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Methodologies for Estimating Emission and Travel Activity Effects of TCMs

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SYSAPP94-92/096

Final Report

METHODOLOGIES FOR ESTIMATING EMISSION AND TRAVEL ACTIVITY EFFECTS OF TCMS

Systems Applications International

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1 INTRODUCTION

The 1990 Clean Air Act Amendments (CAAA) created a range of new, more stringent transportation control requirements. Major federal agencies such as EPA and the Department of Transportation must work together to ensure that transportation projects further attainment of air quality goals (conformity); the private sector must market a new slate of alternative, less polluting fuels; states must take action in the more serious nonattainment areas to offset any emissions growth related to increased vehicle miles travelled (VMT); and many state and local government agencies must implement transportation control measures (TCMs) that modify driving behavior and limit emissions resulting from traffic congestion.

To help understand and meet the new Clean Air Act's requirements, Congress instructed the EPA to publish a number of guidance documents related to transportation control. This document is one of the many EPA-sponsored publications which state and local governments may find useful as they work to achieve their transportation planning goals. The document provides a step-by-step approach for quantitatively estimating the travel and emissions changes that are possible from implementing a number of TCMs suggested in the CAAA.

PURPOSE OF THIS DOCUMENT

This workbook was developed as a tool for applying the Clean Air Act Amendments' (CAAAs) TCM provisions. Title I of the Amendments (provisions for attainment and maintenance of national ambient air quality standards) states that within one year from the enactment of the 1990 amendments, EPA must publish information regarding the formulation of and emission reduction potential of the TCMs listed in §108(f) of the CAA. This document fulfills part of this requirement. Table 1-1 lists the 16 broad TCM categories included in the Clean Air Act Amendments.

Air quality and transportation agencies will have a more focused interest in the §108(f) measures depending upon an area's nonattainment status, the extent to which TCMs may will be relied upon for emission reductions, and the degree of existing implementation.

THIS DOCUMENT IN RELATION TO OTHER TCM EVALUATION METHODOLOGIES

A number of methodologies for calculating the effects of TCMs on travel activity and emissions are available. Ranging from traditional transportation modeling approaches to sketch planning approaches developed in the late 1970s as well as several more recent methodologies developed in California, many currently available techniques have been criticized as being too complex, too optimistic, or not sufficiently linked to appropriate emission categories to be satisfactory for use in air quality planning applications. The methodologies presented here address a number of these criticisms and attempt to provide more useful approaches for estimating the effects of TCMs on travel activity and emissions. The methodologies build upon past efforts but include a number of innovative techniques designed to produce more reliable estimates of TCM effectiveness. It must be stressed that these methodologies are sketch planning techniques and will calculate approximate effects. They generally utilize region-wide estimates of existing travel characteristics and calculate region-scale effects. If corridor, facility, or traffic analysis zone level data is available, it can be used to obtain more precise estimates, particularly with respect to speed changes.

Transportation modeling approaches may provide more detailed and accurate estimates. The methodologies presented here may be most applicable in two general circumstances: (1) regions which do not have transportation modeling tools calibrated for their area, and (2) regions which desire approximate TCM results for the purpose of deciding whether transportation modeling is indicated. In many cases, the effects of TCMs are expected to be much smaller than the uncertainties in the transportation models themselves. In such cases the use of transportation models may not be an appropriate use of scarce resources.

More recently, a number of TCM analysis methodologies have been developed in California. A summary of several of these is provided in Appendix A. All require the use of software and a number do not address factors which may offset TCM benefits. Others provide enhanced analytical techniques but require a transportation modeling environment and are not adequately documented and/or publically available for widespread use. The methodologies presented in this document can be applied using a hand calculator if desired. They also provide specific equations for calculating effects that may partially offset TCM benefits.

METHODOLOGIES PROVIDED IN THIS DOCUMENT

This document includes three main chapters. Chapter 2 presents quantitative methodologies for individual TCMs. Equations for calculating trip reductions, vehicle miles travelled (VMT) reductions, and speed increases are provided for seven example

TCMs. Equations are provided for calculating both direct and indirect effects[1]. VMT reductions resulting from trip reductions are calculated separately from trip length reductions. A number of such procedures are provided in order to ensure that emission calculations are accurate[2]. All TCM effects are quantified in a way that facilitates emission calculations. The methodologies are also structured and presented in a manner that is intended to encourage analysts to adapt them to TCMs and situations other than those specifically presented here. It is important to note that the user will need to input the number of TCM participants before beginning analysis of some of the measures.

Chapter 3 provides a discussion of the emission categories affected by TCMs and provides a quantitative methodology for estimating the emission effects of TCMs. The emission analysis methodology calculates total mass emission changes resulting from the travel activity effects calculated in Chapter 2. If desired, emission reductions from TCM travel effects calculated using procedures other than those presented here can also be quantified using the techniques provided in chapter 3. The procedures focus on the use of the EPA MOBILE emission model and are most directly appropriate for regional scale analysis of hydrocarbons (HC), oxides of nitrogen (NO_x), and carbon monoxide (CO) unless detailed corridor or facility specific data are available for inputs. Some discussion of calculations for particulate matter and microscale carbon monoxide concentrations is also provided.

Chapter 4 presents a methodology for analyzing TCM packages. If a telecommuting and a compressed work week program are instituted at the same workplace and employees can choose either one, how many employees will choose telecommuting? If a parking price increase is implemented together with a ridematching service, how much more ridesharing will result than if just a ridematching program were implemented? The approach presented here provides a method for roughly approximating how TCMs will interact with one another in such situations. The approach is based upon the principal attributes of travel modes and the comparative values of the different modes for each attribute. The only data required are current mode choices, travel costs by mode, and travel times by mode. Chapter 4 presents two example applications of the methodology for two urban areas with very different mode splits. The approach appears to perform well in both cases. It should be stressed that the methodology is new and has not been extensively tested. It is likely that further empirical data will lead to improvements in the future. However, it may prove to be a powerful tool for evaluating other areas and TCM

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[1] Direct effects refer to the primary effect of a TCM. For example, telecommuting seeks to reduce employee work trips. Indirect effects refer to secondary effects resulting from TCM implementation. For example, when a telecommuter works from home, the telecommuter or a member of their household may wish to use the vehicle; thus a potential secondary effect of telecommuting is to increase trips by household members.

[2] For example, if VMT changes due to trip length (i.e., ridesharers drive to a park and ride lot) are summed together with VMT changes due to trips that are eliminated (i.e., ridesharers who are picked up at home), it is difficult to calculate trip start emission changes separately from exhaust emissions.

combinations. At a minimum, it provides a framework within which to identify and analyze the many possible TCM interactions and combinations.

Appendix A briefly reviews a number of other methodologies developed recently in California. Appendix B provides detailed mathematical documentation on the methodological techniques used to calculate how many trips are shifted from peak to off-peak periods by TCMs such as flextime and compressed work weeks.

TABLE 1-1. TCMs listed in the Clean Air Act §108(f).

1. programs for improved public transit;
2. HOV and bus lanes (construction of and conversion of existing lanes to);
3. employer based transportation management plans, including incentives;
4. trip-reduction ordinances;
5. traffic flow improvement programs that reduce emissions;
6. parking facilities for multiple occupancy vehicle programs or transit service;
7. vehicle use restrictions in downtown or other high emission areas, especially during peak use periods;
8. programs providing for all forms of high-occupancy and shared ride services;
9. programs limiting portions of roads or sections of metropolitan areas to non-motorized vehicular use or pedestrian use (both temporal and spatial restrictions);
10. bicycle use incentives in both private and public areas;
11. idling restrictions;
12. cold-start emission restrictions (in accordance with Title II);
13. employer-sponsored programs to permit flexible work schedules;
14. programs and restrictions to promote non-single occupant automobile travel as part of the transportation planning and development efforts of a locality (new shopping centers, special events and other centers of vehicle activity included);
15. programs for new construction of and major reconstructions of paths, tracks, or areas solely for the use by pedestrian or non-motorized means of transportation when economically feasible and in the public interest; and
16. programs to encourage the voluntary removal from use and the marketplace of pre-1980 model year light duty vehicles and pre-1980 model light duty trucks.

2 ESTIMATING TRAVEL ACTIVITY EFFECTS FROM INDIVIDUAL TCMS

This chapter presents screening methodologies for calculating travel activity changes from TCMs. These activity changes include trip, vehicle miles travelled (VMT), and speed changes. The approach draws partly from methodologies developed for the California Air Resources Board (CARB) (Austin, et al., 1991) and the California Department of Transportation (CalTrans) (Sierra Research, 1991). The methodologies offer three particularly important features: (1) they provide an approach for calculating effects that may partly offset TCM benefits (i.e., increased driving as a result of a carpooler or telecommuter leaving a vehicle at home), (2) they explicitly link TCM effects to motor vehicle emissions categories included in the EPA MOBILE emission factor model, and (3) recognizing that the vast number of TCMs and potential implementation strategies makes it impossible to develop and present methodologies to cover every possible situation, the methodologies are structured in a manner that will allow the analyst to quickly adapt them to TCMs and situations other than those specifically presented here.

OVERVIEW OF INDIVIDUAL MEASURE METHODOLOGIES

Many nonattainment areas rely or plan to rely upon TCMs for achieving some portion of emission reductions needed for attainment and maintenance of air quality standards. The procedures used to estimate the effectiveness of TCMs in achieving such reductions must yield realistic results that do not exaggerate the potential benefits of TCMs. Procedures developed in the past typically do not provide techniques for considering offsetting effects, and do not properly link travel changes to emissions.

METHODOLOGY HIGHLIGHTS

- ✓ Apply with hand calculators – not a black box
- ✓ Consider effects such as increased use of autos left at home by ridesharers, telecommuters
- ✓ Explicit links to MOBILE emission factor categories

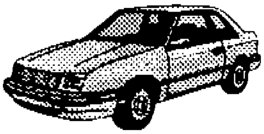
Offsetting effects generally not considered include (1) TCM participants who do not reduce trips (100 new ridesharers does not result in 100 fewer trips as each carpool has a driver, and since some ridesharers drive to park and ride lots) (2) increased driving by household members of carpoolers, telecommuters, or other TCM participants when the vehicle is left at home, (3) increased driving by telecommuters or compressed work week employees on the days they do not commute to work, and (4) increased travel due to reduced congestion. This chapter presents methodologies which address such factors.

Improper linkages of travel activity changes to emissions occur often. A common approach has been to simply assume emission reductions are proportional to activity changes. For example if TCMs are calculated to reduce VMT by 2 percent, then emissions are assumed to be reduced by 2 percent. However, motor vehicle emissions result from a number of different vehicle types (i.e., autos, vans, heavy trucks), and from different vehicle operating modes (i.e., start emissions, exhaust emissions, and evaporative emissions). The vehicle types and emission categories affected by a TCM need to be considered. For example, a ridesharing program may reduce auto use, increase van use slightly, but is not likely to have any effect on heavy duty truck travel. A reduction in VMT will reduce exhaust emissions, but not necessarily start emissions. Further, TCM implementation can significantly affect the timing and location of emissions. For example, diurnal evaporative emissions while vehicles are not in use may occur more often in outlying areas near residences or park and ride lots given widespread implementation of ridesharing, telecommuting, and compressed work week programs. Such changes may not affect the amount of emissions, but may be important in nonattainment areas where emission locations affect pollutant concentrations. The methodologies presented in this chapter produce results that are easily and explicitly linked to emission categories and vehicle classes. Chapter three explains the emission linkages in detail, and provides procedures for estimating emission effects after travel activity effects have been quantified.

The methodologies presented here provide specific, quantitative screening techniques for calculating net trip, VMT, and speed changes for the peak and off-peak periods of an average day. The methodologies for calculating travel activity changes consist of ten steps listed in Figure 2-1. The steps begin by identifying the maximum number of trips that may be reduced by a TCM, refining this and related estimates, and then calculating the resulting emission changes.
Each of the steps are explained in more detail in the following sections. The steps are presented in a series of tables which accompany explanatory text. Both the tables and text present general equations covering each step. The purpose of presenting the methodologies in this manner is to highlight the patterns and various similarities between methodologies for very different TCMs. A key goal in developing the tables and the equations contained in them was to reduce the methodologies to a level where such patterns are visible in order to facilitate the creation of additional methodologies for TCMs not specifically covered here. It is not possible, or even desirable to write down the equations for every possible TCM. However, once the analyst is familiar with the techniques contained in this document, he or she will have many of the tools necessary for developing additional methodologies for other TCMs.

For each general equation we include a TCM-specific term that will differ for each individual TCM. For example, TCM-specific terms applicable to ridesharing may include the average carpool size and the percent of carpoolers who use park and ride lots. Specific terms for HOV lanes might include the time period of operation as an HOV lane, and the number of trips along the route where the HOV lane is added. While such terms may differ for individual TCMs, the way in which they are handled after defining them is very similar. The tables provide equations for calculating this TCM-specific term for each individual TCM included in this document. Also included in the tables are

TCM Analysis Overview



	STEPS	EXAMPLES
10	Calculate emission changes	*Based on changes in trips (start emissions), VMT (exhaust emissions) and speeds*
9	Calculate speed changes	*Speed increases due to decreased volumes*
8	Determine total VMT changes	*Net VMT changes*
7	Calculate VMT changes due to trip length changes	*Multiply difference betweeen average work trip length and satellite work stations by number of telecommuters working at satellite stations*
6	Calculate VMT changes due to trip changes	*Multiply average work trip length by number of work trips reduced*
5	Calculate total trip changes	*Net effect of measures and decreases*
4	Determine peak/off-peak period trip shifts	*Portion of trip changes that occur in the peak versus the off-peak periods*
3	Calculate indirect trip increases	*Number of additional trips due to availability of auto to member of telecommuters household*
2	Calculate direct trip reductions	*Number of trips eliminated through telecommuting*
1	Identify potential direct trip effect and affected trip type	*Number of employees allowed to telecommute*

FIGURE 2-1

example sources for information on the parameters required and example values for the parameters. An example accompanies each step; most examples use real world data from the San Francisco Bay Area. This data is used because it was recent and readily accessible; its use does not signify that it is representative of other urban areas.

Individual TCMs Addressed in This Document

As discussed above, while it is impossible to present detailed methodologies for every possible TCM, the methodologies in this document have been designed and structured in a manner that facilitates the development of additional methodologies by the user. The particular TCMs addressed in this workbook include:

1. Telecommuting
2. Flextime
3. Compressed Work Weeks
4. Ridesharing
5. Parking Management
6. Transit Improvements (one methodology for decreased fares and another for increased service)

The following briefly summarizes each of these TCMs and their primary effects on travel activity.

- Telecommuting: Telecommuting is an employer-sponsored change in work location to either the home or a satellite center. The direct effects of telecommuting are to reduce work trips for those who opt to work at home or to reduce work-related VMT for those who opt to work at a satellite center.

- Flextime: Flextime is an employer-sponsored flexible work scheduling program to reduce peak period travel. Schedules are designed to avoid travel during the most congested times of day. The direct effects of this TCM are to shift work-related trips and VMT from the peak period to the off-peak period in order to reduce traffic congestion.

- Compressed work weeks: Compressed work weeks is another employer-sponsored work scheduling program. Its design is to have employees work a 10 hour day in order to eliminate one work day a week or a 9 hour day in order to eliminate one work day every two weeks. The direct effects are to reduce work trips on the eliminated work days and to also shift the time of work travel to the off-peak period on the working days (due to the increased daily hours of work).

- Ridesharing: Ridesharing or carpooling to the work place has a direct effect on the work-related trips. In this analysis, the distinction is made between ridesharers who join an existing carpool, ridesharers who form new carpools, and ridesharers who utilize park and ride lots. In each of these cases the trip and VMT reduction analysis is unique.

- Parking management: Parking management refers to employer based parking programs to reduce the use of single occupant vehicles. The direct effects include the elimination of work trips due to an increase in transit and ridesharing modes. There is also a percentage of the work force who can opt to use fringe parking facilities.

- Transit Improvements: Transit improvements can encourage individuals to ride buses instead of driving their own vehicles. Two types of transit improvements are covered here: (1) a decrease in fares and (2) an increase in service. Transit improvements can reduce both work and non-work trips as well as VMT. Typically, transit use will result in fewer trip reductions than programs such as ridesharing, as individuals will often need to drive a vehicle to a transit station. The number of trips saved depends on the proximity of the transit stations and stops to individual's homes.

These particular TCMs were chosen from among the many that are possible based in part upon their frequency of application. In addition, a goal was to include specific methodologies for a range of TCMs involving price, behavioral, and system changes. This range is hoped to provide enough specific examples of the ways in which the methodologies can be applied to provide the user with sufficient tools for applying or extending the methodologies to additional TCMs.

DATA REQUIREMENTS FOR APPLYING METHODOLOGIES

CAUTION

✓ Results are only as good as the input data; use of locally representative data whenever possible is crucial

✓ Time spent comparing input values reported by various sources can be very instructive

The most time-consuming step in TCM analysis is the collection of the data needed to conduct the analysis. The quality of the data used in the analysis affects the results more than any other factor. The availability of local data is crucial for calculating reliable results. If no transportation demand model has been developed for the geographic area under study, the data collection process may be challenging, as the needed data may need to be collected from multiple (and possibly conflicting) sources. In this document, example data values are used throughout the text. It must be stressed that these are presented for illustrative purposes only. These example values should not be used in other geographic areas.

Applying the methodologies in this document will require data from a variety of sources. Such data include travel data (i.e., VMT and trips for peak and off-peak periods), data on existing TCM implementation (i.e., average number of people per carpool, average distances to park and ride lots), census data (i.e., number of employed persons, average number of people per household, or vehicle ownership). A list of these data requirements and example data sources is presented in Table 2-1. Not all data is needed for all TCMs; for example, the number of lane miles of new HOV capacity is not used in the telecommuting methodology. In addition, some data not listed here may be necessary for TCMs other than those specifically covered in this document. Finally, the user needs to be cautious in using such data for an entire region. The detail provided in transportation models, which can consider small scale changes in trip and socioeconomic characteristics, is more appropriate (if the data used in calibrating the model is relatively recent). When possible, such detailed estimates should be used to calculate baseline (before additional TCM implementation) conditions from which to calculate TCM effects. As the methodologies presented here will often be used in areas that do not have such models, this data will need to be collected from other sources. Such approaches are characteristic of sketch planning methods which have been in use for some time (for example, approaches developed in 1979 by Cambridge Systematics [CSI, 1979]).

Data Used in Examples and Need For Region-Specific Data When Applying the Methodologies

Example values and example applications of the methodologies are provided in many of the tables and in all of the worked examples. A worked example is provided after each analytical step is presented. These examples utilize travel activity data primarily from the San Francisco Bay Area, since this information was relatively recent and readily accessible to the authors. The use of these values is not meant to imply that they represent a "standard" set of data that could be applied to any location. Individual agencies applying these methodologies need to be sensitive to the wide range of observed values that have been documented for various areas. For instance, the percent of home-based work trips that are made using single occupant vehicles (SOVs) is reported to be 58.8 percent in the San Francisco Bay Area and 71.8 percent in Phoenix, Arizona (DOT, 1988). In addition, different sources of travel activity data may report different values for the same variable; while the Department of Transportation reports that the percent of work trips made using an SOV is 45.1 percent in New York City, the Bureau of the Census reports this value to be 26.3 percent. To obtain the most accurate estimate of TCM effectiveness for a specific region, travel data specific to that region must be used.

Values such as regional VMT, trips per person, and regional trips by mode are values that will vary based upon characteristics of the region itself. These characteristics include the availability of differing transit modes, previous levels of TCM implementation, land use patterns and geographic characteristics of the area, and socio-economic characteristics. TCM-related travel, VMT and mobile source emissions changes will vary according to these characteristics.

TABLE 2-1. Data used in TCM methodologies.

Data Type		Example Sources
Travel data	Single occupant vehicle work and non-work trips per day Shared vehicle work and non-work trips per day (transit separately from carpools) Percent of work and non-work trips occurring in peak period of day VMT by trip type (either for study region as a whole or for subareas) in peak and off-peak periods Average work trip distances (if data available for subareas, particular demographic groups, or other subgroups such as ridesharers this should be used) Average non-work trip distances Average speeds for peak and off-peak periods. It is preferable to have these data for major roadway types or subareas Relative costs of different modes as well as cost ranges (i.e. highest and lowest costs possible for a mode) Elasticity of mode choice with respect to cost Elasticity of speed with respect to volume Length of peak period (number of hours) Average Vehicle Occupancy (should collect two numbers: one total and one without transit)	(1) Generally the best source of data is from local transportation planning agency data and/or projections. In larger urban areas, a designated Metropolitan Planning Organization (MPO) is responsible for collecting and updating transportation-related data. In smaller areas, planning districts or commissions, government associations and the like may collect data. (2) Local ridesharing agencies and local employers who have conducted surveys on employee driving patterns. Early in the data collection process, the need for additional surveys should be evaluated. (3) Regional FHWA office. The nine FHWA regional offices are particularly useful for obtaining relevant traffic count data from the Highway Performance Monitoring System, and for guidance on proper interpretation of these data. (4) National Personal Transportation Survey. Conducted by the Department of Transportation, the most recent survey was conducted in 1990 and interviewed almost 22,000 households. The survey estimates VMT, trips, temporal travel characteristics and many other parameters. Because of the small sample sizes, these data need to be used with caution in specific geographic areas. (5) Publications from the Institute of Transportation Engineers such as the Transportation and Traffic Engineering Handbook, manual of trip generation rates, and others. (6) Journey-to-work data from the U.S. census.

TABLE 2-1. Concluded.

Data Type		Example Sources
TCM data	Average number of people per carpool	Local ridesharing organization statistics (see, for example, RIDES, 1990, or Maltzmann, 1987), or MPO. National data (i.e. census or NPTS) can be used if nothing local is available
	Fraction of carpoolers who do not drive to park and ride lots	
	Fraction of carpoolers who join existing carpools	Same as above
	Fraction of carpoolers who form new carpools	Same as above
	Average distance to park and ride lots	Same as above
	Frequency of ridesharing, telecommuting	Same as above or from literature
	Fraction of telecommuters who work from satellite centers	Either user specified (if specified as a programmatic element) or from literature
	Average distance to satellite centers	Participating employers
		Participating employers
Census data	Number of individuals over 16	Census or local statistics (i.e., State finance department or labor department)
	Number of employed persons	Same as above
	Total population in study region	Same as above
	Number of people per household	Same as above
	Percent of population of driving age that does not own a vehicle	Same as above

The values used in the examples are frequently from a travel demand model (in this case, the MTCFCAST model developed for the Metropolitan Transportation Commission in California). This highlights the manner in which these screening methodologies are used: baseline travel activity data or output from base case transportation modeling is used as the starting point from which to calculate TCM effects. The travel demand model and methodology used to generate these values will obviously affect the values used to calculate the effects of the various TCMs and the subsequent results.

Not all agencies will have region-specific information for all of the required variables. In these cases, several sources of "standard" values are available that may be used as substitutes if no better data are available. A number of these sources are listed in Table 2-2.

Data Relating Changes in Price or Time to Changes in Travel Behavior

Some of the methodologies in this workbook employ elasticity measures in order to predict transportation demand responses to system changes, such as fare increases, tolls, and travel time increases or decreases. The economics concept of "price elasticity" is the informal ancestor of transportation elasticities. This concept, put simply, is "...the percentage change in quantity of commodity or service demand in response to a 1 percent change in price (DOT,1981)." This means that a price elasticity of -0.3 indicates that for a 1 percent increase in price of a good or service there is an 0.3 percent decrease in the demand for that good or service. The negative sign indicates that there is an inverse relationship between demand and price (as the price increases, demand decreases). For example, a 1 percent increase in parking prices might result in a 0.3 percent decrease in parking demand. Transportation elasticities are computed in three ways: point elasticity, arc elasticity, and shrinkage factor methods. These three methods are summarized in Table 2-3.

Users of elasticities should keep in mind that in order for elasticities to be applicable, the change in the transportation system must be a **relative** one. That is, it must involve a quantifiable percentage change in the system parameter involved. Put another way, elasticities can be used to compute the change in transit system use as a result of a change in the overall price of service, but they cannot be applied to predict response to a new transit line. Elasticities are not meant to be used as precise predictive measures. They are intended to serve as an indicator of the likely order of magnitude of response to a change in the transportation system and are very useful in providing first-order, aggregate response estimates (DOT, 1981). This is one reason that elasticities are used in these methodologies, since they are intended to provide information on the relative effects of TCMS. These estimates should then be confirmed through more extensive analysis methods.

Elasticity values are available from a number of sources, including the Transportation and Traffic Engineering Handbook (ITE, 1982) and Traveler Response to Transportation System Changes, (DOT, 1981), or they may be calculated using the formulas given in Table 2-3 using region-specific data.

TABLE 2-2. Selected sources of general travel data.

SOURCE	AUTHOR(S)	INFORMATION OFFERED
National Personal Transportation Survey (NPTS)	U.S. Department of Transportation, 1993 Office of Highway Information Management (for summary reports) Electronic files are available from the Volpe National Transportation Systems Center in Massachusetts.	Presents data from a 1990 survey of almost 22,000 households on total travel, determinants of travel, person trips and miles of travel, vehicle trips and vehicle miles of travel, journey to work and work-related trips, ride sharing and vehicle occupancy, and others.
Characteristics of Urban Transportation Demand	U.S. Department of Transportation, 1988.	Presents data on a wide variety of statistics relaated to urban travel, comprised almost exclusively of post-1970 data.
City and County Data Book 1988	U.S. Department of Commerce, Bureau of the Census, 1988.	Data from the 1980 U.S. Census regarding mode of travel to work and number of workers.
Commuting in America - A National Report on Commuting Patterns and Trends	A. Pisarski, Eno Foundation for Transportation, Inc. 1987.	Describes patterns in commuting over the past thirty years, including changes that have occurred that affect current transportation policy. Many statistics related to commuting, including number of workers, relationships between urban development and commuting behavior, and mode of travel to work.
Highway Capacity Manual, Special Report 209	Transportation Research Board, 1985.	Provides techniques for estimating highway capacity and level of service. Includes information on traffic characteristics and performance and new procedures for capacity analysis of freeways and rural roads. Discusses pedestrian traffic flow and facilities and the effect of bicycles in the traffic stream.
Travel Characteristics at Large-Scale Suburban Activity Centers	JHK & Associates for the Transportation Research Board, National Research Council, 1989.	Travel activity data (trip generation, travel time, etc.) are summarized for 6 geographically representative suburban sites.

TABLE 2-2. Concluded.

SOURCE	AUTHOR(S)	INFORMATION OFFERED
Transportation and Traffic Engineering Handbook, Second Edition	W.S. Homburger, Editor Institute of Transportation Engineers (ITE), 1987.	Various general values related to transportation (including elasticities, mode split, general impacts), along with explanations of many widely used concepts in traffic engineering.
1990 Census of Population - summary publications and data sets	U. S. Bureau of the Census.	Release of summary information from the 1990 Census, including worker statistics and journey-to-work, are being made available continuously. The Census Bureau should be contacted via telephone or modem to determine the availability of updated information.
1980 Census of Population, Vol. 2, Journey to Work: Characteristics of Workers in Metropolitan Areas (PC80-2-6D)	U.S. Bureau of the Census, July 1984.	Similar to the City and County Data Book, this volume focuses more specifically on work travel, type of work, number of workers, commute time, etc.

TALBE 2-3. Methods for computing elasticities.

METHOD	FORMULA	SUMMARY
Point Elasticity	$\epsilon_p = \frac{dQ}{dP} \times \frac{P}{Q}$ ϵ_p = elasticity P = price Q = quantity demanded at price P	Derived directly from the economist's definition of elasticity. Lack of information on the functional relationship between P and Q (the shape of the demand curve) precludes the computation of point elasticites from empirical data (DOT, 1981).
Arc Elasticity	$\epsilon_p = \frac{\Delta \log Q}{\Delta \log P} = \frac{\log Q_2 - \log Q_1}{\log P_2 - \log P_1}$ ϵ = elasticity Q_1, Q_2 = demand before and after P_1, P_2 = price or service before and after	This logarithmic formulation most nearly approximates point elasticity and is frequently employed (DOT, 1981).
Shrinkage Factor (Shrinkage Ratio)	$\epsilon = \frac{\Delta \frac{Q}{Q_1}}{\Delta \frac{P}{P_1}} = \frac{(Q_2 - Q_1)/Q_1}{(P_2 - P_1)/P_1}$	This form of elasticity is historically used in reporting response to transportation system changes. There are certain conceptual difficulties with this method. For instance, consider a specific experimental trasportation price reduction and accompanying travel volume increase. Assume that the demand returns to its original level if the price is raised back to its original state as a second experiment. Intuitively, the elasticity in this hypothetical example should be the same for both experiments (it is if arc elasticity is computed). However, if the changes in price are moderately large, the corresponding shrinkage factors will be different. While this method and the arc elasticity equation will yield very similar results when changes are small, discrepancies arise and values differ when changes are large (DOT, 1981).

It must be stressed that elasticities are very approximate. In a given region, they will vary widely depending on the base costs, travel times, and mode shares.

The remainder of this chapter presents the methodologies. Readers should note that they are presented in a step-by-step fashion and that each step covers all TCMs. If a particular TCM is being evaluated, simply use the equations applicable to that particular TCM.

STEP 1: IDENTIFY THE POTENTIAL DIRECT TRIP EFFECT AND THE TRIP TYPE AFFECTED

Step 1 determines the potential number of vehicle trips[1] affected (PT) by the TCM and the distribution of effects by trip type (work and non-work).

This step identifies the total number of vehicle trips that *might* be reduced. Subsequent steps are used to adjust this estimate to represent the actual reduction which may be achieved. In this first step one also defines the fraction of trip changes which are work related. While many TCMs such as ridesharing and telecommuting aim to reduce work travel, others, such as HOV lanes, may affect both work and non-work travel. Still others, such as school-based trip reduction programs (not specifically covered in this document) may not affect work trips at all. Distinguishing between trip types is important in the context of these methodologies because the trip type affected is used to determine the allocation of trip changes between the peak and off-peak periods.

Potential Direct Trip Effects (PT)

Potential direct trip effects are the maximum number of vehicle trips per day affected. Two possibilities for calculating potential direct trip effects (PT) are presented: (1) the user supplies the number of participants and the frequency of participation (i.e., the number of ridesharers and the number of days per week the average carpooler shares a ride), or (2) the user can use elasticities to determine PT. Elasticities express the percentage change in a variable (i.e., number of transit users) given a change in cost and can be used when a TCM directly influences travel costs (i.e., parking management or transit fare decreases). Elasticities can be thought of as rough approximations for calculations by mode choice models incorporated into traditional transportation demand models. A third alternative sketch planning technique is to use 'utilities', which can relate changes in the desirability of a travel mode (due to changes in cost or travel time) to mode shifts. This method is discussed in detail in (CSI, 1979). It is not included here because the method requires the use of mathematical coefficients derived from detailed surveys and regression analysis of travel behavior. A variant of this approach is used in the methodology for evaluating effects of TCM packages. The techniques described in this document are for use when such detailed data is not available; however, their use

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[1] Unless otherwise noted, "trips" in this document refer to vehicle trips rather than person trips.

may be enhanced by such data when they exist, as they provide a way of addressing factors not considered in earlier documents.

To directly specify the participation rate in units of people per day, the user needs to identify the target number of participants. This approach can be used for TCMs such as ridesharing or telecommuting, which target particular people. For work-related TCMs the number of potential trips can be calculated as:

$$PT = N * F/D * 2 \tag{2-1}$$

where N is the number of participants (people), F is the frequency of participation (days per week), D is the average number of commute days in a week, and the factor of "2" adjusts for trips to and from work. For example, if 500 new ridesharers were expected to result from a new ridesharing program and carpooled an average of 3 days per week, then the average number of new ridesharing trips per day would be 600.

