NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT **232**

GUIDELINES FOR SELECTION OF RAMP CONTROL SYSTEMS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation
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Traffic engineers and highway planners responsible for freeway traffic management and operations in large cities should find this report of direct interest. The use of traffic control devices on entrance ramps to improve flow on congested freeways is described. Detailed guidelines are provided to help determine if ramp control is feasible for a particular facility and, if so, to determine the relative cost-effectiveness of different modes of control. The research findings are based on data from operational ramp control systems in ten cities, limited field studies conducted as part of this project in Dallas and Los Angeles, and traffic simulation studies. Appendix E of this report contains the detailed guidelines which are designed as a self-contained, easy-to-follow user manual; operational, cost, and policy considerations are addressed.

Use of ramp control is not a new traffic management concept; in fact, such control systems have been in operation in this country for about 20 years. Ramp control can be defined as a method of improving overall freeway operations by limiting, regulating, and timing the entrance of vehicles from one or more ramps onto the mainline. Rather than permitting heavy congestion on the freeway, this approach optimizes flow on the mainline by controlling traffic on the entrance ramps. In locations where freeway entrance ramps have adequate storage capacity or where the surrounding street network can accommodate additional traffic, ramp control systems can provide substantial operational improvements under certain combinations of traffic demand and freeway capacity. Often, however, this concept is not fully considered because of the lack of information and guidance on how to determine the feasibility of a ramp control system. Ramp control feasibility is related to both technical (e.g., costs and benefits) and policy (e.g., public acceptance) considerations.

In 1979 NCHRP published a special report, "Freeway Traffic Management," summarizing various options that are available to reduce traffic congestion. That report was directed to transportation administrators and officials to create a general awareness of the relative benefits of each option; primary attention was devoted to freeway control and surveillance systems including their role relative to other options, such as geometric design changes, work rescheduling, ridesharing, transit, and the like. As a logical and valuable complement to the general overview given in "Freeway Traffic Management," detailed guidance related to the feasibility and selection of ramp control systems is presented herein.

The objective of Project 3-22 and 3-22A was to draw from the experience gained from existing ramp control systems, as well as from original research, to develop guidelines for use by others who may want to install similar systems. Stanford Research Institute (SRI) conducted the first phase of this project (3-22), resulting in preliminary guidelines for evaluating and selecting basic ramp control strategies. SRI's final report, "Guidelines for Design and Operation of Ramp Control Systems," is available on loan from the NCHRP if the reader is interested in the background and developmental aspects of this subject. Texas Transportation Institute (TTI) and its two subcontractors, DARO Associates and ESSCOR, accomplished the second phase of this project (3-22A) in which the final guidelines were developed following the collection of extensive information from operators of existing systems, from limited field studies, and from simulation analyses. TTI's original field data collection plan was curtailed because of the perceived inability to detect small differences in system performance caused by incremental traffic control changes. As a result, a traffic simulation model was used to develop most of the data on which the guidelines are based. The reader should understand that although the simulation data are considered to be reasonable and acceptable for use in the guidelines, this information should be supplemented with actual field data whenever possible.

The step-by-step guidelines provided in Appendix E can be used by traffic and planning engineers to evaluate the feasibility and cost of ramp control for a particular facility. Four specific aspects are addressed—should ramp control be used, how does it relate to other alternatives, is it feasible for a specific location, and what mode of control is best for a specific location. This last aspect, mode selection, receives primary attention in the guidelines through the comparison of benefits and costs associated with the three primary modes of control: pretimed (treated as the comparison base), local actuated, and system control. Mode selection is based on which form of control best accommodates the traffic capacity and demand fluctuations and which is most compatible with the specific configuration of interchanges. Benefit and cost ratios are used to compare modes considering both initial installation costs and continuing maintenance and operational costs (1980 costs are reported). Benefits include travel time savings, fuel consumption savings, reduced emissions, and improved operations. Because some important considerations (e.g., community goals) are not easily quantifiable in dollars, a utility and cost analysis is also provided.

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ACKNOWLEDGMENTS

These Guidelines were developed as the major product of a research study performed under NCHRP Project 3-22A. The Texas Transportation Institute (TTI), Texas A&M University, was the prime contractor. Subcontract work was performed by Daro Associates of Menlo Park, Calif., and ESSCOR of San Diego, Calif.

The Texas Transportation Institute served as prime contractor and assumed responsibility for the overall conduct of the study. Personnel from the Texas Transportation Institute that contributed to the project include the following: Mr. Charles W. Blumentritt, Associate Research Specialist, and principal investigator for the project; Dr. Charles Pinnell, Assistant Director; Mr. William R. McCasland, Research Engineer; Dr. Jessie L. Buffington, Research Economist; Dr. William F. McFarland, Research Economist; and Dr. Conrad L. Dudek, Research Engineer.

Daro Associates served as subcontractor and was responsible for conducting and analyzing the questionnaire survey, obtaining data on the cost of entrance ramp control systems, and conducting the simulation analysis of entrance ramp control modes. Personel contributing to the project included Dr. Dale W. Ross, President, and Mr. Jesse Glazer, Systems Analyst.

ESSCOR served as subcontractor and provided and made modifications to the simulation model used in the simulation analysis. Personnel contributing to the project included Dr. Harold J. (Pete) Payne, Principal of ESSCOR.

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GUIDELINES FOR SELECTION OF RAMP CONTROL SYSTEMS

SUMMARY

Continued emphasis on improving the quality of traffic operations on existing freeway facilities has prompted a resurgence of interest in control systems. One significant tool that can be used to increase the safety and efficiency of traffic operation on existing freeways is the use of entrance ramp control. Entrance ramp control is a technique for regulating access to the freeway in a manner that reflects a management plan of freeway operation. Specific freeway operation situations to which entrance ramp control can be applied are:

1. Reduction of stop and go congestion.
2. Accident reduction, both mainline- and ramp-related.
3. Planned diversion.
4. Specific level-of-service operation.

NCHRP Project 3-22A was initiated to provide guidelines for determining the feasibility of entrance ramp control, and if feasibility is decided, to determine the appropriate mode of control: pretimed, local actuated, or system control. In the past, designers had to choose a mode of control without knowing the relative cost effectiveness of each control alternative. Overall guidance was needed on the general hardware configuration associated with each mode of control.

Project 3-22A has developed guidelines for cost-effectiveness evaluation, including the following items of information:

1. Incremental benefits associated with each level of control.
2. User costs, such as vehicle delays, fuel consumption, and emissions.
3. Installation costs.
4. Maintenance and operation costs.

The guidelines are presented as a self-contained document in Appendix E of this report. Chapters One through Four present an overview of the project, including the research approach, findings, applications of the evaluation procedure, and conclusions and suggested research. Additional details of the research effort through which the guidelines were developed are reproduced as submitted by the research agency in Appendixes A through D.

The purpose of the guidelines is to provide a concise, pertinent set of information and technology that can be used by practicing transportation engineers in implementing freeway entrance ramp control systems. The guidelines provide a practical, relatively brief, and easily used methodology that will guide and assist the transportation engineer in making the following critical decisions on freeway entrance ramp control:

1. When should it be considered?
2. How does it relate to other improvement alternatives?

3. Is it feasible for the specific situation under study?
4. What specific mode of control is best for the specific situation under study?

The consideration of the total decision process permits one to relate entrance ramp control to the overall considerations of freeway operation and control and transportation systems management. The process is broad in nature relative to decisions 1 and 2, and then focuses specifically on entrance ramp control through decisions 3 and 4. A synopsis of the suggested implementation procedure for these decisions, as they relate to the guidelines, follows.

Evaluation Procedure

The first step is the recognition that a significant congestion problem exists or will soon exist on a given freeway. This decision initiates a consideration of the various alternatives that can reduce the level of congestion and its detrimental effects. One such means of improving freeway operation may be entrance ramp control. It is recognized that the various agencies that have the responsibility of maintaining and operating freeway systems will have different procedures for collecting data, conducting evaluations, and determining that a serious problem exists. A basic methodology for accomplishing these steps is to quantify those user costs which tend to increase as freeway congestion increases, namely: travel time costs, vehicle operating costs, and accident costs.

Improvement Alternatives

A first step in defining improvement alternatives is to identify the prevalent type of congestion (recurrent or nonrecurrent) that is occurring. If the problem is one of nonrecurrent congestion (i.e., resulting from the occurrence of random or nonpredictable events), an approach involving surveillance and freeway management is needed. If the problem is one of recurrent congestion (i.e., routinely expected at predictable locations during specific time periods), both capacity- and demand-oriented alternatives should be investigated. Examples of demand-oriented alternatives are reduction of overall travel, ride sharing, carpools, vanpools, public transportation, entrance ramp control, mainline control, freeway-to-freeway connector control, corridor control, and peak period dispersion. Examples of capacity-oriented alternatives are construction of additional facilities, revision of entrance and exit ramp locations, expansion of existing facilities, temporary use of shoulders and narrow lanes, geometric modifications, incident detection and removal, incident management (including entrance ramp control), and installation of accident investigation sites.

The most common situation is one where recurrent congestion is further compounded by nonrecurrent congestion, where an approach which attacks both types of congestion is needed.

Feasibility

There is a movement in the direction of warrants for entrance ramp control. Warrants, together with traditional traffic engineering studies, form the basis of a feasibility analysis of entrance ramp control. These studies include bottleneck, geometric, traffic diversion, accident, enforcement, public acceptance, and preliminary cost analyses. The compeltion of these seven studies in a thorough manner provide the decision-maker with a solid data base to use in determining the feasibility of entrance ramp control.

Control Modes

There are basically three modes of entrance ramp control: pretimed, local actuated, and system. Briefly, the pretimed mode operates at a predetermined metering rate based on time of day. The local actuated mode derives its metering rates from mainline traffic conditions in the immediate vicinity of a controlled ramp. The system mode implies the use of a central computer to analyze traffic conditions on a designated section of freeway; metering rates of entrance ramps feeding that section are regulated according to system operating goals.

Each control mode has an associated hardware configuration. The pretimed mode represents the minimum configuration, mainly consisting of signal head(s), pretimed controller and optional detectors. The local actuated mode has a similar hardware configuration, but with a local actuated controller and required main lane detectors. The system mode represents a large hardware increment, possibly requiring additional detectors, but definitely requiring a communications system, interfaces, and control computer.

The computational capability and economy of the microprocessor as an entrance ramp controller make it applicable and essentially equal in cost for all three control modes; for a small number of ramps, it is prudent to use a microprocessor as a central control computer for the system mode as well.

Control System Costs

Costs are variable and are a function of locale, time, and circumstances. Based on average costs of installed systems, a rule of thumb is: If a pretimed mode installation costs X dollars per ramp, a local actuated mode installation will cost 1.25 X dollars per ramp, and a system mode installation will cost 2.00 X dollars per ramp. A good estimate for X is $16,000 in 1980. Thus, for a pretimed configuration costing $16,000/ramp, a local actuated configuration would cost $20,000/ramp and a system configuration would cost $32,000/ramp. The latter figure is exclusive of the cost of the communications medium (i.e., leased or private lines). Annual operation and maintenance costs are roughly 16 percent, 18 percent, and 30 percent of the respective installation costs for pretimed, local actuated, and system modes.

Mode Selection Methodology

The mode selection methodology seeks to evaluate the changes in demand and capacity of a subject system, and the relative ability (compared to pretimed) of local actuated or system control to cope with these changes. The user proceeds with the following basic steps in applying the methodology to his system:

1. Estimates of user costs are made for the target system under the pretimed mode of control. This is accomplished by developing a basic metering plan, which is an analysis of the effect of reduced entrance ramp volumes on freeway operation.
2. The expected variations in freeway and ramp demands are identified and quantified through detailed field studies.
3. The expected variations in freeway capacity are identified and quantified through detailed field studies.
4. The demand and capacity variations are related to a set of curves that quantify the incremental benefits (relative to a base of pretimed control) for local actuated and system control.
5. Incremental costs (relative to a base of pretimed control) are provided in the guidelines for local actuated and system control.

6. Incremental benefit-cost (B/C) ratios are developed.
7. Utility-cost (U/C) ratios are developed.
8. The B/C and U/C ratios are evaluated for the mode selection choice.

Findings

The monetized incremental benefits were found to be dominated by travel time savings; monetized fuel consumption savings are about five to ten times less than the travel time savings. Incidents, poor freeway operating conditions, and shifts (from one day to another) in the level of freeway traffic demand are the principal factors affecting the benefits of traffic responsive metering logics.

The demand growth over the lifetime of an entrance ramp control project reduces the incremental benefits of the responsive control modes. The planner of a ramp control installation should be alert to this effect.

The accident reduction benefits of responsive ramp controls were not investigated in this research. There may well be some such benefit, but no attempt was made to quantify it.

Extension

Continued interest in mainline metering serves to increase the importance of entrance ramp control. The concepts of entrance ramp control are applicable to mainline control and freeway-to-freeway connectors, and can be linked to provide absolute management of freeway operation.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

STATEMENT OF RESEARCH PROBLEM

NCHRP Project 3-22A was initiated to provide guidelines for determining the feasibility of entrance ramp control, and if feasibility is decided, to determine the appropriate level of control (a definition of levels of control is given under the heading "Definitions"). Specific guidelines were needed to assess the costs and benefits associated with each level of control and to define the incremental benefits that are obtained by selecting higher levels of control. Here, levels of entrance ramp control are pretimed, local actuated, and system control. In the past, designers had to choose a level of control without knowing the relative cost effectiveness of each control alternative. Overall guidance was needed on the general hardware configuration associated with each level of control.

In developing the guidelines for cost-effectiveness evaluation, basic information was needed on:

1. Incremental benefits associated with each level of control.
2. User costs, such as vehicle delays, emissions, and fuel consumption.
3. Installation costs.
4. Maintenance and operation costs.

RESEARCH OBJECTIVE

The objective of this research was to develop a methodology and guidelines for comparative evaluation of alternative ramp control system designs. The resulting procedure determined whether or not entrance ramp control could be employed beneficially and, if so, which type of control system was most appropriate. The selection methodology considered pretimed, local actuated, and system control modes. Analysis procedures were needed for quantifying benefits and costs. To accomplish these objectives, the following research tasks were accomplished.

Research Task 1

The variables affecting the benefits attributable to the three basic types of entrance ramp control were identified and defined (*1*). The characteristics of freeway operation from which the variables are derived included variation in flow characteristics, freeway geometrics, incident characteristics, alternate routes, metering rate constraints, vehicle occupancy, and travel patterns.

Research Task 2

A method to conduct a benefit and cost analysis for each increment of ramp control was developed. The costs considered include initial, operating, and maintenance costs. The benefits considered include reduction in travel time, fuel consumption, and vehicle emissions.

Research Task 3

On the basis of the variables identified in Task 1 and the methodology developed in Task 2, the various types of data were acquired to develop the desired guidelines. Techniques included the analysis of available data and collection of new data which were input to a simulation model for evaluation.

Research Task 4

A comprehensive set of guidelines was developed to assist the traffic engineer in selecting the appropriate type of freeway ramp control. The methodology developed in Task 2 is refined to permit direct field application by a practicing transportation engineer. Specific design data are clearly defined. The guidelines are included as Appendix E of this research report.

DEFINITIONS

The research activities involved the comparison of control modes and associated user costs. The following definitions are included to clarify the areas of discussion.

Control Modes

The *pretimed control mode* is defined as any form of entrance ramp metering that is not directly influenced by mainline traffic conditions. This does not necessarily imply the absence of vehicle detectors. Demand and passage detectors can be used to actuate and terminate each metering cycle. These detectors, however, are used to detect entrance ramp vehicles rather than mainline vehicles, and cause an entrance ramp signal to cycle during the control period only when vehicles are present.

The individual metering rates used with pretimed control are solely a function of past traffic observations, which may include origin–destination studies that determine the particular ramps affected by the freeway travel patterns. When the set of rates has been established through a metering plan, metering operation is subsequently independent of all factors other than time-of-day, day-of-week, or special events. Pretimed control can apply to any number of entrance ramps, from a single ramp to many ramps. No interconnection with other entrance ramps is used.

The *local actuated control mode,* in contrast to pretimed control, is directly influenced by the mainline traffic conditions during the metering period. For example, a local actuated controller may implement progressively more restrictive metering as occupancy levels on the mainline increase. Typically, one might associate predetermined occupancy thresholds with metering rates that experimentally have proved effective. In local actuated control, the decision-making mechanism is based primarily on real-time, locally measured traffic conditions based on mainline detectors in the immediate vicinity of the ramp. No interconnection with other ramps is used and no attempt at global optimization is possible, except whatever the combined effect of individual entrance ramp controls may be.

The *system control mode* is the form of entrance ramp metering in which real-time information on total freeway traffic conditions is used for control of a system of entrance ramps. Although such metering is typically imposed by a central, computer-controlled system, the control intelligence may also be distributed among the individual entrance ramps. A significant feature of this class of metering is the interconnection that permits conditions at one location to affect the metering rate imposed at one or more locations. Freeway traffic conditions as reflected by detectors throughout the system are analyzed at a central location and metering rates for all ramps are established according to a real-time metering plan.

User Costs

There are two types of user costs incurred in freeway operation: basic costs and nonbasic costs. *Basic costs* are those costs which accrue when the freeway is operating normally; these are costs such as travel time, vehicle operation, and air pollution emissions. *Nonbasic costs* are the additional costs caused by incidents, variations in demand, or environmental conditions (i.e., rain) that reduce capacity.

The basic user costs (*2*) of freeway operation, with or without ramp metering, are those costs that develop for the average peak period. That is, they are the user costs that would occur day after day if the freeway capacity never varied and the peak period demand pattern never varied from one day to the next. These user costs include travel time, vehicle operating costs, and vehicle emissions. Calculation of basic user costs is a series of computations based on data acquired during freeway studies. Typical parameters and performance measures involved in this calculation are: total travel, demand, capacity, vehicle delay, total travel time (freeway, ramp, and diversion), fuel consumption (uniform speed rates and excess rates), vehicle emissions, vehicle operating costs (running costs, excess running costs, and idling costs), and accident costs.

The nonbasic user costs (*2*) are those (additional) costs that arise when conditions differ, or vary about, the average peak period conditions. Examples of conditions that differ from average peak period conditions are: peak periods in which an incident has occurred, peak periods in which the traffic demand differed from the average peak period demand, and peak periods in which the freeway capacity differed from average capacity because of environmental conditions such as rain or fog. The nonbasic user costs are of importance because they are sensitive to the effects of the three ramp control modes: pretimed, local actuated, or system. If peak period conditions always repeated themselves so that every day was an average day, there would be no unexpected events that would require feedback-type ramp control logic to correct. Pretimed metering could be set up to manage the demand and, even if local actuated or system metering were applied, the control performance would be expected to be about the same as that of pretimed control. If, however, unexpected events, such as incidents, demand variations and environmental changes occur, the relative performances of the different control modes can be expected to differ. In summary, the relative differences in nonbasic costs among the three control modes are keys to linking the incremental benefits to the modes.

