obtained of expected conflict rates as a function of type of intersection are also given.

Traffic accidents are the most direct measure of safety for a highway location. However, attempts to estimate the relative safety of a highway location are usually hampered by the problems of unreliable accident records and the time required to wait for adequate sample sizes. For these reasons, therefore, the Traffic Conflicts Technique (TCT) was developed in an attempt to objectively measure the accident potential of a highway location without having to wait for a suitable accident history to evolve. (Viewed simply, a traffic conflict is a traffic event involving the interaction of two vehicles in which one or both drivers may have to take an evasive action to avoid a collision.)

Most people who have even a fragmentary knowledge of the TCT believe they understand the basic concepts. However, among those who pursue it further, there is a great divergence of opinion, philosophically, about traffic conflict definitions. One school of thought (1) holds that a proper definition of a traffic conflict must ensure that every accident be preceded by a conflict. Although the use of traffic conflicts as accident surrogates is an appealing concept, it can lead to unrealistic data-collection requirements. Also,

attempts to find strong correlations between conflicts and accidents have, for the most part, been either unfruitful or misleading for a number of reasons (2).

In the United States, it is more acceptable to view traffic conflicts as logical indicators of safety or operational problems, even if the relationship cannot yet be placed on sound statistical grounds. Obviously, it is desirable that operational definitions of traffic conflicts imply a relationship with safety, but other attributes are also necessary:

1. Safety-relatedness: At least in a conceptual sense, conflicts should be related to accidents.
2. Site-relatedness: Conflicts should be useful in diagnosing problem locations or measuring the effectiveness of a site improvement.
3. Reliability: The definition should provide minimum variation between different observers who record the same event.
4. Repeatability: The definition should result in an acceptable level of variation in repeated observations by the same observer at the same site under nominally identical conditions. This attribute has an important impact on determining meaningful sample sizes.
5. Practicality: Reliable, repeatable, safety-related, and site-related data should be obtainable in a reasonable time and at reasonable expense.

The research summarized here was a part of NCHRP Project 17-3 (3), which was directed toward the determination of operational definitions of traffic conflicts that best satisfy the last three of the attributes listed above. The first two attributes were considered only to the extent that the limited data permitted.

DEFINITIONS

If they are to be implemented widely in the United States, operational definitions must avoid or minimize the use of sophisticated equipment or painstaking measurements. They must be suitable for direct application by human observers. Therefore, operational definitions must encompass readily observable events.

To be observable, the traffic event must elicit an evasive maneuver (braking or swerving) by the offended driver. In this respect, the operational definitions are like those of the General Motors (GM) study (4,5). An intersection traffic conflict can be described, operationally, as a traffic event involving several distinct stages: One vehicle makes some sort of unusual or unexpected maneuver, a second vehicle is placed in jeopardy of a collision, the second vehicle reacts by braking or swerving, and the second vehicle then proceeds through the intersection. The last stage is necessary to convince the observer that the second vehicle was, indeed, responding to the offending maneuver and not, for example, to a traffic-control device.

Within this framework, a basic set of operational definitions can be stated that correspond to different types of instigating maneuvers. One type, called a left-turn, same-direction conflict, occurs when an instigating vehicle slows to make a left turn, thus placing a following, conflicted vehicle in jeopardy of a collision. The conflicted vehicle brakes or swerves, then continues through the intersection (see Figure 1). A total of 13 basic conflicts were defined as candidates to be field tested. These basic intersection conflicts are

1. Left turn, same direction;
2. Right turn, same direction;
3. Slow vehicle, same direction;
4. Lane change;
5. Opposing left turn;
6. Right-turn cross traffic, from right;
7. Left-turn cross traffic, from right;
8. Through cross traffic, from right;
9. Right-turn cross traffic, from left;
10. Left-turn cross traffic, from left;
11. Through cross traffic, from left;
12. Opposing right turn on red (during protected left-turn phase); and
13. Pedestrian.

Alternative operational definitions were also tested in the field to determine their value relative to these basic definitions. For each of the 13 basic types of conflicts, other more-restrictive or less-restrictive definitions were examined. For the first 3 conflicts listed above, the original GM work specified that the vehicles must be traveling as a pair in a car-following situation. In practice, however, some users prefer to include all situations in which a second vehicle brakes or swerves, even if it came on the leading vehicle several seconds later. The all-inclusive definitions include both paired-vehicle and non-paired-vehicle conflicts. For the other types of conflicts listed, the GM study suggested counting vehicles. An alternative terminology is suggested--the counting of opportunities.

The above descriptions identify 39 different operational definitions of traffic conflicts. All were used, except that pedestrian-related conflicts were so rare that they were not analyzed.

More-restrictive traffic conflicts were defined as those that exceed some threshold level of severity. Specifically, a conflict was said to be severe if the time-to-collision value was less than 1.5 s, as determined subjectively by trained observers. Time-to-collision value is defined as the time interval from when a conflicted vehicle reacts (brakes or swerves) until a collision (or a near miss) would have occurred had there been no reaction (6).

For each conflict type there can also be a traffic event called a secondary conflict that is comparable to the GM previous conflict. The secondary conflict involves an additional vehicle that is affected by the vehicle that slowed or swerved in response to an initial conflict situation.

The above conflict categories, plus others created by grouping or collapsing categories in the analysis process, yielded 62 conflict categories that were subjected to formal analysis. This does not include the severe conflicts, which were analyzed separately by hand.

FIELD STUDIES

Extensive field tests were conducted in the greater Kansas City metropolitan area during the summer of 1978 to obtain data on the candidate operational definitions of traffic conflicts. These tests employed observers without traffic experience who received a special two-week training program.

Experimental Plan

The basic experiment involved 24 intersections that had the descriptive parameters displayed in Table 1. This table also shows 4 additional sites used in a subsidiary experiment. Most of the sites were located in rural and suburban areas. Some were in

areas zoned for business or industry but none in the central business district.

The basic experiment used trained observers who worked in pairs, alternately (every 0.5 h) viewing from opposing legs of the intersections. Each observer collected traffic conflicts and volume data at a specified site for half a day with a designated partner and then moved to another site for half a day to work with a different partner. A four-day, 40-h weekly schedule created a basic experimental phase of three weeks, during which each of 24 sites was observed for three mornings and three afternoons, and each observer worked with every other observer at least twice. Three phases were conducted, the results of which could be analyzed separately, compared, or combined.