To calculate the potential number of trip effects using elasticities, one can use the following equation

$$PT = \epsilon * \Delta V * P_O \tag{2-2}$$

where ϵ is the elasticity of the change in participation level (PT) with respect to a changing variable (ΔV) such as cost or time (both ϵ and ΔV should be expressed as a percent change), and P_O is the number of individuals experiencing the change in cost. Elasticity approaches such as equation (2-2) may be used if the TCM primarily involves a cost or travel time change. For example, suppose a transit agency is willing to implement a 50 percent reduction in transit fares on routes affecting 10,000 people. The agency estimates the elasticity of ridership with respect to fare to be -0.2. The potential number of new transit users may be estimated as 1000.

Table 2-4 provides an equation and a summary description of key parameters for determining the potential trip effect for each TCM specifically covered in this document.

Fraction of work related travel (ω)

The fraction of work related travel of a TCM ,ω , represents the fraction of direct trips associated with TCMs which influence work trips. Thus ω is a number between 0 and 1 where 1 indicates that only work travel is directly affected by a given TCM and 0 indicates no work travel is affected by a given TCM. Since only two types of travel are addressed in these methodologies, the fraction of non-work travel changes equals one minus ω. For a TCM which influences work and non-work travel about equally (e.g. transit increases), ω is assumed to equal a study region's base work travel fraction.

Recommended values for ω are listed in Table 2-5.

TABLE 2-4. Equations for identifying potential trips per day affected.

TCM	Method to determine potential trip effect **(PT)**	Parameter Description
Telecommuting	$PT = N*F/D*2$	F = the number of telecommute days per week.
Flextime	$PT = N*F/D*2$	F = the number of days per week flextime is in operation.
Compressed work week	$PT = N*F/D*2$	F = the number of work days eliminated per week.
Rideshare	$PT = N*F/D*2$	F = the number of days per week that are carpooled.
Transit (decreased fares)	$PT = \epsilon * \Delta FARE * P_O$	ϵ = percent change in ridership given a percent change in fare or travel time ΔFARE = percent change in transit fare
Transit (increased service)	User supplied	MPOs or transit organizations typically can provide estimates of increased ridership
Parking management	$PT = [NSPACE-ALTSPC] * \epsilon * \Delta PRC$	NSPACE = # of parking places subject to prince increase. ALTSPC = # of "spillover" parking places available. ΔPRC = percent change in parking price AVO = Average Vehicle Occupancy

TABLE 2-5. Fraction of direct trip effects assumed to be work related (ω) by TCM.

TCM	Recommended value of ω	Comments
Telecommuting	1	Only work trips influenced
Flextime	1	Only work trips influenced
Compressed work week	1	Only work trips influenced
Rideshare	1	Only work trips influenced
Transit (decreased fares)[1]	WORK	WORK = work trip fraction (work trips/total trips)
Transit (increased service)	WORK	work trip fraction
Parking Management	1	Only work trips influenced
		$WORK_{Pk}$ is the peak period work trip fraction (peak period work trips/ total peak period work trips)[2]

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[1] This is for general transit fare decreases available to all transit users; for the case of employer subsidized transit passes the value of $\omega = 1$ should be used.

EXAMPLE 2-1. PT (Potential Trip Effects)

RIDESHARING

$$PT = N * F/D * 2$$
$$PT = 10{,}000 * 3/5 * 2$$
$$PT = 12{,}000 \text{ (vehicle trips per day)}$$

Discussion

10,000 new ridesharers (N) carpool three times per week (F). Therefore the maximum trip reduction is equal to 12,000 vehicle trips per day. Subsequent steps in this methodology show how this value is reduced by factors such as carpoolers driving to park and ride lots, increased use of the vehicle by ridesharer household members, and considerations such as the fact that each carpool needs a driver (some carpoolers still drive).

STEP 2 - CALCULATE THE DIRECT TRIP REDUCTIONS

This step is used to calculate the direct trip reductions resulting from the potential trip reductions calculated in step 1. (such as work trips reduced by telecommuters). Indirect trip changes are secondary trip effects such as increased nonwork trips by telecommuters on their days off and are estimated in Step 3. The following equations calculate the daily average direct trip reduction for work and non-work trips:

$$\Delta TRIPS_D = \alpha * PT \tag{2-3}$$

$$\Delta TRIPS_{D,W} = \omega * \Delta TRIPS_D \tag{2-4}$$

$$\Delta TRIPS_{D,NW} = (1 - \omega) * \Delta TRIPS_D \tag{2-5}$$

where:

$\Delta TRIPS_D$ = Total trip reduction for work and non-work trips
α = TCM specific factor equal to the fraction of participants who make a direct trip change (trip changes per participant)
PT = is the potential trips affected per day
$\Delta TRIPS_{D,W}$ = Direct work trip reduction
$\Delta TRIPS_{D,NW}$ = Direct non-work trip reduction

In Equation 2-3, α accounts for the fraction of potential trip reductions (PT) which may actually be eliminated. This variable is used to offset the potential trip reductions by considering issues that may reduce the effect of a TCM. For example, some ridesharers drive to park and ride lots, and some may previously be transit users. α is specific to each TCM and the procedure for calculating it is provided in Table 2-6 for each TCM covered in this document.

It is important to account for reduced work trips separately from reduced non-work trips (equations (2-4) and (2-5)). This becomes critical in later steps when speed effects are calculated as a function of reduced VMT in the peak and off-peak periods (speeds are characteristically slower in peak periods than in off-peak periods). Most work trip reductions affect peak period travel while fewer non-work trips do so.

The equations listed in Table 2-6 address a number of issues not covered in other TCM methodologies. The logic behind each is discussed for each TCM below.

Telecommuting

While most telecommuting programs allow employees to work from their homes, an increasing number employ either satellite work centers, or aim to reduce work-to-work trips by using teleconferencing for meetings. The equation in Table 2-6 adjusts the potential trip reductions by the percent of telecommuters who will work from home rather than from satellite work centers. In addition, it adjusts PT to account for the fact that some telecommuters may be transit users or carpoolers. The equation assumes that employees will choose telecommuting days that are not in conflict with their ridesharing days (i.e., that telecommuting will not affect AVO by breaking up carpools). This is reasonable as most individuals share rides only two or three times a week and generally telecommute once a week. Needs for a vehicle such as running errands or making work-to-work trips can be accommodated in a manner similar to before the telecommuting program was instituted.

This equation does not directly address teleconferencing. It can be used to estimate the impact of teleconferencing programs by estimating the number of work-to-work trips saved by such a program (i.e., by calculating the average attendance and frequency of meetings targeted) and substituting a work-to-work trip AVO (employees from the same office frequently share rides to off-site meetings so that AVO for work-to-work trips is higher than average) into the equation listed in table 2-6. The variable "SAT" would be removed from the equation in this case.

Flextime

Flextime does not reduce trip making, but simply influences the time of day trips are made. It has been argued that flextime has the potential to break up carpools (indicating that flextime could potentially increase trips) but evidence on this issue has been mixed. If the employees targeted for a flextime program also rideshare, or if a ridematching or carpool incentive program is instituted at the same time, and there is concern that the two programs may be antagonistic, the TCM packaging approach presented in chapter four may be applied to roughly quantify such effects.

TABLE 2-6. TCM adjustment factor, α, defined in equation (2-3) for each TCM.

TCM	α	Variables	Description	Example Values[1]
Telecommuting	-(1-SAT)/AVO	SAT = fraction of telecommuters who work in satellite office. AVO = Average Vehicle Occupancy (with transit)	Takes into account drivers who did not go to satellite offices or who did not use SOV mode prior to telecommuting.	SAT = 2% (WSEO, 1989) 71.4% (MTC, 1990)
Flextime	0	Not applicable for trips	α is zero to show that no direct trip reductions occur	
Compressed work week	-1/AVO	AVO = Average Vehicle occupancy (with transit)	Takes into account that drivers who switch from a non-SOV mode do not reduce trips.	
Ridesharing	-[NOLD +[NEW * (NCAR-1)\NCAR]/AVO]	NOLD = fraction of ridesharers who join existing carpools and don't drive to park and ride lots NCAR = Average number of people per carpool NEW = Fraction of ridesharers who form new carpools and don't drive to park and ride lots	NOLD accounts for the fact that each ridesharer who joins an existing carpool saves a trip NEW accounts for the fact that for every new carpool, one trip (by driver) still takes place	NOLD is approximately 33% (Pides, 1990), (UMTA, 1985) (Maltzman, 1987) NEW is approximately 62% (same references as for NOLD)
Transit	-1/AVO	AVO = Average vehicle occupancy	takes into account mode shift between different non-SOV modes. (Some ridesharers may switch to transit	1.126 (MTC, 1990)
Parking Management	-[TRAN + (NOLD*RD) + [NEW*RD*(NCAR-1)/NCAR] - FRNG]	TRAN = Fraction of PT who will use transit RD = Fraction of PT who will rideshare NOLD = Defined above NCAR = Defined above FRNG = Fraction of PT who will use fringe parking facilities	"PT" is equivalent to the number of people subject to the parking management program who will use shared modes in response. Of these, some will switch to transit and some to ridesharing. We assume that the proportional switching to each will be in the same proportion as the existing mode split.	TRAN = 37.4% of shared rides in San Francisco Bay Area (MTC, 1990) RD = 62.6% of shared rides in San Francisco (MTC, 1990) FRNG = 0.0% for this example
		Same as above for parking management	Although variables are the same as for parking management, the values of the variables could be different (especially since fringe parking is not an option for HOV lanes).	

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[1] As noted in the text, the example values shown should not be used in other study regions.

Compressed Work Weeks

The potential number of trip reductions due to compressed work weeks is divided by AVO to adjust for participants who are ridesharers.

Ridesharing

The ridesharing equation is somewhat more complex than the others. It accounts for the driver in a new carpool and for the fact that some carpoolers drive to a central location such as a park and ride lot (thus not eliminating a trip). Most methodologies have assumed that each ridesharer reduces a trip. In effect, they assume that the variable "NOLD" (the fraction of ridesharers who join existing carpools and who do not drive to a park and ride lot or other central location) equals one. In reality, many ridesharing programs encourage the formation of new carpools while also increasing participation in existing pools.

The first part of the equation adjusts for the fact that each carpool has a driver; if a new carpool contains three passengers, then only two trips will be saved. To account for this, the equation multiplies the fraction of carpoolers forming new carpools by the percent of passengers that will reduce trips (NCAR-1)/NCAR, or 75 percent in a carpool containing four passengers). Next, the whole equation should be divided by the AVO to account for existing carpoolers or transit users. If a ridesharing program is targeting only SOV users, one should not divide by AVO.

Parking Management

The number of individuals who would shift from SOV to a shared travel mode was roughly estimated using elasticities in the equation given for PT for a parking price increase. If an alternate methodology is used (i.e., a more sophisticated mode choice algorithm) the value should be reported in units of individuals shifting from SOV to shared ride modes (or, ideally, by the number of individuals who will shift to transit and the number that will shift to carpools).

The equation builds upon the same concepts given in the ridesharing equation. Of the individuals who rideshare, some will join existing and some will form new carpools. All transit users are assumed to reduce trips (alternatively, the percent of transit users who drive to bus stops may be used to adjust the variable "TRAN"). It is difficult to calculate the variables "TRAN" and "RD" without using sophisticated mode choice techniques that may require considerable time and resources. However, for an approximation it is probably reasonable to use the base distribution of mode splits between ridesharing and transit (i.e., if 65 percent of shared rides are carpools and 35 percent are transit, then "RD" is assumed to be 0.65, and "TRAN" is assumed to be 0.35. The fraction of individuals who can drive to fringe parking lots near work sites and share rides to work should be subtracted from the result (if any data are available for this). The equation is not divided by AVO in this case, because the parking management program assumed is one that only institutes parking charges for SOV users. If a parking program institutes charges for all vehicles, the equation needs to be divided by AVO. In addition, such a program may make transit more attractive with respect to carpooling. The analyst may wish to approximate the change by using the elasticity of transit use with respect to price. The change in price would be the average parking charge for a carpooler, and the increased fraction of transit use would be used to calculate a new "TRAN" and "RD" for the individuals affected by the parking program.

Example Application of Equation in Table 2-6

An example application of the equations in Table 2-6 is provided below for ridesharing.

First, determine α:

EXAMPLE 2-2. Determining α (TCM Specific Factor to Adjust "PT")

RIDESHARING

$$\alpha = -[NOLD + [NEW * (NCAR - 1)/NCAR]/AVO]]$$

$$\alpha = -[0.33 + [0.62 * (2.28 - 1)/2.28]/1.126]]$$

$$\alpha = -0.61$$

Discussion

Some ridesharers join existing carpools (represented by the fraction "NOLD"), while some form new carpools (represented by the fraction "NEW"). The new carpools each contain a driver. The average number of people per carpool in the example data used in this particular document is 2.28. On average then, 56 percent (1.28/2.28) of the individuals carpooling in new carpools reduce trips. The result is divided by the average vehicle occupancy (1.126 in the sample data set from the San Francisco Bay Area). The result says that approximately 61% of the potential trip reduction will be realized.

then direct trip effects:

EXAMPLE 2-3. TRIP$_D$ (Direct Trip Reduction)

RIDESHARING

$$\Delta TRIP_D = \alpha * PT$$
$$\Delta TRIP_D = -0.61 * 12{,}000$$
$$\Delta TRIP_D = -7{,}320$$

<u>Discussion</u>

In this example, 10,000 ridesharers reduce 7,320 trips per day (direct trips; indirect trip effects calculated in later steps will tend to offset this amount somewhat more). It should be noted that the impact of considering past mode share, whether ridesharers will drive to park and ride lots, and whether they will join existing or form new carpools reduces the estimated benefit by about 40 percent.

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and finally the direct work trip effects:

EXAMPLE 2-4. TRIP$_{DW}$ (Direct Work Trip Reduction)

RIDESHARING

$$\Delta TRIP_{DW} = \omega * TRIP_D$$
$$\Delta TRIP_{DW} = 1 * -7{,}320$$

<u>Discussion</u>

All direct trip effects of ridesharing are work related.

STEP 3 - CALCULATE THE INDIRECT TRIP INCREASES

It is important to also consider effects that may offset TCM benefits. For example, when TCM participants leave their vehicles at home, members of their households may use them for either work or non-work trips. In addition, TCM participants may experience an increase in their 'travel budget' by participating in a TCM program. For instance, a telecommuter saves time and driving costs on telecommuting days. The telecommuter may desire to 'spend' some of these decreased costs on extra non-work related travel.

Table 2-7 presents an initial list of equations that may be used to evaluate such offsetting effects.

The equations in Table 2-7 provide methods for approximating trip increases due to vehicles being left at home. The third equation roughly estimates trip increases due to decreased roadway congestion.

The first equation can be interpreted as follows: The rate at which work trips may increase because a vehicle is left at home depends on: (1) the fraction of the population that does not own a vehicle (and therefore *may* wish to use one for work travel); (2) the fraction of the population that shares a ride to work, (individuals who do not have access to vehicles and who share rides to work may prefer to drive their own vehicle to work); (3) the household size minus 1 (1 is subtracted to account for the fact that one of the household members is the new ridesharer affected by the TCM); (4) the employment rate (unemployed household members will not need to commute to work); and (5) the trip generation rate for SOV drivers. The second equation can be interpreted in a similar fashion except that it considers a different segment of the population (unemployed household members of driving age). As noted in the example, the work trip increase equation is conservative in that it assumes that all household members without a vehicle who share a ride to work (implying that they work too far away to walk or bicycle) will use the vehicle left at home.

If both equations are used, a small overestimation of trip increases may result since double counting of vehicle use may occur. The likelihood that an unemployed individual over 16 who does not own a vehicle lives in the same household as an employed transit or shared ride user without a vehicle could be used to reduce the potential for double counting. The total trip increase can be adjusted by multiplying the sum of INC_{WH} and INC_{NW} by one minus this probability.

An example application for determining the value of INC_{WH} and the total trip effect is provided in the box below.

TABLE 2-7. Indirect Trip Effects.

Equation	Explanations	Variable Definition[2]	Trip Effect
$INC_{W,H}$ = NV * SHR * (SIZE - 1) * EMP * TG_W	This equation estimates the rate of trip increases due to household members of TCM participants who leave their vehicles at home. The total number of trip increases resulting is calculated by multiplying a factor similar to α for direct trips ($INC_{W,H}$) by the direct trip reduction calculated in Step 2.	**$INC_{W,H}$** = Rate of increased SOV work trip making by household members of TCM participants who leave their vehicles at home **NV** = Fraction of population that does not own a vehicle (census data) **SHR** = Fraction of trips made via shared mode (28.6 in Bay Area) **SIZE** = Average household size (Approximately 2.56 in the San Francisco Bay Area) **EMP** = fraction of population that is employed (and over 16) (About 53%) **TG_W** = Work trip generation rate for SOV users (trips per day) (about 1.71 in the San Francisco Bay Area)	$INC_{W,H}$ * $TRIP_{D,W}$ /2 This equation results in the number of trip increases. These are divided by 2 because the number of vehicles left at home is equal to the number of trips saved as ridesharers leave their vehicles at home/2 (assuming that each ridesharer makes two work trips per day - one from home to work and one from work to home

(continued)

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[2] As noted in the text, example values should not be used in other study regions.

TABLE 2-7. (Concluded). Indirect Trip Effects.

Equation	Explanations	Variable Definition	Trip Effect
$INC_{N,H} = NV * SHR * (SIZE - 1) * UNEMP * TG_N$	This equation estimates the rate at which non-work trips will increase due to increased availability of vehicles for non-work trips previously made via transit or shared ride.	$INC_{N,H}$ = Rate of increased non-work trip making by unemployed household members of TCM participants who leave their vehicles at home. UNEMP = fraction of population over 16 that is unemployed.	$INC_{N,H} * TRIP_{D,W} /2$
$e_m(C_0 - C_1)/C_0 * SHR * TRPs$	Vehicle trips could increase if the TCM or TCMs implemented in an area reduce congestion sufficiently enough to encourage individuals to shift from non-SOV to SOV modes. This equation very roughly approximates 'latent demand' possibilities such as shared ride commuters who would prefer to use SOVs.	e_m = Elasticity of mode choice with respect to cost. C_0 = Pre-TCM cost of work travel (for this equation the cost is equal to out-of-pocket costs + regional average hourly wage rate applied to total travel time.)[1] C_1 = Post-TCM travel cost (this cost cannot be calculated until the speed changes are calculated in step 9 and then translated into a cost change due to reduced travel time. In most TCM calculations this effect will not be considered but the equation is included for completeness. TRPs = Total trips per day affected by the speed increase.	

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[1] Studies have shown that in-vehicle travel time is not weighted as heavily as access time (e.g. waiting for the bus). If desired, the travel time could be weighted to adjust for such factors

EXAMPLE 2-5 INC_{WH} (Indirect Work Trip Effect)

RIDESHARING

$$INC_{W,H} = NV * SHR * (SIZE - 1) * EMP * TG_W$$
$$INC_{W,H} = 0.13 \times .107 * (2.56 - 1) * 0.528 * 1.705$$
$$INC_{W,H} = .02$$

Table 2-7 includes a column labeled "trip effect" to show how the rate of increase is used to calculate a number of trips:

$$\Delta TRIPS_{I,W} = INC_{W,H} * -TRIP_{D,W/2}$$
$$INC_{W,H} = .02 * (-(7,320))/2$$
$$INC_{W,H} = 73$$

<u>Discussion</u>

Approximately 2% (in this example) of the vehicles left at home may be used for work trips by household members who previously were ridesharing or using transit. Note that this is a very conservative estimate: it assumes that all household members without vehicles who need to commute to work will use the vehicle now left at home.

STEP 4 - DETERMINE DIRECT PEAK/OFF-PEAK PERIOD TRIP SHIFTS

Many TCMs, including peak period delivery restrictions, flextime, compressed work weeks, and HOV lanes shift travel between peak and off-peak periods. The amount of travel shifted depends on a number of factors, including the length of the peak period and the number of hours individuals are willing (or allowed) to shift the time of their travel. Such shifts are important because of the potential for congestion relief when travel is spread more evenly throughout the day. In general, the higher speeds typical of lower congestion can result in lower emission rates. Step four explains how to calculate the net shifts in work and non-work trips to and from peak and off-peak periods. It should be noted that this step is used only for TCMs which directly shift travel times (i.e., flextime). The allocation of trip reductions calculated in steps 1 - 3 for TCMs such as ridesharing or telecommuting to the peak and off-peak period is accomplished in step 5.

The following two variables are determined in this step (4):

- $\Delta TRIP_{S,P}$ = the change in peak period trips (the subscript S signifies the category of trip shifts), and
- $\Delta TRIP_{S,OP}$ = the change in off-peak period trips.

As an example, a compressed work week plan may eliminate work trips by allowing employees to work four 10 hour days instead of five 8 hour days. Additionally, this TCM also redistributes existing work travel between peak and off-peak periods due to the change in travel times of the participants. The amount of travel that is redistributed depends on the length of the peak period. If the peak period is very long there is a smaller probability that a one or two hour change in the time one departs for work will shift travel to the off-peak periods.

The procedures for flextime and compressed work weeks are presented below.

Flextime

Flextime allows for a broader period of travel to and from work resulting in a shift of work trips from the peak period to the off-peak period. Of the total potential trips affected by a flextime program, only some will actually shift from the peak to the off-peak period. Conceptually, if employees are supposed to be at work by 8:30 a.m. and a full flextime program is instituted wherein employees can arrive and leave from work at any time, as long as they put in a full eight hour day, only some will actually shift their travel out of the peak period. If the peak period runs from 7:00 - 10:00 a.m., these employees would have to shift their travel time by close to two or more hours in order to travel outside the peak period. While some employees may be willing to do so, many may not be. If the peak period is shorter, then obviously more employees will shift their travel to outside the peak period. In the many urban areas which experience long peak periods, the impact of TCMs such as flextime is not likely to be significant.

The effect of peak period length and the fraction of individuals who will actually change their pre-flextime travel patterns so that they shift out of the peak period can be evaluated for both the a.m. and the p.m. period using the following equations:

$$\Delta TRIPS_{S,P} = -\delta_{FLEX,AM} * \frac{PT}{2} - \delta_{FLEX,PM} * \frac{PT}{2} \qquad (2\text{-}7)$$

where **$\Delta TRIP_{S,P}$** is the change in peak period trips (the two terms of this equation are to distinguish between AM and PM peak periods), **PT** is the potential trips identified in Step 1 of this chapter (the factor of 2 is used to divide PT equally between the AM and PM peak periods), and **δ_{FLEX}** is the fraction of the flextime potential trips which will shift from the peak period to the off-peak period. A table of values for δ is provided below, along with a discussion of how these values are derived. The peak period subscript on δ is necessary since its value can differ between AM and PM peak periods. The negative signs in Equation 2-7 indicate a decrease in peak period trips due to flextime implementation.

After $\Delta\mathbf{TRIP}_{S,P}$ is determined, the change in off-peak trips $\Delta\mathbf{TRIP}_{S,OP}$ can then be obtained from Equation 2-8:

$$\Delta TRIPS_{S,OP} = -\Delta TRIPS_{S,P} \tag{2-8}$$

In other words the decrease in peak period trips equals the increase in off-peak period trips.

Intuitively, the fraction of potential trips removed from the peak period, δ_{FLEX}, will vary according to the length of the peak period. For regions with longer peak periods, flextime work scheduling would be expected to have less of an effect when compared to a region of relatively short observed peak period. Moreover, the wider range of flextime travel period (i.e., the period of hours allowed for flextime travel) the higher the probability that more trips would be removed from the peak period.

δ_{FLEX} is approximated here by assuming (1) participants are equally as likely to travel earlier or later (than before flextime implementation); (2) assuming a normal distribution (Gaussian distribution) of work trips; and (3) establishing the average increase in travel period for flextime participants. The average time increase of the flextime participant, can be established from employee surveys. If this is not possible, other estimations can be used. Table 2-8 lists a range of possible values for δ_{FLEX} for a range of peak period lengths and average time period increase of flextime participants. The peak period length is based on data. The average time period increase is either 'guessed' at, or derived from employee survey data. For example, one might assume that employees will travel either a half hour earlier or a half hour later (equalling a total increase of one hour as in row one of Table 2-8). Alternatively, one may reason that employees would be willing to travel up to an hour earlier or later (the fraction of travel shifted out of the peak is listed in row two of table 2-8). A detailed explanation of how such assumptions are translated into values is provided in Appendix B. Appendix B can also be used as a guideline for developing values of δ_{FLEX} other than the examples provided in Table 2-8.

Example 2-6 provides an application of the methodology to estimate trip shifts due to flextime implementation.

TABLE 2-8. Fraction of trips removed (δ_{FLEX}) from peak period by peak period length and increase in travel period of flextime participants.

Average travel period increase for flextime participants	Peak period length.				
	2 hours	2.5 hours	3 hours	3.5 hours	4 hours
1 hour	.139	.094	.060	.046	.094
2 hours	.475	.323	.233	.139	.233
3 hours	.812	.627	.475	.287	.365%

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EXAMPLE 2-6. Trip Shifts of Flextime Participants

Evaluate a flextime program of 10,000 participants.

(1) From Step 1, it is evaluated that number of potential trips, PT = **20,000**. This value of PT assumes F/D = 1 where F is the number of days per week the flextime program is in effect and D is the number of commute days per week. F/D = 1 indicates that the flextime program is in operation every commute day.

(2) Using Equation 2-7 and Table 2-6 to evaluate δ_{FLEX}; assume a AM peak period of 2 hours, a PM of 2.5 hours, and an average increase in flextime travel period of 1 hour for both the AM and PM peak periods.

$$\Delta TRIP_{S,P} = -\delta_{FLEX,AM} * PT/2 - \delta_{FLEX,PM} * PT/2$$
$$\Delta TRIP_{S,P} = -0.139 * 20{,}000/2 - 0.094 * 20{,}000/2$$
$$\Delta TRIP_{S,P} = -2{,}330 \text{ (trips per day)}$$

<u>Discussion</u>

This application shows a net shift of -2,330 trips per day from the peak period. The resulting shift of the off-peak period (from Equation 2-8) would then be +2,330 y trips per day.

Compressed Work Weeks

Compressed work week scheduling as generally implemented adds one or two working hours to every four days in order to eliminate one or two days every two weeks from the work schedule. This daily extension of working hours from a compressed work week schedule results in a percentage of participants experiencing trips shifts outside the peak period as commuters travel earlier to work and return home later.

As for flextime, only a fraction of the total participants will shift out of the peak period. For compressed work week participants, this occurs only on the days which travel has been extended. The number of trip shifts of compressed work week participants can be determined from the following equation:

$$\Delta TRIPS_{S,P} = -\delta_{CWW,AM} * N * \frac{F_{SHIFT}}{D} - \delta_{CWW,PM} * N * \frac{F_{SHIFT}}{D} \qquad (2\text{-}9)$$

where **ATRIP**$_{S,P}$ is the change in peak period trips, N is the number of participants (identified in Equation 2-2 of Step 1), F_{SHIFT} is the number of days per week the participant experiences extended hours (this value is discussed below), D = the number of days per week of commuting (identified in Equation 2-2), and δ_{CWW} is the fraction of compressed work week participants removed from the peak period (this value is discussed below) for each peak period.

The negative sign in Equation 2-9 indicates a decrease in peak period trips due to compressed work week implementation. In general, $\mathbf{F}_{\mathbf{SHIFT}}$ equals four (i.e., compressed work week scheduling adds one or two working hours to every **four** days). The total decrease in peak period trips is equal to the increase in off-peak period trips. Thus after $\mathbf{\Delta TRIP}_{\mathbf{S,P}}$ is determined from Equation 2-9, the increase in off-peak trips $\mathbf{\Delta TRIP}_{\mathbf{S,OP}}$ can be determined from Equation 2-8.

Equations 2-8 and 2-9 can be used to determine the trip shifts due to compressed work week implementation once $\boldsymbol{\delta}_{\mathbf{CWW}}$, the fraction of participants removed from the peak period, has been identified. Intuitively, $\boldsymbol{\delta}_{\mathbf{CWW}}$ varies by the length of the peak period and by the increase in the travel period.

An approximation of $\boldsymbol{\delta}_{\mathbf{CWW}}$ can be made by (1) assuming the increase in travel period is equally distributed between the AM peak period and the PM peak period; (2) assuming a normal distribution (Gaussian distribution) of work trips; and (3) establishing the average time shift of the program. The time shift of the program depends on whether the compressed work week schedule extends working hours 1 or 2 hours every 4 days. If the program extends working hours one hour every four days the anticipated shift would be 1/2 hour earlier in the AM peak period and 1/2 hour later in the PM peak period. If the program extends working hours 2 hours every four days, then the corresponding shifts would be 1 hour in the AM peak period and 1 hour in the PM peak period. Table 2-9 incorporates these assumptions into tabulated values $\boldsymbol{\delta}_{\mathbf{CWW}}$ for a range of peak period lengths and average time shifts of compressed work week participants. A detailed explanation of the methodology used to determine the tabulated values of $\boldsymbol{\delta}_{\mathbf{CWW}}$ is given in Appendix B.

Example 2-7 is an application of the estimation of trip shifts due to compressed work week implementation.

TABLE 2-9. Fraction of trips removed (δ_{CWW}) from peak period by original peak period length and increase in peak period of compressed work week participants. A nine-hour expanded work day corresponds to a 1/2 hour increase in travel period in the AM and the PM peak periods; a 10-hour expanded work day corresponds to a 1 hour increase in each peak period.

Increase travel period length (per peak period) for compressed work week participants	Peak period length				
	2 hours	2.5 hours	3 hours	3.5 hours	4 hours
1/2 hour	0.139	0.094	0.060	0.056	0.046
1 hour	0.475	0.323	0.233	0.175	0.139

EXAMPLE 2-7. Trip Shifts of Compressed Work Week Participants

Evaluate a compressed work week program of 5,000 participants with 2-hour extended work days every four days to eliminate one work day per week.

(1) N is the number of participants (5,000), F_{SHIFT} is the days per week of extended hours (4), D is the number of days per week commuting (4, recall the 5th day is eliminated), and δ_{CWW} identified in Table 2-7 (assume an AM peak period length of 2 hours and a PM of 2.5 hours):

$$\Delta TRIP_{S,P} = -\delta_{CWW,AM}*N*(F_{SHIFT}/D) - \delta_{CWW,AM}*N*(F_{SHIFT}/D)$$
$$\Delta TRIP_{S,P} = -0.475*5{,}000*(4/4) - 0.323*5{,}000*(4/4)$$
$$\Delta TRIP_{S,P} = -3{,}990 \textit{ trips per compressed work week day*)}$$

Discussion

This applications shows a net shift of 3,990 trips per day from the peak period to the off-peak period.

* To calculate average weekday changes in trips, multiply 3,990 by 4/5.