TABLE 1

TWENTY-EIGHT RAMP CONTROL SYSTEMS DEFINED FROM QUESTIONNAIRE RESPONSE

SYSTEM NO.	DESCRIPTION	NO.METERED ENTR.RAMPS
1	Chicago; Dan Ryan Expressway; Northbound and Inbound	6
2	Milwaukee; I-94; Westbound and Outbound	3
3	Milwaukee; I-94; Eastbound and Inbound	4
4	Milwaukee; I-43; Southbound and Inbound	4
5	Minneapolis; I-35W; Northbound and Inbound; 106th St. thru 94th St.	3
6	Minneapolis; I-35W; Northbound and Inbound; 90th St. thru 76th St.	5
7	Minneapolis; I-35W; Northbound and Inbound 66th St. thru Diamond Lake Rd.	4
8	Minneapolis; I-35W; Southbound and Outbound; Highway 190 thru I-94 Westbound	3
9	Minneapolis; I-35W; Southbound and Outbound; I-94 Eastbound thru 106th St.	6
10	Minneapolis; I-35W; Southbound and Outbound; 31st St. thru Diamond Lake Rd.	4
11	Toronto; Q.E.W.; Eastbound and Inbound	4
12	Dallas; North Central Expressway; Southbound and Inbound; McCommas thru Fitzhugh	4
13	Dallas; North Central Expressway; Southbound and Inbound; Caruth thru Mockingbird	5
14	Dallas; North Central Expressway; Southbound and Inbound; Forest Lane thru Loop 12 Eastbound	7
15	Dallas; North Central Expressway; Northbound and Outbound; Haskell thru McCommas	5
16	Dallas; North Central Expressway; Northbound and Outbound; Yale thru Park	7
17	San Antonio; IH 10; Southbound and Inbound; Woodlawn thru Colorado	4
18	Houston; U.S. 59; Westbound and Outbound; Greenbriar thru Newcastle	5
19	Houston; U.S. 59; Eastbound and Inbound; Newcastle thru Shepherd	5
20	Houston; U.S. 59; Westbound and Outbound; U.S. 610 thru Hillcroft	3
21	Houston; U.S. 59; Eastbound and Inbound; Fondren thru Chimney Rock	5
22	Fort Worth; I-30; Westbound and Outbound; Macon thru Clover Lane	7
23	Fort Worth; I-30; Eastbound and Inbound; Guilford thru Clover Lane	5
24	San Jose; I-280; Northbound and AM; Winchester Blvd. thru Wolfe Rd.	5
25	San Jose; Route 17; Southbound; Bascom thru Lark Ave.	7
26*	San Francisco; San Francisco - Oakland Bay Bridge Westbound, Inbound	-
27	Los Angeles; San Diego Freeway; Northbound circumferential; Artesia thru El Segundo Eastbound	8
28**	Los Angeles; Harbor Freeway; Northbound and Inbound; 190th Ave. thru Washington	18

* This system is not a ramp metering system; however, certain data reported for this system are of interest (e.g., weather- and incident-induced capacity reductions).

** Insufficient data supplied to break this into smaller subsystems.

RESEARCH APPROACH

The research studies consisted of the following basic steps: literature review and site visits, questionnaire survey, simulation analyses, field studies, and cost investigation. The basic research activities in each of these steps are briefly reviewed in the following.

Literature Review and Site Visits

A large number of publications and working papers were reviewed by the researchers. It was found that the topic of this research had received very little explicit treatment in the literature. Only one source was found that documented a comparison between pretimed and local actuated control modes. However, a comprehensive body of literature exists that addresses the general subject of entrance ramp control. The early days of entrance ramp control are documented by extensive research activities that peaked in the late sixties. Since that time, the majority of literature has focused on operational systems.

The major United States and Canadian entrance ramp control installations were contacted by telephone. Site visits were made to the Toronto, Minneapolis, and Chicago control projects as well as to Texas and California control projects.

Questionnaire Survey

A number of agencies that operate freeway ramp metering installations were asked to provide data on their installations. For this purpose, a questionnaire was prepared and distributed to ten agencies (nine U.S. and one Canadian). A copy of the questionnaire is shown in Appendix A. Data on 28 ramp control systems were acquired. The subject systems are given in Table 1; note that large installations were segmented as smaller systems.

The purpose of the data request was to assess the variety of designs and traffic conditions found at operating ramp control sites. These variations in design and traffic conditions can affect the relative performances of the three ramp control modes (pretimed, local actuated, and system). Accordingly, the questionnaire data provided the basic imputs for the next phase of the study, which was to identify the travel-time cost, vehicle operating cost, fuel consumption, and vehicle emissions differences (nonbasic costs) among the three control modes. Conditions that cause the metered freeway to have changeable or variable demand and capacity include: incidents, demand variability, and environmental variations (mainly capacity variations due to weather, darkness, or other potential factors).

Simulation Analyses

The initial research plan for the project called for the determination of the incremental benefits of the various control modes from successive field trials of each mode at selected freeway sites. As the project progressed, it became apparent that this research approach was not feasible for the following reasons:

1. Extensive field tests of control mode differences were feasible at only two sites. This was due to the capability of the hardware to operate in all three control modes and to the willingness of the operating agencies to allow mode changes. This limited number of test sites greatly compromised the generality of the test results.
2. Field tests of freeway control systems were an imperfect experimental technique because a large number of very important parameters could not be freely adjusted.
3. The randomness of traffic demand and various freeway operating conditions precluded the duplication of tests over the three mode choices and thus created uncertainty as to what differences in mode performance had actually been observed.

On the basis of the foregoing considerations, it was determined that the use of a freeway simulation model provided the best research approach. Such a model could be used to evaluate a large number of scenarios and determine control mode differences and incremental benefits.

The simulation analyses proceeded through the following steps:

1. Evaluation of existing freeway simulation models and the selection of a single model for project use. Models examined included FREQ, INTRAS, MODEL VI, SCOT, SCOT/GRC, and MACK. The MACK model (*3*) was judged to offer the best possibilities for use.
2. Modification and acceptance testing of the selected simulation model.
3. Design of a sensitivity analysis to be conducted using the simulation model. The simulation runs plan is shown in Appendix B.
4. Conduct of the simulation runs for the sensitivity analysis. A total of 153 runs was required.
5. Evaluation of the sensitivity analysis and the development of incremental benefit curves (*2*).

Field Studies

An objective of the field data collection study was to acquire the appropriate input data for the simulation runs. A second objective was to verify the conclusions reached by the simulation runs (i.e., to determine the measurable differences in freeway performance using three different modes of ramp control). Although the simulation technique offered the advantages of repeatability of traffic flows, a fundamental requirement was that the simulation model replicate the relative differences of variations in traffic parameters as well as control modes. The general veracity of the simulation model was established first by comparison of results to actual freeway flow data prior to modification of the model (i.e., the MACK model), and secondly by comparison of results to existing Dallas and Los Angeles freeway data. The latter comparison was made with the FREFLO model (the MACK model as modified for use by this project was renamed the FREFLO model).

Questionnaire response data were reduced to obtain baseline data for conducting the simulation runs. These data represented a significant effort in the field data collection process.

Two study sites were selected for data collection in systems operating under three control modes. One was a section of the San Diego Freeway, located about 15 miles to the southwest of downtown Los Angeles. The other site was a section of the Dallas North Central Expressway, located about 4 miles north downtown Dallas.

The field studies were designed to collect data at each site while the systems were operated in pretimed, local actuated, and system modes (6-week studies, 2 weeks in each mode). The California site studies were initiated on April 2, 1979, and data were collected for a 2-week period in pretimed mode. For an extended period of time, hardware problems precluded local actuated or system mode studies at the California site. At the same time, the Texas site was unavailable for study, also because of hardware problems. Eventually, the field studies were suspended and full attention was devoted to reporting the research results on the basis of the simulation studies.

Cost Investigation

Cost data were obtained from the literature reviews, personal interviews, and experience background of the research team. This required a detailed inventory of the components of entrance ramp control systems as well as their associated costs.

Specific cost figures were obtained from interviews with California Department of Transportation (CALTRANS) personnel (*4*) and during site visits to the four entrance ramp control installations in Texas. Confirmation of documented costs (*5, 6*) was obtained during site visits to Toronto, Minneapolis, and Chicago.

CHAPTER TWO

FINDINGS

BENEFITS OF ENTRANCE RAMP CONTROL

The idealized benefits of ramp control are summarized in Table 2. These benefits are applicable to the immediate area of influence of the entrance ramp control system, based on the existence of factors that are favorable for the operation of a ramp control system, such as adequate diversion routes, sufficient ramp storage, and the like. The factors necessary for the feasibility of the entrance ramp control system are detailed in Chapter 5 of Appendix E. As an adjunct, the most frequently cited disbenefits of ramp control are given in Table 3.

TABLE 2

GENERAL RAMP CONTROL BENEFITS

Benefit Class	Benefits
THROUGHPUT	Increase vehicle-miles travel
	Increase person-miles travel
DELAY	Reduce freeway delay
	Balance corridor delay
	Increase operating speeds
	Maintain set Level of Service
	Improve Level of Service
	Reduce congestion (stop and go)
	Reduce driver frustration
SAFETY	Reduce freeway accidents
	Reduce ramp/merging accidents
	Reduce incidents
ENVIRONMENTAL	Reduce emissions
	Reduce fuel consumption (for increasing Levels of Service including C)
	Reduce vehicle operating costs
MANAGEMENT	Provide management mechanism
	Accommodate future demands
	Redistribute delay/demand
	Defer capital improvement
	Feedback for monitoring
	Improve accident/incident response
	Popularity with public not being adversely affected

TABLE 3

GENERAL RAMP CONTROL DISBENEFITS

Disbenefit Class	Benefits
ENVIRONMENTAL	Increased Fuel Consumption (manifested above Level of Service C)
MANAGEMENT	Unpopular with public

QUESTIONNAIRE RESPONSES

The questionnaire responses provided detailed information on entrance ramp control system configurations and their operating characteristics. The following topics discuss the major findings of the survey.

Typical Main Lane and Ramp Geometrics

The questionnaire responses regarding the main lane and ramp geometrics are given in Tables 4 and 5, respectively. From these data, the configuration of the baseline freeway was derived for use in the simulation studies.

Demand Profiles

The average bottleneck demand AM and PM curves are shown in Figures 1 and 2, respectively. The AM peak demand curve tends to be skewed to the earlier half of the period and to be unimodal. The PM peak demand tends to be bimodal (has two relative peaks).

Origin–Destination Data

Origin–destination data were reported for 8 inbound systems (AM); insufficient data were available for PM outbound systems. An average origin–destination table for a 5-on-ramp and a 4-off-ramp system is approximated by Table 6, expressed in percentage exiting, which was compatible with the FREFLO simulation model requirements.

Peak Period Duration

Start- and end-time variations of ramp control periods are shown in Figure 3. A correlation of the start and end times indicated that if a peak period started late, it would end early. At sites that do not have a particular vulnerability to incidents and bad weather, a standard deviation of about plus or minus 15 min in peak period duration is indicated.

Demand Variability

Figure 4 shows the general variation in peak period demand. The mean peak hour factor (PHF) for mainline input was found to be 0.90, and the mean on-ramp PHF was 0.72. The peak hour factor is the ratio between the number of vehicles counted during the peak hour and four times the number of vehicles counted during the highest 15 consecutive minutes.

Incident Data

The mean frequency of incident occurrence was 5.28 per year, per peak hour, per lane-mile. The questionnaire response regarding the relative likelihood of incident occur-

TABLE 4

FREEWAY MAINLINE GEOMETRICS

System No.	No. of On-Ramps	#Metered On-Ramps	No. of Off-Ramps	Length of System(mi)	Lane-Miles	% Length w/Shoulder	#Bottle-Neck Lanes	Bottleneck Capacity (VPH)
1	6	6	5	3.07	12.27	100%	4	7900
2	6	3	5	2.74	8.79	100	3	5700
3	6	4	5	3.10	9.73	100	3	5800
4	4	4	3	2.21	6.63	100	3	5700
5	3	3	3	2.88	6.25	81	3	5800
6	5	5	4	1.92	4.02	100	2	3800
7	6	4	2	2.30	6.30	77	3	6200
8	3	3	3	1.78	3.75	100	3	5800
9	6	6	6	3.57	7.94	77	2	3800
10	4	4	3	3.03	10.66	80	3	5800
11	4	4	2	3.76	11.28	90	3	6600
12	4	4	2	0.97	2.91	---	3	----
13	5	5	3	1.61	3.22	---	3	----
14	7	7	6	2.70	5.40	---	2	----
15	5	5	4	1.66	4.97	---	2	----
16	7	7	7	1.98	3.97	---	2	----
17	4	4	1	0.95	1.91	---	2	----
18	5	5	4	2.32	10.16	78	4	7800
19	5	5	4	2.47	10.51	87	4	7800
20	3	3	3	2.63	9.59	100	3	5400
21	5	5	2	3.18	9.93	100	3	5400
22	7	7	7	2.91	8.56	100	2	3600
23	5	5	3	--	--	--	-	----
24	5	5	3	3.62	10.86	100	3.3*	6000
25	8	7	5	--	--	--	3	5400
26			not applicable					
27	8	8	5	3.58	18.66	100	4	7900
28	18	18	16	--	--	--	4	----
Average	5.23**	4.92**	3.85**	2.54	7.84	92.8	2.89**	5905
std. error	1.42**	1.41**	1.59	0.79	3.83	9.80	0.67**	1308

* use of shoulder lane allowed during peak period
** excludes data for system 28

rence under poor (bad weather or darkness) versus normal operating conditions were inconclusive. The data indicated that the time of occurrence of an incident within a peak period can be assumed to be uniformly distributed over a peak period. The locations of high incident frequency were found to be system-specific. The percent capacity reduction created at the site of an incident is given in Table 7, and the duration of incidents is given in Table 8.

Capacity Reduction

The magnitude of capacity reduction because of inclement weather or reduced visibility (i.e., darkness) was dependent on geographic location.

Control Logic and Equipment

Of the 26 applicable systems, 12 used the local responsive control mode, and 12 used the system control mode. It is noteworthy that the use of the pretimed mode is very limited and with application primarily to isolated ramps. Metering rate update periods vary from 0.5 to 3.0 min. In order of decreasing popularity, occupancy, volume, and speed are the main lane parameters used by the control logic; various control logics are used. Time-of-day is the predominant measure of when to turn a system on and off, but it is frequently coupled with a secondary measure such as occupancy.

BASELINE FREEWAY

As a result of questionnaire interpretation, the baseline freeway was determined to have the following characteristics:

1. Three main lanes throughout. The distance between

TABLE 5

METERED ON-RAMP-GEOMETRICS

System No.	No. Metered On-Ramps 1-lane	2-lane	Average Merge(ft.)	Average Storage(veh)
1	6	0	292	22.5
2	3	0	327	16.3
3	4	0	335	12.8
4	4	0	663	23.0
5	2	1	367	20.0
6	4	1	320	24.0
7	4	0	450	21.0
8	2	1	400	47.0
9	3	3	350	41.0
10	4	0	500	21.0
11	3	1	249	41.5
12-14	16	0	142	17.8
15-16	12	0	127	20.2
17	0	4		40.0
18&20	8	0	151	
19&21	10	0	232	13.9
22	7	0	204	17.1
23	5	0	126	17.0
24	3	2	535	47.0
25	insufficient data			
26	not applicable			
27	8	0	294	21.8
28	18?	0?	324	23.1
		mean	319	25.4
		std. error	142	11.1

TABLE 6

AVERAGE O-D TABLE; % EXITING AT OFF-RAMP

		Off-Ramps 1	2	downstream 3	4
(upstream)	On-Ramp 1	7.0%	8.0%	9.0%	10.0%
	On-Ramp 2	0	7.5%	11.0%	12.0%
	On-Ramp 3	0	0	7.0%	8.0%
	On-Ramp 4	0	0	0	6.7%
(downstream)	On-Ramp 5	0	0	0	0

TABLE 7

CAPACITY REDUCTIONS DUE TO INCIDENTS

Incident-Type	Fraction of All Types of Incidents	% Capacity Reduction by No. of Freeway Lanes 2	3	4	5
Vehicle/Persons on Shoulder or Median	0.48 (±0.38)	25.0% (±8.67%)	16.0% (±5.48%)	10.7% (±4.04%)	--*
One-Lane Blockage	0.45 (±0.37)	67.5% --*	46.8% (±4.60%)	44.0% (±9.62%)	25.0% --*
Two-Lane Blockage	0.053 (± .044)	100% --*	78.3% (±5.77%)	66.3% (±6.29%)	50% --*

* Insufficient data; two or less data points.

TABLE 8

DURATIONS OF INCIDENTS

Incident-Type	Fraction of All Types of Incidents	Minutes to Complete Clearing of the Incident
Vehicle/Persons on Shoulder or Median	0.48 (±0.38)	21.9 min. (± 9.03 min.)
One-Lane Blockage	0.45 (±0.37)	18.2 min.* (±13.8 min.)
Two-Lane Blockage	0.053 (±0.044)	23.6 min.** (±18.0 min.)

* First 5-10 minutes usually involves clearing the incident to the shoulder.

** First 10-15 minutes usually involves clearing the incident to the shoulder.

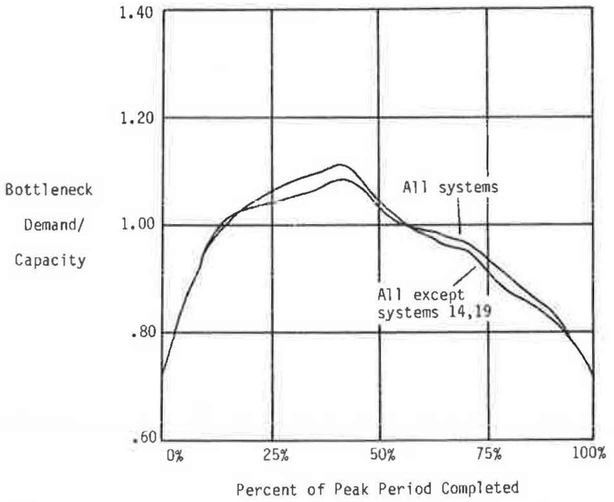


Figure 1. Average bottleneck demand curves—AM, inbound systems.

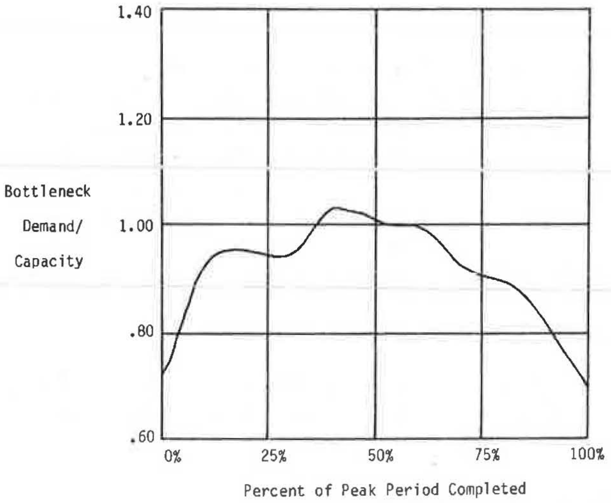


Figure 2. Average bottleneck demand curves—PM, outbound systems.

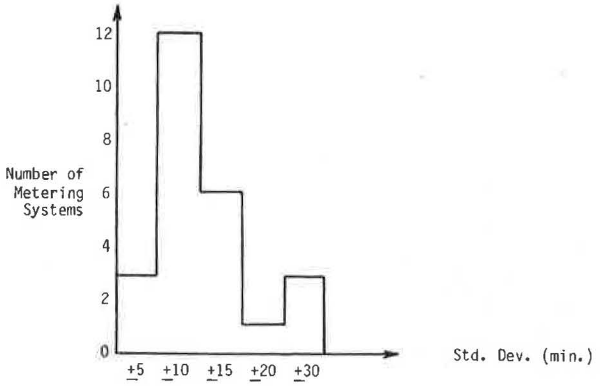
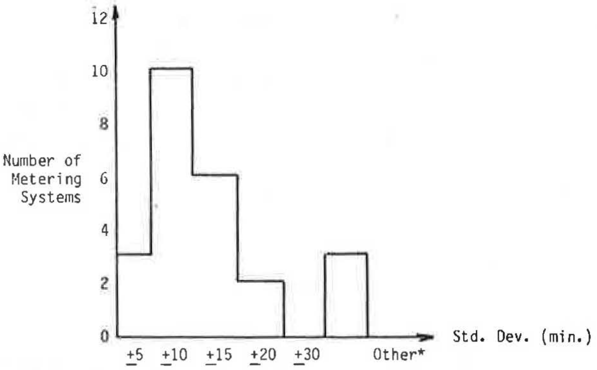


Figure 3. Reported variation in start-time.



*Minneapolis reports that snow conditions can lengthen the peak period by 50-60 minutes.