Statistical Model

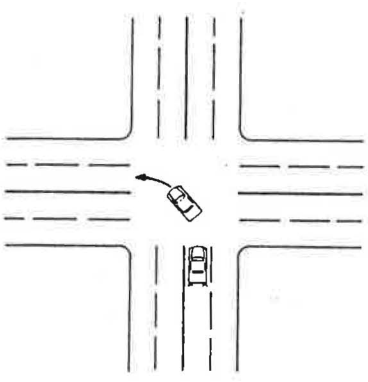
Mathematically, the variance σ_Y^2, obtained as a result of repeated short observations of the same type of conflict (Y) over a period of weeks at numerous sites by different persons and at different times of day on different days, can be assigned to the identifiable factors according to their numerical contributions to σ_Y^2. That is,

$$\sigma_Y^2 = \sigma_O^2 + \sigma_t^2 + \sigma_D^2 + \sigma_N^2 + \sigma_S^2 + \sigma_L^2 + \sigma_\ell^2 + \sigma_C^2 + \sigma_R^2 + \sigma_e^2 \quad (1)$$

where

- σ_O^2 = observer variance (reliability)--the variation resulting from systematic biases between observers,
- σ_t^2 = the variance between the short observation intervals at a site,
- σ_D^2 = the variance between days of week at a site,
- σ_N^2 = the variance between three-leg and four-leg sites,
- σ_S^2 = the variance between low-speed and high-speed sites,
- σ_L^2 = the variance between two-lane and four-lane unsignalized intersections,
- σ_ℓ^2 = the variance between legs at a site,
- σ_C^2 = the variance between signalized and unsignalized four-lane intersections,
- σ_R^2 = the variance between replicate sites of nominally the same type (same speed, number of lanes, and traffic control), and
- σ_e^2 = residual variance, or error, that is the repeatability sought by the project (this is the variance of repeated observations by the same observer under theoretically identical conditions--same physical site, time of day, day of week, etc.).

Figure 1. Left-turn, same-direction conflict.



FIELD STUDY RESULTS

The analyses dealt with 4000 observer hours of conflict and volume counts, and the major results are presented here. More detailed tabulations and discussions may be found in the research report of Glauz and Migletz (3).

Severe Conflicts

A grand total of 104 severe conflicts at the 28 test sites were noted, an average of about 1 per 18 observer hours of observation. Six of these 104 were accidents. Chi-square analyses showed that there were no significant differences in the counts that were attributable to the factors characterizing the sites, nor were there any specific sites that had abnormally high or low severe-conflict counts.

Severe conflicts also showed no significant differences by day of week, and they were rather uniformly distributed throughout the morning and early afternoon hours. However, they were much more prevalent by midafternoon (2:30-3:00 p.m.) and peaked sharply in the late afternoon, as shown in Figure 2.

Severe conflicts were also examined to determine whether they were distributed among types in the same way as regular conflicts. For this purpose four groupings were used: rear-end or same-direction conflicts, opposing left-turn conflicts, cross-traffic-from-right conflicts, and cross-traffic-from-left conflicts. The analysis showed that the distributions of regular conflicts and severe conflicts were greatly different. Whereas about 83 percent of all conflicts were of the same-direction variety, only 55 percent of the severe ones were of this type. Instead, the severe conflicts were more likely to be of the cross-traffic or opposing left-turn variety.

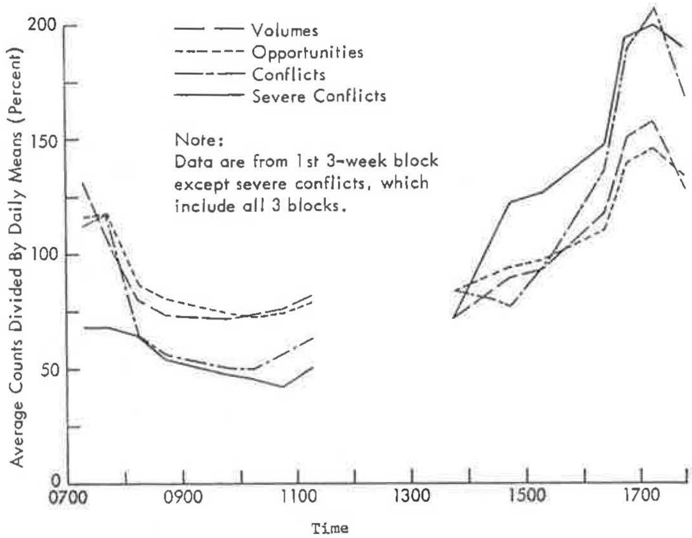
Analyses showed significant differences between observers; 4 of the 17 observers recorded essentially half (51 out of 104) of the severe conflicts. Thus, these traffic measures suffer from a lack of reliability, as well as from being infrequent and not site discriminating, and they are different in nature from other (normal) conflicts.

Table 1. Experimental design framework.

			High Speed[a]		Low Speed[b]	
Experiment	Lanes	Signalization	Four-Way	Three-Way	Four-Way	Three-Way
Basic	4	No	X	X	X	X
	4	Yes	X	X	X	X
	2	No	X	X	X	X
Subsidiary	2	Yes	X	–	X	–

Note: Each X represents two physical sites, each with two legs or approaches being observed.
[a]High-speed intersection = speed limit ≥ 40 mph.
[b]Low speed intersection = speed limit < 40 mph.

Figure 2. Time-of-day effects.



Rarely Observed Conflict Categories

Below are listed the conflict categories routinely recorded that should be dropped as useful concepts because they are so rare as to be impractical observational measures.

Conflict Type	Observer Hours per Occurrence
Right-turn-on-red secondary conflict	None observed
Right-turn-from-left secondary conflict	250.0
Lane-change secondary conflict	62.5
Right-turn-from-left conflict	33.3
Cross-traffic-from-left secondary conflict	23.8
Cross-traffic-from-right secondary conflict	15.9
Opposing left-turn secondary conflict	13.5
Right-turn-from-right secondary conflict	11.6
Left-turn-from-right secondary conflict	11.2
Right-turn-on-red conflict	9.4
Left-turn-from-left secondary conflict	8.3
Lane-change conflict	6.4
Right-turn-from-left opportunity	4.1
Right-turn-on-red opportunity	3.0

Essentially, the tabulated conflicts each occurred (at most) only about once for every eight observer hours of observation, equivalent to about two workdays. The right-turn-from-left opportunity and the right-turn-on-red opportunity were observed somewhat more frequently, but the interobserver variance was unusually high. The majority of the counts were obtained (probably erroneously) by just a few of the observers. The definition of these events is apparently difficult, conceptually.

Reliability

Reliability is the degree to which different observers record identical results when they observe the same traffic events. It is quantified by the interobserver variance σ_o^2. These variances were calculated separately for each of the first two three-week phases and compared. For all practical purposes, they did not differ between phases, i.e., no noticeable differential change between observers occurred as a result of long-term learning or practice effects; the two-week training program had effectively completed this process.

Some of the interobserver variances for one of these phases are given in Table 2 for selected conflict categories. In general, σ_o^2 represents only a small part of the total variation in conflict counts (typically, a few percent); other factors appear to be more important. A few exceptions are notable. The right-turn, same-direction conflicts had poor reliability, as indicated by comparatively large σ_o^2 (more than 10 percent of the total variance), and so did left-turn, same-direction, and paired-vehicle conflicts and all rear-end, paired-vehicle conflicts (not shown). Several other rear-end conflict types had reliabilities nearly as poor, as did some cross-traffic opportunities.

The coefficients of variation ranged from 9 percent to 109 percent; nearly all of them were under 50 percent. The worst was right-turn-on-red opportunities, whose high coefficient of variation (CV) indicates lack of uniform understanding among the observers. All paired-vehicle conflict categories also had high CVs, indicating that observers had difficulties with the paired-vehicle concept. This is clearly illustrated below:

Conflict Category	Coefficient of Variation (σ_o/mean) (%)
Left turn, same direction	
Paired vehicle	67.63
Not paired	35.87
Total	21.19
Right turn, same direction	
Paired vehicle	42.96
Not paired	101.82
Total	19.50
Slow vehicle	
Paired vehicle	54.25
Not paired	34.16
Total	41.20

The overall reliabilities, particularly for the left- and right-turn categories, are very good, but

Table 2. Illustrative conflict-count variances for the first three weeks.