STEP 5 - CALCULATE THE TOTAL TRIP CHANGES

Total net trip changes are determined from the change in trips determined from Steps 2-4. Four totals are distinguished:

- $\Delta NETRP_{W,P}$ = total work peak trip changes
- $\Delta NETRP_{W,OP}$ = total work off-peak changes
- $\Delta NETRP_{NW,P}$ = total non-work peak changes
- $\Delta NETRP_{NW,OP}$ = total non-work off-peak changes

The total trip changes can be estimated as follows:

$$\Delta NETRP_{W,P} = \omega * \Delta TRIPS_{S,P} + PK_W(\Delta TRIPS_{D,W} + \Delta TRIPS_{I,W}) \tag{2-10}$$

$$\Delta NETRP_{W,OP} = \omega * \Delta TRIPS_{S,OP} + (1 - PK_W) * (\Delta TRIPS_{D,W} + \Delta TRIPS_{I,W}) \tag{2-11}$$

$$\Delta NETRP_{NW,P} = (1-\omega) * \Delta TRIPS_{S,P} + PK_{NW}(\Delta TRIPS_{D,NW} + \Delta TRIPS_{I,NW}) \tag{2-12}$$

$$\Delta NETRP_{NW,OP} = (1-\omega) * \Delta TRIPS_{S,OP} + (1-PK_{NW}) * (\Delta TRIPS_{D,NW} + \Delta TRIPS_{I,NW}) \tag{2-13}$$

where ω is the fraction of total trips that are work trips determined in Step 1, $\mathbf{PK_W}$ and $\mathbf{PK_{NW}}$ are the fraction of TCM affected work (subscript W) and non-work trips (subscript NW) trips which occur in the peak period, $\mathbf{\Delta TRIP_{S,P}}$ and $\mathbf{\Delta TRIP_{S,P}}$ are the trip shifts determined in Step 4, $\mathbf{\Delta TRIP_{I,W}}$ and $\mathbf{\Delta TRIP_{I,NW}}$ are the indirect work and non-work trip effects determined in Step 3, and $\mathbf{\Delta TRIP_{D,W}}$ and $\mathbf{\Delta TRIP_{D,NW}}$ are the direct work and non-work trip effects determined in Step 2.

In equations (2-10) through (2-13), the values for $\mathbf{PK_W}$ and $\mathbf{PK_{NW}}$ are the observed fraction of work and non-work trips during the peak period. The values of $\mathbf{PK_W}$ and $\mathbf{PK_{NW}}$ are the same as the fraction of work trips and non-work trips of the total trips for the modeling region *except for HOV lanes, flextime, and compressed work weeks* (since these three TCMs can change this fraction). Values of $\mathbf{PK_W}$ and $\mathbf{PK_{NW}}$ are region-specific and should be obtained by the TCM modeler. Example values are 0.608 for $\mathbf{PK_W}$ and 0.288 for $\mathbf{PK_{NW}}$ (in San Diego in 1986). For HOV lanes flextime, and compressed work weeks, $\mathbf{PK_W}$ and $\mathbf{PK_{NW}}$ should be set to 1.0 as the direct and indirect trip effects of these TCMs occur only at peak periods.

The following example illustrates these concepts:

EXAMPLE 2-8. Allocating Trip Changes Between Peak and Off-peak Periods

RIDESHARING

$$NETRP_{WP} = \omega * \Delta TRIP_{S,P} + PK_W(\Delta TRIP_{D,W} + \Delta TRIP_{I,W})$$
$$NETRP_{WP} = -7{,}247 \times 0.608$$
$$NETRP_{WP} = -4{,}406$$

Discussion

In Example 2-3, the total work trip reduction from ridesharing (after adjusting for driver trips and park and ride lot trips) was calculated as 7,320 trips per day. In Example 2-5, an increase of 73 work trips per day was calculated due to use of the vehicle left at home. Thus, the net work trip reduction $NETTRP_{WP}$ is equal to 7,320 - 73 = 7,247 trips per day. If 60.8% of work travel occurs during peak periods then it is assumed that 60.8% of the work trip reduction affects peak period travel. If a TCM program targets only peak period travellers, this equation should not be used (or the variable PK_W should be set at 1.0).

STEP 6 - CALCULATE THE VMT CHANGES DUE TO TRIP CHANGES

As discussed above, VMT changes occur as a result of trip reductions and changes in trip length. As discussed in detail in Chapter 3, it is important to distinguish between the two kinds of VMT changes. Trip reductions affect vehicle start emissions *and* exhaust emissions, while VMT trip length changes only affect exhaust and related emissions. These two types of VMT changes are calculated in Steps 6 (trip reduction) and Step 7 (trip length changes).

The net VMT reduction resulting from trip reductions determined in Step 5, (for peak and off-peak periods) can be calculated as follows:

$$\Delta VMT_P = (\Delta NETRP_{W,P} * DIST_W) - (\Delta NETRP_{N,P} * DIST_{N,W}) \qquad (2\text{-}14)$$

$$\Delta VMT_{OP} = (\Delta NETRP_{W,OP} * DIST_W) - (\Delta NETRP_{N,OP} * DIST_{N,W}) \qquad (2\text{-}15)$$

where $\mathbf{DIST_W}$ and $\mathbf{DIST_N}$ are the average VMT per trip for work and non-work trips (units of miles per trip).

EXAMPLE 2-9. ΔVMT$_p$ (Change in Peak VMT due to Trip Reductions)

RIDESHARING

$$\Delta VMT_p = (NETRP_{W,P} \text{ x } DIST_W) - (NETRP_{NW,P} \text{ x } DIST_{N,W})$$
$$\Delta VMT_p = -(4{,}406 \text{ x } 27) - (0)$$
$$\Delta VMT_p = -118{,}962$$

Discussion

No example is given for the non-work trip increase (see table 2-8 for equation) so this part of the equation is not used in this example. The net work trip reduction is multiplied by the average work trip distance to calculate the VMT reduction. Statistics have shown that work distances tend to be longer for ridesharers on average, so if possible, data on trip distances for the population participating in a TCM should be used. Here we have used the average distance to work for ridesharers (27 miles) in the San Francisco Bay Area (RIDES, 1990).

STEP 7 - CALCULATE THE VMT CHANGES DUE TO TRIP LENGTH CHANGES

An additional category of VMT changes includes trip length changes. If a telecommuter works from a satellite work center, no trip has been eliminated, but the length of the work trip may be substantially reduced. Some of the TCMs discussed in this document cause trip length changes. Non-work trip lengths are assumed not to change for the TCMs discussed here. VMT changes due to trip length changes can be estimated as follows:

$$\Delta VMT_{L,W} = \beta * PT * -(DIST_W - DIST_{new}) \qquad (2\text{-}16)$$

where **PT** is the number of potential trips reduced (calculated in Step 1), β represents the fraction of those participants who change their trip length (rather than eliminate a trip), $DIST_W$ equals the average work trip length, and $DIST_{new}$ equals the new worktrip length. The new work trip length corresponds to variables such as the average distance to park and ride lots, or to satellite work centers. Suggestions for calculating the variable β are presented in Table 2-10.

For example, all ridesharers who drive to park and ride lots would be changing their trip lengths rather than eliminating trips and the factor α represents the fraction of ridesharers who *do not* drive to park and ride lots (and therefore eliminate trips rather than change their trip length). Similarly, for telecommuters **SAT** represents the number of telecommuters who work from satellite work centers. The number of telecommuters who work from satellite centers reduce their trip length. $\mathbf{DIST_W}$ is the unadjusted average trip per (miles) for work trips, and $\mathbf{DIST_{new}}$ is the new work trip distance (e.g., the distance to the park and ride lot or to the satellite work center).

STEP 8 - DETERMINE THE TOTAL VMT CHANGES

Total VMT changes can be determined from the sum of the VMT changes determined in Steps 6 and 7. This is illustrated by the following equations:

$$\Delta NETVMT_P = \Delta VMT_{T,P} + PK_W * \Delta VMT_{L,W} \tag{2-17}$$

$$\Delta NETVMT_{OP} = \Delta VMT_{T,OP} + (1 - PK_W) * \Delta VMT_{L,W} \tag{2-18}$$

where

$\mathbf{\Delta VMT_{L,W}}$ = the net change in VMT due to trip length changes (Step 7),
$\mathbf{\Delta VMT_{T,P}}$ = the net change in peak period VMT due to trip changes (Step 6),
$\mathbf{\Delta VMT_{T,OP}}$ = the net change in off-peak period VMT due to trip changes (Step 6), and
$\mathbf{PK_W}$ = is the fraction of work VMT that occurs in the peak period.

STEP 9 - CALCULATE SPEED CHANGES

The change in speeds associated with the VMT decreases can be calculated in several ways: volume to capacity relationships, network models, or elasticities of speed with respect to volume. The latter method, shown here, is approximate and it cannot be stressed enough that the elasticities used here are examples only. If elasticities are used, every effort should be made to ensure that they are representative of the study region and circumstances. In particular, elasticities vary widely depending on base conditions (i.e., speeds, mode shares, travel costs). Other considerations of the relationships of speed to traffic volume due to flow and traffic density are described in an Appendix to methodologies developed for the California Air Resources Board (Austin, et al., 1991) .

TABLE 2-10. Trip length changes.

TCM	Value of β	Calculation/Explanation
Telecommuting	SAT	SAT = fraction of people who drive to satellite work stations.
Flextime	0	Flextime does not change trip lengths.
Compressed Work Week	0	Compressed work weeks do not change trip lengths.
Rideshare	1-NOLD-NEW	Accounts for people who drive to park and ride lots from the previously used variables of: NOLD = fraction of ridesharers who join existing carpools and don't drive to park and ride lots, and NEW = fraction of ridesharers who form new carpools and don't drive to park and ride lots.
Transit	DRIVTRAN	DRIVTRAN = fraction of people who drive to the public transit station.
Parking Management	TRANS*DRIVTRAN + FRNG + RD*(1-NOLD-NEW)	Accounts for people who use transit and drive to transit stop, people who use fringe parking facilities, and people who use ridesharing who drive to park and ride lots: TRAN = fraction of participants who will use transit. FRNG = fraction of participants who will use fringe parking facilities. RD = fraction of participants who will use ride sharing. NOLD, NEW, DRIVTRAN: same as defined above.

Change in peak speeds can be determined from the following:

$$\Delta SPD_P = \frac{\Delta NETVMT_P}{TOTVMT_P} * \epsilon_P \tag{2-19}$$

where

ϵ_P = elasticity of peak speed with respect to volume,
$TOTVMT_P$ = total VMT in peak period, and
$\Delta NETVMT_P$ = the net change in peak VMT determined in Step 8 of this analysis.

The change in off-peak speeds is calculated by the same method:

$$\Delta SPD_{OP} = \frac{\Delta NETVMT_{OP}}{TOTVMT_{OP}} * \epsilon_{OP} \tag{2-20}$$

where

ϵ_{OP} = elasticity of off-peak speed with respect to volume,
$TOTVMT_{OP}$ = total VMT in off-peak period, and
$\Delta NETVMT_{OP}$ = the net change in off-peak VMT determined in Step 8.

EXAMPLE 2-10. ΔSPD_P (Change in Peak Speeds)

RIDESHARING

$$\Delta SPD_P = \Delta VMT_P / VMT_P \ x \ \epsilon_S$$
$$\Delta SPD_P = (118{,}962)/(33{,}667{,}580) \ x \ 0.75$$
$$\Delta SPD_P = 0.27\% \text{ increase in peak speeds}$$

Discussion

The net VMT reduction in the peak period is divided by the total VMT in the peak period and multiplied by the elasticity of speed with respect to volume to roughly approximate the percentage change in speeds. The base peak VMT used in this example is for the San Francisco Bay Area in 1987. Note that this example does not include the VMT changes resulting from trip changes.

3 METHODOLOGY FOR CALCULATING EMISSION CHANGES FROM TCM ACTIVITY EFFECTS

This chapter (1) reviews TCM effects on emission categories addressed in emission factor models and (2) provides a methodology for estimating emission effects of TCMs. The methodologies developed in this document quantify how TCMs affect travel behavior and vehicle emissions. From an air quality perspective, TCM evaluations must quantify mobile source emission reductions associated with TCM-induced changes in activity level variables such as trips, VMT, and speeds. Quantifying these changes in travel behavior is the most difficult challenge facing the TCM analyst and is addressed in Chapter 2 of this document. Once changes in travel variables are appropriately quantified, a motor vehicle emission factor model, such as MOBILE, can be used to quantify emission changes.

OVERVIEW

This chapter presents a methodology for calculating emission benefits resulting from the travel activity changes calculated in Chapter 2. The methodology may also be used in conjunction with TCM travel effects generated in another manner. The emission analysis methodology translates the travel activity level changes into total mass emissions through the use of emission factors. Emission factors are expressed in the units of mass per activity level, such as grams per trip or grams per mile, and are calculated by the EPA's motor vehicle emission factor model, MOBILE[1]. Emission changes can be calculated from the activity level changes by multiplying the activity level changes by the appropriate emission factors. The activity level changes are calculated in a manner which links them explicitly to emission categories by addressing the particular vehicle class and activity types considered by MOBILE. In this document, examples of emission factors are provided to illustrate the calculations necessary for the emission analysis of TCMs. Users are reminded that these emission factors are for illustrative purposes only, and any analysis of TCMs will require the use of region-specific emissions factors derived from the most recent MOBILE model. Note that the examples used in this document have not been updated to reflect new MOBILE releases.

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[1] The MOBILE model, referred to singularly in this document, is actually a series of models continually being updated and revised. Use of the model should be restricted to the latest released version. For illustrative examples, this document used the third release of MOBILE version 4.1 dated November 1991.

This chapter focuses on the use of MOBILE - an emission factor developed for states other than California. The EMFAC model is the California equivalent to MOBILE developed by the California Air Resources Board. In general, the methodology presented in this chapter can also be used with EMFAC emission factors, although it is recommended that the user take the time to ensure the compatibility of the units used in reporting emission factors units (EMFAC and MOBILE report some emission categories in different units).

The emissions methodology focuses on HC, CO, and NO_X, the three pollutants reported by MOBILE. A separate model for PM-10 emissions developed by SAI for the EPA to replace the 1985 EPA particulate emission factor model is under review. PM-10 emission factors from this model can be used in conjunction with the methodology of this document without much additional effort. PM-10 emission changes are simpler to calculate than HC, CO, and NO_X because PM-10 emission factors do not vary by speed[2] or trip-type and are therefore, proportional to VMT changes.

The remainder of this overview discusses:

- The MOBILE emission factor model,
- A summary of key emission effects,
- Considerations for micro-scale modeling, and
- An overview of the emission analysis methodology,

and is followed by the detailed, step-by-step emissions analysis methodology.

The MOBILE Emission Factor Model

MOBILE produces motor vehicle emission factors for hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NO_X) at conditions specified by the user. Inputs include vehicle fleet information, vehicle fuel information, vehicle operating conditions, temperature data, and vehicle inspection data. In some instances, the model has available national average data for use as default values if no regional or local data are available. The use of regional or local data is strongly recommended as all of the MOBILE input parameters have a significant effect on the predicted emission factors. EPA has provided guidance documentation outlining the recommended usage of MOBILE and the input data it requires, *Draft User's Guide to MOBILE 5a* (EPA, 1993) and *Procedures For Emission Inventory Preparation, Volume IV: Mobile Sources* (EPA, 1989). Note: these documents are updated frequently. The latter document describes the EPA recommended input data for MOBILE and is currently under revision (draft versions of the update of this report can be obtained from regional EPA offices). Both of these documents should be consulted prior to using the model.

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[2] The current PM-10 model, developed in 1985, did not incorporate speed adjustment factors into the emissions analysis; however, future updates of the PM-10 emission factor model *could* incorporate vehicle speeds.

Emission factors are reported by vehicle class and emission category. Currently, MOBILE defines nine vehicle classes:

- Light-duty gasoline vehicle (LDGV),
- Light-duty gasoline trucks less than 6000 lbs GVW (LDGT1),
- Light-duty gasoline trucks more than 6000 lbs GVW (LDGT2),
- Light-duty gasoline trucks, the total composite of LDGT1 and LDGT2, (LDGT),
- Heavy-duty gasoline vehicles (HDGV),
- Heavy-duty diesel vehicles (HDDV),
- Light-duty diesel vehicles (LDDV),
- Light-duty diesel trucks (LDDT), and
- Motorcycles (MC).

It also reports a fleet average emission factor which is the composite of all vehicle classes. Most TCMs affect trips and VMT of LDGVs and LDGT1s.[3] All vehicle classes are affected by changes in speed.

In addition to vehicle classes, emission factors are reported for the following emission categories:

Exhaust - Vehicle tailpipe HC, NO_X, and CO emissions which occur during the operation. Exhaust emissions are further categorized (according to the operating condition of the vehicle) into start-up emissions (cold and hot) and warmed-up stabilized emissions. These are commonly referred to as cold-start, hot-start and hot-stabilized emissions, respectively.

Hot soak - HC emissions which consist of the evaporation of emissions from the engine and fuel lines immediately following the end of a trip.

Diurnals - Evaporative HC emissions resulting from temperature fluctuations occurring when the vehicle is not in use. These are categorized into partial-day, full-day and multiple-day diurnals according to the period of vehicle non-operation.

Crankcase - HC emissions from the vehicle crankcase during operation, significant only for older model-year vehicles.

Running Losses - HC evaporative emissions which occur during the operation of the vehicle.

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[3] There are TCMs which specifically target heavy-duty vehicles, such as the peak period restriction of heavy-duty vehicles in central business districts; however, these TCMs are not addressed in this report.

Resting Losses - HC emissions resulting from permeation of non-metallic evaporative emission control equipment occurring at all times (when a vehicle is in-use and when it is not in-use).

Refueling - HC emissions resulting from vapor displacement from the vehicle gasoline tank and from gasoline spillage during vehicle refueling.

Emission categories will be treated individually in the following emission analysis with the exception of resting losses. Resting loss emissions occur 24 hours a day and would not be affected by TCM implementation unless a TCM produced fewer vehicles in the vehicle fleet. Although wide-spread and extensive TCM implementation can affect vehicle ownership patterns, this is not addressed in the methodologies presented in this document. For this reason resting losses will not be included in the emissions analysis of this chapter.

Summary of Key Emission Effects

The following summarizes how each component of motor vehicle emissions may be affected by TCMs.

Cold and Hot Start Emissions

Changes in cold and hot start emissions resulting from TCMs are proportional to changes in trips. The number of TCM participants and the number of days per week they participate are good indicators of changes in start emissions.

The average speeds driven in hot and cold start modes may also change as will the relative proportions of trips taken in various operating modes. Conceptually this can change emissions. For a given trip, the number of miles driven in cold start mode as opposed to hot stabilized mode may change. The MOBILE model calculates emission factors for a user-specified distribution of cold-start, hot-start, and hot-stabilized emissions allowing explicit consideration of such changes.

Exhaust and Running Loss Emissions

Exhaust and running loss emissions would change due to a TCM's effects on VMT and trip speeds. A frequent "back of the envelope" approach to estimating TCM emission changes is to linearly link emissions with VMT. However, there are some serious flaws in such an approach. Assume, for example, that a telecommuter reduced his or her total work trip VMT from a 50-mile round-trip commute to a 5-mile round-trip commute to a nearby satellite work center (i.e., a 90 percent VMT reduction). A rough emissions reduction estimate that assumed emissions changes were proportional to VMT reductions would fail to account for the fact that trip end emissions from cold starts and hot soaks would continue to occur. Trip end emissions are a substantial fraction of the total emissions associated with shorter trips; merely linking estimated emissions reductions to VMT reductions would be a poor approximation of the resulting change. In addition, it is also important to consider any shifts in the timing of VMT since exhaust and running loss emissions can be temperature-sensitive.

Speed increases along affected roadways may also result in significant emissions benefits. Exhaust HC and CO emissions drop sharply between speeds of zero to and about 50 mph. NO_X emissions decrease until about 20 mph, after which they increase, particularly after 50 mph. On the other hand, running loss evaporative emissions decrease consistently with increasing speed.

Hot Soak, Diurnal, and Refueling Emissions

Hot soak emissions will change in accordance with a change in vehicle trips, and refueling emissions drop proportionately to decreased VMT. Diurnal emissions are more difficult to analyze than hot soak or refueling emissions. There will be some shift in the number of partial-day, full-day, and multiple-day diurnals related to when vehicles are operated which is influenced by TCMs. Since nearly all vehicles experience some type of diurnal cycle, the net emission change of shift within the diurnal categories can be less significant than the other emission categories.

Considerations of TCM Effects on Microscale Modeling

The current EPA guidance for conducting intersection hotspot carbon monoxide (CO) modeling is contained in the EPA document, *Guideline for Modeling Carbon Monoxide for Roadway Intersections* (Schewe et al, 1990). This guidance contains information regarding evaluation of air quality impacts at one or more roadway intersections where vehicular traffic will cause or contribute to increased emissions of CO. It recommends CAL3QHC as the intersection model of choice. CAL3QHC is a microcomputer-based modeling methodology developed to predict the level of carbon monoxide (CO) or other inert pollutant concentrations from motor vehicles traveling near roadway intersection. Based on the assumption that vehicles at an intersection are either in motion or in an idling state, the program is designed to predict air pollution levels by combining the emissions from both moving and idling vehicles. CAL3QHC is a consolidation of the CALINE-3 line source dispersion model and an algorithm that internally estimates the length of the queues formed by idling vehicles at signalized intersections. Other models available are CALINE4, developed by the California Department of Transportation for use in California, and the TEXIN2/MOBLILE4 model, often used in the state of Texas.

The TCM analysis methodology presented in this document is generally of a regional scale and may not be suitable for microscale analysis unless traffic zone or corridor-specific inputs are used instead of regional inputs. Regional values for several parameters and vehicle characteristics used in this analysis may have significant local variation.

Overview of Emissions Analysis Methodology

The emissions analysis methodology is categorized according into the changes in travel activity levels (trips, VMT and speed). Emission categories influenced by trip changes are: hot-start and cold-start exhaust, hot soak, and diurnal emissions; emission categories affected by VMT changes are: hot-stabilized exhaust, running loss, crankcase, and refueling emissions; and speed changes affect the categories of hot-stabilized exhaust and running loss emissions. The detailed treatment of each emission category affected by changes in vehicle activity is presented in the remainder of this chapter and is divided into the following four steps:

(1) Emission analysis of trip changes resulting from TCM implementation.

(2) Emission analysis of VMT changes resulting from TCM implementation.

(3) Emission analysis of changes due to an overall fleet speed changes.

(4) The total emission change (sum of steps 1 through 3).

To use this methodology, one must calculate emission factors by running the MOBILE program for various scenarios corresponding to conditions identified later in this chapter. It is important to use MOBILE input values representative of the study region. If future-year emission controls are not implemented correctly (i.e. no future-year emission controls), emissions benefits calculated by the methodology presented here will be too optimistic. Guidance on proper estimation of future-year emission factors can be obtained from regional EPA offices.

STEP 1: Emission Analysis of Trip Changes

In this step the emission changes due to the change in trips are evaluated. The emission categories influenced by this evaluation are hot-start and cold-start exhaust, hot soak, and diurnal emissions. Of these categories, the hot-start and cold-start exhaust and hot soak emissions are directly related to the number of trips while diurnal emissions are indirectly influenced by the number of trips. Diurnals result from temperature fluctuations occurring when the vehicle is not in use and can be affected according to the portion of the day the vehicle is not used. The number of trips will also affect the diurnal emissions, as the number of full or multi-day diurnals may increase as trips are forgone. Each emission category mentioned above is evaluated and discussed separately below.

Determine the Distribution of Trip Changes

Prior to evaluating the emissions, it is necessary to determine the distribution of trips among the affected vehicle classes. Most TCMs analyzed in this document affect trips by LDGVs and LDGT1s - these include ridesharing, telecommuting, alternative work schedules and compressed work weeks. Other TCMs such as transit improvements implemented as route additions may affect trips made by heavy-duty vehicles as well. The equations provided account for changes in LDGVs and LDGT1s. If necessary, the adaptation of the equations to other vehicle classes should be obvious. The fraction of trips associated with the LDGVs can be determined for any region from the total trips which are due to the LDGVs ($\mathbf{TRIP_{LDGV}}$) and the total number of trips which are due to the LDGT1s ($\mathbf{TRIP_{LDGT1}}$):

$$\gamma_{TRIP,LDVG} = \frac{TRIP_{LDGV}}{TRIP_{LDGV} + TRIP_{LDGT1}} \tag{3-1}$$

where $\gamma_{\mathbf{TRIP,LDGV}}$ represents the fraction of trips which are LDGV, and since there are only two vehicle classes being analyzed $\gamma_{\mathbf{TRIP,LDGT1}}$ can be determined from:

$$\gamma_{TRIP,LDVT1} = \left(1 - \gamma_{TRIP,LDGV}\right) \tag{3-2}$$

Equations 3-1 and 3-2 assume that a given TCM will influence both LDGV and LDGT according to their trip representation in the vehicle fleet. It is recommended that region-specific trip totals be used in these equations.

If trip data for Equations 3-1 and 3-2 are not available, an approximate value can be obtained from the default vehicle VMT fraction data from the MOBILE model output. The VMT vehicle fractions for LDGV and IDGT1 can be substituted into Equation 3-1 in place of the TRIP data. This approximation assumes that the vehicle trip distribution is equivalent to the vehicle VMT distribution. Note that the MOBILE vehicle VMT fractions are a function of calendar year. For example, in 1990 MOBILE4.1 reports a LDGV VMT fraction of **0.626** (i.e., 62.6% of the total fleet VMT is from LDGVs) and a LDGT1 VMT fraction of **0.171** (national average default values). The approximate value of $\gamma_{\mathbf{TRIP}}$ can be obtained from substituting these values into Equations 3-1 and 3-2 to yield $\gamma_{\mathbf{TRIP,LDGV}} = \mathbf{0.785}$ and $\gamma_{\mathbf{TRIP,LDGT1}} = \mathbf{0.215}$. These values would be interpreted as follows: if a telecommuting program reduced 100 trips per day, 78 of these would be LDGV and 22 would be LDGT1.

Calculate Cold-Start and Hot-Start Trip Changes

First calculate the total number of trip changes due to TCM implementation as the sum of the four trip-type totals determined in Step 5 of Chapter 2. The four trip types are:

- $\mathbf{\Delta NETRP_{W,P}}$ = total work peak trip changes
- $\mathbf{\Delta NETRP_{W,OP}}$ = total work off-peak changes
- $\mathbf{\Delta NETRP_{NW,P}}$ = total non-work peak changes
- $\mathbf{\Delta NETRP_{NW,OP}}$ = total non-work off-peak changes

and the equation for total trip changes equals the sum of the four trip types listed above:

$$\Delta TRIP_{TOTAL} = \Delta NETRP_{W,P} + \Delta NETRP_{W,OP} + \Delta NETRP_{NW,P} + \Delta NETRP_{NW,OP} \quad (3\text{-}3)$$

Second, it is necessary to calculate the total trips which began with the vehicle engine cold (cold-start trip) and trips which began with the vehicle engine warm (hot-start trip). The following equations determine the number of hot-start and cold-start trips changes from the total trip changes:

$$\begin{aligned}\Delta TRIP_{CST} = {} & \gamma_{CST,W} * \left(\Delta NETRP_{W,P} + \Delta NETRP_{W,OP}\right) + \\ & \gamma_{CST,NW} * \left(\Delta NETRP_{NW,P} + \Delta NETRP_{NW,OP}\right)\end{aligned} \quad (3\text{-}4)$$

$$\begin{aligned}\Delta TRIP_{HST} = {} & \left(1 - \gamma_{CST,W}\right) * \left(\Delta NETRP_{W,P} + \Delta NETRP_{W,OP}\right) + \\ & \left(1 - \gamma_{CST,NW}\right) * \left(\Delta NETRP_{NW,P} + \Delta NETRP_{NW,OP}\right)\end{aligned} \quad (3\text{-}5)$$

where the subscripts **CST** and **HST** refer to "cold-start" and "hot-start" respectively and γ_{CST} is the fraction of trips begun in the cold-start operating mode. This fraction depends on the trip type.

In general, work trips involve mostly cold-start trips (i.e. $\gamma_{CST} \approx 1$). For non-work trips, the value of $\gamma_{CST,NW}$ is assumed to correspond to the fraction of cold starts to total starts for the study region. It is ideal to use local values for the fraction of starts which are cold; however, these data are generally unavailable. In the absence of local data, the MOBILE default fraction of cold starts can be used. This fraction is based on the Federal Testing Procedure (FTP) driving cycle. The default fraction of cold starts is 0.43. It is suggested that a fraction of 1.0 cold starts be assumed for work trips and the default fraction of 0.43 for non-work trips.

Determine Hot-Start and Cold-Start Emission Factors

Hot-start and cold-start emissions are the exhaust emissions which occur at the initiation of a vehicle trip. Hot-start and cold-start emission factors need to be determined for each of the three pollutants by running MOBILE for 3 scenarios (100% cold start, 100% hot start and 100% hot stabilized). The results of which are substituted into Equations 3-6 and 3-7 (identified below) to calculate separate hot and cold start emission factors. This produces six trip-start emission factors:

- Exhaust hydrocarbon, hot-start mode (HC_{HST})
- Exhaust hydrocarbon, cold-start mode (HC_{CST})
- Exhaust carbon monoxide, hot-start mode (CO_{HST})
- Exhaust carbon monoxide, cold-start mode (CO_{HST})
- Exhaust oxides of nitrogen, hot-start mode (NOx_{HST})
- Exhaust oxides of nitrogen, cold-start mode (NOx_{CST})

It is necessary to calculate the gram per trip emission factors for each of the categories listed above. The MOBILE model does not explicitly calculate start-up emission in grams per trip, but rather a gram per mile exhaust emission rate combining the start-up and hot-stabilized portions of the emissions. Hot-start and cold-start emission factors in grams per trip can be determined from the following equations using the MOBILE model:

$$CST = \left(EXH_{100\%CST,26MPH} - EXH_{100\%STB,26MPH}\right) * 3.59 \qquad (3\text{-}6)$$

$$HST = \left(EXH_{100\%HST,26MPH} - EXH_{100\%STB,26MPH}\right) * 3.59 \qquad (3\text{-}7)$$

where **CST** and **HST** are the cold and hot-start emission factors in *grams per trip* (which need to be determined for all three pollutants and both vehicle classes), **EXH** is the MOBILE emission factor in *grams per mile*, and **3.59** is the FTP driving cycle trip-start *miles per trip*, and 26 mph is the speed at which the start portion of the FTP cycle is driven. The subscripts of **100% CST, 26MPH**, **100% HST, 26MPH**, and **100% STB, 26MPH** of **EXH** indicate the operating conditions and the speed at which **EXH** is evaluated by MOBILE. **100% CST, 26MPH** indicates 100% cold-start operating mode at 26 mph vehicle speed; **100% HST, 26MPH** indicates 100% hot-start operating mode at 26 mph vehicle speed; and **100% STB, 26MPH** indicates 100% hot-stabilized operating mode at 26 mph vehicle speed.

Equations 3-6 and 3-7 assume the trip-start driving conditions are uniform and comparable to the trip-start driving conditions of the FTP driving cycle. As noted above, the 26 mph and 3.59 miles per trip start represent the average speed and the length respectively of the trip-start portion of the FTP. These values should **always** be used in Equations 3-6 and 3-7. Example 3-1, illustrating the calculation of trip-start emission factors, is presented at the end of Step 1 of this chapter.