Figure 4. Reported variation in end-time.

the upstream-most on-ramp and the downstream-most on-ramp is 2.54 miles, or 13,411 ft.

2. Five metered on-ramps and 4 off-ramps. The on- and off-ramps alternate.

3. The 5 on-ramps are assumed to be uniformly spaced, at 3,353 ft apart. The 4 off-ramps are assumed to be located such that each is approximately 1,240 ft upstream of an on-ramp. Data concerning off-ramp locations were not included in the questionnaire survey; however, the average value of 1,240 ft was obtained from maps supplied by many of the agencies surveyed.

4. The "bottleneck" section is the freeway section immediately downstream of the downstream-most ramp. The "bottleneck" is due to an accumulation of demand rather than that due to geometrics. It has a baseline capacity of 5,782 vph (the average capacity of a 3-lane section—as computed from the survey data).

5. The merge distance (meter to ramp nose) for each on-ramp is assumed to be the survey average of 393 ft. The vehicle storage capacity of each on-ramp is assumed to be the survey average of approximately 26 vehicles.

6. Each on-ramp has 1-lane metering.

7. A shoulder, of at least 4 ft width, is assumed to exist for the entire length of the baseline system.

To transform these physical characteristics into the data base structure of the FREFLO simulation model, the baseline freeway was divided into nine sections. Two additional sections were specified, one at the upstream end of the freeway and one at the downstream end of the freeway, to contain congestion effects and to provide freely flowing traffic at the system boundaries (A FREFLO requirement). The resulting 11-section baseline freeway is shown in Figure 5.

DEMAND SENSITIVITY OF INCREMENTAL BENEFITS

In the initial set of FREFLO simulation studies conducted, it was found that the magnitudes of the incremental benefits of the responsive modes, relative to pretimed control, were sensitive to the composition of freeway demand. A principal effect was that, for a given freeway, the larger the mainline input demand, the smaller the incremental benefits. This is not surprising; as the mainline demand becomes larger, the maximum allowable metering rates become smaller. Accordingly, the permissible metering rates for the responsive modes become more and more constrained and the metering functions more and more like pretimed control. Conversely, as mainline input demand becomes smaller, more traffic can be allowed onto the freeway from the on-ramps. This means that the ramp metering can expect greater control over the quality of the freeway traffic flow. Hence, it is not surprising that larger incremental benefits for the responsive ramp control modes were found for this case.

Because the incremental benefits were found to be highly sensitive to the relative sizes of mainline input demand and on-ramp demand, it was decided that the benefits would be developed as functions of one or more parameters that described the interplay of the two types of traffic demand.

Two parameters were adopted as being measures, for any given freeway, of the degree-of-control that was possible with the responsive control modes. These are discussed in the following two sections.

Controllability Level

The first measure is similar to one suggested, during the course of the project, by Newman of the NCHRP 3-22A project panel. This measure, called "Controllability Index," is defined by:

$$\text{Controllability Level} = \frac{\text{Total metered input with pretimed control} - \text{Total metered input when the minimum metering rates are used}}{\text{Total metered input when the minimum metering rates are used}}$$

This (normalized) measure is obviously an indicator of how much the responsive control can vary metering rates (at least in the direction of decreasing the metering rates). The measure can also be computed from information that will be available once the user of the guidelines has developed:

1. A basic pretimed metering plan for the freeway be-

ing studied. The user must develop this plan for two reasons: (a) so that a further traffic engineering check can be made on the feasibility of (any mode of) ramp control, and (b) so that the basic highway users' costs can be computed for later use in determining the incremental benefits of the responsive control modes.

2. The constraints that apply to the ramp control. In particular, it is necessary to establish the minimum permissible metering rate for each ramp.

Controllability Cases

In the FREFLO simulation studies that were conducted, three basic freeway demand patterns were simulated for the baseline freeway of Figure 5. They were:

1. A "low controllability" scenario with a low on-ramp demand relative to mainline input demand. As its name suggests, there is little flexibility available for the metering rates.
2. A "medium controllability" scenario with a high on-ramp demand relative to mainline input.
3. A "high controllability" scenario with a high on-ramp demand relative to mainline input. As its name suggests, there was quite a large range available for metering rates.

A basic pretimed metering plan was developed for the baseline freeway for each of the three controllability cases identified above. These three basic metering plans were each designed to provide nearly the same level of service for the baseline freeway's mainline and to maintain ramp queues within the available ramp storage capacity. The characteristics of these three scenarios are given in Table 9.

TABLE 9

CHARACTERISTICS OF THE THREE CONTROLLABILITY LEVEL SCENARIOS

Scenario	Mainline Input (veh)	On-Ramp Demand (veh)	Pretimed Metered Input (veh)	Minimum Input* (veh)	Controllability Index	On-Ramp Portion of Demand
Low Controllability	11,500	4,900	3,810	2,825	0.35	0.30
Medium Controllability	11,200	7,000	5,970	2,825	1.11	0.38
High Controllability	10,400	9,100	8,070	2,825	1.86	0.47

* Average of about 190 vph per on-ramp.

INCREMENTAL TRAVEL-TIME BENEFITS OF THE RESPONSIVE RAMP CONTROL MODES

This section gives the graphical results for the travel-time benefits arising from different types of demand and capacity variations.

Incremental Travel-Time Benefits During Incidents

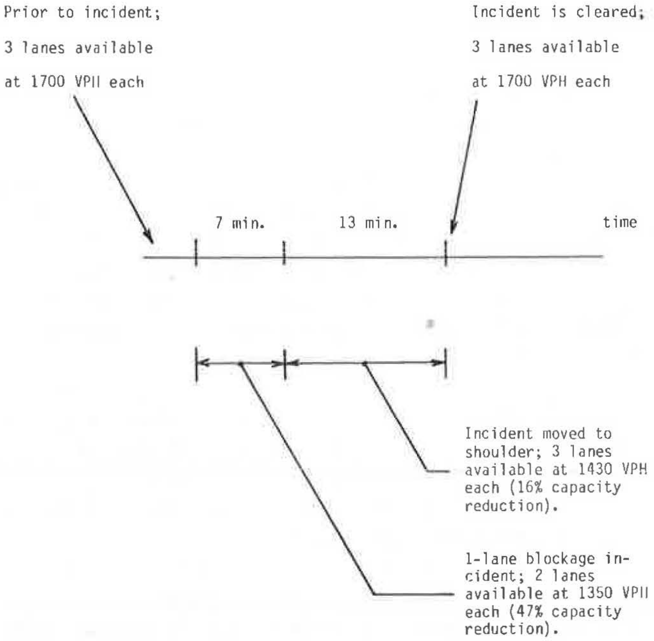


Figure 6. Nominal incident in simulation studies.

A typical incident, defined from survey data, was a 1-lane blockage type of incident having the characteristic shown in Figure 6. Figures 7, 8, and 9 show the incremental travel-time savings (relative to pretimed control) of the two responsive control modes during such a typical incident. The results are shown when the incident occurs early, at mid-peak, and late within the peak period. From Figures 7, 8, and 9 it can be seen that system control provides larger benefits than local actuated control. This is attributed to the fact that system control responds immediately to the incident—allowing metering rates to increase downstream of the incident and to decrease upstream of the incident. However, with local actuated control, the metering rate changes will be delayed an amount of time related

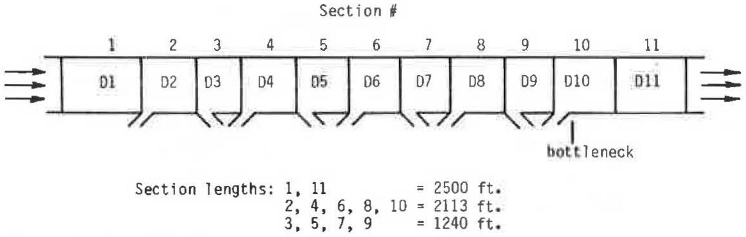


Figure 5. Baseline freeway.

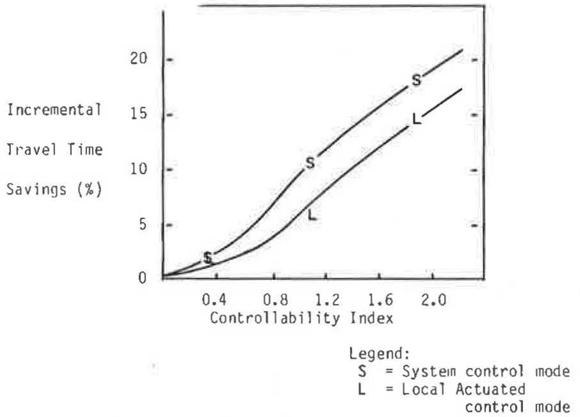


Figure 7. Incremental travel-time benefits; early incident.

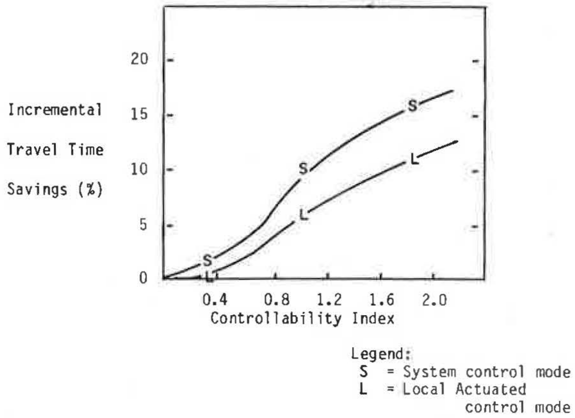


Figure 8. Incremental travel-time benefits; mid-peak incident.

to the speed of traffic (downstream) and the speed of the congestion shock wave (upstream) and the distances between ramps. Also, the benefits of both modes are greatest for an early incident and least for a late incident. This is attributed to the fact that, early in the peak, demand is increasing—causing the mainline queuing delay created with pretimed control to increase more rapidly and to persist for a longer time than had the incident occurred later in the peak period. The benefits of both modes are greater for freeways of high controllability. This follows directly from the definition of controllability.

The effects of an incident's location, duration, and severity on incremental travel-time benefits are shown in Figures 10, 11, and 12. Figure 10 shows the effect of incident location. Figure 11 shows the effect of incident duration. Figure 12 shows the effect of incident severity. Collectively, it was found that as expected, the incremental benefits increase (for both modes) with increasing severity and duration of an incident. The effect of incident location is more subtle. First, the incremental benefits are least for an upstream incident, and the travel-time performance of either responsive mode is not much better than that of pretimed control. This is because the mainline queuing upstream of the incident creates far more delay than is saved (via the responsive modes) downstream of the incident; and, because the incident occurs upstream of all but one metered ramp, the responsive control can do little to affect the travel time. Secondly, system control provides larger benefits the more downstream the incident is located. This is attributed to the ability of system control to decrease all metering rates upstream of an incident as soon as the incident occurs, so that the savings in mainline queuing delay will be greater the greater the length of metered freeway upstream of the incident. Thirdly, local actuated control has a unique behavior in relation to the location of an incident. Unlike system control, it yields a larger travel-time benefit for a "middle" incident than for a "downstream" incident. This is apparently due to the time-delay that occurs before the ramps upstream of an incident can react to the incident; the more control ramps there are upstream of the incident, the more detrimental this time-delay effect is to mainline queuing delay. System control provides larger benefits than local actuated control, although the difference in the benefits becomes very small for upstream incidents, short-duration incidents, and incidents in which the reduction of mainline capacity is very severe. In these cases, the "immediate-response" advantage of system control is greatly diminished because either (1) the incident is upstream of the ramp control—hence, the "immediate-response" advantage is lost; (2) the incident is short-lived—so that the "immediate-response" advantage is held for only a short time; or (3) the mainline capacity reduction is so severe that mainline queuing moves upstream very rapidly—hence, reducing the "immediate-response" advantage of system control. The benefits of both modes are greater for freeways of high controllability in all situations regarding location, reduction, and severity of incidents.

It should be noted that all incidents treated in Figures 10, 11, and 12 are assumed to occur at mid-peak; Figures 7, 8, and 9 show the effect of time-of-occurrence of an incident.

Incremental Travel-Time Benefits During Peak Periods of Reduced Freeway Capacity

Table 10 gives the characteristics of minor, moderate, and major capacity reductions. Figures 13, 14, and 15 show the incremental travel time savings (relative to pretimed control) of the two responsive control modes during such capacity reductions. It can be seen from Figures 13, 14, and 15 that the benefits of system control and local actuated control are essentially the same. Since the capacity reduction is assumed to apply to the entire length of freeway being metered, the "immediate response" capability of system metering gives it no advantage over local actuated control. The incremental travel-time benefits of the two responsive modes are the greatest for a moderate (10 percent) capacity reduction. A major (20 percent) capacity reduction produces such severe mainline congestion that all three control modes have about the same performance; in practice, ramp metering is normally turned off when this condition exists. A minor (5 percent) capacity reduction does not lead to a breakdown in freeway traffic flow with pretimed control (at least for the demand

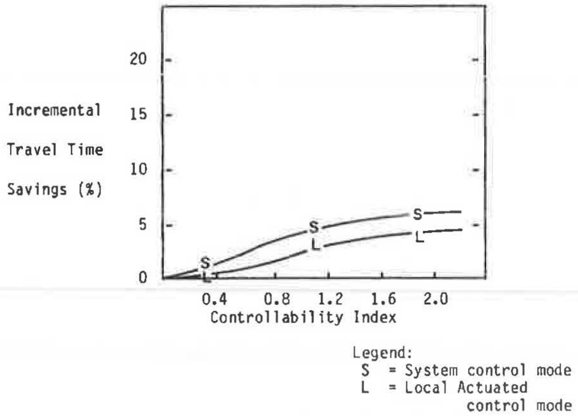


Figure 9. Incremental travel-time benefits; late incident.

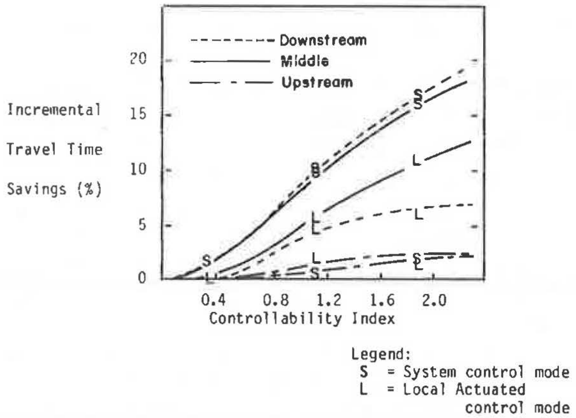


Figure 10. Effect of incident location on incremental travel-time benefits.

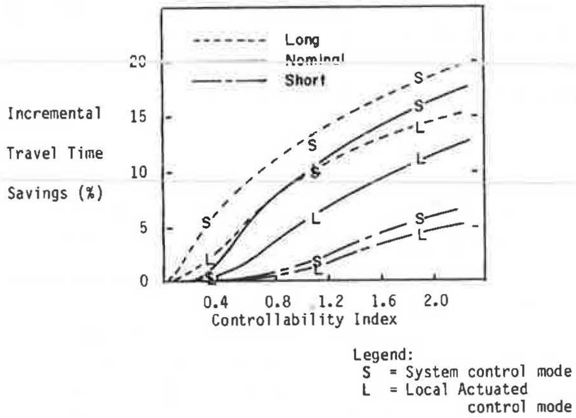


Figure 11. Effect of incident duration on incremental travel-time benefits.

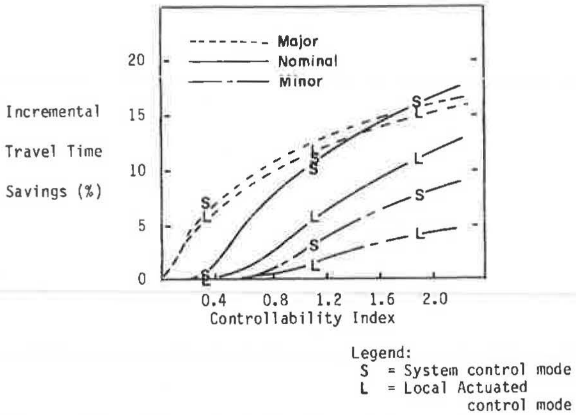


Figure 12. Effect of incident severity on incremental travel-time benefits.

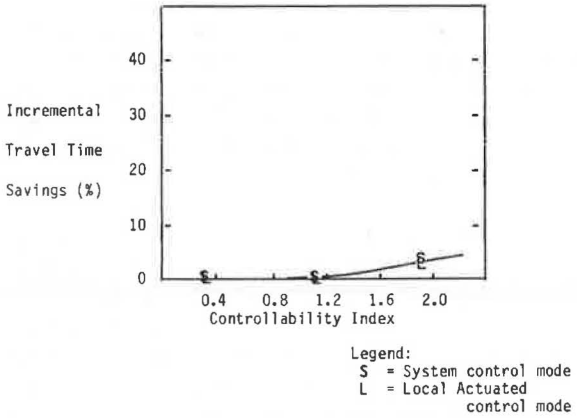


Figure 13. Incremental travel-time benefits; major capacity reduction (20%).

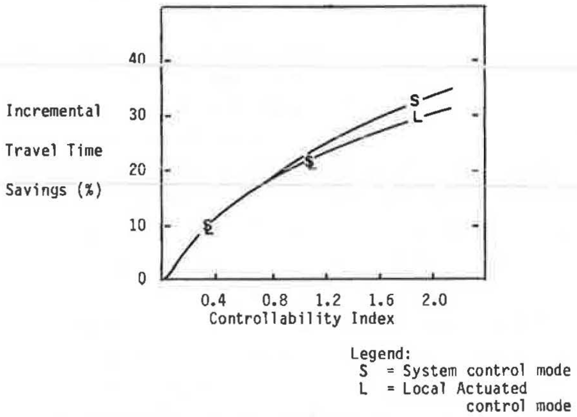


Figure 14. Incremental travel-time benefits; moderate capacity reduction (10%).

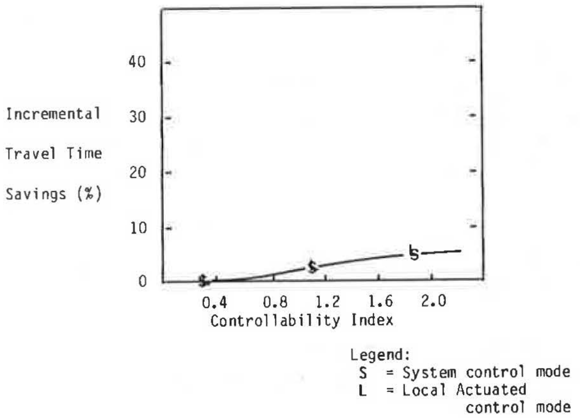


Figure 15. Incremental travel-time benefits; minor capacity reduction (5%).

TABLE 10

MAGNITUDES OF FREEWAY CAPACITY REDUCTIONS IN SIMULATION STUDIES *

Magnitude of Capacity Reduction	Specifications for Simulating Study
Minor Reduction	A 5% capacity reduction; for the baseline freeway, the per-lane capacity drops from 1700 vph to 1615 vph.
Moderate Reduction	A 10% capacity reduction; for the baseline freeway, the per-lane capacity drops from 1700 vph to 1530 vph.
Major Reduction	A 20% capacity reduction; for the baseline freeway, the per-lane capacity drops from 1700 vph to 1360 vph.

* Freeway was assumed to operate at reduced capacity for the entire peak period.

scenarios studied). The moderate (10 percent) capacity reduction was, however, sufficient to create breakdown in freeway traffic flow for a portion of the peak period when pretimed control was in effect; hence the largest incremental benefit occurred in this case because the responsive modes prevented breakdown.