Conflict Category	Mean No. of Conflicts Each 15 min	Conflict Count Variance[a] (σ_y^2)	Residual Variance[b] (σ_e^2)	Observer Variance[c] (σ_o^2)
Left turn, same direction	1.1191	3.3044	2.7847	0.1611
Right turn, same direction	0.5232	1.0687	0.9023	0.2838
Slow vehicle	0.2913	0.5319	0.5143	0.0099
Opposing left turn	0.2435	0.4497	0.4041	0.0035
Right turn from right	0.1664	0.2569	0.2369	0.0069
Cross traffic from right	0.1226	0.1374	0.1281	0.0017
Left turn from right	0.1770	0.3407	0.3108	0.0060
Left turn from left	0.2249	0.4003	0.3580	0.0085
Cross traffic from left	0.0984	0.1104	0.1067	0.0009[d]
All same direction	4.5939	30.6617	22.8934	1.3049
All cross traffic from left	0.2494	0.5393	0.4816	0.0088
All cross traffic from right	0.4030	0.9195	0.7882	0.0380
All conflicts	5.2827	36.3247	26.2166	1.8287

[a]Total variance in the conflict counts.
[b]Repeatability measure (variance not attributable to observers, time of day, site, day of week, or other measured parameter).
[c]Reliability measure.
[d]Not statistically significant at 0.95 confidence level.

they are much poorer (high CV) when subdivided into paired-vehicle and not-paired categories. The table shows a similar tendency for the slow-vehicle categories, but here even the total reliability is not good. Clearly, the observers were not uniform in separating driver responses to slow vehicles from, say, responses to traffic controls or, perhaps, secondary conflicts.

Repeatability

The ability of an observer to count conflicts uniformly at a given site under "identical" conditions is called the repeatability. Conceptually, it could be measured by staging sequences of traffic events to occur repeatedly. A more practical approach might be to videotape such events and review them repetitively in the office or laboratory. However, this procedure lacks realism and may not lead to results easily translated into field practice.

In reality, the observer should view actual traffic many times under conditions as nearly alike as possible. This is, in effect, what we did. The factors that might introduce variability into conflict counts, such as time of day and day of week, were identified and accounted for, as described previously. What remained (the residual variance, σ_e^2) was the result of two effects:

1. The true or theoretical repeatability that might be obtained by a hypothetical experiment as described above and
2. The inherent variability in real conflicts as traffic events, totally analogous to the well-known variance observed in repeated traffic counts.

The combination of these two effects is the practical repeatability--the result that can be expected in real-world, repeated counts.

Repeatabilities were found to improve somewhat (smaller σ_e^2) in the second phase, suggesting that as a group the observers became more repeatable with additional experience. Also, mean conflict counts tended to decrease somewhat, especially for the same-direction conflict categories.

Nevertheless, the residual variances were generally large and represented the major contributors to the total variances in conflict counts--typically, 50-90 percent or more. This probably means that the inherent variability in conflict-event rates is quite large. It is not conceivable that trained observers count so erratically.

This finding can be put in better perspective by comparing the ratios (σ^2/μ) for various traffic events. For accidents, which most believe to have approximately a Poisson distribution, $\sigma^2/\mu = 1$. For the 15-min conflict counts obtained in this project, σ^2/μ is in the range of 1.5-3.5, depending on the type examined (rear end, opposing left turn, etc.). For conflict opportunities the results indicated a range of 3-16 or more for the various types. Finally, analysis of scattergrams and the like presented in the Highway Capacity Manual (7) and the Traffic Engineering Handbook (8) yields values from 9 to 90 percent for σ^2/μ for traffic volume counts.

Coefficients of variation of the repeatability measure for 15-min counts ranged from 73 to 685 percent. The outstandingly bad conflict category, from a repeatability viewpoint, is the right-turn-on-red opportunity; cross-traffic conflict types and opposing left-turn conflicts had CVs of more than 200 percent for 15-min counts.

Observation Periods Required

CVs for repeatability decrease as the observation period increases, according to $\sqrt{n}$. That is, use of a 1-h count instead of a 15-min count would reduce the CV by half, and use of 4-h data sets would yield CVs only one-fourth as large. Thus, the precision of an estimated mean count increases as longer count periods are used.

If one wants to estimate, say, the mean number of hourly traffic conflicts at an intersection within a range of ± p percent with confidence $1 - \alpha$, then the number of hours required is

$$n = (100\,t/p)^2\,\sigma_e^2/\bar{Y}^2 \qquad (2)$$

where

Y = hourly mean value,
σ_e^2 = hourly variance, and
t = statistic from the normal distribution defined by α, as tabulated in most statistics texts, for example, $t = 2.58$, 1.96, 1.65, and 1.28 for $\alpha = 0.01$, 0.05, 0.10, and 0.20, respectively (for large n).

Applications of this principle are demonstrated in Table 3. For same-direction conflicts, the

requirements can be met in about a day of observation, assuming the observer is actively counting conflicts about half the time. For opposing left-turn and summary cross-traffic categories, about one week would be required; nearly two weeks are needed for the individual cross-traffic categories for the conditions stated (± 50 percent with α = 0.10). Use of four times as much data would double all the precisions. However, as described next, some categories (especially cross traffic and opposing left turn) are very site dependent; less observation would be required at sites that have higher-than-average counts.

Site Characteristics

Below are some observations made on site characteristics.

1. Speed--Speed limit did not affect cross-traffic or opposing left-turn conflicts, but there was a tendency for more rear-end conflicts (except to turn right) and conflict opportunities on high-speed routes.
2. Three-way versus four-way intersections--More opportunities and conflicts occurred at three-way intersections, geometrics permitting.
3. Signalized versus unsignalized, four-lane intersections--At signalized intersections there were more rear-end conflicts of all types, except in conjunction with right turns; more opposing left-turn conflicts and opportunities; and fewer cross-traffic conflicts and opportunities.
4. Two-lane versus four-lane, unsignalized intersections--More rear-end conflicts of all types and fewer cross-traffic conflicts were observed at two-lane intersections; no highly significant differences were found in opposing left-turn conflicts or in any types of conflict opportunities.
5. Two-lane versus four-lane, signalized intersections (based on extra-site data)--No significant differences of any kind were noted.

Table 3. Illustrative observation requirements.

Conflict Category	Mean Hourly Count	Hours of Observation
Left turn, same direction	7.14	4.6
Right turn, same direction	4.89	5.1
Slow vehicle	3.21	5.9
Opposing left turn	0.77	21.6
Right turn from right	0.71	23.9
Cross traffic from right	0.31	39.3
Left turn from right	0.59	24.5
Left turn from left	0.78	18.1
Cross traffic from left	0.39	30.0
All same direction	15.48	3.4
All cross traffic from left	0.82	20.0
All cross traffic from right	1.45	14.8

Note: Hours of observation = hours of data required to estimate mean hourly count within ± 50 percent with 90 percent confidence.

Traffic Conflict Rates

In order to calculate conflict rates, several candidate normalizing volumes were examined, such as total intersection volume, main-line volume, cross-traffic volume, and left-turning volume. The best agreement was achieved with the main-line volume.