Determine the Hot-Start and Cold-Start Emission Changes

Once the start emission factors are calculated emission changes due to trip reductions are determined by multiplying the trip changes by the start emission factors for each of the exhaust pollutants (HC, CO, NO_X) and vehicle classes:

$$\begin{aligned}\Delta HC_{CST} = {} & \left(\Delta TRIPS_{CST} * \gamma_{TRIP,LDGV} * CST_{LDGV,HC}\right) + \\ & \left(\Delta TRIPS_{CST} * \gamma_{TRIP,LDGT1} * CST_{LDGT1,HC}\right)\end{aligned} \qquad (3\text{-}8)$$

$$\begin{aligned}\Delta HC_{HST} = {} & \left(\Delta TRIPS_{HST} * \gamma_{TRIP,LDGV} * HST_{LDGV,HC}\right) + \\ & \left(\Delta TRIPS_{HST} * \gamma_{TRIP,LDGT1} * HST_{LDGT1,HC}\right)\end{aligned} \qquad (3\text{-}9)$$

$$\Delta CO_{CST} = \left(\Delta TRIPS_{CST} * \gamma_{TRIP,LDGV} * CST_{LDGV,CO}\right) + \left(\Delta TRIPS_{CST} * \gamma_{TRIP,LDGT1} * CST_{LDGT1,CO}\right) \tag{3-10}$$

$$\Delta CO_{HST} = \left(\Delta TRIPS_{HST} * \gamma_{TRIP,LDGV} * HST_{LDGV,CO}\right) + \left(\Delta TRIPS_{HST} * \gamma_{TRIP,LDGT1} * HST_{LDGT1,CO}\right) \tag{3-11}$$

$$\Delta NOx_{CST} = \left(\Delta TRIPS_{CST} * \gamma_{TRIP,LDGV} * CST_{LDGV,NOx}\right) + \left(\Delta TRIPS_{CST} * \gamma_{TRIP,LDGT1} * CST_{LDGT1,NOx}\right) \tag{3-12}$$

$$\Delta NOx_{HST} = \left(\Delta TRIPS_{HST} * \gamma_{TRIP,LDGV} * HST_{LDGV,NOx}\right) + \left(\Delta TRIPS_{HST} * \gamma_{TRIP,LDGT1} * HST_{LDGT1,NOx}\right) \tag{3-13}$$

In Equations 3-8 through 3-13, the variables **HST** and **CST** are the hot-start and cold-start emission factors (grams per trip) for the subscripted vehicle class and pollutant, $\mathbf{\Delta TRIP_{CST}}$ and $\mathbf{\Delta TRIP_{HST}}$ are defined in Equations 3-4 and 3-5, and $\gamma_{\mathbf{TRIP,LDGV}}$ and $\gamma_{\mathbf{TRIP,LDGT1}}$ were defined in Equations 3-1 and 3-2. The emission factors for all three pollutants are determined from Equations 3-6 and 3-7 using region-specific MOBILE emission factors. Example 3-2 (provided at the end of Step 1) demonstrates how to derive trip-start emissions using Equations 3-8 through 3-13.

Determine Hot Soak Emission Changes

Hot soak emissions are the HC evaporative emissions associated with a vehicle trip end. Equation 3-14 can be used to calculate the change in hot soak emissions ($\mathbf{\Delta HC_{HSK}}$) by multiplying the change in total trips by the emission factor predicted by MOBILE:

$$\Delta HC_{HSK} = \left(\Delta TRIPS_{TOTAL} * \gamma_{TRIP,LDGV} * HSK_{LDGV}\right) + \left(\Delta TRIPS_{TOTAL} * \gamma_{TRIP,LDGT1} * HSK_{LDGT1}\right) \tag{3-14}$$

where **HSK** is the hot soak emission factor (grams per trip) for the subscripted vehicle class reported by MOBILE, $\mathbf{\Delta TRIP_{TOTAL}}$ was defined in Equation 3-3 and $\gamma_{\mathbf{TRIP,LDGV}}$ and $\gamma_{\mathbf{TRIP,LDGT1}}$ were defined in Equations 3-1 and 3-2. The hot soak emission factor in grams per trip can be directly taken from the MOBILE model using version 4.1 or later. Earlier versions of the model do not report individual hot soak emission rates. An example application of Equation 3-14 is included in Example 3-3.

Determine Diurnal Emission Changes

Diurnal HC emissions occur from the daily temperature changes while a car is not in use. MOBILE distinguishes three different types of diurnal emissions depending on the period of day the vehicle is unused:

- Multiple-day diurnal (MDI) - vehicle is unused for two or more consecutive days.
- Full-day diurnal (FDI) - vehicle is unused from 8am to 5pm or is unused all day, but was driven during the previous day.
- Partial-day diurnal (PDI) - vehicle remains unused for only a portion of a day.

MOBILE output combines the partial-day and the full-day diurnals into a combined weighted diurnal (WDI).

Diurnal emissions occur whether a car is or is not driven during a given day, and MOBILE4.1 assumes that 94.3% of the LDGVs and LDGTs experience one type of diurnal. Only vehicles driven during enough intervals through out the day as to not experience a significant temperature rise do not undergo a diurnal. Vehicles which are driven during a given day may undergo a partial-day or full-day diurnal. Vehicles which are not driven during a given day will undergo either a full-day or multiple-day diurnal. TCMs which affect trip making may also affect the distributions of diurnal types.

To evaluate diurnal emission changes one needs to determine when the vehicle is unused. An approximation can be made by making a few assumptions[4] distinguishing between the diurnals for cars driven during a given day and those not driven during a given day. It is assumed that vehicles not driven would experience an increase in multiple-day diurnals relative to the number of full-day and partial-day diurnals. MOBILE currently assumes an average of 23.8% of the LDGVs and LDGTs are not driven during a given day, and the model also assumes 16.1% of the LDGVs and LDGTs experience a multiple-day diurnal. Since the multiple-day diurnal vehicles are a subset of the vehicles not driven, it can be stated that 67.6% (16.1% divided by 23.8%) of the cars not driven experience a multiple-day diurnal based on data within the MOBILE algorithms.

For a given TCM, the number of vehicles unused in a day can be approximated from the net trip changes divided by the number of trips per day. Assuming that 67.6% of the unused vehicles experience a multi-day diurnal, the following four equations (separated by vehicle and trip type) approximate the change in diurnal emissions:

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[4] As is indicated, diurnal emissions occur whether or not a vehicle is driven so that the change in diurnal emissions due to trip activity changes is calculated from the difference of two types of diurnals. Therefore diurnal emissions should have a less significant impact than other emission categories because only a portion of the diurnal emissions is affected, and any assumptions made with respect to diurnal emissions are expected to have minor influences on the results of this analysis. This assumption is verified in the example applications presented at the end of Step 1.

$$\Delta HC_{DNL,W,LDGV} = 0.676 * \frac{\Delta NETRP_{W,P} + \Delta NETRP_{W,OP}}{TPD_W} * \gamma_{TRIP,LDGV} * \left(WDI_{LDGV} - MDI_{LDGV}\right) \tag{3-15}$$

$$\Delta HC_{DNL,NW,LDGV} = 0.676 * \frac{\Delta NETRP_{NW,P} + \Delta NETRP_{NW,OP}}{TPD_{NW}} * \gamma_{TRIP,LDGV} * \left(WDI_{LDGV} - MDI_{LDGV}\right) \tag{3-16}$$

$$\Delta HC_{DNL,W,LDGT1} = 0.676 * \frac{\Delta NETRP_{W,P} + \Delta NETRP_{W,OP}}{TPD_W} * \gamma_{TRIP,LDGT1} * \left(WDI_{LDGT1} - MDI_{LDGT1}\right) \tag{3-17}$$

$$\Delta HC_{DNL,NW,LDGT1} = 0.676 * \frac{\Delta NETRP_{NW,P} + \Delta NETRP_{NW,OP}}{TPD_{NW}} * \gamma_{TRIP,LDGT1} * \left(WDI_{LDGT1} - MDI_{LDGT1}\right) \tag{3-18}$$

where $\mathbf{\Delta HC_{DNL}}$ is the change in diurnal emissions for the subscripted vehicle class and trip type (**W** = work trip, **NW** = non-work trip), $\mathbf{\Delta NETRP_{W,P}}$ is the net trip changes for the indicated trip type and period (**P** = peak period, **OP** = off-peak period) determined in Step 5 of Chapter 2, **MDI** is the multi-day diurnal emission factor for the subscripted vehicle class determined by MOBILE, **WDI** is the weighted diurnal emission factor for the subscripted vehicle class determined by MOBILE, $\gamma_{\mathbf{TRIP}}$ is defined in Equations 3-1 and 3-2 for the indicated vehicle class, $\mathbf{TPD_W}$ is the number of work trips per vehicle commute day (i.e. a commuter makes two trips to and from work on the days commuting by personal vehicle, $\mathbf{TPD_W = 2}$), and $\mathbf{TPD_{NW}}$ is the number of non-work trips per day per vehicle ($\mathbf{TPD_{NW}}$ values are region dependent; example $\mathbf{TPD_{NW}}$ values are illustrated in Table 2-7).

The **MDI** and **WDI** emission factors (grams per vehicle) for Equations 3-15 through 3-18 are determined using MOBILE. Equations 3-15 through 3-18 evaluate the change in diurnal emissions due to a change in vehicle trips as the difference between the multiple-day diurnal and the weighted diurnal. If trips decrease, these equations determine the emission increase due to an increase in multi-day diurnals and a decrease in weighted diurnals which would be observed if fewer vehicles were in-use. Alternatively, if vehicle trips increase multiple-day diurnals would decrease and weighted diurnals would increase.

The net diurnal emission change is then the sum of the changes calculated from Equations 3-13 through 3-15:

$$\Delta HC_{DNL} = \Delta HC_{DNL,W,LDGV} + \Delta HC_{DNL,NW,LDGT} + \Delta HC_{DNL,W,LDGT1} + \Delta HC_{DNL,NW,LDGT1} \tag{3-19}$$

An example application of the calculation for diurnal emission changes is given in Example 3-3.

Total Emission Changes Due to Trip Changes

The following equations can be used to determine the total HC, CO and NOx changes due to trip changes resulting from TCM implementation:

$$\Delta HC_{TRIP} = \Delta HC_{CST}+\Delta HC_{HST}+\Delta HC_{HSK}+\Delta HC_{DNL} \tag{3-20}$$

$$\Delta CO_{TRIP} = \Delta CO_{CST}+\Delta CO_{HST} \tag{3-21}$$

$$\Delta NOx_{TRIP} = \Delta NOx_{CST}+\Delta NOx_{HST} \tag{3-22}$$

The values of $\mathbf{\Delta HC_{TRIP}}$, $\mathbf{\Delta CO_{TRIP}}$, and $\mathbf{\Delta NOx_{TRIP}}$ determined in Equations 3-20 through 3-22 are required later in Step 4 to calculate the total emission change. Example 3-4 demonstrates the use of Equations 3-20 through 3-22.

EXAMPLE 3-1: Hot-Start and Cold-Start Emission Factors

Example MOBILE4.1 Emission Factor Data
National Default Fleet, 75°F, 9.0 psi, 26 mph, 1990 Calendar Year,
No I/M Program

Vehicle Operating Mode	LDGV Emission Factor (grams/mile)			LDGT1 Emission Factor (grams/mile)		
	HC	CO	NO_X	HC	CO	NO_X
100% Cold Start	2.55	30.33	1.88	3.59	42.25	2.42
100% Hot Start	1.35	14.12	1.72	1.99	18.41	2.14
100% Hot Stabilized	0.95	11.03	1.09	1.34	13.68	1.39

(1) Using Equation 3-6 for LDGV exhaust hydrocarbons:

$$CST_{LDGV,HC} = (2.55 - 0.95) * 3.59 = 5.74 \quad \text{(grams per trip)}$$

(2) Using Equation 3-7 for LDGV exhaust hydrocarbons:

$$HST_{LDGV,CO} = (1.35 - 0.95) * 3.59 = 1.44 \quad \text{(grams per trip)}$$

(3) Similarly for the other pollutants and vehicles:

$$CST_{LDGV,CO} = 69.29 \text{ (g/trip)}$$
$$HST_{LDGV,CO} = 11.09 \text{ (g/trip)}$$
$$CST_{LDGV,NOx} = 2.84 \text{ (g/trip)}$$
$$HST_{LDGV,NOx} = 2.26 \text{ (g/trip)}$$

$$CST_{LDGT1,HC} = 8.08 \text{ (g/trip)}$$
$$HST_{LDGT1,HC} = 2.33 \text{ (g/trip)}$$
$$CST_{LDGT1,CO} = 102.6 \text{ (g/trip)}$$
$$HST_{LDGT1,CO} = 16.98 \text{ (g/trip)}$$
$$CST_{LDGT1,NOx} = 3.70 \text{ (g/trip)}$$
$$HST_{LDGT1,NOx} = 2.69 \text{ (g/trip)}$$

Discussion

Using Equations 3-6 and 3-7, the *grams per trip* hot-start and cold-start emission factors (HST and CST) can be calculated directly from the MOBILE exhaust emission factors reported in *grams per mile*. The factor 3.59 of Equations 3-6 and 3-7 is in the units of *trip-start miles per trip*. Emission factors presented here are for illustrative purposes only.

EXAMPLE 3-2: Hot-Start and Cold-Start Emissions Changes

(1) Using MOBILE VMT distributions data in Equation 3-1 and 3-2 to determine the trip distribution:

$$\gamma_{TRIP,LDGV} = 0.626 \,/\, (0.626 + 0.171) = 0.785$$
$$\gamma_{TRIP,LDGT1} = (1 - 0.785) = 0.215$$

(2) Using Equation 3-3 to determine total trip changes with the trip change data from Example 2-8 (this example illustrated the implementation of a rideshare program):

$$\Delta NETRP_{W;P} = -\,4{,}406 \text{ (trips)}$$
$$\Delta NETRP_{W;OP} = -2{,}841 \text{ (trips)}$$
$$\Delta NETRP_{NW;P} = 0$$
$$\Delta NETRP_{NW;OP} = 0$$

$$\Delta TRIP_{TOTAL} = -4{,}406 - 2{,}841 = -{,}247 \text{ (trips)}$$

(3) Using Equations 3-4 and 3-5 to determine the number of hot-start and cold-start trips with the cold-start trip fraction data (γ_{CST}) from Table 3-1:

$$\Delta TRIP_{CST} = 1 * (-7{,}247) = -7247 \text{ (trips)}$$
$$\Delta TRIP_{HST} = 0 * (-7{,}247) = 0$$

(4) Using Equations 3-8 through 3-13 to determine the trip-start emission changes and using the trip-start emission factors from Example 3-1:

$$\Delta HC_{CST}$$
$$= (-7{,}247 * 0.785 * 5.74) + (-7{,}247 * 0.215 * 8.08)$$
$$= -45.3 \times 10^3 \text{ (grams)}$$
$$\Delta HC_{HST}$$
$$= 0 \text{ (grams)}$$
$$\Delta CO_{CST}$$
$$= -554 \times 10^3 \text{ (grams)}$$
$$\Delta CO_{HST}$$
$$= 0 \text{ (grams)}$$
$$\Delta NOx_{CST}$$
$$= -21.9 \times 10^3 \text{ (grams)}$$
$$\Delta NOx_{HST}$$
$$= 0 \text{ (grams)}$$

Discussion

This example illustrates the reduction in hot-start and cold-start emissions due to trip reductions. Use of MOBILE data in this example is for illustrative purposes only.

EXAMPLE 3-3: Hot Soak and Diurnal Emissions Changes

Example MOBILE4.1 Emission Factor Data
National Default Fleet, 60°F to 84°F Temperature Range, 9.0 psi, 26 mph,
1990 Calendar Year, No I/M Program

Emission Category (units)	LDGV Emission Factor	LDGT1 Emission Factor
Hot Soak (g/trip)	3.06	3.60
Weighted Diurnal (grams)	3.30	5.11
Multi-day Diurnal (grams)	6.04	15.33

(1) Using Equation 3-14 to determine hot soak emission changes with example total trip changes and trip distributions calculated in Example 3-2 and with emission factors taken from the data shown above:

$\gamma_{TRIP,LDGV} = 0.785$

$\gamma_{TRIP,LDGT1} = 0.215$

$\Delta TRIP_{TOTAL} = -7{,}247$

$$\Delta HC_{HSK} = (-7{,}247 * 0.785 * 3.06) + (-7{,}247 * 0.215 * 3.60)$$
$$= -23.0 \times 10^3 \text{ (grams)}$$

(2) Using Equations 3-15 through 3-18 to determine diurnal emission changes with the example trip change data calculated in Example 2-2, with emission factors taken from the data above, and with 2 work trips per work day that a vehicle is used to commute ($TPD_W = 2$):

$\Delta NETRP_{W,P} = -4{,}406$ (trips) $\qquad \Delta NETRP_{W,OP} = -2{,}841$ (trips)

$\Delta NETRP_{NW,P} = 0 \qquad \Delta NETRP_{NW,OP} = 0$

$$\Delta HC_{DNL,W,LDGV} = 0.676 * (-4{,}406\text{-}2{,}841)/2 * 0.785 * (3.30 - 6.04)$$
$$= +5.24 \times 10^3 \text{ (grams)}$$
$$\Delta HC_{DNL,NW,LDGV} = 0 \text{ (grams)}$$
$$\Delta HC_{DNL,W,LDGT1} = 0.676 * (-4{,}406\text{-}2{,}841)/2 * 0.215 * (5.11 - 15.33)$$
$$= +9.15 \times 10^3 \text{ (grams)}$$
$$\Delta HC_{DNL,NW,LDGT1} = 0 \text{ (grams)}$$

(3) Using Equations 3-19 to sum the diurnal components:

$$\Delta HC_{DNL} = 5.24 \times 10^3 + 9.15 \times 10^3$$
$$= 14.4 \times 10^3 \text{ (grams)}$$

<u>Discussion</u>

This example illustrates the change in diurnal emissionsdue to a change in trips. As can be seen in (2), a decrease in trips causes an increase in vehicles left at home resulting in a positive diurnal emission change (more multiple-day diurnals). Use of MOBILE data in this example is for illustrative purposes only.

EXAMPLE 3-4: Total Emissions Changes Due to Trip Changes

Using Equations 3-20 through 3-22 to sum all components of the trip emission changes with the data of the components taken from Examples 3-2 and 3-3:

$\Delta HC_{CST} = -45.3 \times 10^3$ (grams) $\Delta HC_{HST} = 0$ (grams)
$\Delta CO_{CST} = -554 \times 10^3$ (grams)
$\Delta CO_{HST} = 0$ (grams)
$\Delta NOx_{CST} = -21.9 \times 10^3$ (grams)
$\Delta NOx_{HST} = 0$ (grams)
$\Delta HC_{DNL} = +14.4 \times 10^3$ (grams)
$\Delta HC_{HSK} = -23.0 \times 10^3$ (grams)

$\Delta HC_{TRIP} = (-45.3 - 23.0 + 14.4) \times 10^3 = -53.9 \times 10^3$ *(grams)*
$\Delta CO_{TRIP} = -554 \times 10^3 + 0 = -554 \times 10^3$ *(grams)*
$\Delta NOx_{TRIP} = -21.9 \times 10^3 + 0 = -21.9 \times 10^3$ *(grams)*

Discussion

Note that the diurnal emissions *increase* with decreased trips and the other emission categories decrease with decreased trips. As is discussed in the text of this chapter, the observed diurnal emission change is smaller than the other emission categories. Moreover, when considering the other HC emission categories such as hot-stabilized exhaust, which is done later in this chapter, the diurnal contribution to the overall HC estimation becomes even less significant.

STEP 2: Emission Analysis of VMT Changes

This step evaluates emission changes due to VMT changes. The emission categories influenced by VMT include hot-stabilized exhaust, running loss, crank case, and refueling emissions. For this analysis it is not necessary to distinguish between the last three categories. In this report they are summed into one category termed "VMT-related evaporative" emissions.

Identify Distribution of VMT Changes

Analogous to the need to define γ_{TRIP}, it is necessary to determine the vehicle distribution of VMT affected by a given TCM (γ_{VMT}). This parameter is similar to γ_{TRIP} except it is based on total VMT and not total trips. Equations 3-23 and 3-24 define the distribution of VMT for the affected vehicle classes (assuming LDGVs and LDGTs):

$$\gamma_{VMT,LDVG} = \frac{VMT_{LDGV}}{VMT_{LDGV} + VMT_{LDGT1}} \qquad (3\text{-}23)$$

$$\gamma_{VMT,LDVT1} = \left(1 - \gamma_{VMT,LDGV}\right) \qquad (3\text{-}24)$$

where $\gamma_{VMT,LDGV}$ represents the fraction of VMT which are from LDGVs, $\gamma_{VMT,LDGT1}$ is the fraction of VMT from LDGT1, VMT is the total VMT for the subscripted vehicle class. Regional VMT estimates should be used in Equations 3-23 and 3-24.

If VMT data for Equations 3-23 and 3-24 are unavailable, an approximate value can be obtained from the vehicle VMT fraction data from the MOBILE model output. The VMT vehicle fraction would then be substituted into Equation 3-23 in place of the VMT data. Note that the MOBILE vehicle VMT fractions are a function of calendar year. As noted in Step 1, in 1990 MOBILE4.1 reports a LDGV VMT fraction of **0.626** (i.e., 62.6% of the total fleet VMT is from LDGVs) and a LDGT1 VMT fraction of **0.171** (national average default values). The approximate value of γ_{VMT} can be obtained from substituting these values into Equations 3-23 and 3-24 to yield $\gamma_{VMT,LDGV}$ = **0.785** and $\gamma_{VMT,LDGT1}$ = **0.215**.

Determine Hot-Stabilized Exhaust Emission Changes

A significant portion of total emission changes are exhaust emission reductions due to reduced VMT (through fewer trips and through reduced trip length). This section explains how to calculate this change in hot-stabilized exhaust due to TCM related VMT changes. Hot-stabilized exhaust emissions are the exhaust emissions after the vehicle has warmed-up and are calculated in grams per mile by MOBILE using 100% hot-stabilized operating mode. The hot-stabilized emission factors calculated by MOBILE vary by the vehicle speed specified by the user. In this analysis, hot-stabilized emission factors should be determined from the vehicle speeds observed **prior** to TCM implementation. Emission changes resulting from the change in speed (before and after TCM implementation) are evaluated separately in Step 3 of this chapter.

The following equations can be used to determine the peak and off-peak period changes in hot-stabilized emissions:

$$\Delta HC_{STB,P} = \left(\Delta NETVMT_{P} * \gamma_{VMT,LDGV} * STB_{LDGV,HC,P}\right) + \left(\Delta NETVMT_{P} * \gamma_{VMT,LDGT1} * STB_{LDGT1,HC,P}\right) \tag{3-25}$$

$$\Delta HC_{STB,OP} = \left(\Delta NETVMT_{OP} * \gamma_{VMT,LDGV} * STB_{LDGV,HC,OP}\right) + \left(\Delta NETVMT_{OP} * \gamma_{VMT,LDGT1} * STB_{LDGT1,HC,OP}\right) \tag{3-26}$$

$$\Delta CO_{STB,P} = \left(\Delta NETVMT_{P} * \gamma_{VMT,LDGV} * STB_{LDGV,CO,P}\right) + \left(\Delta NETVMT_{P} * \gamma_{VMT,LDGT1} * STB_{LDGT1,CO,P}\right) \tag{3-27}$$

$$\Delta CO_{STB,OP} = \left(\Delta NETVMT_{OP} * \gamma_{VMT,LDGV} * STB_{LDGV,CO,OP}\right) + \left(\Delta NETVMT_{OP} * \gamma_{VMT,LDGT1} * STB_{LDGT1,CO,OP}\right) \tag{3-28}$$

$$\Delta NOx_{STB,P} = \left(\Delta NETVMT_{P} * \gamma_{VMT,LDGV} * STB_{LDGV,NOx,P}\right) + \left(\Delta NETVMT_{P} * \gamma_{VMT,LDGT1} * STB_{LDGT1,NOx,P}\right) \tag{3-29}$$

$$\Delta NOx_{STB,OP} = \left(\Delta NETVMT_{OP} * \gamma_{VMT,LDGV} * STB_{LDGV,NOx,OP}\right) + \left(\Delta NETVMT_{OP} * \gamma_{VMT,LDGT1} * STB_{LDGT1,NOx,OP}\right) \tag{3-30}$$

where **ΔNETVMT** is the change in total VMT in the units of total miles for the subscripted period (**P** = peak period, **OP** = off-peak period) determined in Step 8 of Chapter 2; **STB** is the hot-stabilized exhaust emission factor in the units of grams per mile for the subscripted vehicle class, pollutant, and period; and γ_{VMT} is the vehicle VMT fraction for the subscripted vehicle class and is defined in Equations 3-23 and 3-24.

The hot-stabilized emission factors (**STB**) used in Equations 3-25 through 3-30 are determined from MOBILE evaluated at the operating mode of 100% hot-stabilized. The peak and off-peak period subscripts on **STB** are used to distinguish peak and off-peak period speeds which are generally different resulting in different emission factors for peak and off-peak periods. An example application of the calculation of hot-stabilized emissions changes is given in Example 3-5.

Determine VMT-Related Evaporative Emissions

The VMT-related evaporative emissions consist of the VMT-dependent, non-exhaust categories of running loss, crankcase, and refueling emissions. Running loss and crankcase emissions, expressed as gram-per-mile emission factors, occur while the vehicle is in operation and are therefore affected by any change in VMT. Refueling emissions, expressed in grams per gallon of fuel, occur while the vehicle is refueling; however, the grams per gallon emission factor can be converted to grams per mile using fuel economy data (miles per gallon). MOBILE reports refueling emission factors in both grams per gallon and grams per mile, the latter of which is used in this analysis.

The following equations can be used to determine peak and off-peak period VMT-related evaporative emission changes:

$$\Delta HC_{VEVP,P} = \left(\Delta NETVMT_{P} * \gamma_{VMT,LDGV} * VEVP_{LDGV}\right) + \left(\Delta NETVMT_{P} * \gamma_{VMT,LDGT1} * VEVP_{LDGT1}\right) \qquad (3\text{-}31)$$

$$\Delta HC_{VEVP,OP} = \left(\Delta VMTNET_{OP} * \gamma_{VMT,LDGV} * VEVP_{LDGV}\right) + \left(\Delta NETVMT_{OP} * \gamma_{VMT,LDGT1} * VEVP_{LDGT1}\right) \qquad (3\text{-}32)$$

where **$\Delta NETVMT_P$**, and **$\Delta NETVMT_{OP}$** are the peak and off-peak change in total VMT determined in Step 8 of Chapter 2, **VEVP** is the VMT-related evaporative emission factor for the subscripted vehicle class determined from the sum of the gram per mile running loss, crankcase and refueling emission factors reported by MOBILE, and γ_{VMT} is the vehicle VMT fraction for the subscripted vehicle class and is defined in Equations 3-23 and 3-24.

Peak and off-peak VMT-related emission factors are used in Equations 3-31 and 3-32 because running loss emissions are influenced by vehicle speed changes resulting in different emission factors for peak and off-peak periods. An example of the calculation of VMT-related evaporative emissions is given in Example 3-6.

Total Emission Changes Due to VMT Changes

Summing the emission changes of the of peak and off-peak hot-stabilized and running evaporative emission categories into one net emission change, the following equations can be used to determine the total HC, CO and NO_X emissions changes due to VMT changes resulting from TCM implementation:

$$\Delta HC_{VMT} = \Delta HC_{STB,P} + \Delta HC_{STB,OP} + \Delta HC_{VEVP,P} + \Delta HC_{VEVP,OP} \tag{3-33}$$

$$\Delta CO_{VMT} = \Delta CO_{STB,P} + \Delta CO_{STB,OP} \tag{3-34}$$

$$\Delta NOX_{VMT} = \Delta NOX_{STB,P} + \Delta NOX_{STB,OP} \tag{3-35}$$

where the values of $\Delta \mathbf{HC}_{\mathbf{STB}}$, $\Delta \mathbf{HC}_{\mathbf{VEVP}}$, $\Delta \mathbf{CO}_{\mathbf{STB}}$, $\Delta \mathbf{NOx}_{\mathbf{STB}}$ are defined and calculated in Equations 3-25 through 3-32. The resulting values of the total emission changes due to VMT changes, $\Delta \mathbf{HC}_{\mathbf{VMT}}$, $\Delta \mathbf{CO}_{\mathbf{VMT}}$, and $\Delta \mathbf{NOx}_{\mathbf{VMT}}$, determined in Equations 3-33 through 3-35 are required later in Step 4 for the calculation of the total emission change. An example of the determination of $\Delta \mathbf{HC}_{\mathbf{VMT}}$, $\Delta \mathbf{CO}_{\mathbf{VMT}}$, and $\Delta \mathbf{NOx}_{\mathbf{VMT}}$ is presented in Example 3-7.

EXAMPLE 3-5: Hot-Stabilized Exhaust Emission Changes

Example MOBILE4.1 Emission Factor Data
National Default Fleet, 75°F Ambient Temperature, 9.0 psi, 1990 Calendar Year,
No I/M Program

Vehicle Operating Mode, Speed	LDGV Emission Factor (grams/mile)			LDGT1 Emission Factor (grams/mile)		
	HC	CO	NO_X	HC	CO	NO_X
100% Hot Stab., 20 mph	1.23	14.62	1.15	1.77	18.05	1.41
100% Hot Stab., 35 mph	0.69	7.79	1.06	0.94	9.46	1.39

Using Equations 3-25 through 3-30 to determine hot-stabilized exhaust emission changes with hot-stabilized emission factors (**STB**) taken from the data above (assuming a peak period speed of 20 mph and an off-peak of 35 mph), with **ΔNETVMT** (calculated in Step 8 of Chapter 2) taken from Example 2-9, and with γ_{TRIP} determined from MOBILE VMT distribution data:

$\gamma_{VMT;LDGV} = 0.785$

$\gamma_{VMT;LDGT1} = 0.215$

$\Delta NETVMT_P = -118{,}989$ (miles)$\Delta NETVMT_{OP} = -78{,}057$ (miles)

$$\Delta HC_{STB,P} = (-118{,}989 * 0.785 * 1.23) + (-118{,}989 * 0.215 * 1.77)$$
$$= -160 \times 10^3 \ (grams)$$

$$\Delta HC_{STB,OP} = (-78{,}057 * 0.785 * 0.69) + (-78{,}057 * 0.215 * 0.94)$$
$$= -58.1 \times 10^3 \ (grams)$$

$$\Delta CO_{STB,P} = (-118{,}989 * 0.785 * 14.62) + (-118{,}989 * 0.215 * 18.05)$$
$$= -1.83 \times 10^6 \ (grams)$$

$$\Delta CO_{STB,OP} = (-78{,}057 * 0.785 * 7.79) + (-78{,}057 * 0.215 * 9.46)$$
$$= -636 \times 10^3 \ (grams)$$

$$\Delta NOx_{STB,P} = (-118{,}989 * 0.785 * 1.15) + (-118{,}989 * 0.215 * 1.41)$$
$$= -143 \times 10^3 \ (grams)$$

$$\Delta NOx_{STB,OP} = (-78{,}057 * 0.785 * 1.06) + (-78{,}057 * 0.215 * 1.39)$$
$$= -88.3 \times 10^3 \ (grams)$$

Discussion

Using Equations 3-25 through 3-30, the hot-stabilized emission changes can be determined from the VMT changes (ΔNETVMT) determined in Chapter 2. Emission factors presented here are for illustrative purposes only.