Incremental Travel-Time Benefits During a Peak Period That Has Both an Incident and a Freeway Capacity Reduction

The two previous sections discussed the effects of incidents and capacity reductions when each situation occurs separately from the other. Figure 16 shows the effect of the responsive modes on the incremental travel-time benefits when the freeway is operating at a moderate (10 percent) capacity reduction and a typical mid-peak incident also occurs. Referring to Figures 8 and 14, and comparing them to Figure 16, it is seen that the incremental benefits during a combined incident and capacity-reduction case are about mid-way between the benefits of the separate cases. That is, the incremental benefits are slightly less than those occurring for a capacity-reduction alone, and slightly greater than those occurring for an incident alone. These results are attributed to: (1) with the combined events there will be a significant portion of the peak period in which the breakdown of freeway traffic flow will occur regardless of which of the three control modes is in operation—in this case, the incremental benefits will be less than those of the capacity-reduction alone, and (2) with the combined events, the benefits of responsive control accrue over the entire 3-hour peak period and not solely during the interval of the incident—hence, the incremental benefits will be larger than those of an incident alone.

As was the case in the previous situations, the incremental benefits of the responsive control modes are greater the higher is the freeway's controllability.

Incremental Travel-Time Benefits Arising From Demand Variations

Figures 17, 18, and 19 show the incremental travel-time savings (relative to pretimed control) of the two responsive control modes during demand variations. Figure 17

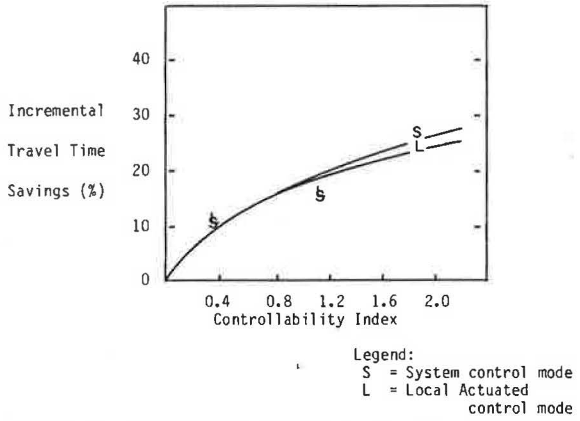


Figure 16. Incremental travel-time benefits; typical incident during a moderate (10%) capacity reduction.

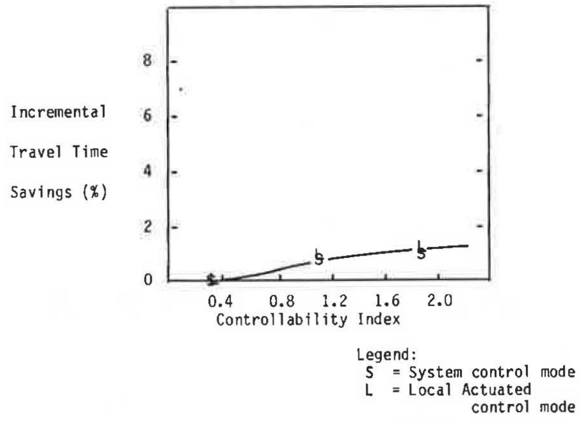


Figure 17. Incremental travel-time benefits; typical increase in peak period demand.

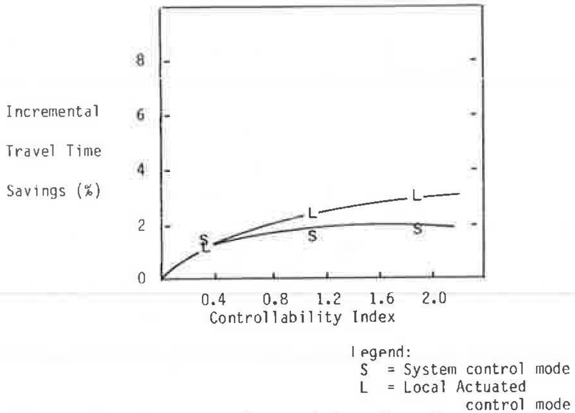


Figure 18. Incremental travel-time benefits; typical decrease in peak period demand.

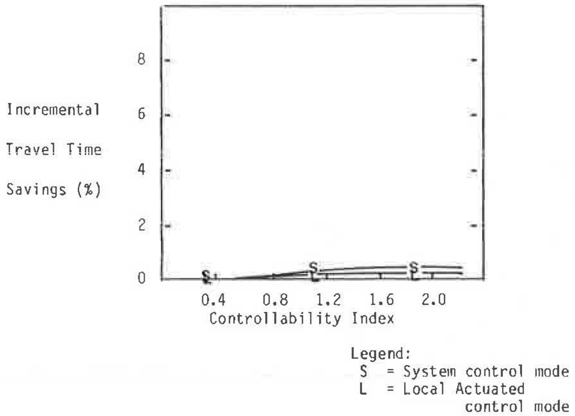


Figure 19. Incremental travel-time benefits; typical demand fluctuations during peak periods.

shows the effect of an upward shift in freeway demand. Figure 19 shows the effect of short-term fluctuations in mainline input to the metered freeway. It is seen that the effects of all types of demand variations are much smaller than the effects, previously shown, of incidents and capacity reductions. At least this is the case of typical magnitudes (about ±5 percent) of demand variations. All demand variations yield incremental travel time benefits of at most 2 or 3 percent.

Although they are small, slightly greater benefits occur during a shift downward in demand than during a shift upward in demand. Ramp delay increases proportionately more than mainline delay is reduced when an upward shift occurs, whereas the opposite is true for a downward shift. The effect of random fluctuations in mainline input is almost negligible. As before, the incremental benefits are greater the higher is a freeway's controllability.

INCREMENTAL FUEL-CONSUMPTION BENEFITS OF THE RESPONSIVE RAMP CONTROL MODES

The incremental fuel consumption benefits of the responsive ramp control modes are orders of magnitude less than the travel-time benefits. A discussion of the incremental fuel consumption benefits is given in Appendix C.

INCREMENTAL VEHICLE EMISSIONS BENEFITS OF THE RESPONSIVE CONTROL MODES

The incremental vehicle emissions benefits of the responsive ramp control modes can be quantified but, in general, cannot be monetized. A discussion of the incremental vehicle emissions benefits is given in Appendix D.

COSTS OF ENTRANCE RAMP CONTROL INSTALLATIONS

The cost of installing entrance ramp controls is a highly variable area that cannot be specifically determined until the bids are received for a particular installation. Prices vary according to geographic area, and the dearth of recent installations over a wide geographic area create data biases. The research approach was to enumerate the various components that are required for a typical installation and obtain cost estimates of these items. Naturally, this is the standard procedure that any agency follows in estimating the costs of an installation.

Typical 1980 cost estimates are cited in Glazer and Ross (*4*). The guidelines provide a checklist of the items that are typically required in an entrance ramp control installation. These items are grouped by subsystem, and subsystem costs are expressed as a percentage of the total system cost. On a per ramp basis, the average costs in 1980 are expected to be: pretimed mode, $16,000/ramp; local actuated mode, $20,000/ramp; and system mode, $32,000/ramp (exclusive of interconnection).

CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATIONS

The research findings have resulted in the structure of a logical procedure for the practicing traffic engineer to follow in the preliminary decisions involved in installing a new entrance ramp control system or in upgrading an existing one. This step-by-step procedure is presented in Appendix E. The curves used in the guidelines to indicate relative travel-time savings, reduction in fuel consumption, and reduction in vehicle emissions are an amalgam of the curves presented in Chapter Two and Appendixes C and D.

The incremental, nonbasic user benefits attributable to local actuated or system modes of control have heretofore been unresearched. The results produced by the simulation model are quite reasonable in terms of matching predicted values.

These incremental benefits alone are but a component of a selection system that is a traffic management decision process. The macroscopic components of this decision process are:

- Decision Level 1—Basic Analysis of Freeway Operation.
- Decision Level 2—Detailed Analysis of Freeway Operation and Selection of Improvement Alternatives.
- Decision Level 3—Determining Feasibility of Ramp Control as Improvement Alternative.
- Decision Level 4—Analysis of Site Variables and Mode Selection.

Decision level 1 is concerned with monitoring congestion levels with studies and estimates that are routinely made by the agency in charge of freeway traffic operations. The procedure is abbreviated and is concerned with obtaining an estimate of the user costs of the freeway operation. If user costs are found to be excessive, the next decision level is entered.

Decision level 2 develops a more detailed analysis of freeway operation. The studies involved would generally be more comprehensive than normal ongoing studies and, thus, would require specific budgeting. The purpose of these studies is to provide data for an evaluation of improvement alternatives. One of these alternatives is ramp control.

Decision level 3 is used to establish the feasibility of an entrance ramp control system. The data previously gathered should be sufficient to conduct the necessary bottleneck, geometric, traffic diversion, accident, enforcement, public acceptance, and preliminary cost analyses. If feasibility is established, the next detailed level is entered for a final analysis of mode choice.

Decision level 4 similarly utilizes the detailed freeway operation data. A pretimed metering plan is formulated to develop the basic user costs. The variables sensitive to control mode are analyzed to develop nonbasic user benefits. Together, these costs and benefits are used in the benefit-cost analysis (tangible benefits) and in the utility-cost analysis (intangible benefits). The user is thus able to determine the most effective entrance ramp control installation or incremental modification for given freeway conditions.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

Guidelines have been developed on the benefits of local actuated and system control, relative to pretimed control. The guidelines develop a detailed procedure by which the planner of a ramp control installation can estimate the incremental benefits of responsive controls relative to pretimed control. The procedure is simple to use, being based on readily understood tabular and graphical data. The procedure has been illustrated, throughout, for a hypothetical freeway ramp metering project.

The basic benefits offered by the pretimed control versus no control are increased operating speeds, greater throughput (vehicles per hour per lane), reduced travel times, and reduction of the number of occurrences of incidents. Beyond this, the monetized incremental benefits are dominated by travel-time savings; monetized fuel-consumption savings are about five to ten times less than the travel-time savings. Incidents, poor freeway operating conditions, and shifts (from one day to another) in the level of freeway traffic demand are the principal factors affecting the benefits of traffic responsive metering logics.

The demand growth over the lifetime of a ramp-metering project reduces the incremental benefits of the responsive control modes. The planner of a ramp control installation should be alert to this effect.

Throughout the analysis developed in this report, it has been assumed that the ramp control equipment operates free from malfunction. It is therefore essential that the planner provide, among the project costs, a sufficient amount for equipment maintenance. Otherwise, the benefits will be overstated and the costs assumed by the planner will be understated, making the responsive modes appear more cost-effective than they actually are.

The accident reduction benefits of responsive ramp controls have not been estimated in this report. There may well be some such benefit, but no attempt was made to quantify it. Figures reported from various projects using responsive ramp control indicate a range from 10 to 33 percent reduction.

SUGGESTED RESEARCH

Areas recommended for further research are:

1. The effect of traffic demand growth, over the lifetime of a ramp control project, on the relative benefits of the three ramp control modes.
2. The effects of equipment malfunctions on the incremental benefits of local actuated and system control relative to pretimed control. Vehicle detector and ramp controller malfunctions and inadequate maintenance practices all act to reduce the incremental benefits. How are the benefits, the level of maintenance effort, and the basic reliability of the equipment related?
3. The effects of bus and carpool priority treatment, when integrated with ramp control, on project costs and benefits.
4. The effects of changing vehicle mix, size of vehicles, and passenger occupancies on control strategies and mode selection.
5. The effect of fuel availability and escalating costs on mode selection.

REFERENCES

1. Blumentritt, C. W., et al., "A Summary of Variables and Benefits Accruing to Ramp Control." NCHRP Project 3-22A, *Report RF 3507-1,* Texas Transportation Institute, Texas A&M University (Sept. 1978).
2. Ross, D. W., and Glazer, J., "Study of the Benefits of Traffic-Responsive Methods of Freeway Ramp Metering." NCHRP Project 3-22A, Subcontract P700118 Task III Report, Daro Associates, Menlo Park, Calif. (June 1979). Loan copy available on request to NCHRP.
3. Goodwin, D. N., Miller, S. D., and Payne, H. J., "MACK: A Macroscopic Simulation Model of Freeway Traffic." Technology Service Corporation (July 1974).
4. Glazer, J., and Ross, D. W., "Costs of Freeway Ramp Metering." NCHRP Project 3-22A, Subcontract P700118 Task I Report, Dara Associates, Menlo Park, Calif. (June 1979).
5. Masher, D. P., et al., "Guidelines for Design and Operation of Ramp Control Systems." NCHRP Project 3-22 Final Report (Dec. 1975). Loan copy available on request to NCHRP.
6. Everall, P. F., "Urban Freeway Surveillance and Control: The State of the Art." U.S. Department of Transportation, Federal Highway Administration, Washington, D.C. (Nov. 1972).

APPENDIX A

QUESTIONNAIRE . . .

A REQUEST FOR DATA AND INFORMATION
ON OPERATING
FREEWAY RAMP METERING SYSTEMS

For: National Cooperative Highway Research Program Project 3-22A,
Guidelines for Design and Operation of Ramp Control Systems

Prepared by: Texas Transportation Institute,
and Daro Associates

April, 1978

INTRODUCTION AND INSTRUCTIONS

Your agency has been identified as one that operates one or more freeway ramp metering installations. We would appreciate your assistance in helping us to compile design and operating characteristics of ramp control systems. This compilation will be instrumental in our research efforts on Project 3-22A, Guidelines for Design and Operation of Ramp Control Systems, sponsored by the American Association of State Highway and Transportation Officials.

The objective of this research is to develop an analytic procedure and guidelines for comparative evaluation of alternative ramp control system designs. The procedure and guidelines will be applicable to determining whether or not ramp control can be employed beneficially and, if so, the type of control system that is most appropriate for a given application. Three basic types of control systems are considered: (1) local pretimed ramp control, (2) local responsive control, and (3) systemwide control.

The purpose of this data request is to assess the variety of designs and traffic conditions attendant to operating ramp control systems. You will notice that many of the questions in Part One are seeking information on the ranges of variations in traffic flows and on the frequency and severity of random events such as incidents or inclement weather. It is essential that the Guidelines reflect the variety of these conditions in establishing the relative merits of the three types of ramp control.

This data request is divided into two parts. Part One should be

completed by all agencies, and concerns information on the traffic, freeway design, and other factors that form the operating environment for the ramp control system. Part Two should, in addition to Part One, be completed by those agencies that operate a local responsive ramp control system or a systemwide control system. These two ramp control systems are defined as:

local responsive control: a basic class of ramp metering that is a function of actual traffic conditions during the time of the metering. The control for each on-ramp is based on traffic measurements made only in the vicinity of that on-ramp.

systemwide control: a basic class of ramp metering that is a function of actual traffic conditions during the time of the metering. The control for each on-ramp is based on systemwide traffic measurements, including those taken a considerable distance away from that on-ramp.

In completing this data request, you should confine your answers to a single freeway ramp control system* in your locale; that is, your answers should not be generalized to a whole urban area. Therefore, if your agency has many ramp control systems in operation, we ask you to complete separate copies of this data request for as many separate ramp control systems as you can. To this end, we are supplying the number of separate data request sets that you indicated in our previous telephone conversation. Recall that we need separate data for each system consisting of one direction of traffic flow.

---

* Here a "single" ramp control system is understood to be a length of freeway (one direction) and an adjoining set of ramps that have logically been considered as a unit during both the planning for and implementation of the ramp control system.

It would be most helpful if, in answering this questionnaire, you:

1. Try to answer as many questions as possible - yet feel free to leave questions blank if the data are unavailable or if you cannot make an estimate or "guesstimate."
2. Estimates or "guesstimates" are encouraged. Even if you have limited data for answering a given question - feel free to make an estimate. However, please signify an estimate by circling it; on the contrary, do not circle data that are substantiated by data records.

Thank you for your assistance; we hope to receive a reply from you in the next few weeks.

PART ONE

OPERATING ENVIRONMENT
OF THE
RAMP CONTROL SYSTEM

I. GENERAL INFORMATION FOR THE RAMP METERING INSTALLATION

1. Name (if any) of installation: ____________
2. Location of installation: City ____________
State ____________
Freeway Name or Route No. ____________
3. Operating Agency: ____________
4. Responsible Traffic Engineer: Name: ____________
Tel. No.: ____________
Address: ____________
5. Date that metering first went into operation:
Month/Year: ____________
6. Type of traffic metered: Inbound to CBD ______
Outbound from CBD ______
Other (describe) ______
7. Direction of traffic flow (check one):
Ebd ____ Wbd ____ Nbd ____ Sbd ____
8. Usual hours of day, days of week for ramp metering:
Hours: ____________ to ____________
Days (check): Sun M T W Th F Sat
9. Please list any reports or descriptive material that have been prepared on this ramp metering installation (report copies would be appreciated):

II. FREEWAY GEOMETRICS

1. Freeway Mainline:

Freeway Lanes, Ramp Spacing, Grades, and Location of Metered or closed ramps: if possible, please furnish maps with the data shown in Figure A-1; otherwise, provide a sketch similar to Figure A-1 in the space provided beyond that Figure.

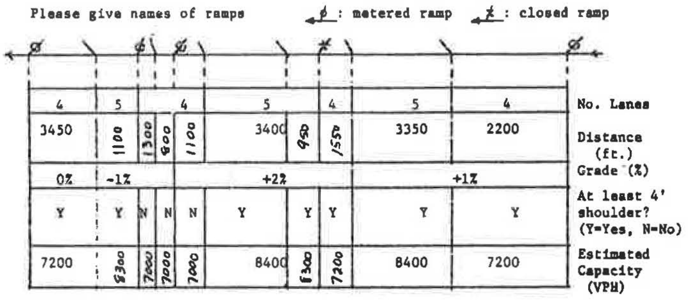


Figure A-1 Example Sketch of Freeway Mainline Geometrics

2. On-Ramps:

Number the metered on-ramps consecutively: 1,2,3, --- starting with the one farthest upstream. For each numbered on-ramp, please fill in Table A-1.

III. AVERAGE PEAK PERIOD DEMAND AND ORIGIN-DESTINATION PATTERN

1. Freeway Demand:

Please provide the approximate cumulative volume (number of vehicles) of traffic entering at each on-ramp and at the mainline input - as a function of time - for an average metered peak period. Table A-2 is provided for these data. Note that on-ramp demand is defined as that traffic entering the on-ramp, not the metered volume.

If you have on-ramp demand data in another form (graphs or other tabulations) and prefer to provide copies of your existing data -- please feel free to do so.

2. Exit Volumes:

Also, please provide the approximate cumulative volume of traffic leaving via the downstream end of the metered freeway as well as via the exit ramps (exit ramps are numbered consecutively, starting with the most upstream off-ramp). Table A-3 is provided for these data.

Again, if you have exit volume data in another form (graphs or other tabulations) and prefer to provide copies of your existing data -- please feel free to do so.

3. Origin-Destination Information:

If available, please indicate the approximate average percentage of each on-ramp's volume and the mainline input volume

TABLE A-1 ON-RAMP GEOMETRICS

upstream ↓ downstream

On-Ramp No.	Distance, Ramp Meter to Nose (ft.)	Non-Priority Metering		Priority Treatment*	
		No. of Lanes	Storage Capacity Prior to Ramp Meter (vehs.)	Metered Lane	Bypass Lane
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					

* Place a check mark in the appropriate column if there is any priority treatment of buses or carpools.

TABLE A-2 ACCUMULATED TRAFFIC VOLUMES (VEHICLES) FOR AN AVERAGE PEAK PERIOD

upstream → downstream

Vehicle Entry Point	Time During Peak Period*														
	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.
Mainline Input															
On-ramp 1															
On-ramp 2															
On-ramp 3															
On-ramp 4															
On-ramp 5															
On-ramp 6															
On-ramp 7															
On-ramp 8															
On-ramp 9															
On-ramp 10															
On-ramp 11															
On-ramp 12															
On-ramp 13															
On-ramp 14															
On-ramp 15															

* Record the accumulated vehicle count at each entry point at the different points in time during an average peak period. (It is desirable to have 15-minute counts - although it is not necessary.)