Analyses of variance were conducted of various average conflict-count rates by using main-line volume to determine significant site characteristics. Average conflict rates by type of site, as well as the standard errors, are shown in Table 4.

Typical rates for cross-traffic conflicts ranged from 0.18 to 4.43 per 1000 main-line vehicles, depending on the type of site. The only significant factor, however, is the presence or absence of signalization. Other things being equal, signalized intersections experienced only about one-tenth as many cross-traffic conflicts as did unsignalized intersections.

The most significant difference between sites for

Table 4. Average conflicts per 1000 main-line vehicles.

Intersection Type	High Speed Four-Way	High Speed Three-Way	Low Speed Four-Way	Low Speed Three-Way
Cross-Traffic Conflicts (S_e = 0.75)				
Four-lane, unsignalized	4.43	2.96	2.98	2.74
Four-lane, signalized	0.48	0.18	0.56	0.26
Two-Lane, unsignalized	3.78	3.98	4.02	3.53
Same-Direction Conflicts (S_e = 4.07)				
Four-Lane, unsignalized	15.57	12.78	16.65	12.45
Four-lane, signalized	12.14	14.24	21.34	13.92
Two-Lane, unsignalized	53.85	35.62	33.62	28.52
Opposing Left-Turn and Same-Direction Left-Turn Conflicts (S_e = 4.18)				
Four-lane, unsignalized	5.23	8.13	8.26	0.96
Four-lane, signalized	5.57	7.51	14.70	6.38
Two-lane, unsignalized	31.82	21.13	12.69	7.72
All Conflict Opportunities (S_e = 82.4)				
Four-lane, unsignalized	315.8	295.6	107.3	119.5
Four-lane, signalized	69.4	33.2	74.6	81.0
Two-lane, unsignalized	196.7	271.0	258.5	160.5
All Conflicts (S_e = 5.45)				
Four-lane, unsignalized	15.97	13.45	18.04	13.92
Four-lane, signalized	11.71	13.67	12.11	11.55
Two-lane, unsignalized	48.50	31.87	29.60	27.71

same-direction conflict rates resulted from the number of lanes on the main-line approach: Two-lane roads experienced nearly three times as many as four-lane roads. It is also noteworthy that fewer same-direction conflicts are seen at three-way intersections than at four-way intersections, other things being equal.

Figure 3. Opposing left-turn accidents and conflicts.

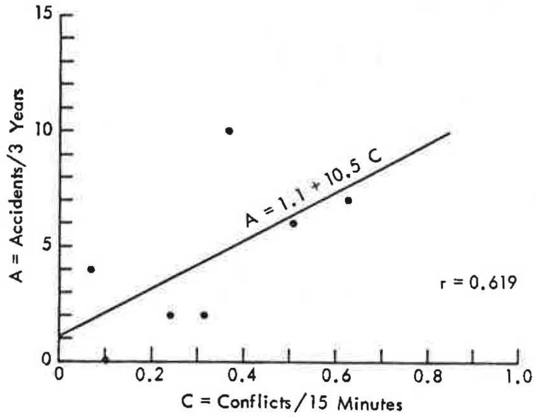


Figure 4. Cross-traffic accidents and conflicts.

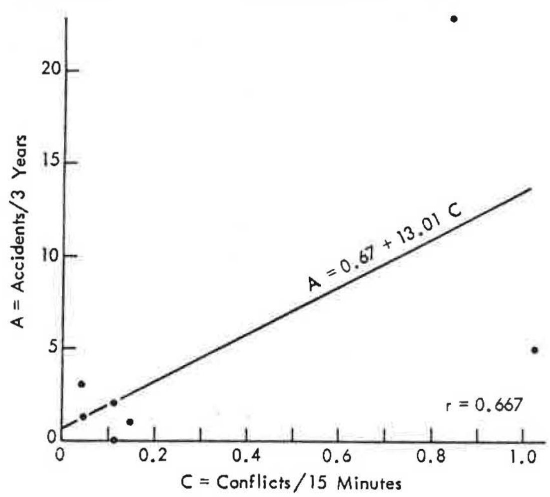
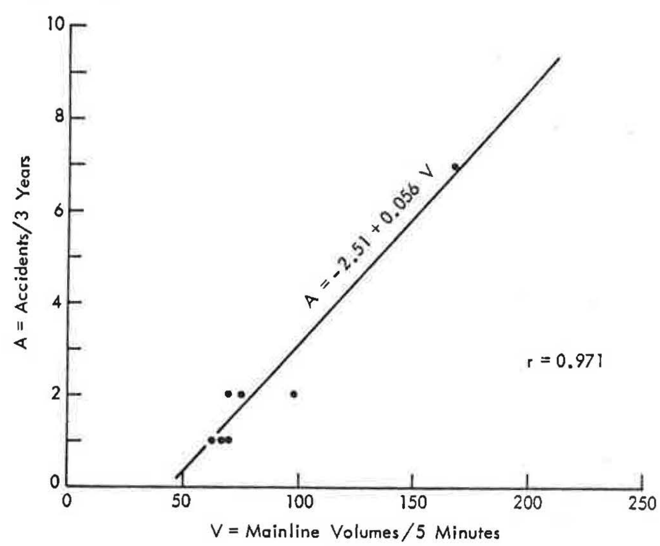


Figure 5. Same-direction accidents and volumes.



The conflict rates related to left-turn movements were significantly higher on two-lane roads. It is also noteworthy, although not statistically significant, that so few conflicts per 1000 vehicles were seen at low-speed, three-way, four-lane unsignalized intersections.

There were significantly fewer total conflict opportunities at signalized intersections than at others, as expected. The lack of other significant findings results in part from the very large standard error (S_e), which is about half of the overall average of 165.2 conflict opportunities per 1000 main-line vehicles. Generally, total conflicts exhibited the same sort of results as did same-direction conflicts.

Day-of-Week and Time-of-Day Effects

There were no clear-cut, uniform differences in conflict counts by day of week. Mondays may have experienced a few more conflicts of some types than did other weekdays, and Fridays may have experienced more conflict opportunities of some types.

Time-of-day effects for severe conflicts were described earlier and depicted in Figure 2. Whereas severe conflicts exhibit only an afternoon peak, both morning and afternoon peaks exist for volumes and opportunities. Other traffic conflicts tend to have both morning and afternoon peaks, but the latter peak is far more pronounced. The observation of higher conflict rates in the afternoon is in agreement with general accident experience, and both imply that driving habits, on the average, deteriorate late in the day.

Accident Relationships

Limited accident data for the intersections used in this study provided some insight into conflict-accident relationships. Overall correlation coefficients between total accidents over a three-year period and several categories of conflicts at the experimental sites were relatively meaningless. Total traffic volumes correlated as well as anything.

When accidents of certain types were compared with conflicts of analogous types, much better relationships were obtained. Opposing left-turn accidents and cross-traffic accidents, particularly, yielded good (significant) correlations with analogous conflicts (see Figures 3 and 4).

Comparisons between accidents and analogous conflict opportunities were mostly unproductive. Most correlation coefficients were essentially zero. The exception was rear-end accidents, which had a high correlation coefficient with main-line volumes (0.971), based on very limited data (see Figure 5).

DISCUSSION

Uses of Traffic Conflicts

To apply the TCT is somewhat time consuming, so it should not be used indiscriminately. Rather, the TCT should be applied only for one of several well-defined reasons.