EXAMPLE 3-6: VMT-Related Evaporative Emission Changes

Example MOBILE4.1 Emission Factor Data
National Default Fleet, 75 °F Ambient Temperature, 9.0 psi,
1990 Calendar Year, No I/M Program

Emission Category (Speed)	LDGV Emission Factor (grams/mile)	LDGT1 Emission Factor (grams/mile)
Running Loss (20 mph)	0.22	0.22
Running Loss (35 mph)	0.12	0.13
Crankcase (all speeds)	0.03	0.06
Refueling (all speeds)	0.19	0.25

(1) Calculating the VMT-related evaporative emission factor as the sum of running loss, crankcase and refueling emission factors (assuming a peak period speed of 20 mph and an off-peak period of 35 mph):

$$VEVP_{LDGV,P} = 0.22 + 0.03 + 0.19 = 0.44 \ (grams/mile)$$
$$VEVP_{LDGV,OP} = 0.12 + 0.03 + 0.19 = 0.34 \ (grams/mile)$$
$$VEVP_{LDGT1,P} = 0.22 + 0.06 + 0.25 = 0.53 \ (grams/mile)$$
$$VEVP_{LDGT1,OP} = 0.13 + 0.06 + 0.25 = 0.44 \ (grams/mile)$$

(2) Using Equations 3-31 and 3-32 to determine the VMT-related evaporative emission changes with VEVP emission factors determined in (1), with ΔVMT_{TOT} (calculated in Step 8 of Chapter 2) taken from Example 2-X, and with γ_{TRIP} determined from MOBILE VMT distribution data:

$\gamma_{TRIP,LDGV} = 0.785$

$\gamma_{TRIP,LDGT1} = 0.215$

$\Delta NETVMT_P = -118,989$ (miles) $\Delta NETVMT_{OP} = -78,057$ (miles)

$$\Delta HC_{VEVP,P} = (-118,989 * 0.785 * 0.44) + (-118,989 * 0.215 * 0.53) = -54.7 \times 10^3 \ (grams)$$

$$\Delta HC_{VEVP,OP} = (-78,057 * 0.785 * 0.34) + (-78,057 * 0.215 * 0.44) = -28.2 \times 10^3 \ (grams)$$

Discussion

Using Equations 3-31 and 3-32, the VMT-related evaporative emission changes can be determined from the VMT (ΔNETVMT) changes determined in Chapter 2. Emission factors presented here are for illustrative purposes only.

EXAMPLE 3-7: Total Emission Changes Due to VMT Changes

Using Equations 3-33 through 3-35 to sum all components of the VMT-related emission changes with the data of the components taken from Examples 3-5 and 3-6:

$\Delta HC_{STB,P}$ = -160×10^3 (grams)
$\Delta HC_{STB,OP}$ = -58.1×10^3 (grams)
$\Delta CO_{STB,P}$ = -1.83×10^6 (grams)
$\Delta CO_{STB,OP}$ = -636×10^3 (grams)
$\Delta NOx_{STB,P}$ = -143×10^3 (grams)
$\Delta NOx_{STB,OP}$ = -88.3×10^3 (grams)
$\Delta HC_{VEVP,P}$ = -54.6×10^3 (grams)
$\Delta HC_{VEVP,OP}$ = -28.2×10^3 (grams)

$$\Delta HC_{VMT} = (-160 - 58.1 - 54.7 - 28.2) \times 10^3 = -301 \times 10^3 \text{ (grams)}$$
$$\Delta CO_{VMT} = -1.83 \times 10^6 - 636 \times 10^3 = -2.47 \times 10^6 \text{ (grams)}$$
$$\Delta NOx_{VMT} = (-143 - 88.3) \times 10^3 = -231 \times 10^3 \text{ (grams)}$$

Discussion

This example illustrates the total VMT-related emission changes. In comparison to the total trip-related emission changes of Example 3-4, the VMT-related emissions changes are significantly larger.

STEP 3: Emission Analysis of Fleet Speed Changes

This step evaluates emission changes due to the changes in vehicle speeds. The emission categories influenced by this evaluation are hot-stabilized exhaust and running loss emissions. This step differs from Steps 1 and 2 in that all vehicle classes are affected by speed changes. It is important to note again that the methodology used here considers regional average speeds and will not capture the complexities implied by the fact that vehicles are traveling at different speeds in different parts of the region. The parameters required to complete the speed change emissions analysis are:

- $\mathbf{SPEED_{P,BASE}}$ - speed for peak period (P) prior to TCM implementation (indicated by the subscript **BASE**).
- $\mathbf{SPEED_{OP,BASE}}$ - off-peak period (OP) base speed.
- $\mathbf{SPEED_{P,TCM}}$ - peak period speed after TCM implementation (indicated by the subscript **TCM**).
- $\mathbf{SPEED_{OP,TCM}}$ - off-peak period speed after TCM implementation.
- $\mathbf{VMT_{P,TCM}}$ - total peak period VMT for modeling region after TCM implementation.
- $\mathbf{VMT_{OP,TCM}}$ - total off-peak period VMT for modeling region after TCM implementation.

Of these parameters, the base speeds are region dependent and should be known prior to this analysis. The TCM speeds can be determined from:

$$SPEED_{P,TCM} = SPEED_{P,BASE} + \Delta SPD_P \tag{3-36}$$

$$SPEED_{OP,TCM} = SPEED_{OP,BASE} + \Delta SPD_{OP} \tag{3-37}$$

where $\mathbf{\Delta SPD_P}$ and $\mathbf{\Delta SPD_{OP}}$ were determined in Step 9 of Chapter 2. The values of $\mathbf{VMT_{P,TCM}}$ and $\mathbf{VMT_{OP,TCM}}$ can also be determined from the parameters used in Step 9 of Chapter 2:

$$VMT_{P,TCM} = VMT_P + \Delta VMT_P \tag{3-38}$$

$$VMT_{OP,TCM} = VMT_{OP} + \Delta VMT_{OP} \tag{3-39}$$

where the parameters of Equations 3-38 and 3-39, $\mathbf{\Delta VMT_P}$, $\mathbf{\Delta VMT_{OP}}$, $\mathbf{VMT_P}$, and $\mathbf{VMT_{OP}}$, were also identified in Step 9 of Chapter 2.

The emission change due to a change in speed is determined from the difference in emission factors (hot-stabilized exhaust and running loss) evaluated at the speed prior to TCM implementation and at the speed subsequent to TCM implementation. This is expressed in the following equations which can be used to determine the net emission change due to an overall peak period fleet speed change:

$$\Delta HC_{SPD,P} = VMT_{TCM,P} * \left(STB_{FLT,HC,P,TCM} + RNL_{FLT,P,TCM}\right) - VMT_{TCM,P} * \left(STB_{FLT,HC,P,BASE} + RNL_{FLT,P,BASE}\right) \quad (3\text{-}40)$$

$$\Delta HC_{SPD,OP} = VMT_{TCM,OP} * \left(STB_{FLT,HC,OP,TCM} + RNL_{FLT,OP,TCM}\right) - VMT_{TCM,OP} * \left(STB_{FLT,HC,OP,BASE} + RNL_{FLT,OP,BASE}\right) \quad (3\text{-}41)$$

$$\Delta CO_{SPD,P} = VMT_{TCM,P} * \left(STB_{FLT,CO,P,TCM} - STB_{FLT,CO,P,BASE}\right) \quad (3\text{-}42)$$

$$\Delta CO_{SPD,OP} = VMT_{TCM,OP} * \left(STB_{FLT,CO,OP,TCM} - STB_{FLT,CO,OP,BASE}\right) \quad (3\text{-}42)$$

$$\Delta NOx_{SPD,P} = VMT_{TCM,P} * \left(STB_{FLT,NOx,P,TCM} - STB_{FLT,NOx,P,BASE}\right) \quad (3\text{-}44)$$

$$\Delta NOx_{SPD,OP} = VMT_{TCM,OP} * \left(STB_{FLT,NOx,OP,TCM} - STB_{FLT,NOx,OP,BASE}\right) \quad (3\text{-}45)$$

where the subscript **SPD** (i.e. $\mathbf{\Delta HC_{SPD}}$) indicates speed-related changes of the indicated pollutant, **STB** and **RNL** are the hot-stabilized and running loss emission factors for the subscripted pollutant, and the subscript **FLT** indicates fleet emission factors. The subscripts **OP** and **P**, indicating off-peak and peak period, and **BASE** and **TCM**, indicating base speed and TCM-related speed, are used to identify the correct speed used in the evaluation of the emission factor.

The overall emission change is the combined changes observed in the peak and off-peak period and is calculated by the following equations:

$$\Delta HC_{SPD} = \Delta HC_{SPD,P} + \Delta HC_{SPD,OP} \quad (3\text{-}46)$$

$$\Delta CO_{SPD} = \Delta CO_{SPD,P} + \Delta CO_{SPD,OP} \quad (3\text{-}47)$$

$$\Delta NOx_{SPD} = \Delta NOX_{SPD,P} + \Delta NOx_{SPD,OP} \quad (3\text{-}48)$$

The values of $\mathbf{\Delta HC_{SPD}}$, $\mathbf{\Delta CO_{SPD}}$, and $\mathbf{\Delta NOx_{SPD}}$ determined in equations (3-41) through (3-43) are required later in Step 4 for the calculation of the total emission change. An example application of determination of emission changes due to speed changes is given in Example 3-8.

EXAMPLE 3-8: Total Emissions Changes Due to Speed Changes

Example MOBILE4.1 Emission Factor Data
National Default Fleet, 75°F Ambient Temperature, 9.0 psi, 1990 Calendar Year,
No I/M Program

Scenario (speed)	Fleet Emission Factors (grams/mile)			
	HC	CO	NO_X	Run. Loss
BASE, Peak Period (20 mph)	1.676	18.421	2.739	0.212
BASE, Off-peak Period (35 mph)	1.938	9.916	2.528	0.120
TCM, Peak Period (22 mph)	1.524	16.670	2.674	0.195
TCM, Off-peak Period (36 mph)	1.906	9.614	2.532	0.116

(1) Using Equations 3-40 through 3-45 to determine hot-stabilized exhaust emission changes with hot-stabilized (**STB**) and the running loss (**RNL**) emission factors taken from the data above at the indicated speeds, and with $\mathbf{VMT_{TCM}}$ provided for illustrative purposes:

$$\mathbf{VMT_{P,TCM}} = 33.4 \text{ x } 10^6 \text{ (miles)}$$
$$\mathbf{VMT_{OP,TCM}} = 40.7 \text{ x } 10^6 \text{ (miles)}$$

$$\Delta HC_{SPD,P} = 33.4 \text{ x } 10^6 * (1.524+0.195) - 33.4 \text{ x } 10^6 * (1.676+0.212)$$
$$= -5.64 \text{ x } 10^6 \text{ (grams)}$$
$$\Delta HC_{SPD,OP} = 40.7 \text{ x } 10^6 * (1.906+0.116) - 40.7 \text{ x } 10^6 * (1.938+0.120)$$
$$= -1.47 \text{ x } 10^6 \text{ (grams)}$$
$$\Delta CO_{SPD,P} = 33.4 \text{ x } 10^6 * (16.670-18.421) = -58.5 \text{ x } 10^6 \text{ (grams)}$$
$$\Delta CO_{SPD,OP} = 40.7 \text{ x } 10^6 * (9.614-9.916) = -12.3 \text{ x } 10^6 \text{ (grams)}$$
$$\Delta NOx_{SPD,P} = 33.4 \text{ x } 10^6 * (2.674-2.739) = -24.7 \text{ x } 10^6 \text{ (grams)}$$
$$\Delta NOx_{SPD,OP} = 40.7 \text{ x } 10^6 * (2.532-2.528) = -1.63 \text{ x } 10^6 \text{ (grams)}$$

(2) Using Equations 3-46 to 3-48 to sum the peak and off-peak components:

$$\Delta HC_{SPD} = (-5.64-1.47) \text{ x } 10^6 = -7.11 \text{ x } 10^6 \text{ (grams)}$$
$$\Delta CO_{SPD} = (-58.5-12.3) \text{ x } 10^6 = -70.8 \text{ x } 10^6 \text{ (grams)}$$
$$\Delta NOx_{SPD} = (-24.7-1.63) \text{ x } 10^6 = -26.3 \text{ x } 10^6 \text{ (grams)}$$

Discussion

This application of emission changes from speed changes is provided for illustrative purposes only. In the emission analysis of the rideshare program which has been used in the examples until this one, the speed change analysis given in Example 2-11, calculated negligible speed changes. Thus the emission change of that particular rideshare program would be zero. In this example, a hypothetical set of speed changes were assumed (20, 22, 35 and 36 mph). It can be seen from the calculations shown above that even a change in speeds of a couple of miles per hour can generate large emission changes. However, it is important to note that speed changes realized by a TCM program would rarely reach the magnitude illustrated in this example.

STEP 4: Total Emission Changes Due to TCM Implementation

The final emission change realized by a region due to the implementation of a TCM is the sum of the emission changes determined in Steps 1 through 3, and can be calculated in the following equations:

$$\Delta HC = \Delta HC_{TRIP} + \Delta HC_{VMT} + \Delta HC_{SPD} \quad (3\text{-}49)$$

$$\Delta CO = \Delta CO_{TRIP} + \Delta CO_{VMT} + \Delta CO_{SPD} \quad (3\text{-}50)$$

$$\Delta NOx = \Delta NOx_{TRIP} + \Delta NOx_{VMT} + \Delta NOx_{SPD} \quad (3\text{-}51)$$

where **ΔHC**, **ΔCO**, and **ΔNOx** are the final emission changes which combine emission changes due to trip changes determined in Step 1, VMT changes in Step 2, and speed changes in Step 3. An example application of Equations 3-49 through 3-51 is given in Example 3-9.

EXAMPLE 3-9: Total Emissions Changes Due to Speed Changes

Using Equations 3-49 through 3-52, the total emission changes are the sum of the trip-related, VMT-related, and speed-related emission changes determined in Steps 1,2 and 3 respectively:

ΔHC_{TRIP} = -301×10^3 (grams)
ΔHC_{VMT} = -53.9×10^3 (grams)
ΔHC_{SPD} = 0
ΔCO_{TRIP} = -554×10^3 (grams)
ΔCO_{VMT} = -2.47×10^6 (grams)
ΔCO_{SPD} = 0
ΔNOx_{TRIP} = -21.9×10^3 (grams)
ΔNOx_{VMT} = -231×10^3 (grams)
ΔNOx_{SPD} = 0

$\Delta HC = (-301 - 53.9 + 0) \times 10^3 = 355 \times 10^3$ *(grams)*
$\Delta CO = (-2{,}470 - 554 + 0) \times 10^3 = 3.02 \times 10^6$ *(grams)*
$\Delta NOx = (-231 - 21.9 + 0) \times 10^3 = 253 \times 10^3$ *(grams)*

<u>Discussion</u>

ΔHC, ΔCO, and ΔNOx are the final emission changes realized by TCM implementation. Note the discussion of Example 3-8 for the evaluation of emission changes due to speed changes. Useful conversion factors for the conversion of emissions in grams to tons (1.10×10^{-6} tons/gram) or kilograms (1×10^{-3} kg/gram) can be used.

4 TCM INTERACTIONS AND MODE CHOICE DEPENDENCE ON MULTIPLE ATTRIBUTES

INTRODUCTION

Few agencies are likely to implement only one TCM at a time. More often, several TCMs will be implemented together. However, TCMs are rarely independent of one another, thus separate analyses of individual TCMs in a package may be misleading. Two issues should be considered when conducting an analysis of a package of TCMs: (1) measures overlap target audiences and it is possible to double count the effectiveness of TCMs lacking consideration of this overlap. For example, one person cannot both ride the bus and carpool to work. Similarly, some measures may be effective but may attract participants from other, preexisting programs. For instance, a rideshare participant may switch to transit if transit passes are offered); and, (2) the implementation of some measures either improves or diminishes the chances for successful implementation of other TCMs. These synergies need to be recognized while analyzing the effectiveness of a given TCM (one example: parking pricing strategies improve the success rate of other programs such as rideshare).

This chapter presents a method for evaluating packages of TCMs rather than individual measures. By conducting the analyses presented below, analysts will be able to predict changes in the mode split[1] of a target population in response to different packages of TCMs. Once the TCM participation rates are known (e.g., an additional 5 percent of all peak period trips will be rideshare trips, or an additional 5 percent of works trips made by people working for a major employer will be made using transit), analysts can evaluate measures individually to determine their travel and emission impacts. The packaging methodology in this discussion builds upon analytical approaches developed by the authors under separate sponsorship (Austin et al., 1991; Eisinger et al., 1991).

The relationship between TCMs and mode choice is a subject in its infancy of development. Mode choice behavior is difficult to predict for several reasons. One reason is that mode choice is a behavioral response to a variety of factors, many of which cannot easily be quantified. For example, a person may choose to take public transit one day just because he/she is simply not in the mood to sit in gridlock traffic on the freeway that day, and the same person may choose to drive alone the following day because of an

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[1] Traditional mode split generally refers to the distribution of travel among SOVs, ridesharing, and transit. Mode split here refers to the distribution among all possible modes, including modes that may be introduced by TCMs such as telecommuting or compressed work weeks.

uncomfortable experience on the bus. Such factors, which can sometimes be arbitrary, add a large random element to a person's mode choice. Adding to the difficulty of predicting human behavior with respect to mode choice, TCMs most often are not independent of one another. For example, the introduction of flextime to a population that already has a successful rideshare program may encourage SOV drivers to drive during off-peak hours and may also disrupt carpools. The methodology presented here provides an analytical framework for identifying and roughly quantifying the impact of such relationships.

There exist transportation models that may be used to study the change in mode splits resulting from the implementation of packages of TCMs. A good example includes TRIPS (Harvey, 1991), which is based on 5,000 households in Los Angeles. The model uses empirical equations that have been statistically calibrated from a particular database (from the Los Angeles area). Often the data used to calibrate such models is outdated or only representative of the region from which it was collected. These models require extensive data to be supplied by the user (typically collected in surveys and individual trip diaries), such as average household disposable income, the number of workers in a household, in-vehicle travel time, and number of autos in the household. If a recently calibrated transportation model is available and the user has the extensive input data required, more accurate estimates of TCM package effects may be made in this manner than with the more approximate approach suggested here.

Other approaches requiring less data are also available. A good example is the pivot point technique (CSI, 1979), which calculates incremental mode shifts as a function of the utility of each mode. The model, still in use, applies a multinomial logit formulation and coefficients from a 1968 Washington, D.C. travel survey. A limited comparison of the coefficients with 1967 Los Angeles and 1963 New Bedford coefficients found them to be quite similar. The pivot point model does not address modes other than SOV, carpooling, and transit, and does not address nonwork trips. Pivot point, with the original coefficients, is used in a California Air Resources Board model for TCMs called AQAT (Randall and Diamond, 1990). AQAT is described in Appendix A together with a number of other California methodologies.

The TCM packaging methodology presented here is not an empirical model statistically calibrated from an extensive database. Rather, it is based on principle attributes of travel modes and the comparative values of the different modes for each attribute. It provides a framework for the analyst to think through the transportation alternatives available to the population (or region) being studied, and is a means to identify the strengths and weaknesses of different TCMs combinations, and an opportunity to better understand the factors influencing the current mode split and what it would take to alter the mode split significantly. The analyst selects every coefficient in the model to represent the population under study. The only data required for the approach are current mode choice splits, costs, and travel times. The minimal data requirements make it inexpensive to use, and its calibration flexibility makes it transportable to different regions and populations. This approach is recommended for use when the resources required to run a detailed transportation model accurately are not available. However, because this model is largely conceptual, the analyst should be prepared to demonstrate the reasonableness of the coefficients chosen to represent the population of study. The selection of coefficients should be guided by empirical data from regions with similar demographics. The predicted mode splits should not be viewed as exact, but as approximations.

The rest of this chapter includes five discussions: (1) a brief overview (the "big picture") of how the packaging methodology works, (2) a discussion outlining key mode choice considerations, (3) a step-by-step discussion that describes in detail how to conduct a packaging analysis, (4) sample applications of the methodology using empirical data from San Francisco and the Phoenix metropolitan area, and (5) example applications of a TCM.

OVERVIEW OF THE PACKAGING METHODOLOGY

The packaging methodology is founded upon the premise that individuals choose their travel mode based upon the attributes of each mode choice option. Example attributes influencing mode choice include the convenience of SOV use, the lower costs associated with rideshare, or the convenience and cost savings of not having to make a trip when telecommuting. The packaging methodology focuses on valuing individual TCMs based upon how well each TCM rates in consideration of several important mode choice attributes[2]. TCM participation rates are quantitatively estimated based upon the total value of a specific measure in comparison to the value of other mode choice options available to the trip maker.

Interdependent TCMs are easily addressed using this methodology. The overlap among TCMs is accounted for by comparing the relative value of each TCM based upon mode choice attributes. More valuable measures are assumed to attract a greater percentage of a given target audience (such as individuals making work trips). Synergies are accounted for by the way in which TCMs alter the value of a mode's rating for an individual attribute. As an example, if a parking management program combined with a ride matching program increases the costs of using a SOV while decreasing the inconvenience of ridesharing, then the total value of SOV travel diminishes and the total value of ridesharing increases in the methodology's ranking system.

A key component of the methodology involves validating the approach using actual mode split data. As an initial step in evaluating packages, one sets up TCM rankings so that the methodology replicates existing mode splits. Once this is done, one can then alter variables to estimate the participation rates among new or enhanced TCMs.

The methodology is most easily implemented using a spreadsheet or a simple FORTRAN program. The example applications included in this chapter were developed using a FORTRAN program. First the selected coefficients were validated by illustrating model agreement with actual mode splits and then the inputs were altered to reflect the

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[2] As discussed in more detail later in this section, the literature on mode choice decisions points to four key attributes that individuals weigh: time, cost, reliability, and convenience of travel

hypothesized implementation of a set of TCMs. The program enables the user to easily modify data inputs and to quickly adjust the validated inputs to reflect the TCMs.

MODE CHOICE CONSIDERATIONS

The foundation of the packaging methodology is the ability to understand and rank the key factors individuals consider when determining mode choice. Specific TCMs alter trip making behavior if the measures affect the factors that people consider in deciding upon the nature and frequency of their trip making. To analyze the effects of a package of measures it is important to understand how each measure (both individually and in concert with other measures) affects the key variables that people weigh when deciding upon mode choice.

Individuals directly and indirectly consider numerous attributes of the mode choice opportunities they have when deciding what trips to make and how to make them. The four most important factors are travel costs, time, reliability, and convenience.

Cost and Travel Time

For most mode choice decisions, travel time and cost are two of the most important factors and have been the key variables used in mode choice models for some time (Hutchinson, 1974). As Wachs (1990) states in a paper summarizing implications of behavioral research on transportation demand, "Applications of behavioral science to transportation planning give greatest emphasis to travel time and travel cost as the characteristics of travel modes most likely to influence choices made by commuters." Recent findings still support this relationship. For example, Willson, et. al. (1989) summarizes existing studies of the relationship between parking subsidies and SOV users in a number of areas.

Certain costs are more important than others. Analyses of specific TCMs support the idea that day-to-day costs are the most important cost considerations. Feeney (1989) says that parking costs are weighted more heavily than mileage related or car maintenance costs. Wachs states that "Many studies of commuters' willingness to carpool have shown that commuters consider the out-of-pocket costs of carpooling versus driving alone to be among the two or three most important factors influencing the choice between these modes, the others being travel time and convenience..." (Wachs, 1990).

Similarly, certain time costs are more important than others. "Excess time" (time spent other than just driving enroute) has substantially greater disutility than driving time (e.g., some studies show that walking time has twice the disutility of in-vehicle time; Feeney, 1989). Wachs (1990) states "A variety of studies, conducted in different environments, involving different trip purposes and different modes, have shown that people psychologically weight 'out-of-vehicle time' somewhere between two and three times as heavily as they weight 'line-haul' time or moving time in their travel decisions."

Other Attributes Weighed By Trip Makers

While the four factors listed above are key, others can also influence TCM choices. Analysts should be sensitive to whether these factors may be operative in their study region, and incorporate them into the analysis to the extent possible. It is recommended that this be accomplished through adjustments to the weights assigned to the four primary factors. The discussion presented below is intended to introduce some of these factors. Regarding transit, for example, Wachs (1990) observes that the following variables (listed in order of importance, beginning with most important) determine whether transit is taken: cost, reliability, travel time savings, comfort (climate control, exposure to rain, snow and hot sun), space for packages. Among the range of important considerations identified in other behavioral studies are the following:

Ridesharing: There is a strong correlation between commute distance and mode choice; the longer the commute distance, the higher the ride sharing rates (Crain, 1984; DOT, 1985). A major deterrent to carpooling is incompatibility of people's schedules. Valdez and Arce (1990) found in a study on ridesharing that about 42 percent of respondents "believed that depending on others was not worth the money carpooling would save, higher proportions (55 to 58 percent) believed that achieving time savings in commuter lanes or fulfilling the requirement for pooling to obtain a guaranteed parking space at work would be worth depending on others or leaving work at a fixed time each day." Childcare issues also serve to deter potential ridesharing; people want to be able to respond to emergencies if necessary (Crain, 1984; DOT, 1984), and "parents who need to leave children at child care facilities, or are concerned about their ability to react to emergency situations involving their children are reluctant to rideshare" (Valdez and Arce, 1990). Part-time carpooling is viewed more positively than regular (i.e., daily) carpooling. In one study, one group expressed a willingness to rideshare on a part-time basis, for example 2 or 3 times per week. The other days they either have specific obligations that require car availability or they simply wish to have their car for the freedom it offers. Some factors considered by people when deciding whether or not to rideshare or take transit involve the other individuals they would travel with; personal characteristics such as smoking can either encourage or discourage potential ridesharers, depending upon their feelings about these habits (Crain, 1984; DOT, 1984).

Transit Use: The principle factors influencing choice transit riders are, "...the relative service properties of competing transport modes such as in-vehicle travel times, excess travel times, out-of-pocket costs and the overall convenience of travel" (Hutchinson, 1974). A main transit problem (as cited by SOV commuters) is the length of time necessary to take the bus to work. Surveys reveal a perception that driving takes substantially less time than a transit trip. Another perception is that bus service may be unreliable (Crain, 1984; DOT, 1984). Also, perceived difficulties in deciphering bus and other transit schedules can deter inexperienced transit users from considering transit as a viable alternative to driving (Crain, 1984). Some commuters, especially women, feel that their personal safety is at risk while waiting at or walking to bus stops, especially in the dark (Crain, 1984).

Other Factors Influencing Mode Choice: Childcare issues can affect commuter mode choice. Many individuals cite the need to respond to child health emergencies and childcare needs as reasons for driving to work rather than taking transit. Many non-work related trips during the day are generated by parents shuttling children to daycare, doctors appointments, and other commitments. This trend is more prevalent with women in the work force than men (Crain, 1984; Raux et al., 1986; DOT, 1985). Also, commuters often underestimate or are not aware of their true commute costs; for example, one woman estimated her commute costs, including insurance, gas, maintenance, etc. to be around four cents per mile--in actuality, the total cost was around 18 cents per mile.

Summary of Important Attributes

The major attributes of travel choices can be broken down into four broad categories: (1) cost--including long- and short-term costs; (2) time--including direct travel time enroute plus excess time from the origin and destination to the mode choice; (3) convenience--including comfort, safety, and flexibility of the mode choice; and (4) reliability--focusing on the predictability of the mode choice's ability to reliably deliver the rider to her or his destination.

STEP-BY-STEP APPROACH TO CONDUCTING A TCM PACKAGE ANALYSIS

TCM packages can be evaluated by defining how, when packaged with the other measures, each individual measure compares across the four major attributes determining travel characteristics. For example, when two TCMs overlap a common audience, trip makers will choose whether or not to participate in one or another of the TCMs based on each TCM's ability to offer cost, time, convenience, or reliability improvements to the traveller's driving conditions. Figure 4-1 illustrates how a mode choice can be described as a function of these attributes; the figure also describes units of measure for each attribute. The basis for the packaging methodology is frequently referred to as a "multi-attribute analysis." It is based on conceptual analytical methodologies described in decision analysis literature (see Stokey and Zeckhauser, 1978).

Conceptually, the idea behind the packaging methodology is simply to value each TCM using the attributes of cost, time, convenience, and reliability as a framework for assigning a total value to any one measure. Since each of these four attributes has a different unit of measure (dollars, minutes, etc.), a mathematical framework is constructed to translate these attributes into a common unit of measure, and then they are summed across the attributes and estimate a total value or "utility" for a given measure. Analysts can use the methodology to compare measures that overlap target populations in terms of their total value and to define mode choice preferences. The concept of overlap is key; measures which do not overlap can be analyzed individually. Most important, analysts can use the methodology to consider the synergies among measures. For example, assume that SOV users are not participating in a rideshare program (i.e., assume that the total value of SOV use in terms of cost, time, convenience, and reliability is greater than the total value of rideshare). To encourage ridesharing, an employer

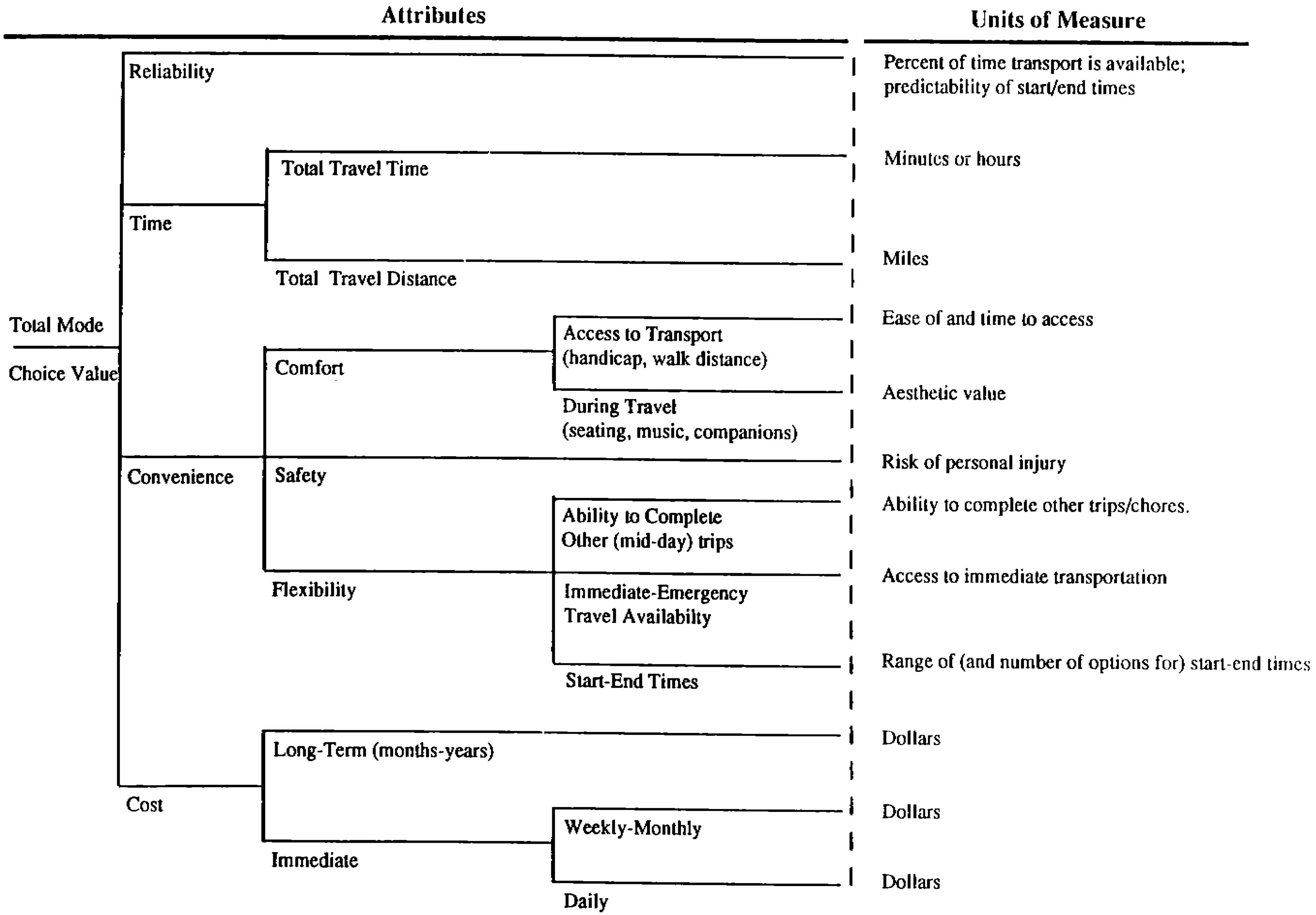

FIGURE 4-1. Attributes of travel choices.