TABLE A-3 ACCUMULATED EXIT VOLUMES (VEHICLES) FOR AN AVERAGE PEAK PERIOD

upstream → downstream

Vehicle Exit Point**	Time During Peak Period*														
	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.	Time: Vehs.
Off-ramp 1															
Off-ramp 2															
Off-ramp 3															
Off-ramp 4															
Off-ramp 5															
Off-ramp 6															
Off-ramp 7															
Off-ramp 8															
Off-ramp 9															
Off-ramp 10															
Off-ramp 11															
Off-ramp 12															
Off-ramp 13															
Off-ramp 14															
Off-ramp 15															
Downstream Mainline															

* Record the accumulated vehicle count at each exit point throughout the peak period (it is desirable to have 15-minute counts - although it is not necessary).

** While the table allows up to 15 off-ramps, cross out any unused entries for this table.

that exits at each off-ramp and at the downstream end of the metered freeway during a peak period. Table A-4 is provided for these data.

If you have origin-destination data in another form and prefer to provide copies of your existing data -- please feel free to do so.

TABLE A-4 ORIGIN DESTINATION PERCENTAGES*

DESTINATIONS

upstream → downstream

ORIGINS	Off-Ramp No. 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Downstream End
Mainline Input (upstream)																
On-ramp 1																
On-ramp 2																
On-ramp 3																
On-ramp 4																
On-ramp 5																
On-ramp 6																
On-ramp 7																
On-ramp 8																
On-ramp 9																
On-ramp 10																
On-ramp 11																
On-ramp 12																
On-ramp 13																
On-ramp 14																
On-ramp 15 (downstream)																

upstream → downstream

* Percentage must sum to 100 for each row.

IV. VARIATION IN PEAK PERIOD DURATION

1. How much variation (one day to another) is there in the time at which a section of the metered freeway first reaches the operating condition for which you desire metering to begin? Would you say the standard deviation in this start of the peak period is (check one):

____ ± 5 minutes, one day to another?

____ ± 10 minutes?

____ ± 15 minutes?

____ ± 20 minutes?

____ ± 30 minutes?

____ Other: ________

What is the criterion for beginning metering?

2. Similarly, how much variation (one day to another) is there in the time at which all sections of the freeway reach the level of service at which you desire metering to end? Would you say the standard deviation in this end of the peak period is (check one):

____ ± 5 minutes, one day to another?

____ ± 10 minutes?

____ ± 15 minutes?

____ ± 20 minutes?

____ ± 30 minutes?

____ Other: ________

What is the criterion for ending metering?

3. Are the start- and end-times for the peak period, as defined in questions (1) and (2) related? That is, if, on a given day, the start-time is later than usual - is the end-time also likely to be later than usual? Which statement most applies (check one and fill in the blank data):

____ There is no relationship between start- and end-time.

____ There is a slight chance (__%) that the end-time will be later than usual if the start-time was later than usual.

____ There is a good chance (__%) that the end-time will be later than usual if the start-time was later than usual.

____ There is a slight chance (__%) that the end-time will be earlier than usual if the start-time was later than usual.

____ There is a good chance (__%) that the end-time will be earlier than usual if the start-time was later than usual.

4. If you were to record the duration (end-time minus start-time) of a number of peak periods, how do you estimate they'd be distributed (fill in the blanks below)?

90% less than ____ hours ____ minutes

70% less than ____ hours ____ minutes

50% less than ____ hours ____ minutes

30% less than ____ hours ____ minutes

10% less than ____ hours ____ minutes

V. VARIATION IN PEAK PERIOD DEMAND

Data given in your answer to item 1 (Freeway Demand) of Section III could be summed up to obtain the total peak period demand (total vehicles desiring to use the metered freeway in a peak period). How variable is this total demand, from one day to another? Estimate its standard deviation (check one of the choices given):

____ ± 1% of the average total peak period demand

____ ± 5% of the average total peak period demand

____ ± 10% of the average total peak period demand

____ ± 20% of the average total peak period demand

____ Other (describe):

VI. SHORT-TERM VARIABILITY IN MAINLINE INPUT FLOW AND ON-RAMP DEMAND VOLUMES

The rate of flow, both entering and leaving the metered freeway, during short-time intervals within the peak period, is seldom constant. One measure of these short-term variations in flow is the so-called peak-hour factor (phf) -- defined as the ratio of the volume occurring during an hour to the peak rate of flow (expressed as an hourly volume) during a 5-minute interval within that hour. For instance, if the mainline input to a section reached a peak flow rate of 5,000 VPH in one 5-minute interval of an hour in which the total hour's flow was 4,000 VPH - then the phf would have been 0.80.

Estimate the phf for each of the freeway demands; Table A-5 is provided for these data.

TABLE A-5 FREEWAY DEMAND PEAK HOUR FACTORS*

	Entry Point	Estimated Peak Hour Factor
upstream	Mainline Input	
	On-ramp 1	
	On-ramp 2	
	On-ramp 3	
	On-ramp 4	
	On-ramp 5	
	On-ramp 6	
	On-ramp 7	
	On-ramp 8	
	On-ramp 9	
	On-ramp 10	
	On-ramp 11	
	On-ramp 12	
	On-ramp 13	
	On-ramp 14	
downstream	On-ramp 15	

* On-ramp demands are traffic volumes entering each ramp, not the metered volumes.

VII. INCIDENTS

1. Frequency of Incidents:

What is the estimated number of incidents that occur per year when the freeway is being metered: _____/year. Note: Incidents can include:

a. The presence of stopped vehicles due to an accident.
b. The presence of disabled vehicles due to mechanical failure, lack of fuel, etc.
c. Spilled vehicle loads.
d. The presence of an emergency or repair vehicle.
e. Vehicles or people on the freeway shoulder or median.

2. Effect of Inclement Weather and Reduced Visibility:

What is the estimated breakdown of this number of incidents into (fill in percentages):

____ % at times of inclement weather
____ % at times of reduced visibility (darkness)
____ % at normal times

3. Distribution of Peak Period Conditions

On an annual basis, what is the estimated breakdown of peak period operating time into (fill in percentages):

____ % time operating during inclement weather
____ % time operating with reduced visibility (darkness)
____ % time operating with normal conditions

4. Time of Occurrence Within Peak Period:

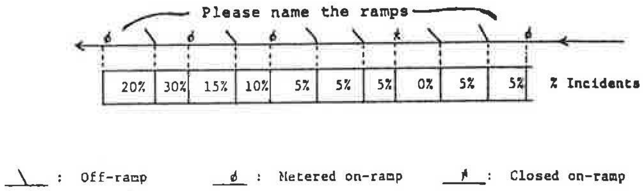
Estimate the percentages of peak period incidents that occur within each of the following portions of the peak period:

____ % between the start and 1/4-way through the peak period
____ % between 1/4- and 1/2-way through the peak period
____ % between 1/2- and 3/4-way through the peak period
____ % between 3/4-way through and the end of the peak period

5. Section Location of Incidents:

Please estimate the percentage of peak-period incidents that occur in each of the sections of the metered freeway. A sketch similar to Figure A-1 can be used to summarize these estimates. You may draw your own such sketch below the example sketch that is provided below.

Example:



6. Severity of Capacity Reduction:

Estimate the breakdown of incidents by type, and for each type estimate the percentage capacity reduction at the site of the incident:

Incident Type	% of Total	% Capacity Reduction
a. One-lane blockage due to minor accident or stall		on 3-lane section ____
		on 4-lane section ____
		on 5-lane section ____
		on 6-lane section ____
b. Two-lane blockage due to major accident		on 3-lane section ____
		on 4-lane section ____
		on 5-lane section ____
		on 6-lane section ____
c. Vehicles/people on shoulder or median		on 3-lane section ____
		on 4-lane section ____
		on 5-lane section ____
		on 6-lane section ____

7. Duration of Incidents:

Estimate the average length of time from the beginning of an incident to the time it is cleared:

Incident Type	Duration (Minutes)
a. One-lane blockage due to minor accident/stall	______

b. Tow-lane blockage due to major accident _______

c. Vehicles/people on shoulder or median _______

VIII. WEATHER AND VISIBILITY

1. **Frequency and Magnitude of Capacity Reductions:**

Estimate the percentages of peak periods that have the following levels of capacity reduction due to inclement weather or reduced visibility (e.g. darkness):

less than 5% reduction in freeway capacity ____ %

5% reduction in freeway capacity ____ %

10% reduction in freeway capacity ____ %

20% reduction in freeway capacity ____ %

other (______________________________) ____ %

2. **Duration of Capacity Reductions:**

Estimate the average duration, in hours and minutes, of capacity reductions that are due to inclement weather or reduced visibility - when they occur:

Very slight reduction in capacity (less than 5%): ___ hour ___ min.

Slight reduction in capacity (5%): ___ hour ___ min.

Medium reduction in capacity (10%): ___ hour ___ min.

Large reduction in capacity (20%): ___ hour ___ min.

PART TWO

QUESTIONS FOR AGENCIES THAT OPERATE EITHER
LOCAL RESPONSIVE RAMP CONTROL OR
SYSTEMWIDE RAMP CONTROL

1. What type of ramp control system is in operation at this installation (check one)?

local responsive ____

systemwide control ____

2. Describe briefly your control logic (what traffic measurements are taken and how they are used to determine each ramp's metering rate). Provide any written material, flowcharts, or logic diagrams that are available.

3. Describe briefly the ramp control equipment that is used:

a) ramp controller:

b) systemwide controller or computer:

c) communications equipment (if systemwide control is used):

d) vehicle detectors (type, location, and sensed traffic parameters):

4. How often are ramp meter rates updated by the control logic?

____ each 30-seconds

____ each minute

____ each 5-minutes

____ other ________

5. What mainline (on the freeway) traffic parameters are used in the control logic? (Check those used and answer the questions):

____ vehicle speed

Over what time-frame are vehicle speeds averaged? ________

Do you average over adjacent lanes? ________

What detector sample rate is used? ________

What accuracy do you aim for? ________

Are all lanes measured? ________

____ percent occupancy

Over what time-frame is occupancy measured? ________

Do you average over adjacent lanes? ________

What detector sample rate is used? ________

Are all lanes measured? ________

____ vehicle counts

What time-frame are counts collected for? ________

What accuracy do you aim for? ________

Are all lanes measured? ________

6. Describe briefly the logic that is used to begin ramp metering and to end it for a peak period. Is it simply done by time-of-day, or are mainline detector measurements used? Provide any flow charts or logic diagrams that may be available.

APPENDIX B

SIMULATION RUNS PLAN

DESIGN OF THE FREFLO SIMULATION RUN SERIES (2)

Once: (a) the baseline freeway had been specified, (b) the three baseline or reference demand patterns (low, medium, and high controllability) had been specified, and (c) the demand and capacity variations to be studied were also defined -- then a plan was developed for the conduct of the FREFLO simulation runs.

The entire series of FREFLO runs was structured into the following sub-sets of runs:

Baseline Runs

These were the reference case runs without capacity and demand variations. The three reference demand patterns were simulated with each of the three ramp control modes in effect. A total of nine baseline runs were conducted:

Baseline runs (9)

(3 controllability levels) x (3 ramp control modes) = 9 baseline runs.

Incident Runs

The next set of runs was devised to test the sensitivity of each ramp control mode's performance to the occurrence of an incident. A "nominal incident" was first defined and then simulated for each mode and each controllability level. A total of nine nominal incident runs were made:

Nominal incident runs (9)

(3 controllability levels) x (3 ramp control modes) x (1 nominal incident) = 9 nominal incident runs.

Next, a set of runs was conducted to test the influence of the different characteristics of an incident:

- Time-of-occurrence of the incident within the peak period
- Location of the incident along the metered freeway
- Duration of the incident
- Severity of the incident (in terms of capacity-reduction).

The nominal incident assumed an average value for each of these characteristics. Therefore, to test the sensitivity of the ramp control performance to these characteristics, it was necessary to make two perturbations (away from the nominal value) for each characteristic -- a "low" and a "high" perturbation. A total of seventy-two incident-type sensitivity runs were made:

Incident-type sensitivity runs (72)

(2 perturbations of each characteristic from "nominal") x (4 characteristics: time-of-occurence, location, duration, severity) x (3 control controllability levels) x (3 ramp control modes) = 72 incident-type sensitivity runs.

Capacity-Reduction Runs

The next set of runs was devised to test the sensitivity of each ramp control mode's performance to a reduction in the freeway capacity (due to, say, rain) that affected the entire peak period and the entire freeway. Three magnitudes of capacity reduction were studied--leading

to 27 capacity-reduction runs:

Capacity-Reduction Runs (27)

(3 magnitudes of freeway capacity-reduction) x

(3 controllability levels) x (3 ramp control modes) =

27 capacity-reduction runs.

Incidents During Reduced-Capacity

One departure was made from the sensitivity analysis approach. With sensitivity analysis, the assumption is made that the various factors contributing to highway users' costs can be considered one by one, and that the effects of the various factors are additive. It was thought that the sensitivity analysis could be inaccurate for the occurrence of an incident during a peak period in which the freeway was operating at reduced capacity. These two factors (incidents and capacity-reductions) had large effects on user's costs when considered separately -- the combined effects were unlikely to be additive.

To test the sensitivity of each ramp control mode's performance to the occurrence of an incident (a nominal incident) during a peak-period of moderate capacity-reduction, a total of nine runs was made.

Incident runs during reduced capacity (9)

(3 controllability levels) x (3 ramp control modes) x (1 occurrence of a nominal incident during a peak period of moderate capacity reduction) = 9 incident runs during reduced capacity.

Shifts of the Demand Level

The next set of runs was devised to test the sensitivity of each ramp control mode's performance to a shift (up or down) of the demand

level from the nominal peak period demand pattern.

Shift of demand-level runs (18)

(2 shifts in demand; up/down from nominal) x (3 controllability levels) x (3 ramp control modes) = 18 shift of demand-level runs.

Temporal Variation of Mainline Input

The final set of runs was devised to test the sensitivity of each ramp control mode's performance to short-term fluctuations in the mainline input demand for each of the three controllability-level conditions.

Temporal demand variation runs (9)

(3 randomized demand patterns, corresponding to the 3 controllability levels) x (3 ramp control modes) = 9 temporal demand variation runs.

SUMMARY OF THE FREFLO SIMULATION STUDY DESIGN

In summary, the simulation-based, sensitivity analysis was conducted via selected FREFLO simulation runs. These runs are given in Table B-1.

Table B-1 FREFLO Simulation Runs Made for the Sensitivty Analysis

Set of Runs	Purpose	Number of FREFLO Simulation Runs
1. Baseline Runs	To establish the reference performance values to which the performance values for the various demand and capacity variations could be compared.	9
2. Incident Runs a) Nominal Incident	a) To establish the average effect of an incident, with each control mode	a) 9
b) Incident-Type Sensitivity Runs	b) To establish the effects of departures of incident characteristics from those of the average or nominal incident	b) 72
3. Capacity-Reduction Runs	To establish the effect of reduced-capacity peak periods on the performance of each mode	27
4. Incidents During Reduced-Capacity	To establish the degree to which the effects of an incident and a capacity-reduction are not additive	9
5. Shift of Demand-Level Runs	To establish the effect of shifts in demand level upon the performance of each mode	18
6. Temporal Demand-Variation Runs	To establish the effects of brief temporal fluctuations in traffic flow upon the performance of each mode	9

TOTAL NO. OF RUNS: 153

APPENDIX C

INCREMENTAL FUEL-CONSUMPTION BENEFITS

INCREMENTAL FUEL-CONSUMPTION BENEFITS OF THE RESPONSIVE RAMP CONTROL MODES (2)

Results for the fuel-consumption benefits of the responsive ramp control modes are presented in this Appendix.

Incremental Fuel-Consumption Benefits During Incidents

A typical incident, defined from survey data, was a 1-lane blockage having the characteristics depicted previously in Figure 6. Figures C-1, C-2, and C-3 show the incremental fuel-consumption savings (relative to Pretimed control) during such a typical incident. More specifically, these figures give the results when the incident occurs early, at midpeak, and late, respectively, within the peak period, and it can be seen that:

- System control and Local Actuated control have nearly the same fuel-consumption performance. Figure C-2 shows that there may be a slight (only about one-half of one percent) advantage of System control over Local Actuated control during mid-peak incidents.
- Generally speaking, the fuel-consumption benefits of either System control or Local Actuated control during incidents are quite small. They are much smaller (as a percentage of fuel consumption for the nominal peak period) than the travel time savings. Figures C-1, C-2, and C-3 show that, even for a freeway that has a very high controllability index, the reduction in fuel consump-

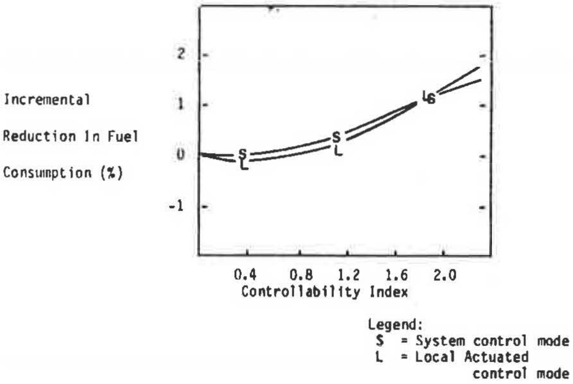


FIGURE C-1 INCREMENTAL REDUCTION IN FUEL CONSUMPTION; EARLY INCIDENT

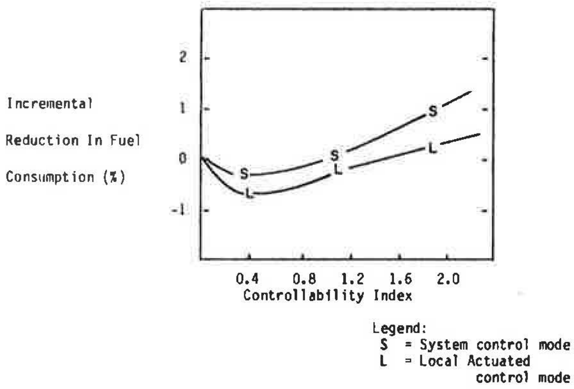


FIGURE C-2 INCREMENTAL REDUCTION IN FUEL CONSUMPTION; MID-PEAK INCIDENT

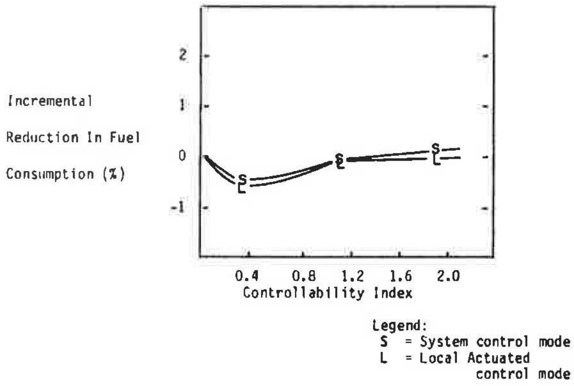


FIGURE C-3 INCREMENTAL REDUCTION IN FUEL CONSUMPTION; LATE INCIDENT

tion (relative to Pretimed control) is never more than about 1-1/2%; travel time savings, however, can be as large as 20%.

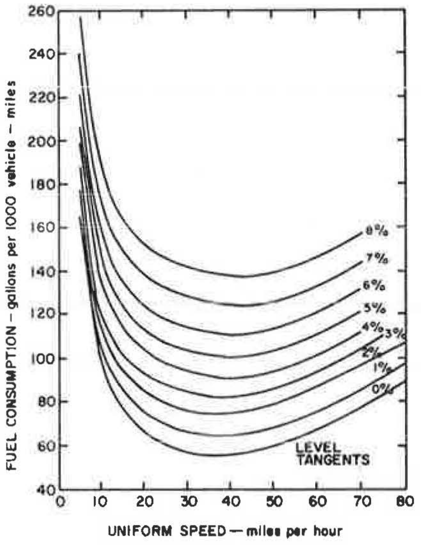
- The fuel-consumption benefits of both modes increase with the controllability index of the freeway. (A slight anomaly is noted for Figures C-1 and C-2; the benefits decrease - i.e., fuel-consumption increases - at very small controllability index values. No explanation of the decrease has been developed; it is so small that it may be within the numerical accuracy bounds of the simulation results and the computations performed in normalizing the results to obtain %-changes.)