The TCT is an excellent tool for diagnosing safety and operational problems of intersections that have previously been singled out for attention, usually because of an adverse accident history. It is not, however, appropriate for identifying hazardous intersections, because of the cost per intersection required for its application. However,

traffic conflicts are well suited to confirming (or denying) suggestions that a specific site has an accident problem or has inherent safety problems not yet illuminated by an extensive accident history. Typical sources of such suggestions are citizen complaints, a prominent serious or fatal accident, or a short-term rash of accidents at a particular intersection.

The TCT is also applicable to before-and-after evaluations of intersection improvements, both on a site-specific basis and in gathering research data on countermeasure effectiveness. One must be careful, however, in order to ensure that changes in conflict counts are causally and logically related to the type of improvement implemented.

Conflict Categories

The traffic conflict categories to be observed and recorded in the field should be reliable, repeatable, practical, and have at least face validity, if not a strong accident correlation. Following these guidelines, the conflict categories that should be used are right turn, same direction; left turn, same direction; slow vehicle, same direction; opposing left turn; right turn from right; cross traffic from right; left turn from right; cross traffic from left; and left turn from left. For each of these, secondary conflicts should also be observed and recorded. Simultaneously with conflicts, main-line traffic volume should be counted. The observers should always note any special occurrences, particularly the apparent cause of slow-vehicle conflicts.

Preliminary observation of a site, accident records, or citizen complaints may indicate that other, more specialized categories might also be noted in certain instances. These special categories include right turn on red, lane change, pedestrian, and bicycle.

For an analysis of conflict counts, certain categories should be combined to obtain more robust figures. First, the secondary conflicts should all be summed with their respective causative conflicts. Then, the following sums should be created: all same-direction conflicts; opposing left-turn and left-turn, same-direction conflicts; all conflicts involving vehicles from the right; all conflicts involving vehicles from the left; and all conflicts involving cross traffic.

Conflict Observations

Traffic conflicts can be observed at an intersection by either one or two persons. In either case, individuals should observe opposite legs of the intersection alternately. A basic work segment of 30 min is recommended. In each segment, traffic conflicts should be observed for 20 min. The other 10 min should be used for recording the counts and other data and for moving to the opposing leg. Detailed conflict-observation procedures are described in the research report previously cited (3).

Application of Conflicts Results

The numbers of conflict counts to be expected, or even those numbers that are indicative of safety or operational problems, cannot be stated unequivocally at present. Sufficient research on this topic has not yet been accomplished. However, several things are apparent. First, the counts, themselves, are not useful comparative indicators. Even the limited number of intersections used in this study illustrated the extreme variations in counts between nominally similar intersections. Counts should be normalized (divided) by traffic volumes, yielding conflict rates. The main-line volumes appear to be most appropriate for this purpose, rather than total volumes, cross-traffic volumes, etc. Table 4 provides some guidance as to average conflict rates and standard errors for various types of intersections.

To evaluate intersection improvements, conflict counts may be used in before-after comparisons, provided no major changes in traffic volumes have occurred. The counts may be compared by using standard statistical tests such as t-tests, provided transformations are first applied, as discussed in Glauz and Migletz (3).

Training and Implementation

An agency that intends to use the TCT should be aware that properly trained and experienced observers are necessary for success. Otherwise, only inaccurate and unreliable data can be expected. Available options are to (a) contract such work with qualified consultants or (b) train and maintain traffic technicians in house. The latter option may be most cost effective if use of TCT will be widespread; the former may be more appropriate for occasional needs or unusual applications (e.g., nights or weekends).

Training concepts are presented in the report previously cited (3). There is no substitute for field practice and experience, which will accustom the trainees to the variety of real-world happenings and help them develop a consistency of interpretation.

CONCLUSIONS

1. The use of the TCT at intersections is most suitable for diagnosis, improvement evaluation, and confirming or denying the presence of safety hazards or operational problems at suspect locations. It is not recommended for routine hazardous-location identification because of the large amounts of data collection that would be required.
2. Traffic conflicts data should be viewed as supplements to, not replacements of, accident data.
3. The recommended traffic conflicts data can be obtained reliably by traffic technicians who have moderate training, a minimum of special abilities, and no equipment other than a mechanical count board and a watch.
4. Traffic conflicts, as stochastic traffic events, vary quite markedly in number and rate from day to day, even under nominally identical conditions, just as do other traffic events such as accidents and turning volumes. Thus, they are not as repeatable as would be desirable.
5. Cross-traffic and opposing left-turn accidents are usually the most prevalent and serious safety problems at intersections. The TCT is particularly useful for these problems.
6. Rear-end accidents at intersections seem to be more strongly associated with main-line traffic volumes than with rear-end conflicts, although observations of the latter may help to discover the reasons for rear-end accidents.
7. The identification of severe conflicts, as distinguished from others, may be of general interest, but they occur too infrequently to be of use as diagnostic or evaluative measures.
8. The amount of data collection needed to obtain reasonably precise conflict-rate estimates depends on the type of conflict and the type of intersection but is typically on the order of a few hours to a few days.

9. Traffic conflicts and traffic conflict rates (especially severe conflicts) increase substantially from about 2:30 p.m. through about 5:00 p.m.

10. The training of persons in the TCT should rely heavily on supervised and/or critically reviewed field practice.

RESEARCH NEEDS

This research led naturally to ways and means of implementing the observation, recording, and analysis of traffic conflicts. Methodologies, definitions, etc., that are operationally feasible have been determined, and no further research along these lines is recommended.

Two needs that relate to the application of the TCT at intersections are apparent. One need is to determine the relationships between traffic conflicts of certain types and accidents of analogous types. Suggestions regarding such relationships are now available, but much more work is required. The other important need is to establish norms and warrants for various categories of traffic conflicts, dependent on site characteristics. Expected, as well as abnormal, conflict-rate guidelines should be established for individual types of intersections.

The present research was limited to intersection conflicts. However, the literature contains many examples of other areas of application, including midblock locations, freeway entrances and exits, weaving areas, construction zones, and pedestrian crossings. Further research is needed to clarify and standardize procedures to be used for these other applications.

ACKNOWLEDGMENT

This paper summarizes the experimental findings obtained in NCHRP Project 17-3. We are indebted to many researchers and practitioners of traffic conflict techniques, both in the United States and abroad. We are particularly thankful for the contributions of our colleagues John C. Glennon, Michael C. Sharp, and Rosemary Moran. Finally, we express our appreciation to the 17 individuals who spent a summer collecting conflicts counts, so that we might, it is to be hoped, slightly advance the state of the art of traffic engineering.