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begins to charge for SOV parking; thus the employer's parking management program now interacts synergistically with the rideshare program. Using the analytical approach presented in this chapter, this synergy can be explicitly captured--the total value of a trip made by SOV now drops relative to the total value of a rideshare trip because the "cost" attribute associated with SOV use is now more expensive.

Three broad steps need to be completed to conduct a packaging analysis: (A) gathering of travel data and establishing base-case conditions; (B) establishing a validated base case; and (C) conducting the TCM package analyses (an eight-step process described below).

A. Collect Travel Data, Establish Base Case Conditions

A full discussion on the collection of data is included in Chapter 2. Data requirements for individual and TCM packages are similar. We recommend dividing the population (or region) of interest into smaller segments to study whether characteristics vary substantially across segments. Factors to address when collecting relevant data include the following:

(1) *Establish the preexisting conditions in the areas to be analyzed.* This includes to what extent TCMs have already been implemented, what AVO (average vehicle occupancy) levels have been achieved during peak and off-peak periods, what types of trips occur in the region, and what mode choices are available. Determine the percentages of people who travel via each of these modes (i.e., the mode split).

(2) *Determine the relative costs of the different modes.* The costs to consider consist of out-of-pocket expenses. For example, the cost for driving a SOV may include the cost of gasoline, parking, and tolls. The cost of taking transit consists of the fare. Ridesharers may or may not have to pay the cost of parking or tolls, depending on the programs affecting the population. Telecommuters pay nothing on the days they stay home, but they may pay the same as SOVs on the days they travel to work. Thus average travel costs over the entire work week are lower.

(3) *Determine the relative travel times of the different modes.* How long does the average trip take driving a SOV, taking transit, or ridesharing? If these travel times are not directly available, they may be estimated by dividing trip distances by average speeds. For a TCM such as telecommuting, we recommend averaging the travel times over all days in the week.

(4) *Estimate the relative convenience of the different modes.* For example, to what extent are the different travel options available within the region of interest? How widely dispersed are transit services? How available is transit during peak and off-peak hours? Are there express services? What park and ride lots are available and what percent of their parking spaces are vacant? What kind of immediate access is available, and how easy is it to complete mid-day trips (i.e., can you come and go as you please)? How safe and comfortable are the different travel

options? Note that these estimates are "guessed at" by the analyst. They are to be used in Step 1 below. If they are slightly off, the calibration procedure will identify this.

(5) *Determine the relative reliability of the different modes.* How often is transit on time? How often are carpools on time? Do people often get held up in traffic jams? These estimates are to be used in Step 1 below.

B. Establish "Validated" Base Case

Analysts will need to use the eight-step packaging methodology twice: once to establish base case conditions, and a second time to establish potential participation rates given new or enhanced TCMs. Replicating base case conditions validates the approaches and in essence creates a model of the region's mode choice decision making. The validation process runs through the eight-step approach using variables that reflect existing conditions. These variables include the values of the different attributes of the modes of travel (i.e., the cost, convenience, travel time, and reliability) to the target population of each of these attributes. A set of reasonable variables must be determined that accurately characterizes the current travel patterns of the target population.

C. Eight Steps to Conduct Packaging Analysis

The eight steps described below establish base case conditions that calibrate the approach, and then adjust the base case inputs to reflect new or enhanced TCMs.

Step 1: Determine the cost, time, convenience, and reliability for each mode of travel; i.e., determine the "attribute profile" of each mode. For example, the time associated with an average transit work trip in the modeling region is 1 hour.

The convenience and reliability measures are determined based on the factors discussed above. They represent the study population's perception of how convenient and reliable each mode is. This perception is dependent on factors such as levels of service, safety, and timeliness.

Step 2: For a given trip type (work or non-work trips) determine the best and worst limits of the attribute profile; i.e., determine the best and worst cost, convenience, travel time, and reliability that are possible in the region being analyzed for the TCM package. For example, the worst cost could be $4.00 per trip, and the best possible cost could be $0.85 per trip. The best possible convenience could be immediate access, and the worst possible convenience could be only trip-end access.

A general guideline to follow when selecting the best and worst limits for attribute values is that the median value of all the modes should be close to 0.5. This ensures that the mode values are not all clustered toward 0.0 or toward 1.0. If the mode values cluster toward 1.0 for a particular attribute, then that attribute is artificially given more weight in the final calculation, and similarly, if they cluster toward 0.0, then the attribute is artificially weighted less.

Step 3: Scale the cost, convenience, travel time, and reliability associated with each mode of travel on the "best to worst" scale for that trip type. Figure 4-2 provides an example. This should be done separately for work and non-work trips.

The convenience and reliability of a mode of travel must be given a value between 0 and 1, where 0 is the worst possible value and 1 is the best possible value. Travel time and cost values may be calculated directly as follows:

$$\text{COSTVAL}_k = (\text{worst cost} - \text{COST}_k)/(\text{worst cost} - \text{best cost}) \qquad (4\text{-}2)$$
$$\text{TIMEVAL}_k = (\text{worst time} - \text{TIME}_k)/(\text{worst time} - \text{best time}) \qquad (4\text{-}3)$$

where

k = the travel mode (if there are 3 modes being analyzed, then k will range from 1 to 3),
COST_k = the cost of travel of mode k,
TIME_k = the travel time of mode k,
COSTVAL_k = the cost value of mode k, and
TIMEVAL_k = the time value of mode k.

Step 4: Determine a weight profile (or set of coefficients) $(\lambda_{\text{cost}}, \lambda_{\text{convenience}}, \lambda_{\text{time}}, \lambda_{\text{reliability}})$, for the population in the region.

When measuring the potential change that would occur from a set of TCMs, the importance the target audience places on the four attributes must be estimated. For example, if a traveler values cost far more than reliability, time, and convenience, then increasing their cost of travel will more likely alter their behavior than decreasing the reliability. This step involves assigning the relative importance of each attribute to the average member of the study population. This relative importance is called the "weight profile". Note that if the mode values for a particular attribute cluster toward 1.0 or 0.0, as discussed in step 2 above, then the choice of the weight profile will be influenced by the artificial weighting created by the choice of best and worst values.

The λ's are assigned the percentage of importance of each of the attributes. They must sum to 1.

Based on the mode choice literature, a reasonable weighting of each attribute's importance for work trips might be: 0.3 for cost, 0.3 for travel time, 0.2 for convenience, and 0.2 for reliability (summing to 1.0). Analysts are encouraged to select weights appropriate to their specific areas and trip types.

Step 5: Calculate the total utilities of each mode of travel. The total utilities will reflect the relative weight coefficient of each attribute (from Step 4), and each measure's scaled value (between 0.0 and 1.0) for that attribute (from Step 3). See Figure 4-3.

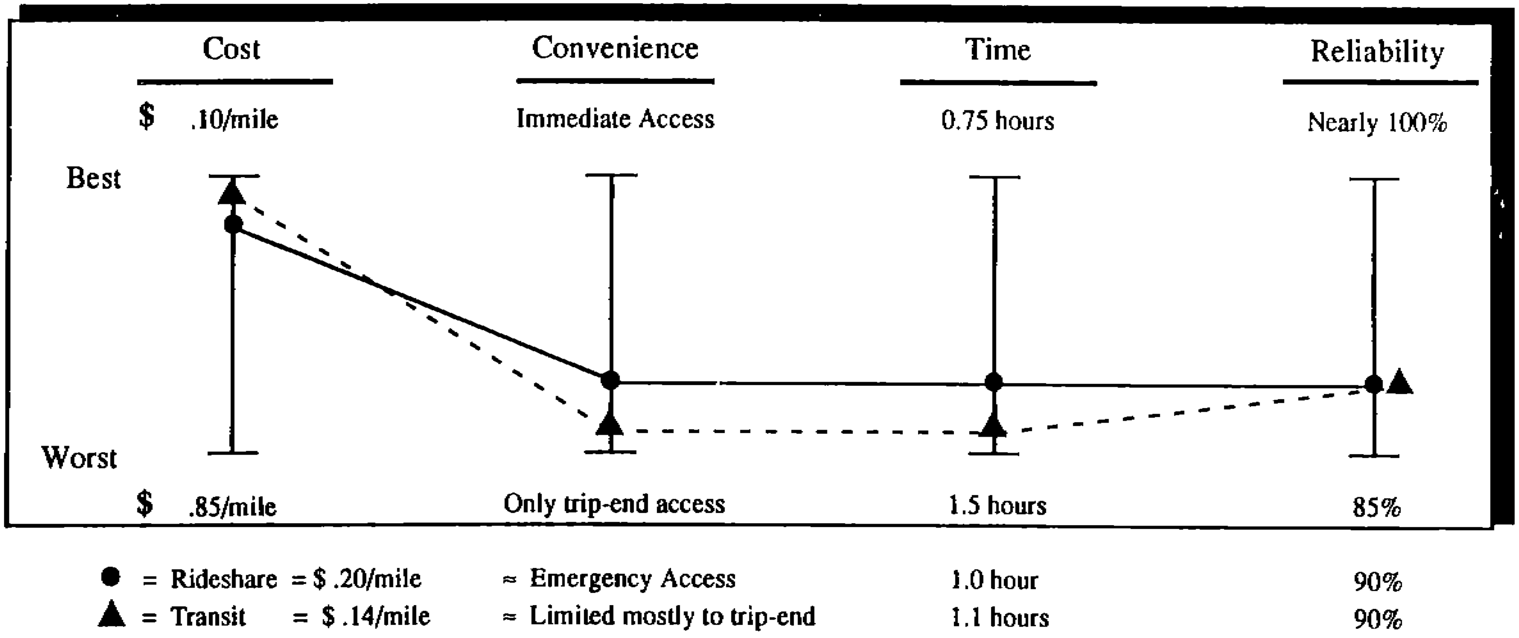
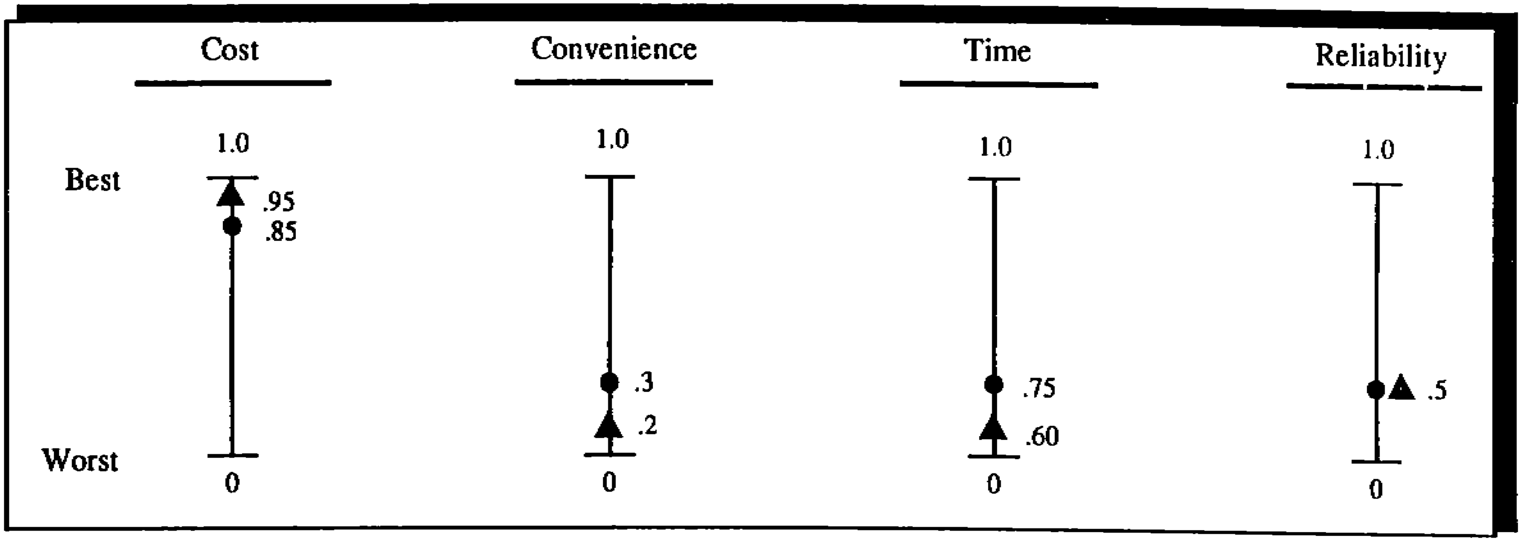


FIGURE 4-2. Sample hypothetical attribute profile for two measures, rideshare and transit.



Indicates "value function" of each measure's attributes.

● = Rideshare
▲ = Transit

FIGURE 4-3. Value function for each attribute for rideshare and transit.

The calculation of the total utility for a particular travel mode, k, and weight profile, $(\lambda_1,\lambda_2,\lambda_3,\lambda_4)$, is:

$$TU_k = COSTVAL_k*\lambda_1 + CONVVAL_k*\lambda_2 + TIMEVAL_k*\lambda_3 + RELIVAL_k*\lambda_4 \qquad (4\text{-}4)$$

where

TU_k = the total utility of mode k,
$COSTVAL_k$ = the cost value of mode k,
$CONVVAL_k$ = the convenience value of mode k,
$TIMEVAL_k$ = the time value of mode k,
$RELIVAL_k$ = the reliability value of mode k,
λ_1 = the relative weight of cost,
λ_2 = the relative weight of convenience,
λ_3 = the relative weight of time, and
λ_4 = the relative weight of reliability with respect to the other attributes.

Step 6: Calculate the estimated percentage of time a person from the target population group with weight profile $(\lambda_1,\lambda_2,\lambda_3,\lambda_4)$ will travel via mode k relative to the travel modes considered.

Presented is a mathematical representation of how to estimate the percent of the target audience that will use the individual travel modes. Suppose there are N different modes of travel that are available to the travelers that are targeted for the TCM package (for example, N might be 4, representing SOVs, transit, rideshare, and telecommuting). For each person, there is a set of values TU_k for $k = 1$ through N, where TU_k represents the total utility of TCM "k." The probability that a person will travel using mode k will depend upon the TU of k in relation to the TU of their remaining mode choice options. For example, if a person has a total mode utility value of 0.9 for single occupant travel and only 0.1 for public transit, then it is unlikely that this person will travel on public transit. However, if a person has a TU of 0.41 for single occupant travel and 0.40 for public transit, then it is only slightly more likely that this person will ride in a single occupant vehicle instead of taking public transit. In precise terms, the packaging methodology must consider that the percentage of people that will travel via mode k is dependent upon the differences in magnitude between TU_k and all the other TU numbers for that population.

When extending a travel mode's total utility to an entire target market of trip makers, the total utility serves as a surrogate for the degree to which a specific measure will be utilized. To relate total utility to percent of time a TCM is utilized, it is important to represent that measures of little value are not likely to be utilized, while measures of greater value are likely to be substantially utilized. As a concrete example, consider one of the packages just discussed: a person has a total mode utility value of 0.9 for single occupant travel and only 0.1 for public transit. With such a large disparity in utility between these two travel options, it is unlikely that transit will be utilized. It is therefore inappropriate to linearly relate target market for a TCM to its total utility. In other words, it is unlikely that 10 percent of the target market would utilize transit. A better mathematical approach relating total utility to target market use of a TCM is to relate the percent of time that the target audience will utilize a given TCM as a function of $e^{6.5TU}$, where "e" is the exponential function, TU is the total utility of that mode choice. The constant 6.5 was determined empirically to provide the most reliable results. Mathematically, using the exponential function accentuates the differences between measures that have widely different utilities, while maintaining a closer balance between measures that have similar utilities. Note that the methodology poses this mathematical relationship as a model to estimate travel behavior; the relationship is not developed from a large sample of empirical data.

Equation 4-5 illustrates how to calculate percentages of mode travel for a person with TU values TU_1 through TU_N:

$$P_k = \frac{e^{(6.5)TU_k}}{\sum_{j=1}^{N} e^{(6.5)TU_j}} \tag{4-5}$$

where

P_k = the probability that a person from the target group (or the percentage of the target group) will travel via mode k relative to the N modes examined.

Note that if all possible modes available to the target population are not examined, this probability (or percentage) captures the percent of people who will travel via mode k out of the total population traveling only via modes 1 through N.

It is important to note the methodology assumes that the relationship between the percentage of time a person travels via mode k does not depend linearly on TU_k.

When validating a base case, if the analyst is not reaching reasonable agreement with actual mode splits, then we recommend first reconsidering the choice of λ's (because of their greater degree of uncertainty). If after adjusting the λ's, the analyst still has difficulty getting the methodology to agree with actual mode splits, we then recommend reexamining the best and worst limits chosen in step 2 (keeping in mind that the mode values should not cluster toward 1.0 or 0.0).

Step 7: Determine the new mode values (cost, time, convenience, and reliability) that reflect the implementation of a TCM package. With these new values and the weight profile determined from the base case, repeat steps 2-6 above to determine the new percentages of time people will travel via the different N modes of travel (once the TCMs are implemented). The new percentages are the results of the "control case" and the old percentages are the results of the "base case".

At this point in the analysis, it is possible to introduce a new travel mode that was not previously available to the target audience (such as telecommuting). In this case, depending on the total utility of the new mode, one might expect a decrease in all previously available modes from members of the target population choosing to use the new mode.

Step 8: After repeating Steps 2 - 6 with new model values reflecting the TCM package, compare the differences in the percentage of people that will travel via each mode after the implementation of a TCM package. This is the difference between the control case and the base case, and reveals the potential impact of each measure in the TCM package.

EXAMPLE APPLICATION OF PACKAGING METHODOLOGY

The first task in applying the methodology involves calibrating the model against base-case values using "real world" data. Using mode split and travel time information for work trips to the city of San Francisco as our target values (MTC, 1991), a FORTRAN program was used to calculate total utility and percent use using the formulas presented earlier in this chapter. The analyst may find that using a spreadsheet or other program will make it easier to quickly evaluate the impact of altering attribute values on the total value and percentage use of each TCM.

The second task in applying the methodology involves estimating the changes that a TCM package would have on the attribute values of the different modes of transportation. For this task, we assumed a 1% increase in the cost of transit and then compared the results to the elasticity of price with respect to demand calculated in MTC's three-mode work mode choice model (see Figure 4-8).

Assumptions and Calculations for the Base Case Simulation of the City of San Francisco

To establish base case conditions and "validate" the model approach, this example simulates work trips to the city of San Francisco using 1987 statistics of the available modes of travel, their travel times, and the percentages of mode splits (MTC, 1991). This data established base conditions for three possible mode choices: SOVs, public transit, and ridesharing.

The travel times are calculated as follows: the average SOV trip length to the city is 11.33 miles, and the average peak period speed is 24.63 mph (MTC, 1991). This corresponds to 0.46 hours travel time per trip. Assuming that carpoolers travel an additional 2 miles per trip, their average travel time is assigned 0.54 hours. The average work trip via transit is 18.24 minutes (MTC, 1991). Adding an additional 8.76 minutes for walking and waiting time (27 minutes altogether), the average transit time assigned is 0.45 hours.

The out-of-pocket travel costs for a SOV are calculated from the following: the 1987 cost of gasoline is assumed to be $1.00 per gallon (1987 prices, MTC, 1991), and the average fuel economy of light duty vehicles is 23.4 miles per gallon (from MOBILE4.1 data). The average parking price (calculated by averaging parking prices in different city zones from MTC, 1991) is assumed to be about $.37 per hour, or $3.00 per day. The average bridge toll is assumed to be $1.00. Then, the cost per trip is calculated as:

(distance)*($ per gallon) / (fuel economy) + parking fee + bridge toll
= (11.33)*(1.00/23.4) + 3.00 + 1.00
= $4.48 per trip.

The out-of-pocket travel costs for ridesharers is calculated as follows: the bridge toll is assumed to be waived, but the parking price is not waived. The average vehicle occupancy of carpools is 2.28 (MTC, 1991), and the costs are assumed to be equally split among all members of the carpool. So the cost is calculated as:

[(distance)*($ per gallon) / (fuel economy) + parking fee] / (vehicle occupancy)
= [(13.33)*(1.00/23.4) + 3.00]/2.28
= $1.56 per trip

The out-of-pocket travel costs for transit riders is calculated by taking a weighted average of the transit fees from different origins into the city. The fees are weighted by the population traveling into the city from different origins (given by MTC, 1991). This weighted average is $1.03 per trip. (Note that most of the work trips to San Francisco originate in San Francisco, and so the transit cost is less than from outlying areas.)

The convenience of SOVs is rated high. It is not set equal to 1 but 0.8 because driving in the city is congested and parking can be hard to find. The convenience of transit is rated slightly lower than 0.5. The frequency of transit and the availability is reasonably high in the city, but is less so in outlying areas. In addition, the transit rider may have to walk to transit, which may be inconvenient during odd hours of the day or night, lowering the convenience, so it is assigned the value 0.4. The convenience of ridesharing is set equal to 0.3, lower than transit because ridesharers are restricted to specific travel times set by the carpool. Immediate access is not readily available, and members of the carpool may not have flexible schedules.

The actual 1987 mode splits (from MTC, 1991) for work trips into San Francisco are 39.8% SOV, 40.7% transit, and 19.5% rideshare. Figure 4-4 shows an example input file for a simple FORTRAN program that applies the packaging methodology for this base case simulation. The first approximation of the weight profile is chosen to be 0.3, 0.3, 0.2, and 0.2 for cost, time, convenience, and reliability, respectively.

Figure 4-5 shows the program output with different weight profiles. Rideshare, in the first approximation, is assigned too large a percentage of the population. It is rated high in cost and time, so the next weight profile is lowered in cost and time, but raised in convenience and reliability to be 0.29, 0.29, 0.21, and 0.21. This reduces the gross error from 3.8% in the first attempt to 1.08%. The next weight profile again lowers cost

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4                # of titles
Base Case Simulation
Illustration of Calibration Technique and
Selection of Reasonable Weight Profiles for
The City of San Francisco.
base.out
3                # of modes
SOV
Transit
Rideshare
0.00  8.0        ** BEST cost and WORST cost (in
dollars)
4.48             cost of SOV
1.03             cost of transit
1.56             cost of rideshare
0.0  1.0         ** BEST time and WORST time (in hours)
0.46             time of SOV
0.45             time of transit
0.54             time of rideshare
0.8              convenience of SOV
0.4              convenience of transit
0.3              convenience of rideshare
0.8              reliability of SOV
0.6              reliability of transit
0.4              reliability of rideshare
0.398 0.407 0.195
```

FIGURE 4-4. San Francisco base case input file.

```
Mode Attribute Values:
              Cost          Time          Convenience   Reliability
SOV           0.440         0.540         0.800         0.800
Transit       0.871         0.550         0.400         0.600
Rideshare     0.805         0.460         0.300         0.400
```

```
Weight Profile:
              Cost          Time          Convenience   Reliability
              0.300         0.300         0.200         0.200

Total Utilities:
SOV                       0.614
Transit                   0.626
Rideshare                 0.520

                        PERCENTAGES:
MODE:                   Calculated    Actual Split   %Difference
SOV                        38.098       39.800        -4.276
Transit                    41.289       40.700         1.448
Rideshare                  20.613       19.500         5.707
Mean Error:     1.135
Gross Error:    3.810%
```

```
Weight Profile:
              Cost          Time          Convenience   Reliability
              0.290         0.290         0.210         0.210

Total Utilities:
SOV                       0.620
Transit                   0.622
Rideshare                 0.514

                        PERCENTAGES:
MODE:                   Calculated    Actual Split   %Difference
SOV                        39.781       39.800        -0.048
Transit                    40.292       40.700        -1.004
Rideshare                  19.928       19.500         2.193
Mean Error:     0.285
Gross Error:    1.082%
```

FIGURE 4-5. **Base case simulation illustration of calibration technique and selection of reasonable weight profiles for the city of San Francisco.**

```
Weight Profile:
              Cost         Time         Convenience  Reliability
              0.280        0.280        0.220        0.220

Total Utilities:
SOV                      0.626
Transit                  0.618
Rideshare                0.508

                       PERCENTAGES:
MODE:                  Calculated   Actual Split  %Difference
SOV                       41.488      39.800       4.240
Transit                   39.270      40.700      -3.513
Rideshare                 19.242      19.500      -1.323
Mean Error:     1.125
Gross Error:    3.025%
```

```
Weight Profile:
              Cost         Time         Convenience  Reliability
              0.310        0.310        0.190        0.190

Total Utilities:
SOV                      0.608
Transit                  0.631
Rideshare                0.525

                       PERCENTAGES:
MODE:                  Calculated   Actual Split  %Difference
SOV                       36.443      39.800      -8.435
Transit                   42.261      40.700       3.835
Rideshare                 21.296      19.500       9.211
Mean Error:     2.238
Gross Error:    7.160%
```

FIGURE 4-5. Concluded.

and time and raises convenience and reliability. Now the gross error increases to 3.02%, and so the previous weight profile is a better choice. Finally, the last weight profile entered into the program is 0.31, 0.31, 0.19, and 0.19. The gross error corresponding to this weight profile is yet larger than the gross error from the first weight profile, 0.3, 0.3, 0.2, 0.2. From this simulation, we determine that 0.29, 0.29, 0.21, 0.21 is the best weight profile, and the model is calibrated for San Francisco work trips.

Control Simulation for the City of San Francisco

This control simulation reflects the change in mode split corresponding to a 1% increase in transit fares. This TCM has been selected so that the results of the simulation can be compared with elasticity data calculated from a logit model based on a 1980/81 data base in Harvey, 1989. Figure 4-6 shows an example input file for a FORTRAN program that applies the packaging methodology for this control scenario, and Figure 4-7 shows the program output. The last line of Figure 4-6 consists of the calculated mode splits corresponding to the weight profile 0.29, 0.29, 0.21, 0.21 from the base case simulation.

The result shows a -0.14 percent change in transit use. The calculated elasticity from Harvey, 1991 for a 40% mode share and a $1.00 base travel cost is -0.21. The elasticity for a 50% mode share is -0.17. These elasticities are in the same general range, especially given that -0.3 is a widely used transit fare elasticity (ITE, 1982) for a smaller mode share. The national average transit ridership is around 7 percent, while San Francisco's is about 41%.

Assumptions and Calculations for the Base Case Simulation of the Maricopa County Metropolitan Area, Arizona

The travel characteristics of the Maricopa County metropolitan area come from the Maricopa Association of Governments Freeway/Expressway Plan, 1987, and from MAG TPO personnel (Howell, 1992).

The actual work-trip mode shares in the Phoenix area are: 77.4% SOV, 17.4% rideshare, 1.6% city bus, 1% motorcycle, 1% walk, 1.5% bicycle. People who walk or bicycle must live close to where they work (less than a couple of miles if they walk). Because the average person in the metropolitan area commutes 10 miles to work, they do not have the option of walking or riding a bicycle (given current land use), so these travel modes are not included in this example analysis. The percentage of people who ride motorcycles to work is insignificant in comparison to the SOV share and not substantially different from SOVs, so we have also not designated motorcycles as a separate mode from SOVs.

The actual mode shares have been renormalized to represent the fraction of people who travel by SOV, transit, or rideshare out of the number of people who previously travel by SOV, transit, and rideshare. These new fractions are: 80.3% SOV, 18.04% rideshare, and 1.66% transit. Note that these three fractions sum to 100%.

```
2                # of titles
Control Simulation
1.0% Increase in Transit Fares in San Francisco
control.out
3                # of modes
SOV
Transit
Rideshare
0.00  8.0        ** BEST cost and WORST cost (in dollars)
4.48             cost of SOV
1.04             cost of transit
1.56             cost of rideshare
0.0  1.0         ** BEST time and WORST time (in hours)
0.46             time of SOV
0.45             time of transit
0.54             time of rideshare
0.8              convenience of SOV
0.4              convenience of transit
0.3              convenience of rideshare
0.8              reliability of SOV
0.6              reliability of transit
0.4              reliability of rideshare
.39781 .40292 .19928
```

FIGURE 4-6. Control scenario input file for the city of San Francisco.

```
Mode Attribute Values:
              Cost         Time         Convenience  Reliability
SOV           0.440        0.540        0.800        0.800
Transit       0.870        0.550        0.400        0.600
Rideshare     0.805        0.460        0.300        0.400
```

```
Weight Profile:
              Cost         Time         Convenience  Reliability
              0.290        0.290        0.210        0.210

Total Utilities:
SOV                     0.620
Transit                 0.622
Rideshare               0.514

                      PERCENTAGES:
MODE:                  Calculated   Base Case  %Difference
SOV                      39.819      39.781        0.094
Transit                  40.235      40.292       -0.142
Rideshare                19.947      19.928        0.093
Mean Difference:     0.038
Gross Difference:    0.110%
```

FIGURE 4-7. Control simulation 1.0% increase in transit fares in San Francisco.

Demand Elasticities with Respect to Travel Cost *

Base travel cost (cents)	Base Mode Share 0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
50	-0.16	-0.14	-0.12	-0.10	-0.09	-0.07	-0.05	-0.03	-0.02
100	-0.31	-0.28	-0.24	-0.21	-0.17	-0.14	-0.10	-0.07	-0.03
150	-0.47	-0.42	-0.37	-0.31	-0.26	-0.21	-0.16	-0.10	-0.05
200	-0.63	-0.56	-0.49	-0.42	-0.35	-0.28	-0.21	-0.14	-0.07
250	-0.78	-0.70	-0.61	-0.52	-0.43	-0.35	-0.26	-0.17	-0.09
300	-0.94	-0.83	-0.73	-0.63	-0.52	-0.42	-0.31	-0.21	-0.10
350	-1.10	-0.97	-0.85	-0.73	-0.61	-0.49	-0.37	-0.24	-0.12
400	-1.25	-1.11	-0.97	-0.83	-0.70	-0.56	-0.42	-0.28	-0.14
450	-1.41	-1.25	-1.10	-0.94	-0.78	-0.63	-0.47	-0.31	-0.16
500	-1.57	-1.39	-1.22	-1.04	-0.87	-0.70	-0.52	-0.35	-0.17

FIGURE 4-8. Demand elasticities with respect to travel cost. (Source: Creig Harvey, "Screening of Transportation Control Measures for the San Francisco Bay Area," working paper for the Metropolitan Transportation Commission, 1989).

The travel times for the three modes are calculated as follows: the average commute distance for SOVs is 10 miles, and the average speed is 27 mph. This corresponds to an average commute time of 0.37 hours. Assuming that ridesharers travel an additional 3 miles (to pick up the other members of the carpool), for a total of 13 miles, and that their average speed is also 27 mph, we calculate an average commute time of 0.48 hours. The actual average transit trip is 6 miles in the area. However, in order to compare the travel time per mile of transit to the other modes, we consider the travel time of a transit trip over 10 miles. Assuming that the average speed of a city bus is 18.3 mph (from San Francisco Bay Area data, MTC, 1991), the travel time for 10 miles is 33 minutes. Because city buses do not run frequently throughout Phoenix, an additional 20 minutes was added to the 33 minutes to account for waiting for the bus and walking to the bus stop. This is a total of 53 minutes, or 0.88 hours.

The out-of-pocket costs of traveling using a SOV are calculated from the following: the cost of gasoline is currently about $1.23 per gallon. The average fuel economy is assumed to be 23.4 mph (MOBILE4.1 data). Parking costs are rare in the metropolitan area, and parking is abundant. There are no bridges, and hence, no tolls. The cost of a commute trip, is then:

(distance)*($ per gallon)/(fuel economy)
= 10*(1.23/23.4)
= $0.52

The only difference in cost for ridesharers is that the distance is slightly longer, and that the members of the carpool split the cost. Assuming the vehicle occupancy of a carpool is 2, the cost of a rideshare trip is:

[(distance)*($ per gallon)/(fuel economy)] / (vehicle occupancy)
= 13*(1.23/23.4) / 2.0
= $0.34

The cost of transit is assumed to be the cost of a bus fare, $0.85.

Figure 4-9 shows an example input file for a FORTRAN program that applies the packaging methodology for the base case scenario, and Figure 4-10 shows the output from the simulation. In this simulation, the error is minimized when the weight profile is 0.28, 0.28, 0.22, and 0.22 for cost, time, convenience, and reliability, respectively. The gross error consists mostly of the error in trying to simulate the low transit share. Even though the model calculates only 2.4 percent transit ridership, the percentage difference between 2.4 and 1.66 is 44.6 percent because 1.66 is a small number. Note that the mean error is only 0.494, which is extremely small. Given that the mean error is this small, the weight profile 0.28, 0.28, 0.22, and 0.22 is satisfactory for the base case calibration.