The comments given above generally imply that the fuel-consumption benefits of the responsive control modes during incidents are not very significant. As an example, in absolute terms the savings (relative to Pretimed control) in fuel consumptions for the baseline freeway would never be more than about 1.5% of 3,260 gallons of fuel - or about 48 gallons of fuel per peak period with an incident. At present 1980 gasoline prices this would be a monetary savings of no more than $60. By comparison, the travel time savings for the baseline freeway during an incident can be as much as about 20% of 1,010 veh-hrs. Or, assuming an average vehicle occupancy of 1.25 persons - this would be a savings of about 250 travel hours. Even if these travel time savings were valued as low as one dollar per hour, they would be over four times as large, monetarily, as the fuel-consumption savings.

A principal reason that the responsive control modes do not offer much advantage, relative to Pretimed control, regarding fuel-consumption

savings is that fuel consumption is speed dependent in such a way that the same aggregate fuel consumption can be obtained for a heavily congested freeway as for one that is relatively free-flowing. Figure C-4 shows the speed-dependence of fuel consumption. During an incident, the responsive modes can allow the metering rates at ramps downstream of the incident to be high and the travel speed downstream of an incident will be high. Upstream of an incident, the responsive modes will lessen mainline queuing while also diverting more traffic than does Pretimed control. Both of these effects of responsive control on traffic upstream of an incident will tend to save travel time, hence increase average travel speed - relative to Pretimed control. The average speed of traffic (considering the entire peak period) will drop due to an incident, regardless of the control mode being used. For example, on Figure C-4 the average speed may shift downward from 40 mph to 30 mph - tending to move the freeway's operating condition closer to the "bottom of the bowl" of the fuel-consumption versus speed function. For a zero-grade freeway, the responsive modes may operate slightly to the right of the minimum fuel-consumption point, while Pretimed control may operate slightly to the left of that point - with the result that the fuel consumption is about the same regardless of mode.

The effects of an incident's location, duration, and severity upon incremental fuel-consumption benefits are shown in Figures C-5, C-6, and C-7. Figure C-5 shows the effect of incident location. Figure C-6 shows the effect of incident duration. Figure C-7 shows the effect of incident severity. From these figures it can be seen that:



(SOURCE: A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements, AASHTO, 1977)

FIGURE C-4 TOTAL AUTOMOBILE FUEL CONSUMPTION FOR VARIOUS SPEEDS AND GRADES

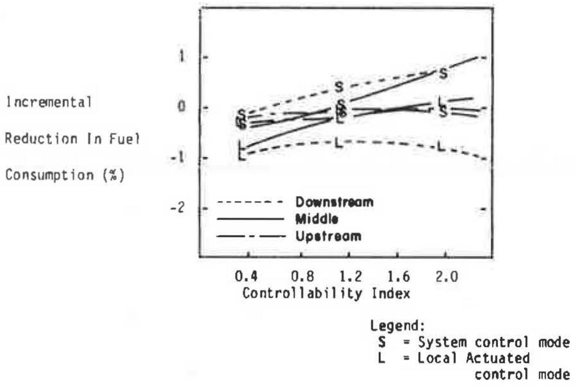


FIGURE C-5 EFFECT OF INCIDENT LOCATION UPON INCREMENTAL REDUCTION IN FUEL CONSUMPTION

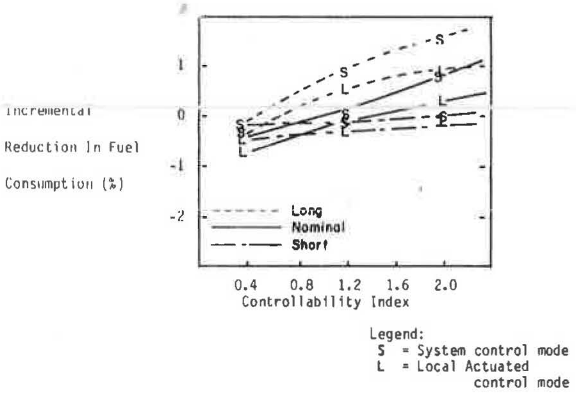


FIGURE C-6 EFFECT OF INCIDENT DURATION UPON INCREMENTAL REDUCTION IN FUEL CONSUMPTION

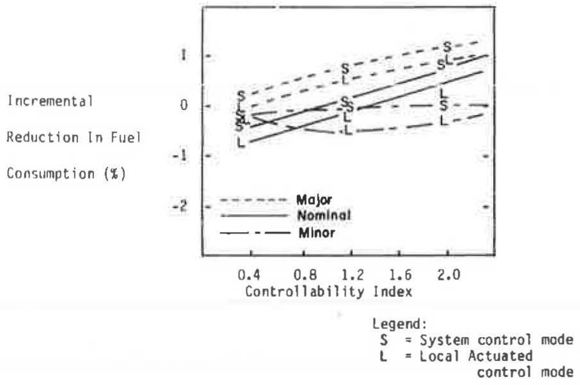


FIGURE C-7 EFFECT OF INCIDENT SEVERITY UPON INCREMENTAL REDUCTION IN FUEL CONSUMPTION

- Again, System control and Local Actuated control have nearly the same fuel-consumption performance. There is generally a slight (a fraction of a percent) advantage to System control.
- Generally speaking, the fuel-consumption benefits of either System control or Local Actuated control during incidents are quite small - regardless of the location/duration/severity circumstances surrounding any particular incident.
- The fuel-consumption benefits of both modes increase slightly with the controllability index of the freeway. The exceptions are upstream incidents, short-duration incidents, and minor-severity incidents for which the incremental benefit curves are virtually "flat."
- The incremental fuel-consumption savings increase (for both modes) with increasing severity and duration of an incident. However, the increase savings is only about 1 to 1-1/2% of the total fuel consumption in a nominal peak period. The effect of incident location is not clear - the incremental benefit curves (Figure C-5) seem to be scattered about zero savings in fuel consumption.

It should be noted that all incidents treated in Figures C-5, C-6, and C-7 are assumed to occur at mid-peak; Figures C-1, C-2, and C-3 show the effect of time-of-occurrence of an incident. Strictly speaking, in order to estimate the incremental fuel consumption benefits of the responsive modes, the user of the Guidelines should decide what "mix" of incident characteristics are to be considered. As a practical matter, however, it does not make much difference what mix is assumed since all incremental fuel consumption savings are quite small.

INCREMENTAL FUEL-CONSUMPTION BENEFITS DURING PEAK PERIODS OF REDUCED FREEWAY CAPACITY

Figures C-8, C-9, and C-10 show the incremental fuel-consumption savings (relative to Pretimed control) of the two responsive control modes during such capacity reductions. From these figures it is seen that:

- The fuel-consumption performance of the responsive modes can actually be worse than that of Pretimed control. This occurs during minor capacity reductions and major capacity reductions. However, during peak periods with a moderate reduction of freeway capacity, there are positive incremental benefits for the responsive modes.
- System control provides better incremental fuel-consumption performance than does Local Actuated control.
- Generally speaking, the incremental fuel-consumption performance of the responsive modes, relative to Pretimed control, improves with increasing controllability.
- For moderate capacity reductions, the incremental fuel-consumption benefits of the responsive modes are significantly larger than they were for incidents.

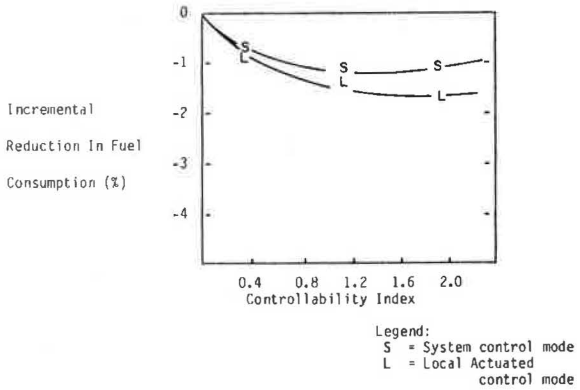


FIGURE C-8 INCREMENTAL REDUCTION IN FUEL CONSUMPTION; MINOR CAPACITY REDUCTION (5%)

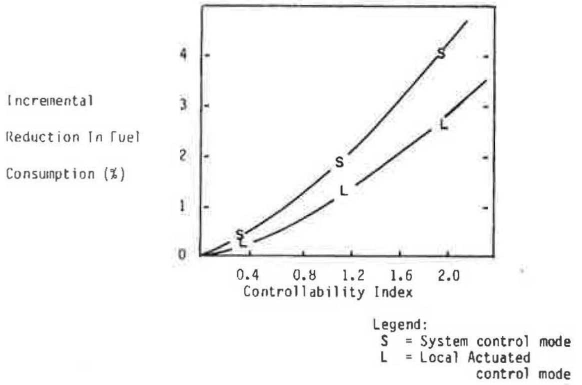


FIGURE C-9 INCREMENTAL REDUCTION IN FUEL CONSUMPTION; MODERATE CAPACITY REDUCTION (10%)

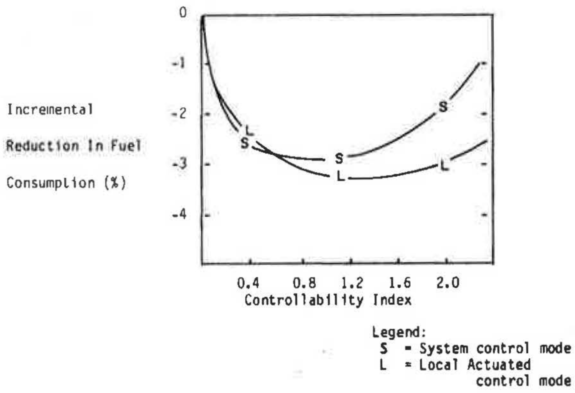


FIGURE C-10 INCREMENTAL REDUCTION IN FUEL CONSUMPTION; MAJOR CAPACITY REDUCTION (20%)

The results displayed in Figures C-8, C-9, and C-10 parallel the results on travel time savings, previously displayed in Figures 14, 15, and 16. There too, only a moderate capacity reduction yielded significant incremental benefits. The apparent reason for this is that when there is a moderate capacity reduction, the responsive modes are capable of preventing breakdown of the freeway mainline - whereas Pretimed control is not; this yields significant incremental fuel-consumption (and travel time) benefits for the responsive modes. During minor capacity reductions, however, breakdown does not occur, even with Pretimed control. The result is only small incremental travel time benefits, and small negative fuel-consumption benefits. During major capacity reductions none of the three control modes is capable of preventing breakdown of mainline traffic flow - with the result that there are only slight incremental travel time benefits and negative incremental fuel-consumption benefits.

Incremental Fuel-Consumption Benefits During a Peak Period That Has Both an Incident and a Freeway Capacity Reduction

Figure C-11 shows the effect of the responsive modes upon the incremental fuel-consumption benefits when the freeway is operating at a moderate (10%) capacity reduction and a typical mid-peak incident also occurs. Referring back to Figures C-2 and C-9, and comparing them to Figure C-11, it is seen that the incremental benefits during a combined incident and capacity reduction case are about midway between the benefits of the separate cases. This same result was found for the travel time benefits. With the combined events, there will be a significant portion of the peak period in which breakdown of freeway traffic flow

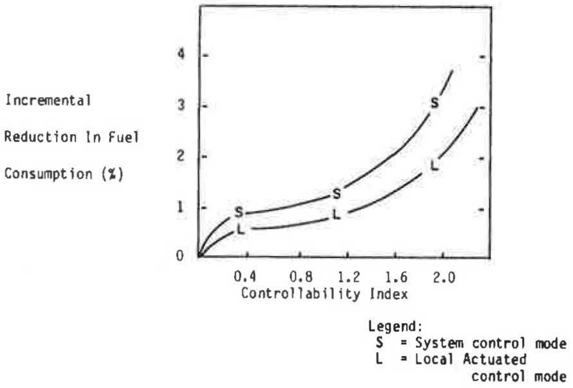


FIGURE C-11 INCREMENTAL REDUCTION IN FUEL CONSUMPTION; TYPICAL INCIDENT DURING A MODERATE (10%) CAPACITY REDUCTION occurs regardless of which of the three control modes is in operation. For this reason, the incremental benefits will be less than those of the capacity reduction alone. Similarly, the benefits of responsive control accrue over the entire 3-hour peak period - not solely during the interval of the incident - hence the incremental benefits will be larger than those of an incident alone.

As was the case in the previous situations, the incremental fuel-consumption benefits of the responsive modes increase with the freeway's controllability.

Incremental Fuel-Consumption Benefits Arising From Demand Variations

Figures C-12, C-13, and C-14 show the incremental fuel-consumption savings (relative to Pretimed control) of the two responsive control modes during demand variations. Figure C-12 shows the effect of an upward shift in freeway demand; Figure C-13 shows the effect of a downward shift in freeway demand and Figure C-14 shows the effect of short-term fluctuations in mainline input to the metered freeway.

From Figures C-12, C-13, and C-14 it is seen that:

- Regardless of the type of demand variation, the benefits of System control and Local Actuated control are virtually the same.
- The positive benefit in the case of a downward shift in demand is cancelled by the negative benefit of responsive control for an upward shift in demand. Since the nominal peak period demand is assumed to be an average demand pattern for a freeway, upward and downward demand shifts will occur with about the same frequency. This implies that the net fuel-consumption benefit of

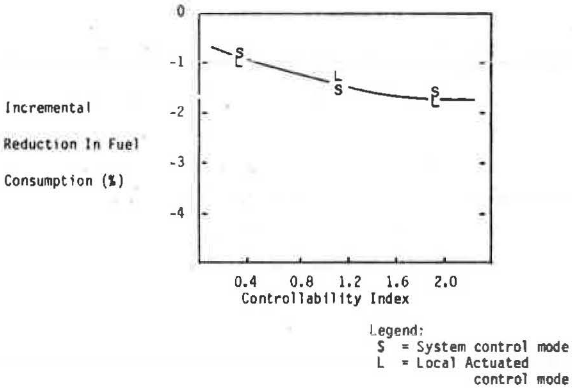


FIGURE C-12 INCREMENTAL REDUCTION IN FUEL CONSUMPTION; TYPICAL INCREASE IN PEAK PERIOD DEMAND

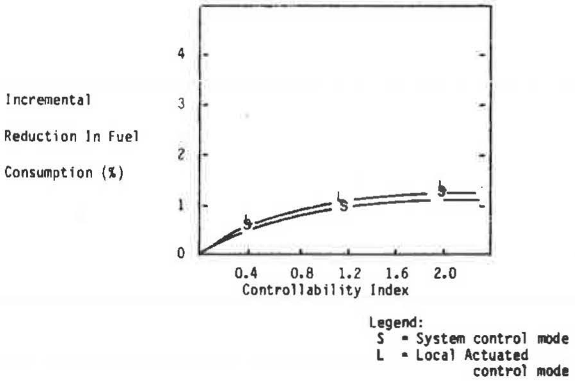


FIGURE C-13 INCREMENTAL REDUCTION IN FUEL CONSUMPTION; TYPICAL DECREASE IN PEAK PERIOD DEMAND

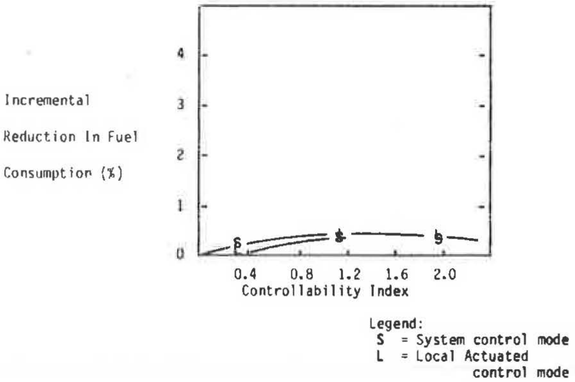


FIGURE C-14 INCREMENTAL REDUCTION IN FUEL CONSUMPTION; TYPICAL DEMAND FLUCTUATIONS DURING PEAK PERIODS

the responsive modes, in response to demand shifts, is in the long run essentially zero.

- A very small (fraction of a percent) incremental benefit accrues to the responsive modes because of demand fluctuations. This benefit increases slightly with freeway controllability. Even though the benefit is very small, this benefit can be expected for each day of normal freeway operation.

The incremental benefits of the two responsive modes are virtually equal because none of the demand variations create a situation for which the coordination of System control provides an advantage over Local Actuated control (as it does for incidents).

APPENDIX D

INCREMENTAL VEHICLE EMISSIONS BENEFITS

INCREMENTAL VEHICLE EMISSIONS BENEFITS OF THE RESPONSIVE CONTROL MODES (2)

Results for the vehicle emissions benefits of the responsive ramp control modes are presented in this Section.

Incremental Vehicle Emissions Benefits During Incidents

A typical incident, defined from survey data, was a 1-lane blockage having the characteristics depicted previously in Figure 6. Figures D-1 through D-9 show the incremental vehicle emissions benefits (relative to Pretimed control) of the two responsive control modes during such a typical incident. Figures D-1, D-2, and D-3 display the results for hydrocarbons (HC), Figures D-4, D-5, and D-6 display the results for carbon monoxide (CO), and Figures D-7, D-8, and D-9 display the results for nitrous oxides (NO_x) Each triplet of figures gives the results when the incident occurs early, at mid-peak, and late, respectively, within the peak period. The conclusions drawn from Figures D-1 through D-9 are:

- Positive incremental benefits occur for both modes in regard to HC and CO emissions, whereas negative benefits are obtained in regard to NO_x emissions. The responsive controls generate reductions, relative to Pretimed control, in HC and CO emissions; this results from both lower fuel consumption and better oxidation of the hydrocarbons as the traffic flow improves. This