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Comparison of Three Loran Position-Determination Techniques in the Los Angeles Area

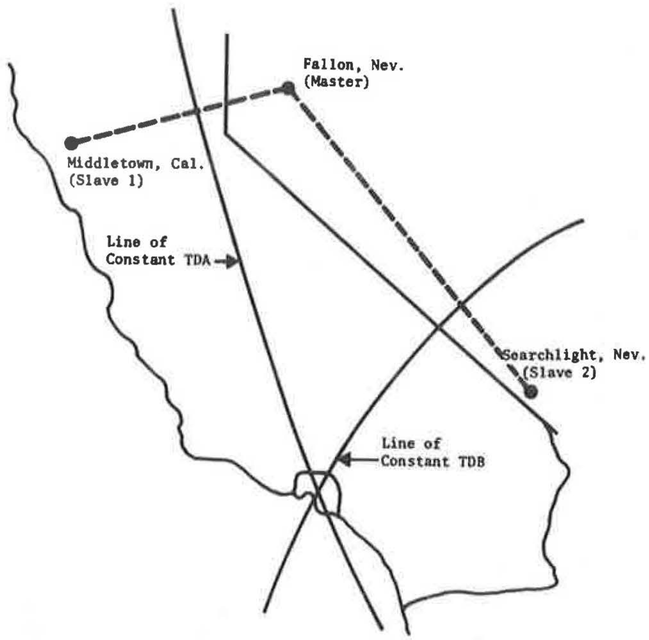
J. S. LUDWICK, JR.

A multiuser automatic vehicle monitoring system being developed for deployment in Los Angeles is discussed. In addition to the basic signpost technique to be used along transit routes and in the central business district, relatively inexpensive long-range navigation (loran) receivers will be used in a few vehicles to provide general location information over the entire 1000-km^2 (400-mile^2) Los Angeles Basin. Three techniques to convert loran time differences (TD) of arrival information to latitude and longitude were evaluated for accuracy, computation time, and memory requirements. The three methods are an empirical regression technique that uses best-fit equations to fit measured TDs to locations, a theoretical technique that uses a geometric earth model and a radio-wave-propagation model to determine location based on travel times from the known transmitters, and a combination technique that computes the position theoretically and then provides an empirical correction. All techniques gave approximately the same accuracy. It is possible that subdivision of the larger area into sectors could improve the overall accuracy to that of the central area, but not enough data were available to test this. It appears that TD grid warpages in the Los Angeles area are large enough and not sufficiently regular to be compensated for by standard techniques.

Automatic vehicle monitoring (AVM) systems provide the locations of members of a fleet of vehicles to a central control point. An AVM system will usually include radio communication links from the control center to the vehicles. The combination of location information and communications allows the efficiency of vehicle fleet use to be improved. For instance, police cars or taxis can be dispatched in an optimum manner, or transit bus drivers can be advised when they are exceeding permissible schedule deviations.

The Urban Mass Transportation Administration (UMTA) and the Transportation Systems Center are developing a multiuser AVM system to be deployed in a demonstration in Los Angeles (1). The basic fixed-route subsystem (for buses) uses low-power, high-frequency "signposts" at intervals along the routes covered. A portion of the central business district (CBD), including the high-rise area, will be furnished with signposts at a density high enough

Figure 1. Hyperbolic time-difference geometry in Los Angeles area.



to provide sufficient accuracy for random-route vehicles in this area. In addition, a number of vehicles will be instrumented with a hybrid location subsystem, which also includes a loran-C receiver and differential odometer, for operation over the entire 1000 km² (400 miles²) of the Los Angeles basin.

Although the characteristics of loran in seaborne application is well known, its use in land mobile applications, and especially in urban areas, is still in an exploratory stage. Loran-C was used during a test of candidate AVM technologies in Philadelphia; however, there were many parts of the city in which the signal was inadequate for accurate position determination, and signpost augmentation was required for system operation (2). The West Coast loran chain, which only recently became operational, gave promise of providing a high-quality signal in the Los Angeles demonstration area.

Three commonly used techniques for conversion of loran time-difference-of-arrival measurements to position estimates have been analyzed by using accuracy and processing requirements as criteria. The techniques varied in complexity; the comparison was designed to determine whether a particular technique appeared substantially better with respect to accuracy, performance, and costs than the others. Even if the more complex techniques could provide better accuracy (which has not been demonstrated), the incremental accuracy improvement might not justify the increased processing, which could only be performed at the central site.

The three basic types of algorithms tested were an empirical regression technique that uses best-fit equations to fit measured time differences (TDs) to locations, a theoretical technique that uses a geometric earth model and a radio-wave propagation model to determine location based on travel times from the known transmitters, and a combination technique that computes the position theoretically and then provides an empirical correction based on the relative position within a calibrated region. Data measured in the demonstration area in Los Angeles were used to determine the required coefficients, which were then used with a second set of data to evaluate the accuracy of each technique. A variety of graphical and statistical techniques was used to analyze the results. Processing time and core requirements were also measured for each method. A detailed description of the algorithms and the analysis techniques is presented by Ludwick (3).

All techniques gave approximately the same accuracy; mean and 95th-percentile errors over an 80-km² (30-mile²) central area were approximately 200 m (650 ft) and 500 m (1700 ft), respectively, and for the entire 1000-km² (400-mile²) area the figures were approximately 450 m (1500 ft) and 850 m (2800 ft), respectively. The results suggest that the wide-area accuracy could be improved significantly by subdividing it into sectors, each of which has its own set of coefficients. Insufficient data were available to test this; however, further subdividing the central area did not result in further improvements there. Comparative storage requirements were approximately the same for all methods; the regression technique was approximately five times as fast as the theoretical technique and approximately eight times as fast as the combination method.

Plots of the predicted position versus actual position showed the predictions of all three methods at most points to be relatively near each other. This seems to indicate that the large TD warpages (if they are not actually random) are not sufficiently regular to be compensated for by standard techniques. The plots, overlaid on U.S. Geological Survey maps, did reveal a number of large errors near railroad tracks, although other points seemingly similarly located did not show such errors.

LORAN THEORY AND OPERATION

The loran [long-range navigation] technique uses a network of transmitters at known locations that transmit accurately synchronized pulse trains. Based on the difference in time of arrival of signals from the "master" and a "slave" transmitter at a receiver site, a hyperbolic line of position is defined on the surface of the earth. A second set of TDs between the master and a second slave defines another hyperbolic line of position whose intersection with the first line determines the location of the receiver (Figure 1).

Loran-C has been in general use for 15 years; transmitter chains have generally been established to provide coverage of coastal confluence areas. (There is also loran-A, developed during World War II, which is less accurate and has a shorter range, and loran-D, a lower-power system intended for tactical military use.) Initially, the equipment required to locate vehicles by using loran was expensive, or large, or required time-consuming manual methods. Trade-offs could be made among these factors, depending on the space and response-time constraints, for shipborne or airborne use; in any case, cost was relatively small compared with the total cost of the vehicle. Use of such equipment for land vehicles would not have been feasible.

The advent of microcircuit technology has reduced the size and cost of receivers and has provided increasingly more-sophisticated processing internal to the unit. The size, cost, and ease of use of loran receivers now make their use feasible in mobile applications on land. However, there is no large body of data available to indicate the performance of such equipment in an urban environment. Closely controlled loran tests have been performed in Philadelphia, but the accuracy and

coverage attained were inadequate for transit use. However, that environment has been described as a worst case by loran proponents.

It was originally anticipated that the Los Angeles area would enjoy good loran signal reception, since the farthest transmitter is only 650 km (400 miles) away. However, during the collection of calibration-point data, it was determined that the signal level of the master, which affects the computation of both TDs, was substantially lower than that of the two slaves. In addition, in many areas high noise, evidently caused by increasing use of silicon-controlled rectifier (SCR) controllers, was transmitted along power lines. Carrier-current signaling by utilities over transmission lines and some inductive-loop traffic detectors use frequencies within the loran receiver bandpass; such frequency overlap also resulted in severe interference in certain areas.