```
2                # of titles
Base Case Simulation
Maricopa County Metropolitan Area
baseMAG.out
3                # of modes
SOV
Rideshare
Transit
0.00 1.00        ** BEST cost and WORST cost (in dollars)
0.52             cost of SOV
0.34             cost of Rideshare
0.85             cost of transit
0.0  1.5         ** BEST time and WORST time (in hours)
0.37             time of SOV
0.48             time of rideshare
0.88             time of transit
1.0              convenience of SOV
0.4              convenience of rideshare
0.1              convenience of transit
0.9              reliability of SOV
0.3              reliability of rideshare
0.2              reliability of transit
0.803 0.1804 0.0166
```

FIGURE 4-9. Base Case Input File for the Maricopa County Base Case Simulation

```
Mode Attribute Values:
              Cost          Time          Convenience   Reliability
SOV           0.480         0.753         1.000         0.900
Rideshare     0.660         0.680         0.400         0.300
Transit       0.150         0.413         0.100         0.200
```

```
Weight Profile:
              Cost          Time          Convenience   Reliability
              0.300         0.300         0.200         0.200

Total Utilities:
SOV                       0.750
Rideshare                 0.542
Transit                   0.229

                        PERCENTAGES:
MODE:                   Calculated   Actual Split   %Difference
SOV                        77.366       80.300       -3.653
Rideshare                  20.016       18.040       10.956
Transit                     2.617        1.660       57.655
Mean Error:        1.956
Gross Error:      24.088%
```

```
Weight Profile:
              Cost          Time          Convenience   Reliability
              0.290         0.290         0.210         0.210

Total Utilities:
SOV                       0.757
Rideshare                 0.536
Transit                   0.226

                        PERCENTAGES:
MODE:                   Calculated   Actual Split   %Difference
SOV                        78.771       80.300       -1.904
Rideshare                  18.720       18.040        3.772
Transit                     2.508        1.660       51.101
Mean Error:        1.019
Gross Error:      18.926%
```

FIGURE 4-10. Base case simulation for Maricopa County metropolitan area.

```
Weight Profile:
              Cost         Time         Convenience   Reliability
              0.280        0.280        0.220         0.220

Total Utilities:
SOV                      0.763
Rideshare                0.529
Transit                  0.224

                       PERCENTAGES:
MODE:                  Calculated   Actual Split  %Difference
SOV                       80.110       80.300      -0.236
Rideshare                 17.488       18.040      -3.058
Transit                    2.401        1.660      44.656
Mean Error:     0.494
Gross Error:   15.983%
```

```
Weight Profile:
              Cost         Time         Convenience   Reliability
              0.270        0.270        0.230         0.230

Total Utilities:
SOV                      0.770
Rideshare                0.523
Transit                  0.221

                       PERCENTAGES:
MODE:                  Calculated   Actual Split  %Difference
SOV                       81.384       80.300       1.350
Rideshare                 16.320       18.040      -9.536
Transit                    2.296        1.660      38.335
Mean Error:     1.147
Gross Error:   16.407%
```

FIGURE 4-10. Concluded.

Control Simulation for the Maricopa County Metropolitan Area, Arizona

Figures 4-11 and 4-12 show the input file and output files for the control scenario. A 1% increase in transit fares is assumed. The calculated mode split is taken from the base case results with the weight profile (0.28, 0.28, 0.22, 0.22). The percent change in transit ridership is -1.75. The elasticity from Harvey, 1989, for a 10% mode share and $1.00 base travel cost is -0.31. The elasticities in the Harvey report increase, however, both with respect to an increase base cost and with respect to a decrease in base mode share. In this scenario, the base mode share is substantially less than 10%. In addition, the elasticities in the Harvey report do not take into account the costs of other travel modes available to the study population relative to transit. Considering the substantial difference in the perceived cost of transit compared to ridesharing and SOV, the predicted -1.75% change in transit ridership is reasonable.

Summary

Overall, the model reflects the general trends one would expect from the increase in transit fares in two very different cities. The modal shares in San Francisco and Phoenix could hardly be more different, yet the model replicates each city fairly well. The predicted elasticity in San Francisco is small, in accordance with the large base case mode share, and the relatively similar cost of transit and rideshare. The predicted elasticity in Maricopa County is quite large, reflecting the large difference in the perceived (i.e., out-of-pocket) base case costs, and the substantially lower total utility measure of transit with respect to SOV and rideshare.

As a final note, it should be stressed that this approach is very new and has not been extensively tested for other urban areas or for different sets of TCMs. It is likely that the model will evolve over time as it is applied in more situations. However, the analytical framework it provides is expected to prove a useful tool for TCM evaluation.

```
2                # of titles
Control Scenario
1.0% Transit Fare Increase in the Maricopa County Metropolitan Area
cntlMAG.out
3                # of modes
SOV
Rideshare
Transit
0.00 1.00        ** BEST cost and WORST cost (in dollars)
0.52             cost of SOV
0.34             cost of Rideshare
0.86             cost of transit
0.0  1.5         ** BEST time and WORST time (in hours)
0.37             time of SOV
0.48             time of rideshare
0.88             time of transit
1.0              convenience of SOV
0.4              convenience of rideshare
0.1              convenience of transit
0.9              reliability of SOV
0.3              reliability of rideshare
0.2              reliability of transit
.80110 .17488 .02401
```

FIGURE 4-11. Control scenario input file for the Maricopa County metropolitan area.

```
Mode Attribute Values:
              Cost         Time         Convenience  Reliability
SOV           0.480        0.753        1.000        0.900
Rideshare     0.660        0.680        0.400        0.300
Transit       0.140        0.413        0.100        0.200
```

```
Weight Profile:
              Cost         Time         Convenience  Reliability
              0.280        0.280        0.220        0.220

Total Utilities:
SOV                      0.763
Rideshare                0.529
Transit                  0.221