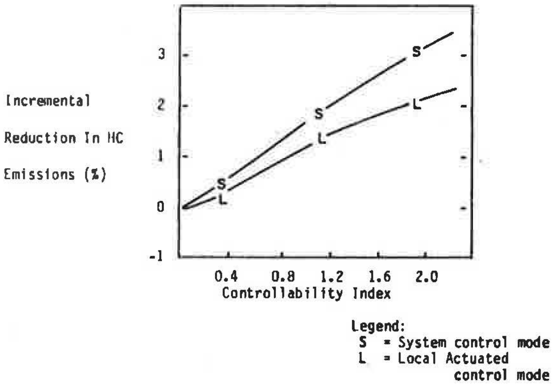


FIGURE D-1 INCREMENTAL REDUCTION IN HC EMISSIONS; EARLY INCIDENT

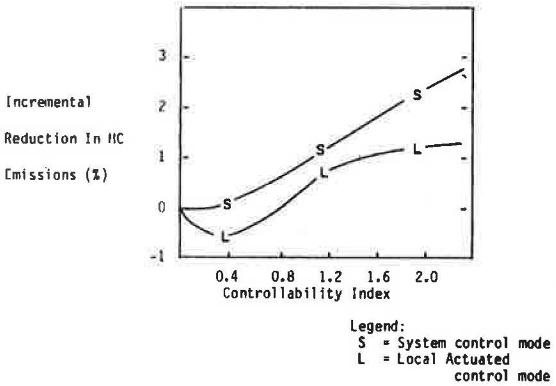


FIGURE D-2 INCREMENTAL REDUCTION IN HC EMISSIONS; MID-PEAK INCIDENT

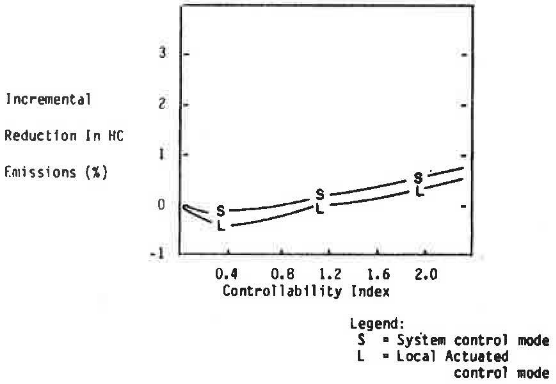


FIGURE D-3 INCREMENTAL REDUCTION IN HC EMISSIONS; LATE INCIDENT

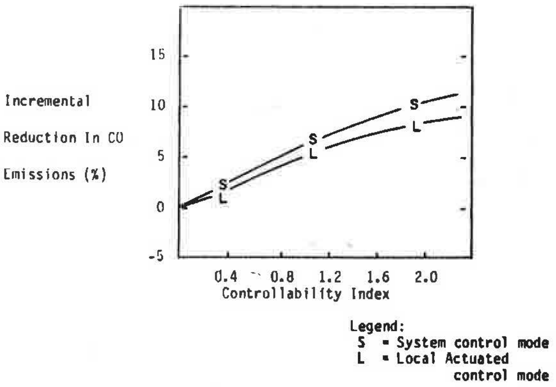


FIGURE D-4 INCREMENTAL REDUCTION IN CO EMISSIONS; EARLY INCIDENT

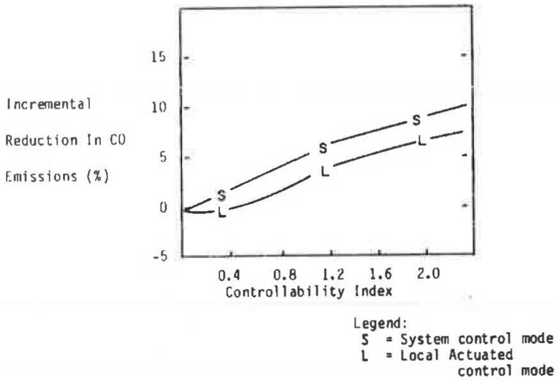


FIGURE D-5 INCREMENTAL REDUCTION IN CO EMISSIONS; MID-PEAK INCIDENT

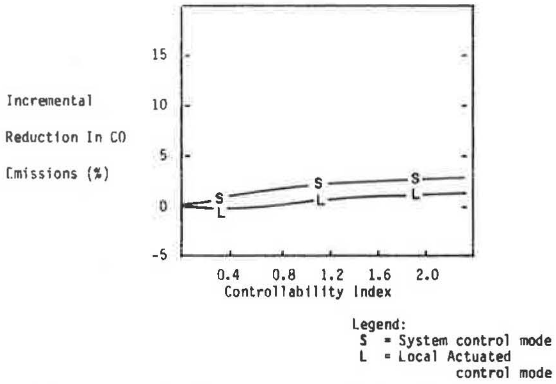


FIGURE D-6 INCREMENTAL REDUCTION IN CO EMISSIONS; LATE INCIDENT

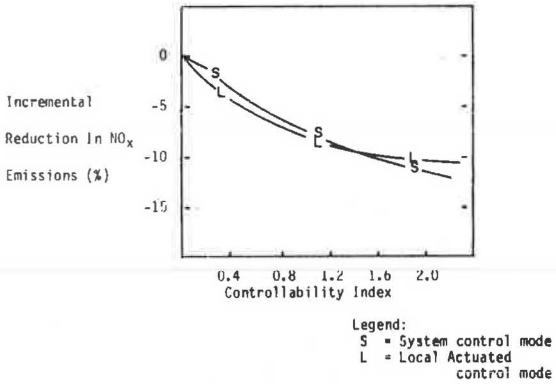


FIGURE D-7 INCREMENTAL REDUCTION IN NO$_x$ EMISSIONS; EARLY INCIDENT

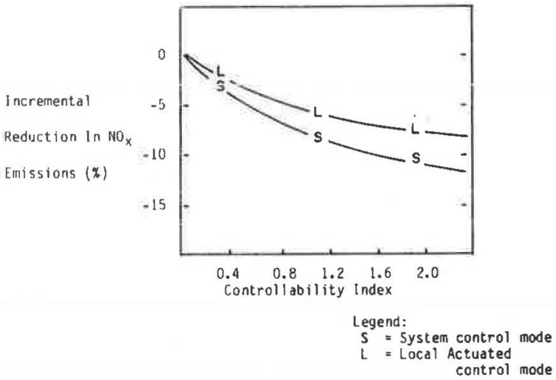


FIGURE D-8 INCREMENTAL REDUCTION IN NO$_x$ EMISSIONS; MID-PEAK INCIDENT

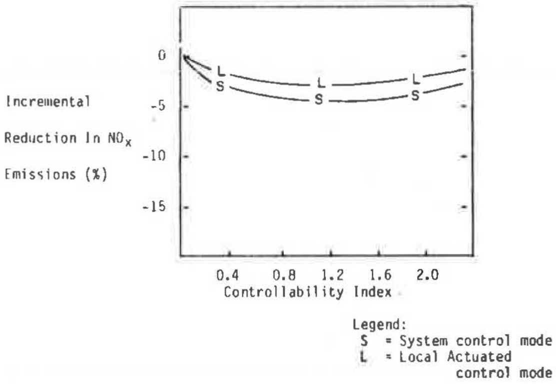


FIGURE D-9 INCREMENTAL REDUCTION IN NO$_x$ EMISSIONS; LATE INCIDENT converts more of the HC and CO into water (H_2O) and carbon dioxide (CO_2) -- improving the air quality. However, when better oxidation of HC and CO occurs, the same occurs for nitrogen and its oxides. In other words, more (not less) NO_x emissions are created.

- System control provides the greater incremental benefits regarding HC and CO emissions. Local Actuated control has smaller negative benefits in regard to NO_x emissions.
- While the incremental benefits regarding HC emissions are small, the CO emissions reductions are significant (up to a 10% reduction, relative to Pretimed control). On a percentage basis, the magnitude of the negative NO_x benefits is about the same as that of the (positive) CO benefits (although, by weight, the change in CO emissions is larger).
- The emissions benefits, like the travel time and fuel-consumption benefits, are largest for an early incident and smallest for a late incident.
- The emissions benefits increase as the freeway controllability increases.

The effects of an incident's location, duration, and severity upon incremental vehicle emissions benefits are shown in Figures D-10 through D-18. Figures D-10, D-11, and D-12 display the results for hydrocarbons, Figures D-13, D-14, and D-15 display the results for carbon monoxide, and Figures D-16, D-17, and D-18 display the results for nitrous oxides. Each triplet of figures gives the respective results with re-

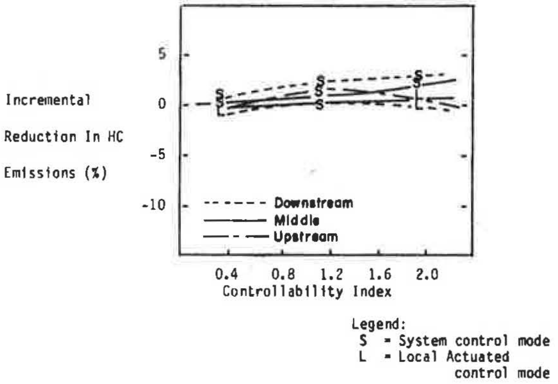


FIGURE D-10 EFFECT OF INCIDENT LOCATION UPON INCREMENTAL REDUCTION IN HC EMISSIONS

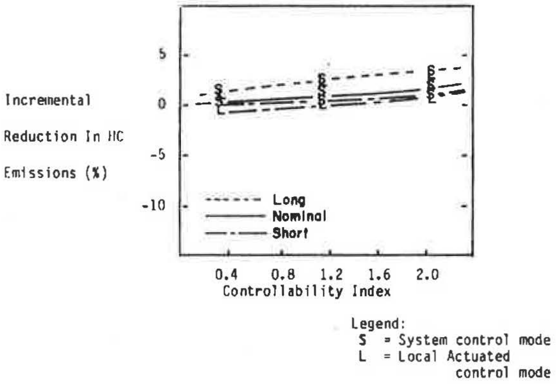


FIGURE D-11 EFFECT OF INCIDENT DURATION UPON INCREMENTAL REDUCTION IN HC EMISSIONS

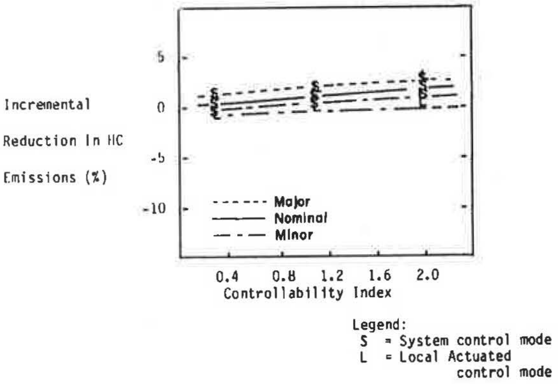


FIGURE D-12 EFFECT OF INCIDENT SEVERITY UPON INCREMENTAL REDUCTION IN HC EMISSIONS

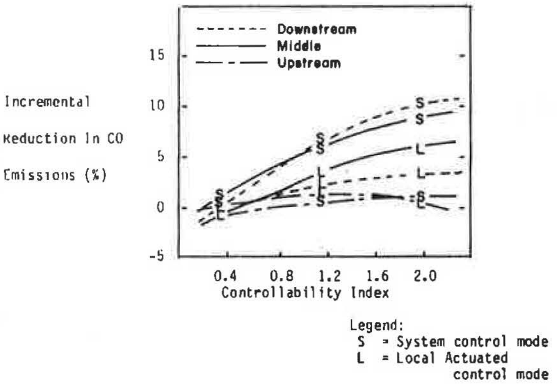


FIGURE D-13 EFFECT OF INCIDENT LOCATION UPON INCREMENTAL REDUCTION IN CO EMISSIONS

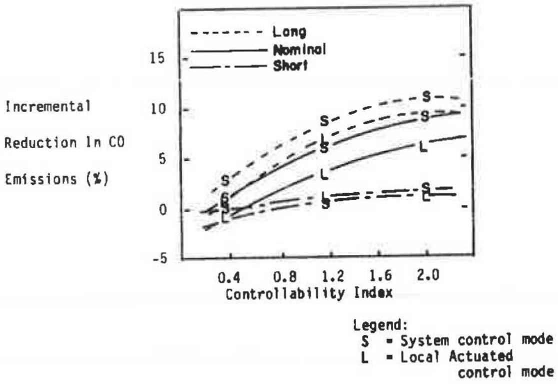


FIGURE D-14 EFFECT OF INCIDENT DURATION UPON INCREMENTAL REDUCTION IN CO EMISSIONS

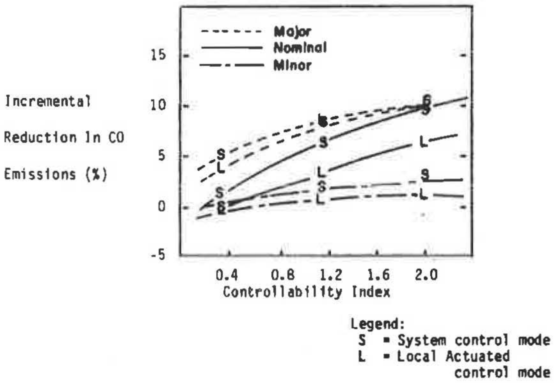


FIGURE D-15 EFFECT OF INCIDENT SEVERITY UPON INCREMENTAL REDUCTION IN CO EMISSIONS

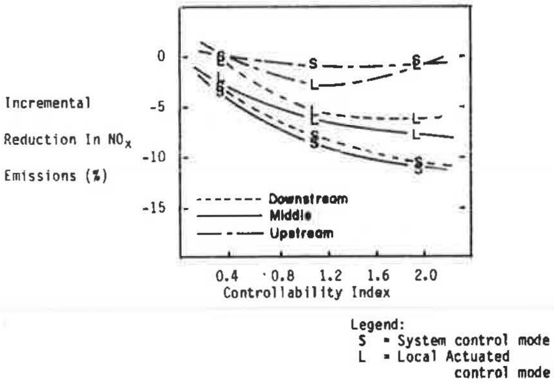


FIGURE D-16 EFFECT OF INCIDENT LOCATION UPON INCREMENTAL REDUCTION IN NO_x EMISSIONS

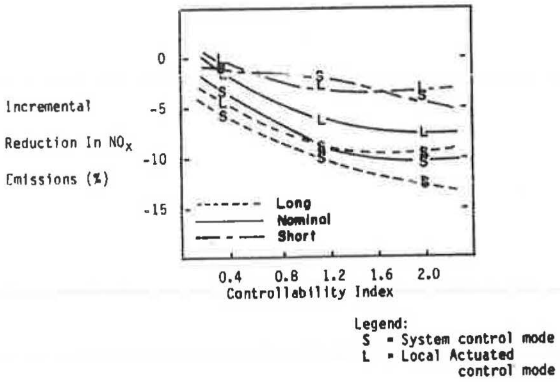


FIGURE D-17 EFFECT OF INCIDENT DURATION UPON INCREMENTAL REDUCTION IN NO_x EMISSIONS

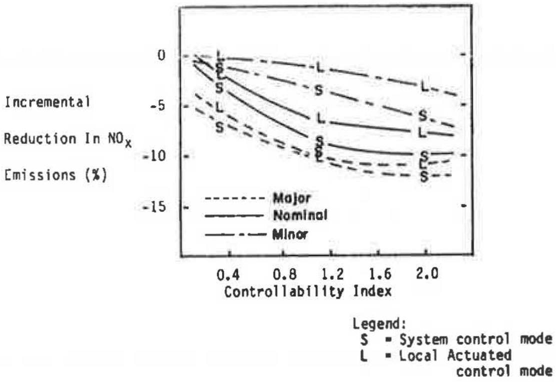


FIGURE D-18 EFFECT OF INCIDENT SEVERITY UPON INCREMENTAL REDUCTION IN NO_x EMISSIONS gard to incident location, duration, and severity. The Figures show that:

- The HC and CO benefits increase as (a) the incident location becomes closer to the downstream end of the metered freeway, (b) the incident duration increases, and (c) the incident severity increases. The magnitude of the (negative) NO_x benefits increase in the same manner.
- The range of incremental benefits has nearly the same sensitivity to incident location, duration, or severity. In other words, the three factors appear about equally important.
- While the magnitudes of the CO and NO_x incremental benefits increase significantly with increasing controllability, the HC emissions increase only slightly with increasing controllability.

As noted previously, all incidents considered in Figures D-10 through D-18 were assumed to occur at mid-peak; Figures D-1 through D-9 show the effect of time of occurence of an incident.

Incremental Vehicle Emissions Benefits During Peak Periods of Reduced Freeway Capacity

Figures D-19 through D-27 show the incremental vehicle emissions benefits (relative to Pretimed control) of the two responsive control modes during such capacity reductions. Figures D-19, D-20, and D-21 display the results for hydrocarbons, Figures D-22, D-23, and D-24 display the results for carbon monoxide, and Figures D-25, D-26, and D-27 display the results for nitrous oxides. Each triplet of figures gives

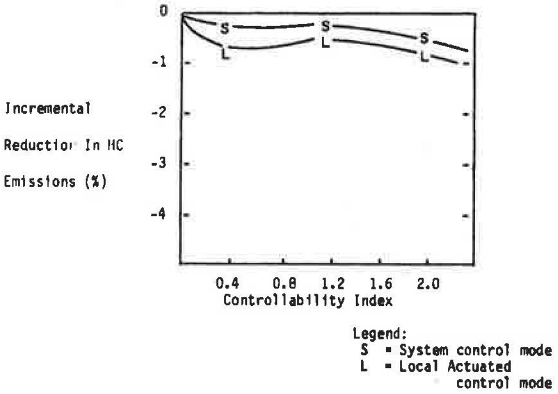


FIGURE D-19 INCREMENTAL REDUCTION IN HC EMISSIONS; MINOR CAPACITY REDUCTION (5%)

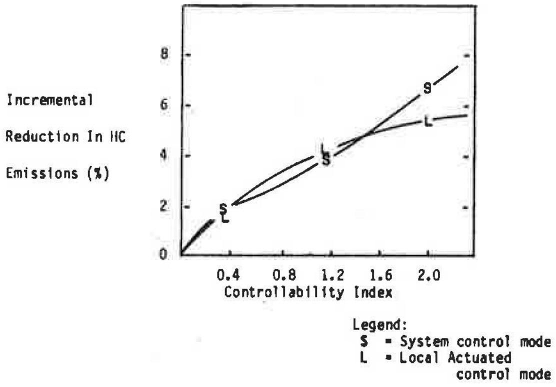


FIGURE D-20 INCREMENTAL REDUCTION IN HC EMISSIONS; MODERATE CAPACITY REDUCTION (10%)

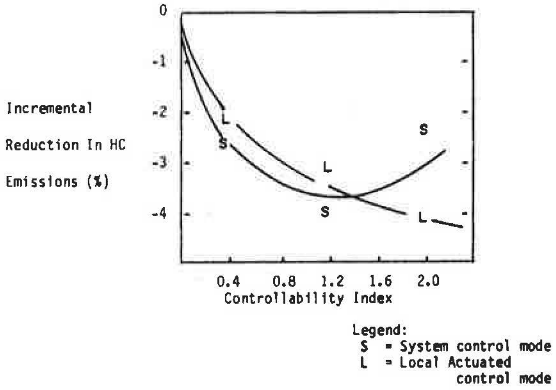


FIGURE D-21 INCREMENTAL REDUCTION IN HC EMISSIONS; MAJOR CAPACITY REDUCTION (20%)

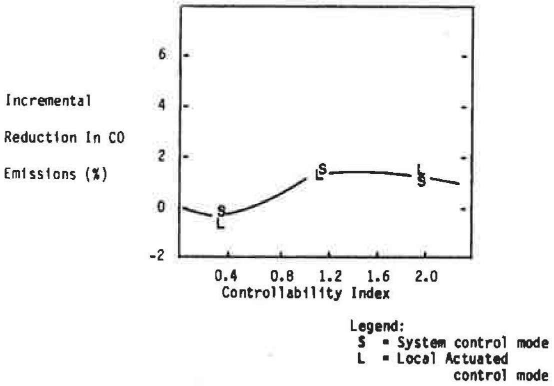


FIGURE D-22 INCREMENTAL REDUCTION IN CO EMISSIONS; MINOR CAPACITY REDUCTION (5%)

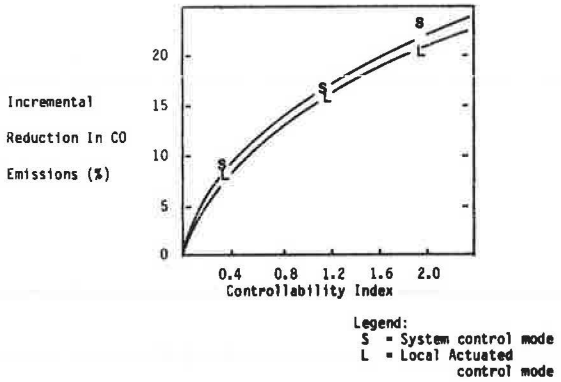


FIGURE D-23 INCREMENTAL REDUCTION IN CO EMISSIONS; MODERATE CAPACITY REDUCTION(10%)

D-26

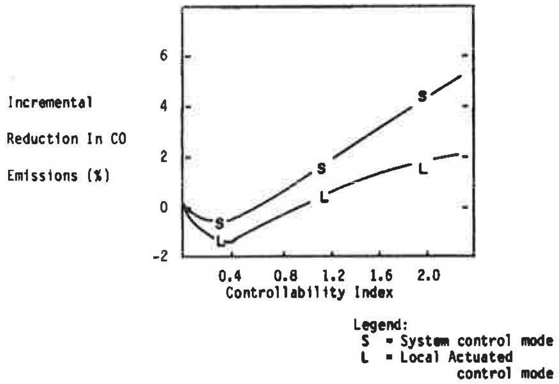


FIGURE D-24. INCREMENTAL REDUCTION IN CO EMISSIONS; MAJOR CAPACITY REDUCTION (20%)