Obviously, the use of algorithms to determine coordinate location based on TDs cannot compensate for lack of signal. (Other techniques can be used to extrapolate a probability contour based on the last received point, direction and speed of travel, and route and schedule data.) However, some methods do attempt to account for the TD grid warpages encountered in an urban area.

LORAN POSITION-DETERMINATION TECHNIQUES

The techniques tested fall into three classes: a completely empirical curve fitting, or regression, technique; a theoretical, or interactive, geometrical technique; and a technique that combines the theoretical and regression methods. The regression technique tested was developed by Teledyne (4) and used by that company during the Philadelphia test; the theoretical technique used is described by Howard (5); and the combination technique is the method used in the AN/ARN-101 loran receiver (6).

Empirical

In the empirical approach, a functional relation between two sets of measured data is derived. In this application, the data are TDs and location. The locations can be expressed in nearly any coordinate system--longitude and latitude are used here--but relative position on a cathode-ray tube (CRT) is equally valid. It is assumed that some actual relationship exists between the data measured at the calibration points that can be approximated by a series of functions, the coefficients of which are determined from the measured data. Here the functions are powers of longitude and latitude (actually their difference from a reference position), and the technique is polynomial regression. Powers up to the fifth order can be handled by the program as it currently exists.

Standard least-square techniques are used to determine the best-fit coefficients. The program generating the coefficients is composed of 13 FORTRAN IV subroutines that consist of approximately 600 statements. If a functional relationship actually exists between the measured variables of the same form as that used in the regression, the fit should be very good. Since lines of constant TD are known to be hyperbolas, a second-order polynomial should fit well. However, since it is known that there are TD distortions in urban areas, higher-order polynomials may give better fits. Also, if it is assumed that there may be anomalies that affect all measurements in a given area, breaking the area up into a number of sectors, each of which has its own empirically determined set of coefficients, may improve overall accuracy. The regression technique is unequalled in speed of computation, since received TDs are just plugged into an equation, the output of which is the desired location. Coefficients for the equations have to be stored, however (up to 30 per sector for a fifth-order regression), and a certain amount of computer time is required to chose the proper sector. Also, since the coefficients were chosen to fit points within a certain area, TDs from points outside that area may result in large errors.

Theoretical

The second major technique is here called theoretical because it uses an earth model and a propagation model to actually compute signal travel times between the known transmitter sites and the assumed receiver site. The amount by which the computed TDs differ from the received TDs is used with a gradient equation that relates changes in TDs to changes in location in order to improve the estimate of the assumed receiver position. This process is repeated until successive position estimates are close enough, 3 m (10 ft) in the program tested, or until some iteration threshold (here, nine) is exceeded. Signal travel times are composed of a primary component (the time taken for light to travel in air between the transmitter and the assumed receiver position) and a secondary component (an additional delay caused by transmission over finitely conducting earth).

Three types of earth models were used in different tests of the theoretical technique: two forms of flat-earth models with corrections and a more complex precision earth model. The simplest earth model uses plane geometry to determine range and bearing between points and modifies the range by use of a flattening constant and a correction that acounts for the convergence of longitude lines as they approach the poles. The more complex flat-earth model includes higher powers of the flattening constant and an additional bearing correction. The precision earth model employed was taken from the combination method and uses much more complex functions of four spheroidal constants. Range and bearing accuracy is improved by an order of magnitude for each level of complexity, but loran position-determination accuracy is not necessarily improved, since the process of choosing the conductivity values compensates for these biases.

Since this technique is iterative, it is more time consuming than the use of regression equations. It does have the advantage of being relatively accurate over areas outside of where it was calibrated. (Changes in distance of the signal path are handled by the earth model, but large changes in the composition of the earth crossed by signals cannot be so handled.)

Combination

The third technique combines aspects of the theoretical and empirical techniques. The primary phase is computed as described for the theoretical method by using the precision earth model. The secondary-phase contribution, however, is calculated on the basis of coefficients previously computed from calibration-point data. Once the total signal-travel times are computed, the iterative process of determining location is the same as for the theoretical technique.

The program to determine the coefficients first forms an effective impedance map for each transmitter over the area of interest (i.e., a map of how much the signal is impeded at the calibration points) and then fits a set of functions to each

impedance map by using least-squares techniques. The program, consisting of 35 subroutines and 3000 statements, was originally written in FORTRAN for Control Data Corporation equipment; I converted it to run on IBM computers.

This technique is more time consuming than either of the two previous ones, since it combines the iterative theoretical computation with a series of regression equations, look-up tables, and other computations more complex than the empirical technique. Like the theoretical technique, it is relatively accurate outside its calibration area.

It may be questioned whether any theoretical justification exists for believing that a given order of regression applied in the combination technique should provide any more accuracy than the same order of regression applied in the empirical technique. Intuitively, it does seem that, by fitting functions to each of the three transmitters and by using the results only to correct for differences from primary travel times separately computed, more flexibility is available than by using a direct TD to XY curve fit. However, only two independent pieces of information are available for use in either technique (the two TDs) and to use them in three equations instead of two is no guarantee of improved performance. Essentially the question is whether an impedance function (perturbed by the existing noise) provides better fit than the direct conversion of TDs (perturbed by the existing noise) to XY. At least when applied to the Los Angeles environment and the types of TD perturbations encountered there, the end results seem to indicate little difference between the two techniques.

ANALYSIS TECHNIQUES

The desired output from the analysis of the various loran position-determination algorithms is some measure of performance and cost. The performance relates to the accuracy of the technique, mainly represented here by the mean, standard deviation, and 95th-percentile accuracy. The cost relates to the processing time and storage requirements of a given technique, since a simple-enough technique could be performed on board a vehicle. In addition to relieving the central processor of a large amount of routine processing, an on-board processor could perform continuous smoothing and reasonability checks by using data that could not be available to the central computer.

The analysis technique was designed to simulate the manner in which the algorithms would be used. A data base of 800 points in an 80-km^2 (30-$mile^2$) area that includes the CBD (the central area) and 100 points over a 1000-km^2 (400-$mile^2$) area that includes most of the Los Angeles basin (the wide area) was collected in July 1978 by Teledyne during an earlier phase of the project. Figure 2 shows these areas. The raw data as received required a substantial amount of effort to be converted to a form suitable for analysis. Separate analyses were made of the central- and wide-area data. Every 10th data point was selected from the random-route area, and every other point was selected from the wide area to be used to generate the coefficients or conductivities required by the different techniques. A second sample, of the same size as the first and including completely different points, was then chosen to simulate the system use. The previously determined coefficients were used to predict the locations at these points, based on the received TDs, and the predicted and actual locations were compared.

The raw data were in the form of one data sheet for each measurement point, including three sets of

Figure 2. Los Angeles: wide area and central area.

TD pairs (TD-A and TD-B), the location of the point with respect to the nearest intersection, and comments (e.g., "near power line," "lost track"). After sample data points were selected, longitude and latitude were then determined by plotting the locations on 7.5' U.S. Geological Survey maps. The simplest flat-earth model was then used with the measured TDs to generate a set of predicted longitudes and latitudes, and a plotter program was used to create a map overlay by drawing a vector between the actual and predicted locations. A similar technique used the flat-earth model with the actual positions to compute TDs; the differences from TDs were measured at the point being plotted. Examination of the printout and plots for unusually large errors led to the discovery of some data-entry errors, some points incorrectly located on streets, and some points that obviously suffered "cycle slip" [caused when the wrong cycle of the loran signal is chosen to determine TDs, resulting in errors of multiples of approximately 3.2 km (2 miles)]. After all such points were corrected, the two sets of processed data points were used to evaluate the algorithms.