                       PERCENTAGES:
MODE:                    Calculated   Base Case  %Difference
SOV                        80.145      80.110       0.044
Rideshare                  17.496      17.488       0.046
Transit                     2.359       2.401      -1.749
Mean Difference:     0.028
Gross Difference:    0.613%
```

FIGURE 4-12. Control scenario 1.0% transit fare increase in the Maricopa County metropolitan area.

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APPENDIX A

SUMMARY OF RECENT TCM METHODOLOGIES DEVELOPED IN CALIFORNIA

APPENDIX A

SUMMARY OF RECENT TCM METHODOLOGIES DEVELOPED IN CALIFORNIA

Spurred by TCM requirements in the California Clean Air Act and the Clean Air Act Amendments of 1990 as well as continuing nonattainment problems, many California agencies have developed TCM methodologies for use in air quality planning. This appendix reviews a number of these methodologies in order for the reader to better understand the range and type of methodologies that are being developed and used for TCM analysis. The appendix covers five methodologies developed for (1) the San Diego Association of Governments and the California Department of Transportation (SANDAG/Caltrans), (2) the Sacramento Metropolitan Air Quality Management District (SMAQMD), (3) the San Francisco Bay Area Metropolitan Transportation Commission (MTC), (4) The California Air Resources Board (ARB) Technical Services Division, and (5) the ARB Mobile Source Division. Each summary presents a brief description of the methodology, and a preliminary assessment of its strengths and weaknesses.

SANDAG/CALTRANS

Responding to the requirements of the California Clean Air Act (CCAA), the California Department of Transportation (CALTRANS) provided a grant to the San Diego Association of Governments (SANDAG) to study the relationship between transportation control measures (TCMs) and emissions reductions. Guided by a state-wide Steering Committee, Sierra Research and JHK & Associates (Sierra/JHK, 1991) developed a three-part methodology for quantifying the travel, emissions, and cost impacts of different TCMs. The entire set of methodologies were then incorporated into a PC-compatible software package.

The three modules of this methodology include a transportation module, emissions module, and a cost-effectiveness module. The transportation module is designed to estimate the effect of selected TCMs on trips, vehicle miles of travel (VMT), and speeds. There are 25 pre-defined TCMs included in the software and user options to define five additional measures not included as defaults. Ongoing work slated for completion at the end of 1992 is expected to include development of three additional non-work related TCM methodologies (Valerio, 1992). Local estimates of travel activity are combined with assumptions about how travelers will respond to individual TCMs in a Lotus spreadsheet program. This spreadsheet produces a summary of the baseline travel characteristics and the effects of each TCM on peak and off-peak period trips, VMT, and speed. These outputs are used as inputs to both the emissions and cost-effectiveness modules.

The emissions module consists of a computer program (written in FORTRAN) which combines the TCM-specific travel impacts (calculated by the transportation module) with the emission factor data contained in the EMFAC7E and BURDEN models (specific to California) and selected default parameters (defined by Sierra and JHK) to create a baseline emissions estimate that includes reactive organic gases (ROG), carbon monoxide (CO), nitrogen oxide (NO_x), and particulates (PM). This baseline estimate is then used to determine the emissions impacts of each TCM evaluated. The two output files from this module summarize the pollutant-specific percentage reductions for each TCM (used by the cost-effectiveness module) and a print file that contains information summarizing the specific run, the baseline emission estimates, the emissions estimates after each TCM is implemented, and a pollutant-specific percentage reduction for each TCM (Sierra, 1991).

The cost-effectiveness module is a Lotus spreadsheet program which uses the travel impact information from the transportation module and the percent emission reductions generated by the emissions module, in combination with additional user-supplied information, to calculate the costs and cost-effectiveness of each TCM to be evaluated. The user-supplied information includes baseline parameters (e.g. year, study area, pollutants of interest and daily emissions totals for each of these pollutants) and default parameters that include basic cost per unit data and other parameters. These default parameters were developed by Sierra based upon a survey of transportation planning and other agencies in California. The user's guides for each of these three modules all stress the importance of customizing default values to better characterize the region being studied.

Methodology Application

The following summarizes the procedure for evaluating a TCM, in this case ridesharing, using the Sierra/JHK methodologies.

Step 1: Transportation Module

There are three types of data required by the spreadsheet program:

> Baseline Travel Characteristics - These define the baseline travel patterns for the analysis year and for the region for which the TCM is being evaluated; for instance, all examples given in the user's guide for this module use values for the San Diego County area in the year 2010. These parameters include (for ridesharing) drive alone share of commute trips; total commute (person) trips; percent of commute trips in peak period; average commute trip length; and total peak and off-peak VMT. The values in the spreadsheet are default values: user's have the option to input values more specific to their region of interest.
>
> TCM Specific Parameters - These factors are supplied by the user and for ridesharing would include percent increase in non-drive-alone modes; percent of the maximum VMT realized due to circuity of ridesharing or access to transit; average carpool size; and percent of employees affected.
>
> Assumptions - For ridesharing, the assumptions embedded in the spreadsheet program include a value for the elasticity of speed with respect to volume. The default value for this was developed by Sierra/JHK based upon the San Diego County region.

The calculations performed by the spreadsheet for ridesharing include:

Reduction in trips (person trips, peak, off-peak, and total)
Reduction in VMT (peak, off-peak, and total)
Percentage change in speeds (peak and off-peak)

Output from this module includes a summary of these travel effects for each TCM evaluated, including an output file suitable for input to both the emissions and cost-effectiveness modules.

Step 2: Emissions Module

This module is designed to estimate the influence of selected TCMs (for this example, ridesharing) on mobile source emissions. Inputs to this module include both required and optional values. Required inputs include air basin of interest (in California), county, year, TCM data file name (generated by the transportation module), I/M indicator (indicates whether emission factors are applied with or without I/M credits), and the output file name. Optional inputs include the file name for an ambient temperature profile and eight sets of input data that the user can specify that will replace the default values of the program. These default values include travel information (e.g. speeds, trip fractions, vehicle fleet mix) that can be specific to the user's region of interest.

After all necessary information is supplied either by the user or the default values, the program proceeds to calculate the emissions reductions for each TCM of interest. Upon completion of this step, two output files have been created: a summary report file containing the tabulated baseline and post-implementation emissions and an emissions reduction file suitable for input into the cost-effectiveness module.

Step 3: Cost Effectiveness

This spreadsheet program uses values calculated by the other two modules in combination with user-specified inputs and an extensive set of default values to determine the cost and cost-effectiveness of each TCM. The reason for the use of the multitude of default values is due to the nature of these values and the extensive amount of data required for region-specific applications. Data such as plan preparation cost, administrative costs, O&M costs, etc., make this module the most data-intensive of the three. User's are advised that "..it is critical that users identify and document the use of proper cost data and other information for their particular area."

After the spreadsheet calculations are complete, the user may choose to view the results or generate printouts of these results.

Strengths and Weaknesses of Methodology

The Sierra/JHK methodology provides a relatively easy-to-use software package that is based upon extensive survey information, literature reviews, and professional expertise. It provides the user with a convenient tool for evaluating the consequences of their assumptions about travel, operating conditions and costs on emissions and cost-effectiveness. It represents a collaborative effort between the air quality and transportation communities to develop a comprehensive model of TCM effects. However, there are some weaknesses:

- In order to apply these methods, the user must have access to a PC-compatible computer with the LOTUS 1-2-3 software installed.

- The extensive use of default values indicates the region-specific nature of these calculations. Although the developers of the user's guide for the methodology frequently point out the importance of customizing these default values to better describe the region of interest, little guidance is given as to the procedure for obtaining or calculating the necessary values (e.g. elasticities). Many areas may not have access to the extensive information used by Sierra/JHK to generate the default values. In these cases, use of the defaults may result in inaccurate estimates of TCM-related emissions reductions and cost-effectiveness.

- The documentation states that the spreadsheet for the transportation module requires user-input of information, such as jobs/housing balance or urban density, for only a few TCMs (due to the area-specific nature of these variables). However, more than half of the TCMs require user input of TCM effectiveness (i.e. the user enters the percent increase in non-drive alone modes). The appearance that the system calculates these for the user (because it translates such inputs into trip or VMT changes) may encourage misuse of the system.

- The system may incorrectly estimate effects on start emissions. For example, it assumes that the trip reduction is directly related to the number of new non-drive alones in the ridesharing example referred to above.

- Calculations of travel and emissions impacts do not sufficiently consider potentially offsetting effects; for example,

    For telecommuting there is no accounting of the potential increase in non-work related trips by the telecommuter or a member of the telecommuter's households as a result of increased vehicle availability. The model calculates an average change in travel activity for a weekday but does not account for the existence of "favored days" (e.g. more people telecommute on Wednesday than on Friday), which could make the daily estimates differ. Further, not all people work five days per week, while others often and/or regularly work more than five days per week. Commuting to satellite centers is also not covered, which means that the authors assume that all telecommute days reduce work trips (and therefore cold starts). Finally, some individuals working in occupations that would be appropriate for telecommuting may also be participating in compressed work week programs.

In ridesharing, a default percentage for the realization of potential VMT reductions (e.g. 80% of potential reductions will be realized when accounting for circuity of ridesharing routes or distance to transit), but little guidance is offered regarding the methods used to arrive at this value for the user to draw upon when calculating a value specific to the region of interest.

For staggered work hours/flextime, mode changes that could result, such as decreased or increased ridesharing, are not calculated. Changes in non-work trips latent demand, or peak spreading (the length of the peak period increases) are not addressed. The potential for shifting peak trips out of the peak for areas such as Los Angeles where the peak period is defined as running from approximately 6 a.m. to 10 a.m. is not addressed. Further, these TCMs can function to move trips only partially out of the peak period rather than completely out of the peak.

- This methodology is designed to evaluate the emissions impacts and cost-effectiveness of individual TCMs. While it addresses numerous public and private costs and their relationship to individual driving patterns, there are a number of key issues such as latent demand and effects on non-work travel that are not addressed. Also, although the user's guide includes guidance for qualitatively evaluating interactions among groups of measures, the software does not include a consideration of the effects of combining various measures. User's are cautioned the effects of these combinations are not likely to be additive, but little information is given as to the benefits and shortcomings of these combinations.

SACRAMENTO METROPOLITAN AIR QUALITY MANAGEMENT DISTRICT

The 1991 Air Quality Attainment Plan for the Sacramento Metropolitan Air Quality Management District (SMAQMD) contains a program for the evaluation and subsequent inclusion of selected transportation control measures (TCMs) in the Plan. Volume Five of the Plan (SMAQMD, 1991) describes the methodology used for this TCM evaluation. The work done for this Plan is characterized as a starting point for a series of predicted improvements to be implemented when developing future plans.

The first step in TCM selection begins with the identification of possible TCMs. From a series of "brainstorming" sessions of the Technical Advisory Committee, a list of 317 potential TCMs was assembled. This list was then initially screened using a two-dimensional matrix that considered the effectiveness and feasibility of each TCM. The top 30% from this screening process were immediately added to a list for future evaluation. The bottom 30% were immediately discarded, and the remaining measures were re-evaluated, with the top measures from this evaluation being included on the list for additional evaluation (in this case, 122 measures in all were included on this list)

Subsequent screening for redundancy and duplication resulted in a final list of 38 measures for consideration. These 38 were subdivided into three implementation "terms": near-term (1991-1993), mid-term (1994-1996), and long term (1997-2010). In this study, 20 of the TCMs were designated "near-term" TCMs, with the remaining 18 classified as mid- or long-term measures for future consideration. It should be noted that the methodology used for this Plan focused only upon the near-term measures.

Modeling Methodology

The modeling methodology used by the District to evaluate the candidate near-term TCMs involves three parts: transportation impacts, emissions impacts, and cost-effectiveness. A combination of computer models, combined with other qualitative analyses, was used to conduct this evaluation. It should be noted that for the District's application, all candidate near-term TCMs were evaluated as a **package** of measures. Each TCM was evaluated for transportation/air quality impacts based upon the assumption that the total package would be adopted and implemented according to a pre-determined schedule.

The transportation impacts evaluated for each candidate TCM include cold start trips, hot start trips, vehicle miles travelled (VMT), idling time, average speed, and time of day. Additionally, each measure was considered in terms of the number of GRACIE travel markets affected. The term GRACIE is an acronym for six travel markets that TCMs could potentially affect: Goods Movement, Recreation, Activity Center, Commercial, Institutional, Employment. The effectiveness of each measure varied with the number of travel markets affected. The first computer model, TCMARK, determines the scope of TCMs in each of the GRACIE travel markets. Each of these markets has some unique characteristics that lend themselves to different sets of TCMs, such as demographics, trip lengths, time, parking price, and mode shift characteristics (SMAQMD, 1991). Each of the near-term TCMs were run through this model and assigned a "yes" or "no" rating for each of the six GRACIE markets based upon whether or not the measure would impact that market.

TCMPACT is the second component in the system. Each candidate TCM is qualitatively ranked either positive or negative on a scale of 1-6 (each number representing a range of emission reductions in percent) based on its impact on each of these emissions categories. A negative ranking indicates that the measure would increase an emission source. It is possible for a TCM to have negative impact on a particular emission category, but be determined to have a positive overall impact on emission reductions.

The TRAVDEM component of the modeling methodology is the travel demand forecasting model used to evaluate the transportation and cost-effectiveness impacts of each TCM. This model incorporates information regarding trip purposes, modes, and specific figures for number of trips (both person and vehicle) and VMT to produce estimates of average trip time, average trip distance, and mode split for each of four trip purposes for each year between 1989 and 2010. Travel characteristics for each mode are then converted to regional vehicle trips and VMT by trip purpose. These regional figures are then converted to GRACIE travel markets and market shares.

EMISSION is the estimation model that produces the planning inventory of on-road mobile source emissions for the SMAQMD region. This model is based upon data supplied from the EMFAC/BURDEN models (specific to California). For each of five modeling years (1987,1991, 1997, 2000, 2010) a total daily planing inventory of emissions of ROG, NO_x, and CO were identified separately and assigned to specific travel aspects: VMT emissions, cold-start emissions, hot-start emissions, and hot-soak emissions. Values for each of these emission categories were then interpolated for each year between 1987 and 2010, ultimately yielding estimates for each emission category. It is unclear from the documentation whether temporal variations in travel caused by TCMs are addressed.

The final component of the TCM modeling methodology is the calculation of net-present value for each TCM of interest. Each of the candidate measures are ranked in terms of cost per unit pollutant reduced ($/ton per day) in 1987 dollars, calculated using a simple spreadsheet program that incorporates output from the other model modules described above.

In addition to the modeling methodology summarized above, an additional qualitative evaluation was made to determine the technical feasibility and public acceptance of each candidate measure. This analysis was based upon the professional judgment of the analysis team, combined with information regarding TCM implementation in other regions.

Strengths and Weaknesses of the Methodology

The TCM evaluation methodology developed by the District provides a starting point for the future development of a more comprehensive program. It represents a first-step in determining which combination of TCMs would be most effective in achieving desired mobile source emissions reductions in the SMAQMD region. Because of the interim nature of this methodology, however, there are areas for improvement which can be identified:

- There are numerous places in the methodology where a lack of sufficient, accurate data are identified. Information or quantitative estimates regarding TCM effectiveness, both as individual measures and packages, for the SMAQMD region would result in more accurate estimates of TCM impacts. Additionally, a lack of up-to-date travel activity information, including the relationships between vehicle technology and trip purpose or GRACIE travel market, for the six GRACIE travel markets is noted in the TCM evaluation documentation. Since the GRACIE evaluation criteria are integral to this methodology, inadequate data could result in inaccurate estimates of TCM effectiveness. In addition to the GRACIE travel activity information, more precise estimates of idle, speed, and time-of-day related emissions would clearly improve the model's predictive abilities.

- This methodology is based upon the evaluation of a complete package of candidate TCMs. There are no provisions made for evaluating a single TCM for its impact in a localized area, nor is there a simple way to alter the package of measures evaluated without repeating the entire modeling procedure. Additionally, the synergistic effects of combining different TCMs is assumed to be accounted for by the GRACIE modeling process. As noted above, the information regarding the GRACIE travel markets is preliminary, so these effects may be somewhat inaccurate. Also, this method of assigning TCM impacts focuses primarily on shifting between modes by the commuter. The generation of additional trips resulting from increased vehicle availability (e.g. a member of a telecommuter's household can now use the vehicle on certain days) is not addressed.

- Many areas of this methodology rely upon qualitative evaluations. The initial ranking of TCMs to be included in the package; the division of TCMs into near-, mid-, and long-term measures; and the evaluation of technical feasibility and public acceptance are all based upon "professional judgment" that could be highly variable. The accuracy of the model's prediction is likely to improve if, at a minimum, the method for conducting this "guesswork" is more clearly defined.

- This methodology is specific to the SMAQMD region and is largely dependent upon the availability of computing resources for implementation. While there are some conceptual contributions that can be made for other agencies, there is little transferability to other locations. This lack of transferability is also augmented by the subjective nature of many of the evaluation steps. There are few criteria outlined in the methodology that could be used as a guide for other air quality/transportation agencies.

AQAT-3: AIR QUALITY ANALYSIS TOOLS

The AQAT package was developed by the California Air Resources Board Stationary Source Division and links four computer tools for assessing air quality impacts of transportation programs: URBEMIS, EMFAC, CALINE4, and PIVOT POINT. The package is supplied on two diskettes and can be used with any IBM compatible microcomputer with 128K of memory, a color graphics video adaptor, and a disk drive. The four components of the package are described below under modeling methodology.

Modeling Methodology

URBEMIS can be used to estimate emissions from vehicular traffic associated with new or modified land uses based on changes in the number of trips associated with a given land use, and the VMT for each trip type. The user inputs whether the project under analysis changes residential or commercial trip generators. The user then sets up EMFAC parameters (study region or default EMFAC inputs) for vehicle fleet mix, temperatures, trip speeds, trip lengths, the percent of travel by operating mode (hot and cold starts), and percent of travel by trip type.

EMFAC7PC estimates on-road emission factors (i.e. grams per mile travelled) for a vehicle fleet. The model has streamlined the fleet characterization and some other aspects of the mainframe EMFAC (used in place of the MOBILE models in California). Rather than the detailed model year by model year information contained in EMFAC, EMFAC7PC details the percent of vehicles by vehicle class (i.e. light duty auto, light duty truck), fuel (leaded, unleaded, or diesel) and the percent of travel by each vehicle class (and fuel type within each class).

CALINE4 was developed by Caltrans to calculate pollutant concentrations near roadways, based on Gaussian algorithms. Users define source strength, site geometry and other cite characteristics, and meteorology, the model calculates pollutant concentrations for receptors within 150 meters of the roadway.

PIVOT POINT is a sketch planning methodology for estimating the impact of transportation control measures on the use of various travel modes (i.e. single occupant vehicle, carpool, transit). The methodology was originally developed by Cambridge Systematics (CSI, 1979) as a manual worksheet method. Pivot Point evaluates the change in mode choice based on changes in travel time or travel costs for specific transportation modes. The model is based on a mathematical formulation frequently used in transportation mode choice models (multinomial logit). The model considers that the probability of choosing a given travel mode is a function of the utility of the mode divided by the sum of the utilities of all possible modes. Pivot Point calculates revised probabilities based on an existing base mode share and estimated changes in the utilities (i.e. lower transit costs equal higher transit utilities).

Inputs to Pivot Point include, for each population subgroup analyzed, income, employment, and auto ownership information, base mode shares, the average carpool size, and average trip lengths for work and non-work trips. The user then translates each TCM being analyzed into potential level of service changes. These are entered in units such as changes in round-trip in-vehicle travel time, round trip out-of-vehicle travel time, or out-of-pocket travel costs.

Strengths and Weaknesses

The AQAT package utilizes a number of commonly used computer software programs and may be a reasonable screening approach for looking at TCMs. There are a number of weaknesses as well. A primary one is that the documentation is not sufficient to understand the precise techniques that are used to calculate changes. Such 'black box' techniques may be problematic for agencies preparing or reviewing TCM emission estimations. Key for the TCM travel effects changes is the use of the pivot point model. The model calculates only work trip changes and it uses regression coefficients developed from a 1968 Washington DC travel survey. The model itself is a useful way to roughly approximate modal shares resulting from changes in level of service. It does not precisely calculate how the changes in modal shares would translate to trip, VMT, and speed changes. With respect to the emission factors, the effect of the use of abbreviated inputs for fleet characterization is not discussed although this may significantly affect the results. Finally, the model is very California specific and would not be easily transportable to other states.

SYSTEMS APPLICATIONS INTERNATIONAL/CALIFORNIA AIR RESOURCES BOARD

The California Clean Air Act (CCAA) requires nonattainment areas to adopt TCMs to reduce vehicle activity levels, and growth in these levels due to population increases. The Federal Clean Air Act Amendments (CAAA) of 1990 also require TCMs to be adopted in many nonattainment areas. Both State Implementation Plans and attainment plans required under the CCAA must include detailed evaluations of the emission reductions associated with the TCMs proposed. However, no comprehensive methodology for evaluating the effects of TCMs was available when these provisions were promulgated. The Mobile Source Division of the California Air Resources Board (ARB) sponsored a study to provide such a methodology.

One of the primary purposes of this methodology was to address what were felt to be numerous overly simplistic assumptions that had been used in past TCM evaluation efforts. It was felt that these assumptions produced exaggerated estimates of a TCM's effectiveness, making it difficult to rely on control strategies which utilize them. For instance, it is often assumed that each new ridesharer will reduce one trip, or that employees working a four-day work week will reduce trips by 20 percent. In reality, a ridesharer may drive to a park-and-ride lot (reducing VMT but not trips), while compressed work week workers may make extra non-work trips on their days off from work. Other simplifying assumptions have been made regarding TCM packages. Combinations of TCMs are frequently assumed to be additive in their effects although some may not be (i.e. one cannot ride a bus and carpool simultaneously) and some may be synergistic.

The methodologies developed by SAI for the ARB provide methods for evaluating both individual measures and packages of measures, much like the work currently underway for EPA. The individual methodologies cover a limited number of TCMs: ridesharing, telecommuting, parking management, flextime/staggered work hours, compressed work weeks, traffic flow improvements, and traffic signal synchronization. This set was chosen to represent most of the key analytical problems associated with TCM analysis as well as to include commonly implemented TCMs. Other TCMs may be assessed by slightly modifying approaches that are similar. These individual methodologies attempt to quantify both the total effect on overall trips (and, consequently, emissions) of each measure, taking into account as many variables as could be quantified and that could potentially affect the overall benefit of the TCM.

The packaging methodology was designed to enable user's to employ a multi-attribute analysis of groups of TCMs, in order to assess the overall effect of the package and account for phenomenon such as overlap and synergy between various measures.

Methodology Application - Comparison with EPA Methodology

As noted above, the methodologies developed for ARB are similar in nature and function to the methodologies presented in this document. The key similarities and differences are highlighted below:

- The ARB methodologies for individual TCMs were designed for a specific set of measures (listed above). While the user can generally apply the methodologies to other measures by making slight modifications to one that is provided, the approach for doing such modifications was not discussed at length. Recognizing that the vast number of TCMs and potential implementation strategies makes it impossible to develop and present methodologies to cover every possible situation, the methodologies developed for the current work for EPA are structured in a manner that allows the analyst to quickly adapt them to TCMs and situations other than those specifically presented in this document. An effort to make the evaluation of individual measures much more generalized and streamlined, focusing on the logic behind the TCM analysis and providing guidance to the user on modifying a methodology for a specific need. Attention has also been focused on clarifying the theory and assumptions behind these methodologies to make them more intuitive to the user. It is intended that these modifications will ultimately result in methodologies that are more widely applicable than those developed for ARB.

- The calculation of emissions impacts of TCMs in the ARB report were based upon the EMFAC7E model, which is specific to California. The EPA methodologies utilize the MOBILE4.1 model, making them applicable on a nation-wide scale.

- The packaging methodology developed for ARB involved the manual calculation of the impacts of groups of measures based upon the evaluation criteria given. Because the packaging methodology requires a variety of qualitative decisions be made by the user, the calculation of a multitude of scenarios could be very cumbersome, confusing, and time consuming. The packaging methodology included in this report represents a "second generation" of the ARB methodology. The process has been automated via a computer software package, so many scenarios using a variety of utilization rates can be quickly screened. Additionally, more complete guidelines for making decisions regarding the application of the packaging methodology have been provided, making the entire model easier to use and more intuitive than that which was developed for ARB.

- The packaging methodology presented in this report utilizes a normalizing function that is an exponential and not a square. This was changed to more closely resemble the widely accepted logit model used in the transportation community, as well as to obtain results that are better than those obtained using the ARB methodology.

Shortcomings of the ARB Methodology

- There are number of potential effects of TCMs that are not addressed by the ARB methodologies. These include changes in work habits, auto hold/purchase decisions, employee residence location, employee office location, and overall changes in land use as a result of altered commute patterns. It is conceivable that these effects could be addressed in later revisions to the methodology.

- There are areas in the methodology that require professional judgment in assigning key values. An example is the determination of the utility values for cost, convenience, time, and reliability that are relied upon by the packaging methodology. These values are highly subjective, and users of the methodology should be sensitive to this.

- Several of the individual TCM methodologies employ elasticity values in order to calculate the response of the commuter to changes in the transportation system. For instance, the ridesharing methodology employs the elasticity of peak speed with respect to volume. Elasticities are by nature very specific to the region being studied. They are intended to be used as a screening tool only, and should be supplemented with more complete information. This report includes a discussion of how elasticities are calculated in order to provide the user with guidance on developing region-specific values for the necessary elasticities.

- As noted above, all of these methodologies are data-intensive. In order to obtain the best estimate of a TCM's impact in a specific region, the user is encouraged to use as much local data as is available. This may be a problem for smaller districts that do not have the resources to have region-specific travel surveys and other forms of data collection. In these cases, users will be forced to use less accurate data from sources such as the U.S. Bureau of the Census and Department of Transportation. This is likely to result in less accurate estimates of a TCM or package TCM's effects on travel behavior and emissions.

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APPENDIX B

Methodology to Evaluate Peak Period Trip Shifts of Flextime and Compressed Work Participants

This appendix is provided as a supplement to Step 4 of Chapter 2 where in peak period trip shifts were evaluated for flextime and compressed work week participants. The details of the methodology, presented here for completeness, was separated from the main report since an understanding of the exact methodology is not required to complete the TCM activity level assessment of Chapter 2. Flextime is the scheduling of work hours allowing for a broader period of travel to and from work; compressed work week scheduling adds one or two working hours to every four days in order to eliminate one or two days every two weeks from the work schedule. In both cases, the daily changes in the travel period of the participants results in a fraction of work trips made by the participants which shift from the peak to the off-peak period.

The evaluation of peak period trip shifts centers on the identification of the fraction of the total trips which will shift from the peak period to the off-peak period. This parameter, δ_{FLEX} for flextime participants and δ_{CWW} for compressed work week participants will vary by the length of the peak period and by the change in length of the participant travel period. For example, the longer the peak period the less likely a flextime or a compressed work week trip is going to be removed from the peak period. An evaluation of δ_{FLEX} and δ_{CWW} can be made by establishing a few assumptions in regard to the expected travel changes and the distribution of work trips. In this methodology, it is assumed that the distribution of targeted work trips can be predicted by a normal (or Gaussian) distribution.

The remainder of this appendix is divided into 3 sections:

(1) Discussion of the Gaussian distribution and comparison of the Gaussian distribution with actual work trip distribution data,

(2) Evaluation of the fraction of the total trips which will be removed from the peak period for flextime participants (δ_{FLEX}), and

(3) Evaluation of the fraction of the total trips which will be removed from the peak period for compressed work week participants (δ_{CWW}).

The analysis of the two TCMs are handled individually, as the travel characteristics of each is unique. Flextime participants experience a broadening of travel period due to flexible work scheduling; compressed work week participants experience earlier travel during the AM peak period and later travel in the PM peak period due to extended working hours.

Using a Gaussian Distribution to Simulate the Work Trip Distribution

The Gaussian distribution, also known as the normal distribution or the "bell-shaped curve" is a symmetrical distribution which represents the distribution of occurrence of many phenomena (Figure B-1). The probability density function, f(x), of the normal distribution shown in Figure B-1 is defined by the following equation with mean, μ, and variance, σ^2:

$$f(x) = \frac{e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}}{\sqrt{2\pi}} \qquad [-\infty < x < +\infty] \tag{B-1}$$

The continuous distribution function, $F(x_0)$, is the area under the probability density curve, f(x) representing a total number of occurrences for the interval between $x=0$ and $x=x_0$. This function is defined by:

$$F(x_0) = \int_0^{x_0} f(x) \tag{B-2}$$

In assuming a normal distribution of work trips, f(x), becomes the trip density function of the independent variable x, which in this case is time. The standard deviation of the trip density function, σ, will be determined from the peak period length and is illustrated in the TCM applications that follow this section. $F(x_0)$ is then the total number of trips occurring between time $x=0$ and $x=x_0$. The total number of trips between an interval defined as $x=x_1$ and $x=x_2$ is determined from $F(x_2)$ - $F(x_1)$.

Since the probability density function, f(x), is difficult to integrate, Equation B-2 is seldom used to directly evaluate the continuous distribution function, and a standard normal table is used instead. The standard normal table is based on a normal distribution with mean, μ_z, of 0 and a standard deviation, σ_z, of 1 where z indicates the standard normal value of x. The use of the standard normal table requires the conversion of a value of x_0 to its corresponding standard normal value (z):

$$z = \frac{x_0 - \mu}{\sigma} \tag{B-3}$$

Values in the standard normal table represent the probabilities that the value of x is between 0 and z, which is the area under the distribution density curve up to point z. Standard normal tables are widely available and are generally published in mathematical and engineering reference manuals.

In the following analyses, a Gaussian distribution is used to model the work trip distribution. For comparative purposes, an actual time distribution of work trips for the Phoenix region is illustrated in Figure B-2. From this figure, the bell-shaped nature of

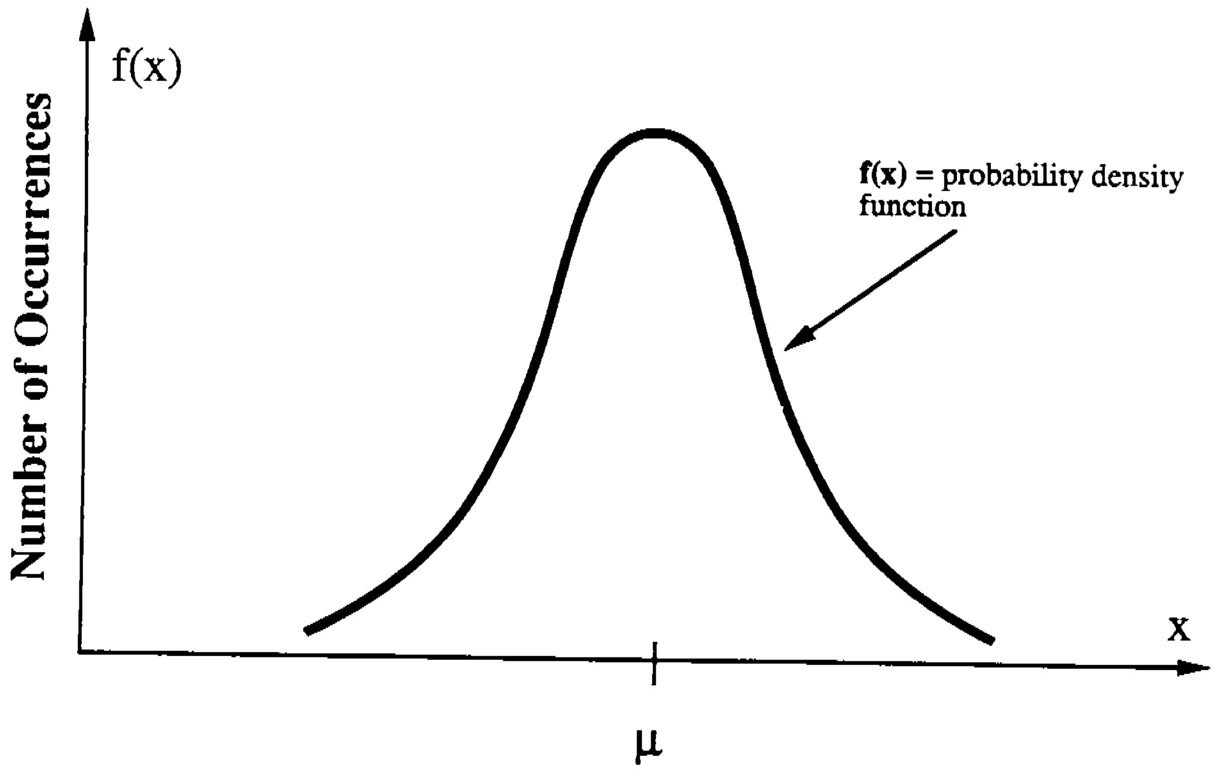


FIGURE B-1. Example illustration of the Gaussian or normal distribution curve showing f(x), the probability density function and μ, the mean value of the independent variable, x. In the case of f(x) equaling the trip density function, x represents time, and μ represents the mean value of the peak period.

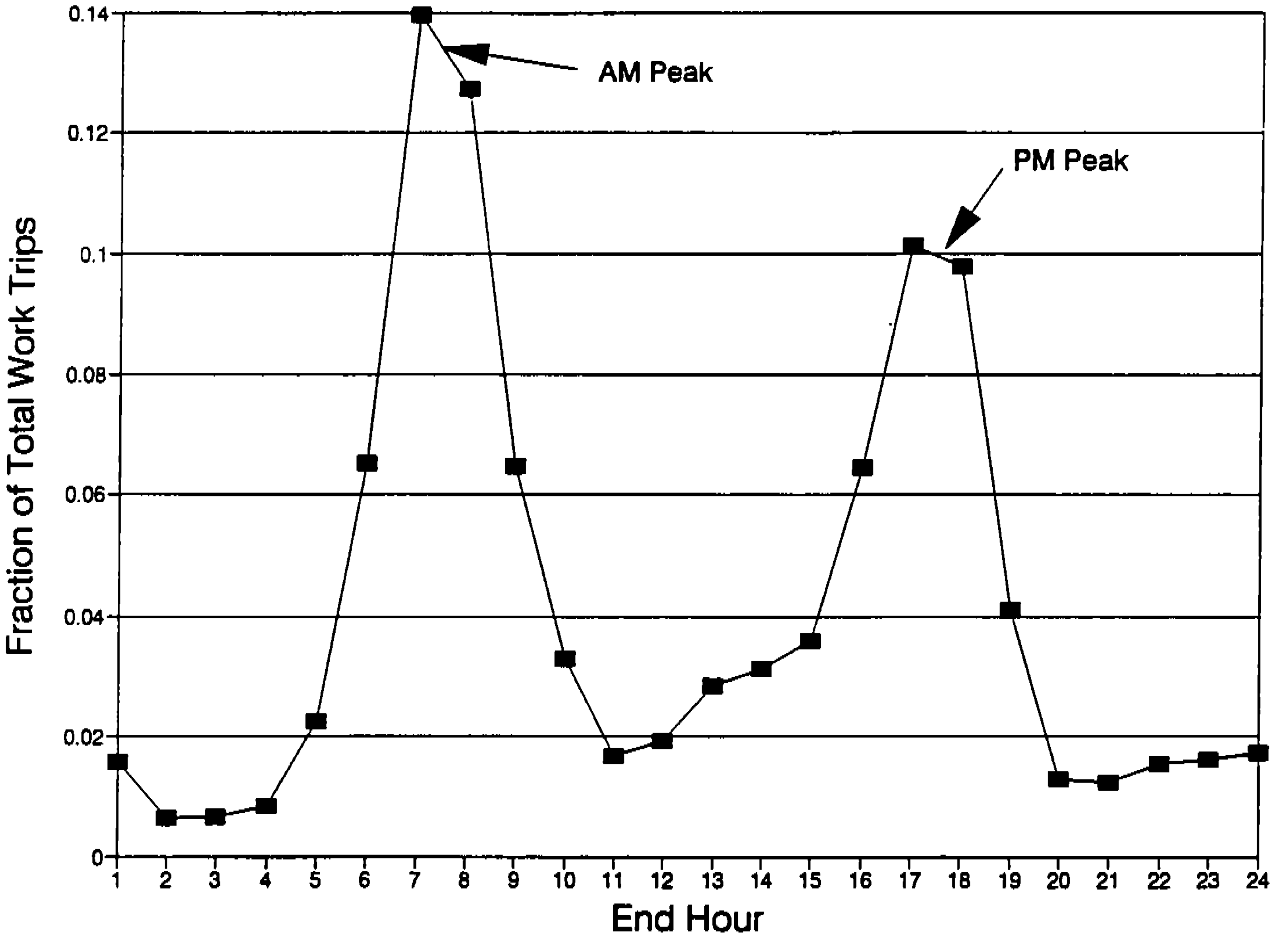


FIGURE B-2. Actual hourly work trip distribution data for Phoenix, AZ showing the bell shaped curves of the AM and PM peak periods.

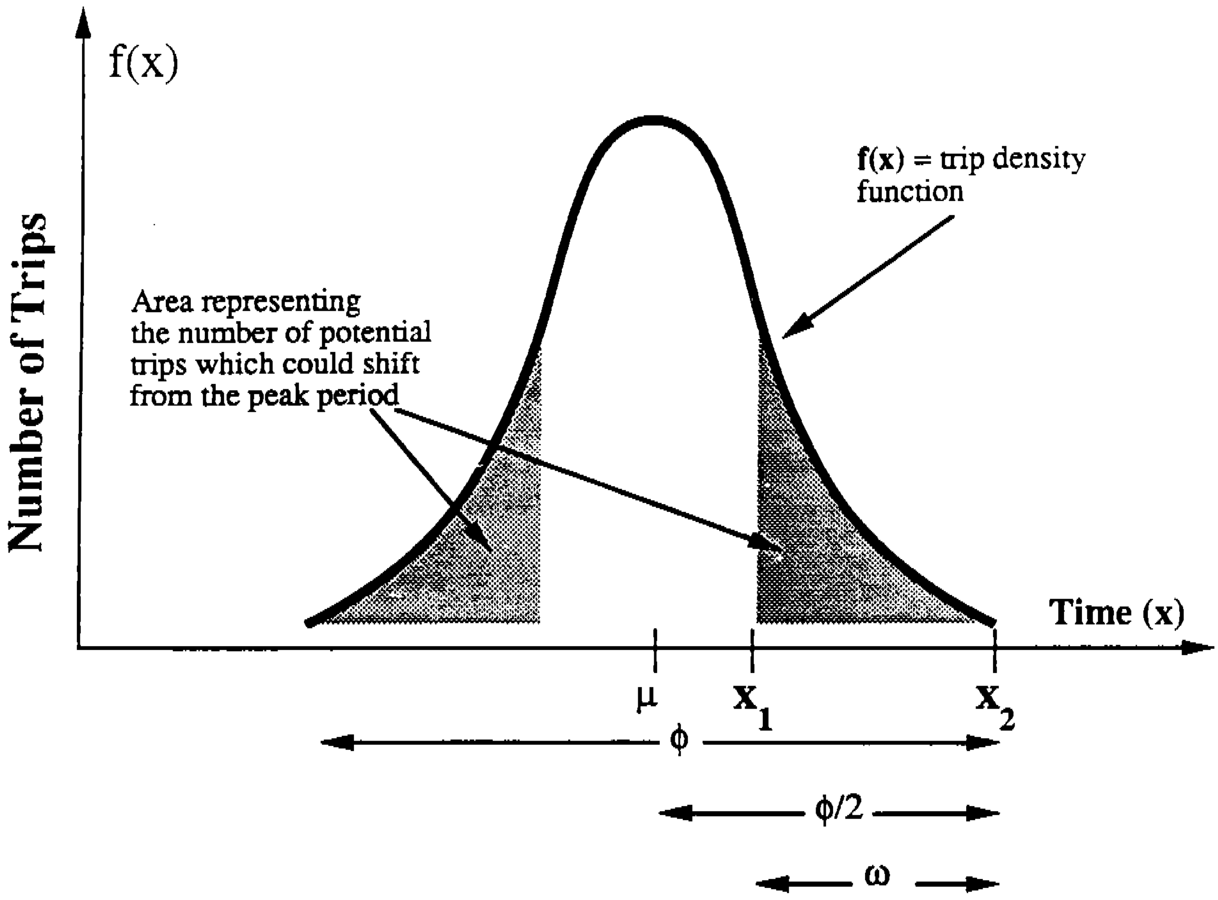
the AM and PM peak periods is apparent confirming the assumption that work trip distributions are similar to the Gaussian distribution and can be modeled as such. Furthermore in this analysis, the targeted work trips (i.e. the TCM participants) are assumed to have an equivalent normal distribution of trips.

Evaluation of Peak Period Trip Shifts For Flextime Participants

This analysis determines the net trip shift from the peak period due to flextime work scheduling. Flextime allows for a broader period of travel to and from work resulting in a shift of work trips to before or after the normal peak period. Only a fraction of the total trips made by flextime participants will experience a shift from peak period to the off-peak period making it necessary to define and identify fraction of the total trips made by the participants which will shift from the peak period to the off-peak period. This fraction is identified by the symbol δ_{FLEX}.

The value of δ_{FLEX} can be determined by establishing the average increase in travel period for flextime participants, by assuming the change in travel time is equally as probable to occur earlier or later (than before flextime implementation), and by assuming a normal distribution (Gaussian distribution) of targeted work trips. For example, examine the trip density curve illustrated in Figure B-3 where the peak period length is shown by ϕ. Let ω, shown in Figure B-3, be the average shift in time the flextime participant is willing to travel. All work trips which occur within ω hours of the endpoints of the peak period ***have the potential*** to shift out of the peak period. Of those, it assumed that 1/2 of the people representing these potential trips will choose to travel earlier and 1/2 will choose to travel later. The 1/2 of the trips identified at the earlier endpoint which choose to travel earlier and the 1/2 of the trips identified at the later endpoint which choose to travel later will be removed from the peak period; therefore, only 1/2 of the trips originally identified in the region which is within ω hours of the endpoints of the peak period will actually experience a trip shift. The assumption that people are equally likely to travel earlier as later is conservative estimate. Since there is more incentive to move away from the peak period (due to traffic considerations) it is likely that more that 1/2 of the people would move away from the peak in the trip distribution. The value of δ_{FLEX} is then calculated to be the fraction of the total trips which are removed from the peak period, and can be seen to be a function of ϕ (peak period length) and ω (average time shift of flextime participants).

If a normal distribution of targeted work trips is assumed, then δ_{FLEX} can be calculated from the continuous distribution function defined in Equation B-3. Using the Equation B-3 to determine the value of the standard deviation, σ, and assuming a curve that captures



Coordinates of x_1 and x_2:

$$x_1 = \phi/2 - \omega + \mu$$

$$x_2 = \phi/2 + \mu$$

FIGURE B-3. Example Gaussian work trip distribution curve for a peak period length, ϕ. The shaded areas indicate the fraction of targeted work trips which occur within ω hours of the endpoints of the peak period where ω indicates the average amount of time a flextime participant is willing to shift.

95% of the trips within the endpoints[1]:

$$1.96 = \frac{\phi/2}{\sigma}$$

where 1.96 is the value of z corresponding to a 95% of the total trips determined from a standard normal table and $\phi/2$ (i.e. 1/2 the length of the peak period) is the value of $x_2-\mu$ (x_2 equals one of the endpoints shown in Figure B-3). Solving for σ yields:

$$\sigma = \frac{\phi}{3.92} \qquad \text{(B-4)}$$

All work trips which occur with in ω hours of the endpoints is equivalent to two times the trips which occur between the time interval $x_1=\phi/2-\omega+\mu$ and $x_2=\phi/2+\mu$ (shown in Figure B-3) where the factor of 2 is to account for both areas at each side of the curve. Of these, it was indicated above that only 1/2 will fall out of the peak period, so the 2 and the 1/2 cancel each other, and the fraction of trips removed from the peak period can be determined from the area of the curve between the time interval $x_1=\phi/2-\omega+\mu$ and $x_2=\phi/2+\mu$. This area of the curve is determined by evaluating the difference of the continuous distribution function F(x) at x_1 and x_2:

$$\delta_{FLEX} = F\left(\frac{\phi}{2}+\mu\right) - F\left(\frac{\phi}{2}-\omega+\mu\right); \qquad \left[for\ \omega \le \frac{\phi}{2}\right]$$
$$\delta_{FLEX} = F\left(\frac{\phi}{2}+\mu\right) + F\left(\frac{\phi}{2}-\omega+\mu\right); \qquad \left[for\ \omega > \frac{\phi}{2}\right]$$

In this equation, the value of the endpoint $F(\phi/2+\mu)$ is already known to be 0.475 (half of 95% occurs between the mean and each endpoint) so these equations can be simplified to become:

$$\delta_{FLEX} = 0.475 - F\left(\frac{\phi}{2}-\omega+\mu\right); \qquad \left[for\ \omega \le \frac{\phi}{2}\right]$$
$$\delta_{FLEX} = 0.475 + F\left(\frac{\phi}{2}-\omega+\mu\right); \qquad \left[for\ \omega > \frac{\phi}{2}\right] \qquad \text{(B-5)}$$

δ_{FLEX} can be evaluated using Equation B-5 where the value of $F(\phi/2-\omega+\mu)$ can be evaluated using Equation B-2 or a standard normal table. If a standard normal table is used, then the value of $x=\phi/2-\omega+\mu$ can be translated in to z coordinates using Equation B-3 with the value of σ determined in Equation B-4 yielding:

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[1] A curve that captures 100% of the trips is ideal, but due to the asymptotic nature of the normal distribution, identifying a curve that captures 100% of the trips produces unrealistic results.

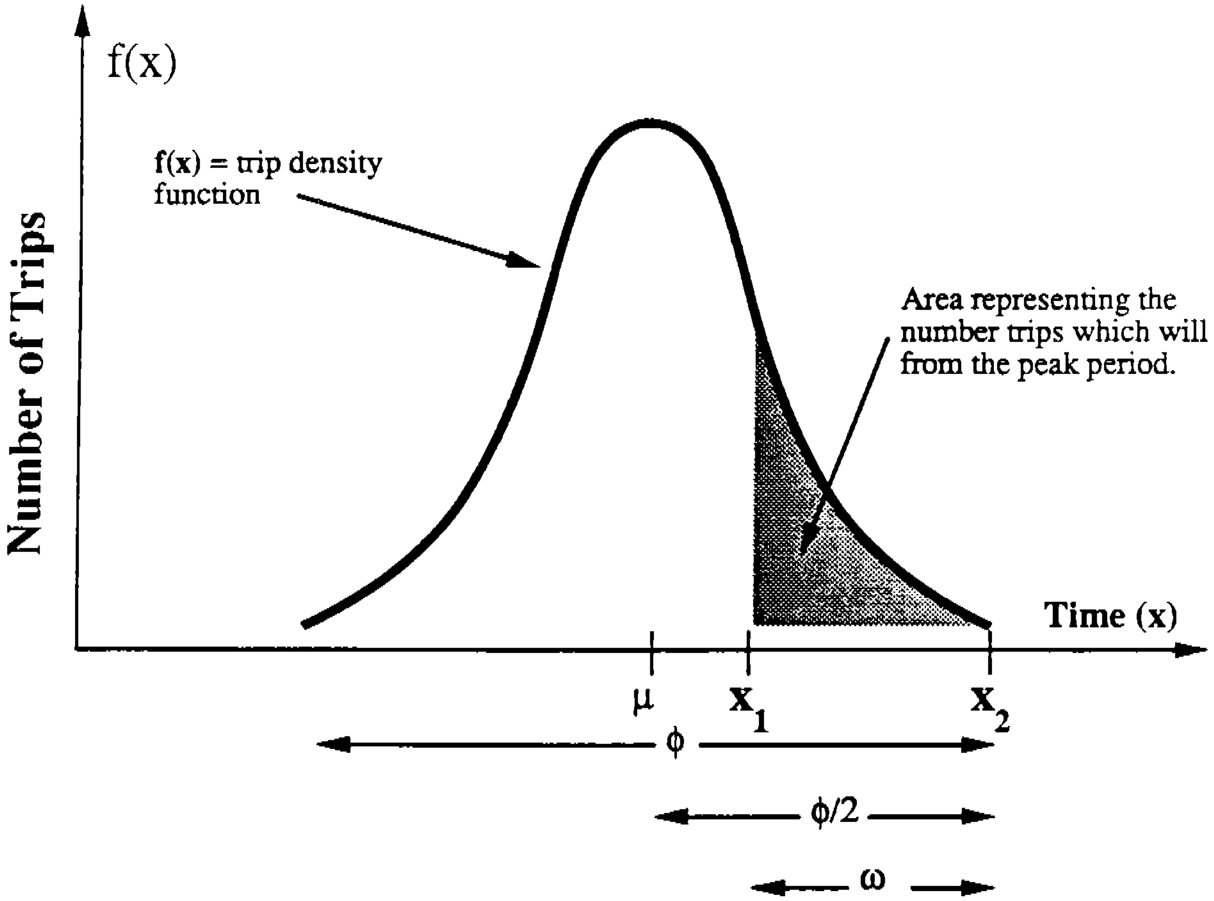
$$z = \frac{\frac{\phi}{2} - \omega + \mu - \mu}{\frac{\phi}{3.92}} = 1.96 * \left(1 - \frac{2\omega}{\phi}\right) \qquad \text{(B-6)}$$

The value of δ_{FLEX} can be determined for any combination of ϕ (peak period length) and ω (average time shift of flextime participants) using Equation B-5 and a standard normal table with z identified in Equation B-6. For example, for a peak period length of 3 hours and an average time shift of 1 hour for flextime participants, z is determined to be 0.653 from Equation B-6. From this value of z, the corresponding continuous function value is 0.242 determined from a standard normal table. Then using Equation B-5 to determine δ_{FLEX}, results in $\delta_{FLEX} = 0.233$. 0.233 is the fraction of trips removed from the peak period for the conditions of $\phi=3$ and $\omega=1$. The results of this methodology are given in Table 2-6 (included in the text of Chapter 2) for a range of ϕ and ω.

Evaluation of Peak Period Trip Shifts For Compressed Work Week Participants

This analysis determines the net trip shift from the peak period due to compressed work week scheduling. Compressed work week scheduling adds one or two working hours to every four days in order to eliminate one or two days every two weeks from the work schedule. This daily extension of working hours from a compressed work week schedule results in a fraction of participants experiencing trips shifts outside the peak period as commuters travel earlier to work and return home later. This fraction of trips removed from the peak period is identified by the symbol δ_{CWW}.

The value of δ_{CWW} can be determined by establishing the average increase in travel period for compressed work week participants, and by assuming a normal distribution (Gaussian distribution) of targeted work trips. For example, examine the probability density curve illustrated in Figure B-4 where the peak period length is shown by ϕ and where this is assumed to be an PM peak period. Let ω, shown in Figure B-4, be the average shift in travel time per peak period experienced by the compressed work week participant (i.e. a compressed work week participant who works a nine-hour day instead of an 8-hour day will shift AM travel time 1/2 hour earlier and PM travel time 1/2 hour later). Since this figure represents a PM peak period, the participants travel period will all be shifted to a later time. For compressed work week scheduling, all work trips which occur within ω hours of the earlier end of the AM peak period and within ω hours of the later end of the PM peak period ***will*** shift out of the peak period. The value of δ_{CWW} is then calculated to be the fraction of the total trips which are removed from the peak period, and can be seen to be a function of ϕ (peak period length) and ω (average time shift of compressed work week participants).



Coordinates of x_1 and x_2:

$$x_1 = \phi/2 - \omega + \mu$$
$$x_2 = \phi/2 + \mu$$

FIGURE B-3. Example Gaussian work trip distribution curve for a PM peak period length, ϕ. The shaded areas indicate the fraction of targeted work trips which occur within ω hours of the later endpoint of the PM peak period where ω indicates the average amount of time per peak period a compressed work week participant will shift in order to accommodate longer working hours.

If a normal distribution of targeted work trips is assumed, then δ_{CWW} can be calculated from the continuous distribution function defined in Equation B-3. Using the Equation B-3 to determine the value of σ and assuming a curve that captures 95% of the trips within the endpoints[2]:

$$1.96 = \frac{\phi/2}{\sigma}$$

where 1.96 is the value of z corresponding to a 95% of the total trips determined from a standard normal table and $\phi/2$ (i.e. 1/2 the length of the peak period) is the value of $x_0-\mu$ at the endpoints. Solving for σ yields:

$$\sigma = \frac{\phi}{3.92} \tag{B-4}$$

All work trips which occur with in ω hours of one of the endpoints is equivalent to the trips which occur between the time interval $x=\phi/2-\omega+\mu$ and $x=\phi/2+\mu$ (shown in Figure B-4) and the fraction of trips removed from the peak period can be determined from the area of the curve between the time interval $x_1=\phi/2-\omega+\mu$ and $x_2=\phi/2+\mu$. This area of the curve is determined by evaluating the difference of the continuous distribution function F(x) at x_1 and x_2: and the fraction of trips removed from the peak period can be determined from the following values of the continuous distribution function F(x):

$$\delta_{CWW} = F\left(\frac{\phi}{2}+\mu\right) - F\left(\frac{\phi}{2}-\omega+\mu\right); \qquad \left[for\ \omega \le \frac{\phi}{2}\right]$$
$$\delta_{CWW} = F\left(\frac{\phi}{2}+\mu\right) + F\left(\frac{\phi}{2}-\omega+\mu\right); \qquad \left[for\ \omega \succ \frac{\phi}{2}\right]$$

In this equation, the value of the endpoint $F(\phi/2+\mu)$ is already known to be **0.475** (half of 95% occurs between the mean and each endpoint) so these equations can be simplified to become:

$$\begin{aligned} \delta_{CWW} &= 0.475 - F\left(\frac{\phi}{2}-\omega+\mu\right); \qquad \left[for\ \omega \le \frac{\phi}{2}\right] \\ \delta_{CWW} &= 0.475 + F\left(\frac{\phi}{2}-\omega+\mu\right); \qquad \left[for\ \omega \succ \frac{\phi}{2}\right] \end{aligned} \tag{B-5}$$

δ_{CWW} can be evaluated using Equation B-5 where the value of $F(\phi/2-\omega+\mu)$ can be evaluated using Equation B-2 or a standard normal table. If a standard normal table is

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[2] A curve that captures 100% of the trips is ideal, but due to the asymptotic nature of the normal distribution, identifying a curve that captures 100% of the trips produces unrealistic results.

used, then the value of $x = \phi/2 - \omega + \mu$ can be translated in to z coordinates using Equation B-3 with the value of σ determined in Equation B-4 yielding:

$$z = \frac{\frac{\phi}{2} - \omega + \mu - \mu}{\frac{\phi}{3.92}} = 1.96 * \left(1 - \frac{2\omega}{\phi}\right) \tag{B-6}$$

The value of δ_{CWW} can be determined for any combination of ϕ (peak period length) and ω (average time shift of compressed work week participants) using Equation B-5 and a standard normal table with z identified in Equation B-6. For example, for a peak period length of 2.5 hours and an average time shift per peak period of 1 hour (indicating a 10-hour work day), z is determined to be 0.392 from Equation B-6. From this value of z, the corresponding continuous function value is 0.152 determined from a standard normal table. Then using Equation B-5 to determine δ_{CWW}, results in $\delta_{CWW} = 0.323$. 0.323 is the fraction of trips removed from the peak period for the conditions of $\phi = 2.5$ and $\omega = 1$. The results of this methodology are given in Table 2-7 (included in the text of Chapter 2) for a range of ϕ and ω.

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