After all explainable data-base errors had been corrected, there remained points with relatively large errors that would only be attributed to the types of TD perturbations that it was hoped the various curve fits could improve. Coefficients were generated both with and without those points in the data base and were tested against the second sample. In general, better results were obtained when they were included.

To evaluate the cost side of the analysis, relative processing time and storage required were examined. Special-purpose subroutines that allowed

one to determine how much central processing unit (CPU) time has elapsed between calls were used to determine only the time required for the position computation, excluding program initialization, extraneous read-and-write instructions, and the accumulation and statistical analysis of data. Core storage requirements were determined by compiling only the instructions required for the algorithm's computation. No attempt was made at optimization of either CPU time or storage but, because the same general programming philosophy and techniques were used for all cases, the relative comparisons should be valid. The time-and-storage requirements for the programs used to generate the various coefficients were not evaluated, since they are off-line programs that would be seldom used after the initial application (for example, if sufficiently large seasonal variations made this desirable, or if experimentation with choice of sector boundaries were carried out).

RESULTS

Accuracy

Table 1 summarizes the results of the tests performed. These data result from using the first sample to determine the best-fit coefficients or conductivities and then using these constants with the second sample to simulate actual performance. In general, it can be seen that all methods gave approximately the same results: mean and 95th-percentile errors correspond to one and three blocks in the central area and to three and five blocks over the wide area.

From previous discussion, it is obvious that more tests were performed than are shown. However, in general, the others give no better results and so are not included. For example, regressions from first to fifth order were run, but the second order gave results as good as, or better than, the others. (As was previously discussed, a second-order regression would perfectly fit TDs that have no error--evidently the errors that do occur are not sufficiently regular to be better fit by a higher-order regression.) Also, three forms of earth models were used in the theoretical method, and all had approximately the same accuracy. However, the flat-earth model with extensive corrections required less computer time than the others, since it (and the precision earth model) required fewer iterations to converge than did the simplest flat-earth model and since the precision earth model required more processing time per iteration. Although the numbers are not exactly the same for the various techniques, it is obvious, based on the size of the standard deviation compared with the differences in means or 95th percentiles, that no significant difference in accuracy exists between the various methods.

It is also obvious that the accuracy obtainable over the wide area is substantially degraded from that in the smaller central area. This is not to suggest that larger grid warpages occur outside the random-route area but that the variations over the larger area may be sufficiently large and variable from area to area that one set of coefficients does not suffice. This seems to imply that subdividing the area into subareas, each of which has its own set of coefficients, should give better results. To test this hypothesis would require a density (not available) of data points over the wide area equivalent to that collected in the central area. It was found, however, that subdividing the points in the central area into geographically separated subareas, each of which had its own set of regression coefficients, gave results inferior to treating the area as a whole. These results seem to define an approximate range for the size of area for which it is reasonable to compute separate coefficients; i.e., 1000 km^2 (400 $miles^2$) is too large and 80 km (30 $miles^2$) is much better, but 40 km^2 (15 $miles^2$) is no better than 80 km^2.

Table 2 shows how well coefficients generated from the first sample fit the first sample and can be viewed as a best-case accuracy. When Table 2 is compared with Table 1, it can be seen that the empirical and theoretical methods behave similarly. Thus, the best-case results over the wide area are approximately 50 percent worse than those for the central area, e.g., 245 m (800 ft) mean error versus 170 m (555 ft) by using the empirical method. When the coefficients so generated are used to predict locations for the second sample, errors over the wide area are approximately 150 percent worse than those for the central area--540 m (1765 ft) versus 195 m (640 ft). This seems to reinforce the previous hypothesis: The variations over the larger area cannot be fit as well as those in the random-route area, and the effect of the greater variation is magnified when the second sample, which simulates actual use, is used.

It was previously noted that the radial-error statistics for the three methods are similar. In fact, map overlays show that all three techniques give similar predicted locations for the same data points. The predicted locations are closer to each other than they are to the actual point; the mean radial differences are approximately half the mean radial error and the 95th-percentile differences are one-half to one-third of the 95th-percentile radial area.

Table 1. Algorithm accuracies.

	Radial Error (m)					
	Central Area			Wide Area		
Technique	Mean	SD	95th Percentile	Mean	SD	95th Percentile
Empirical (second-order regression)	195	165	505	540	525	860
Theoretical (flat earth and corrections)	195	170	520	470	465	855
Combination	190	200	560	465	525	865

Computer Requirements

Core required by the computational parts of the FORTRAN program is approximately 30 kilobytes for each method, and the times required to compute the location for one data point are

Technique	Time (ms)
Empirical	15
Theoretical	
Flat-earth model and mid-latitude correction	85
Flat-earth model and extensive corrections	65
Precision earth model	105
Combination	125

Numbers shown are specific to operation on an IBM 370/148 computer using a FORTRAN IV, G1 compiler--it is the relative differences that are important. That is, the empirical regression method is four times as fast as the next method, the theoretical

Table 2. Accuracy of fit to original sample.

	Radial Error (m)					
	Central Area			Wide Area		
Technique	Mean	SD	95th Percentile	Mean	SD	95th Percentile
Empirical	170	155	425	245	170	570
Theoretical	185	165	420	260	125	400
Combination	155	195	565	300	220	605

flat-earth model with extensive corrections. In turn, this is faster than the simplest flat-earth model, since fewer iterations are required for convergence. Further improvement in range and bearing accuracy provided by the precision earth model did not further decrease the number of iterations required and, since the precision earth model is also used in the combination method, there is no offsetting of the increased time required by their more complex calculations.

Other Analyses

Since all of the techniques, as used here, require that calibration points be chosen to determine the best set of coefficients to represent the given area, the question of how to select the best calibration points is of interest. One method that has been suggested is to choose points that exhibit small TD variability with repeated measurements; the theory is that a more stable measurement is also more accurate. Analysis showed that, although those points that have the largest errors do seem to follow a linear (or quadratic) relationship with TD variability, this does not help in choosing, a priori, which points to use in determining the best coefficients.

CONCLUSION

Based on the analysis, none of the techniques would be sufficiently accurate to meet the stringent random-route accuracy requirements of the AVM demonstration program. Consequently, loran alone would not be adequate to replace the signposts for this function. To improve on this accuracy, the hybrid technique currently being developed for the Los Angeles demonstration uses on-board loran processing, differential odometer data, and Kalman filtering. Further tests will determine the extent of the accuracy improvement.

The accuracy attainable by using only loran, however, may be adequate for many applications. Inasmuch as all of the algorithms gave approximately the same results, the second-order regression technique is the one to choose for use in an area of any reasonable size, e.g., on a metropolitan-area scale, since it is the simplest and fastest one to execute. It can be performed on board a vehicle by using a microprocessor and can even include coefficients for multiple sectors. For application in larger areas that require many sectors, e.g., on a statewide scale, the flat-earth method would probably give more-satisfactory results and could also be implemented aboard a vehicle.

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