D-27

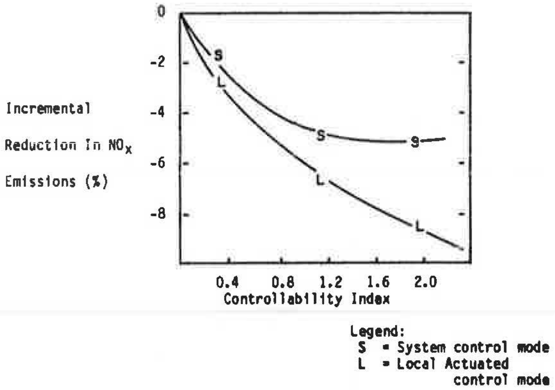


FIGURE D-25 INCREMENTAL REDUCTION IN NO_x EMISSIONS; MINOR CAPACITY REDUCTION (5%)

D-28

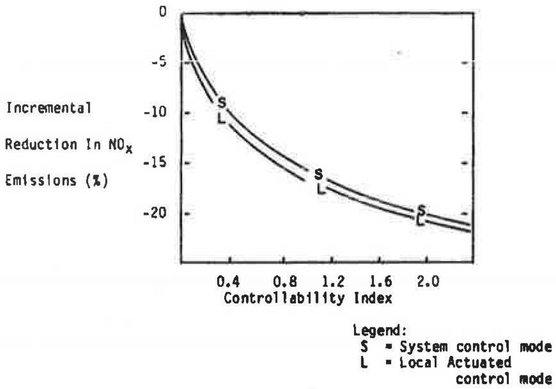


FIGURE D-26 INCREMENTAL REDUCTION IN NO_x EMISSIONS; MODERATE CAPACITY REDUCTION (10%)

D-29

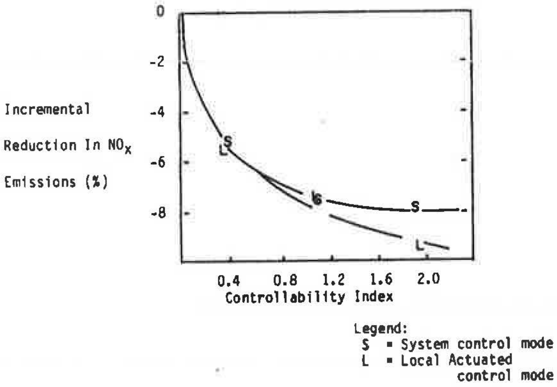


FIGURE D-27 INCREMENTAL REDUCTION IN NO_x EMISSIONS; MAJOR CAPACITY REDUCTION (20%)

D-30

the respective results for minor, moderate, and major capacity reductions. The results displayed in these three figures show that:

- As was the case with travel time benefits and fuel-consumption benefits, there is a "threshold effect." Namely, the capacity reduction has to be a certain magnitude before there is much benefit to the responsive modes. That is, a minor (5%) capacity reduction yields only small benefits (on the order of ± 1% for HC and CO emissions and no more than 8% (negative) for NO_x emissions). A moderate (10%) capacity reduction yields much larger benefits (up to about 6% for HC, up to about 20% for CO, and up to about 20% (negative) for NO_x).
- A major capacity reduction yields small incremental benefits (a little larger than those of a minor capacity reduction, and considerably less than those of a moderate capacity reduction).
- The emissions performance of the two responsive control modes is nearly the same.

Incremental Vehicle Emissions Benefits During A Peak Period That has Both an Incident and a Freeway Capacity Reduction

Figures D-28, D-29, and D-30 show the incremental vehicle emissions benefits (relative to Pretimed control) when the freeway is operating at a moderate (10%) capacity reduction and a typical mid-peak incident also occurs. Referring back to the pairs of figures: D-2 and D-11, D-5 and D-14, and D-8 and D-17 - and comparing them to Figures D-28, D-29, and D-30 respectively - it is seen that the incremental benefits during a combined incident and capacity reduction case lie between the benefits of the separate cases. However, the results are closest to those for the moderate capacity reduction.

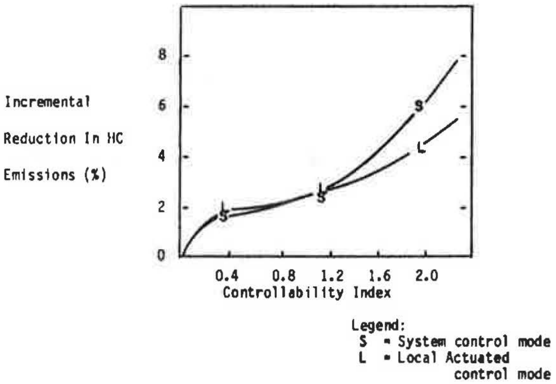


FIGURE D-28 INCREMENTAL REDUCTION IN HC EMISSIONS; TYPICAL INCIDENT DURING A MODERATE (10%) CAPACITY REDUCTION

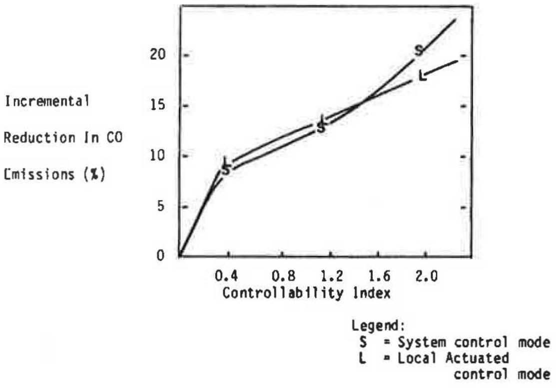


FIGURE D-29 INCREMENTAL REDUCTION IN CO EMISSIONS; TYPICAL INCIDENT DURING A MODERATE (10%) CAPACITY REDUCTION

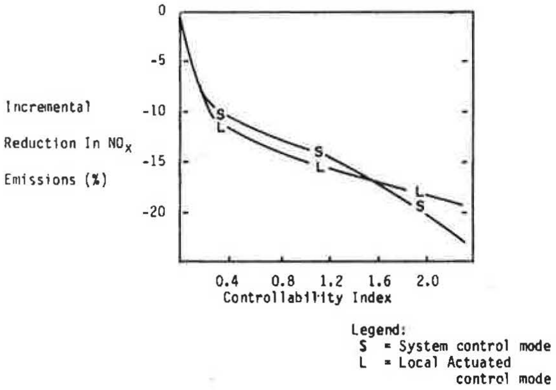


FIGURE D-30 INCREMENTAL REDUCTION IN NO_x EMISSIONS; TYPICAL INCIDENT DURING A MODERATE (10%) CAPACITY REDUCTION

Incremental Vehicle Emissions Benefits Arising From Demand Variations

Figures D-31 through D-39 show the incremental vehicle emissions benefits (relative to Pretimed control) of the two responsive control modes during demand variations. Figures D-31, D-32, and D-33 show the effects upon HC emissions, Figures D-34, D-35, and D-36 show the effects upon CO emissions, and Figures D-37, D-38 and D-39 show the effects upon NO_x emissions. Each triplet of figures shows the effect of a downward shift in freeway demand, an upward shift in freeway demand, and short-term fluctuations in mainline input, respectively. These Figures show that:

- Positive incremental benefits regarding HC, CO, and NO_x emissions occur for downward shifts in peak period demand. This is largely offset by negative incremental benefits that occur for upward shifts in peak period demand. Since the nominal peak period demand is assumed to be an average demand pattern for a freeway, upward and downward demand shifts will occur with about the same frequency. This implies that the net emissions benefit of the responsive modes, in response to demand shifts, is in the long run nearly zero.
- A very small (fraction of a percent) incremental emissions benefit accrues to the responsive modes because of demand fluctuations. Even though the benefit is very small, it will exist for a large number of peak periods in a year (each day of normal freeway operation).

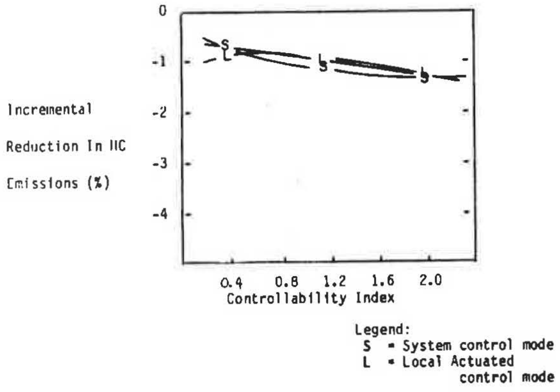


FIGURE D-31 INCREMENTAL REDUCTION IN HC EMISSIONS; TYPICAL INCREASE IN PEAK PERIOD DEMAND

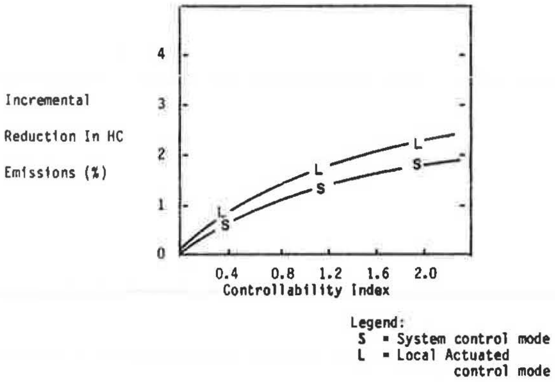


FIGURE D-32 INCREMENTAL REDUCTION IN HC EMISSIONS; TYPICAL DECREASE IN PEAK PERIOD DEMAND

D-37

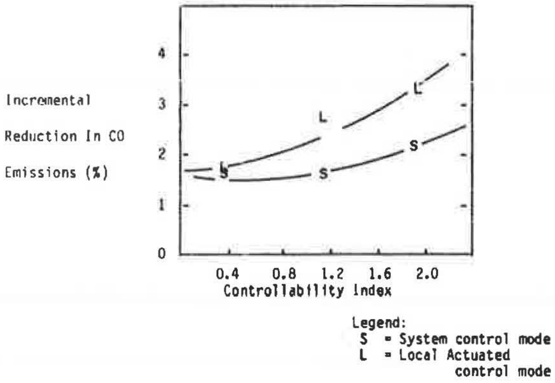


FIGURE D-35 INCREMENTAL REDUCTION IN CO EMISSIONS; TYPICAL DECREASE IN PEAK PERIOD DEMAND

D-40

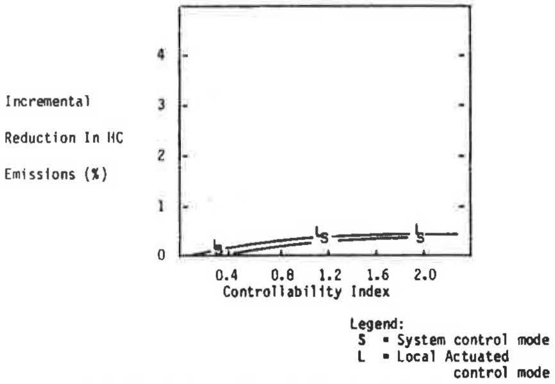


FIGURE D-33 INCREMENTAL REDUCTION IN HC EMISSIONS; TYPICAL DEMAND FLUCTUATIONS DURING PEAK PERIODS

D-38

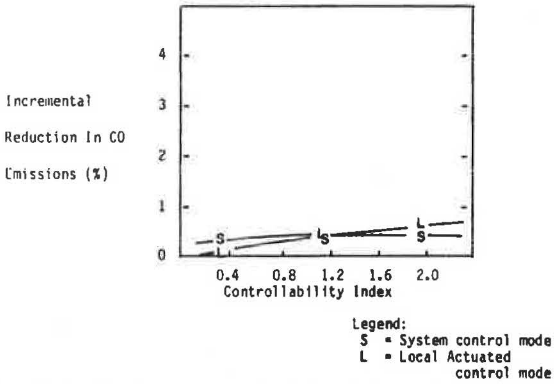


FIGURE D-36 INCREMENTAL REDUCTION IN CO EMISSIONS; TYPICAL DEMAND FLUCTUATIONS DURING PEAK PERIODS

D-41

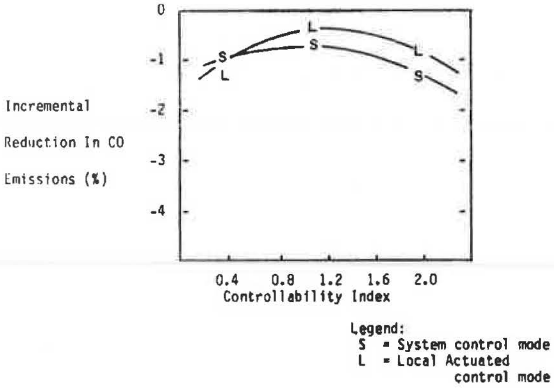


FIGURE D-34 INCREMENTAL REDUCTION IN CO EMISSIONS; TYPICAL INCREASE IN PEAK PERIOD DEMAND

D-39

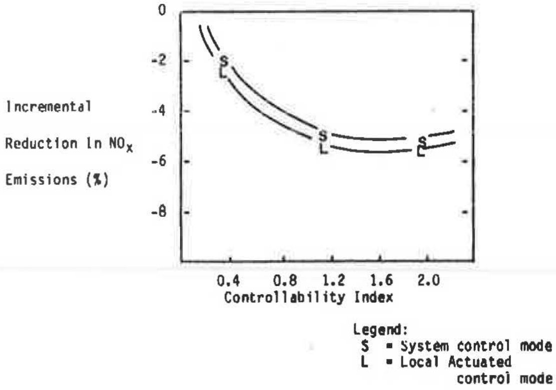


FIGURE D-37 INCREMENTAL REDUCTION IN NO_x EMISSIONS; TYPICAL INCREASE IN PEAK PERIOD DEMAND

D-42

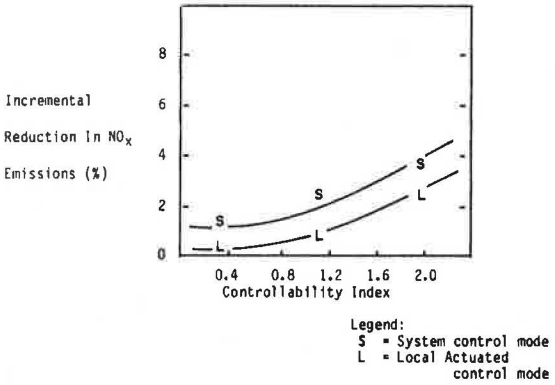


FIGURE D-38 INCREMENTAL REDUCTION IN NO_x EMISSIONS; TYPICAL DECREASE IN PEAK PERIOD DEMAND

D-43

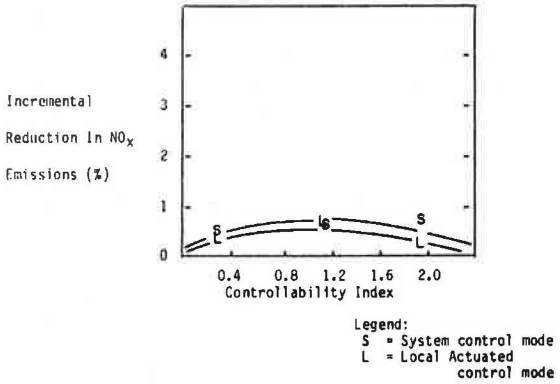


FIGURE D-39 INCREMENTAL REDUCTION IN NO_x EMISSIONS: TYPICAL DEMAND FLUCTUATIONS DURING PEAK PERIODS

D-44

- System control generally provides higher incremental benefits regarding HC and NO_x emissions. On the other hand, Local Actuated control provides higher incremental benefits for CO emissions. The reasons for this behavior are not clear.
- The incremental benefits (both positive and negative) generally increase in magnitude with increasing controllability.

D-45

APPENDIX E

GUIDELINES—SELECTION OF RAMP CONTROL SYSTEMS

CHAPTER 1

INTRODUCTION

PURPOSE AND SCOPE OF THE GUIDELINES

Powerful social and economic factors have greatly impacted urban transportation during the decade beginning in 1970. During this period there has been increasing public pressure to preserve the quality of the urban environment, This concern has manifested itself in terms of air pollution, noise, aesthetics, and the overall quality of urban life. At the same time, serious problems with inflation and energy availability have been encountered.

These varied social and economic factors have combined to produce an effect that has greatly reduced the highway construction program. Freeway construction, in particular, has been severely limited even though travel demand has significantly increased. Although increased emphasis has been placed on the development and use of public transportation, there has been no significant reduction in the use of the private automobile.

In most urban areas of 100,000 population or greater, the freeway system is a very significant part of the street and highway network that provides for the movement of persons and goods. Because the ability to expand a given freeway system to meet traffic demands has been significantly reduced, if not virtually eliminated, it becomes readily apparent that transportation officials must obtain maximum efficiency in the use of the existing freeway facilities.

One significant tool that can be used to increase the safety and efficiency of traffic operation on existing freeways is the use of entrance ramp control. Entrance ramp control is a technique for regulating access to the freeway in a manner that reflects a plan of freeway operation. The aim of this publication is to provide a logical and systematic set of guidelines for the selection and use of freeway entrance ramp controls.

The purpose of the guidelines is to provide a concise, pertinent set of information and technology that can be used by practicing transportation engineers in implementing freeway entrance ramp control systems. The guidelines are intended to provide a practical, relatively brief, and easily used methodology that will guide and assist the transportation engineer in making the following critical decisions on freeway entrance ramp control:

1. When should it be considered?
2. How does it relate to other improvement alternatives?
3. Is it feasible for the specific situation under study?
4. What specific mode of control is best for the specific situation under study?

DEFINITIONS

A number of terms will be used in the guidelines that perhaps need definition and clarification. A list of the terms and their definitions are provided as follows:

Bottleneck—Physical or geometric features of a street or freeway which reduce the facility's capacity (or ability to accommodate traffic flow) as compared to other locations on the same facility.

Capacity-Oriented Improvements—Roadway modifications intended to increase the ability of the roadway to accommodate vehicles in order to maximize the number of vehicles that can pass a point on the roadway during periods of heavy demand. An example of this type of improvement would be the addition of a lane at a bottleneck location.

Connector Control—Regulation, warning, or guidance of traffic on connecting facilities of freeways.

Corridor—A freeway and the system of roadways influenced by the freeway which accommodates travel demands along a predominate directional line in a portion of an urban area.

Corridor Control—Coordinated regulation, warning, and/or guidance of traffic on a system of roadways which accommodate travel demands within a corridor.

Demand-Oriented Improvements—Modifications intended to change the number of vehicles that utilize a roadway, generally during a specific time period. An example of this type of improvement would be the promotion of vanpools or carpools to increase vehicle occupancy and reduce the number of vehicles utilizing a given section of roadway.

Gaper's Block—The effective reduction in level of service as a result of driver distraction.

Goal—Broad statement which expresses long-range overall desires, policies, and positions.

Incident—An occurrence in a traffic stream that causes a disturbance in the normal flow of traffic. Common incidents include accidents, stalled vehicles, spilled loads, etc.

Latent Demand—Total number of potential users desiring to use a facility (street or freeway) at a given point.

Level of Service—Generally, six categories of roadway operating conditions reflecting a qualitative measure of flow characteristics defined by thresholds of speed and travel time, traffic interruptions, freedom to maneuver, safety, driving comfort and convenience, and operating costs. See the *Highway Capacity Manual* for additional discussion of this subject.

Local Actuated Entrance Ramp Control—Regulation of access control to a freeway by a device which meters vehicles at a rate determined by freeway traffic conditions in the immediate vicinity of the access point.

Main Lane Control—Regulation, warning, or guidance of traffic on the mainline of a freeway.

Manifest Demand—Number of users observed to use (or actually using) a facility (street or freeway) at a given point.

Metering Rate—Number of vehicles allowed to enter a given section of a roadway per unit time.

Microcomputer—A programmable computer whose central processor is a microprocessor.

Microprocessor—An integrated circuit, single-chip device that contains a programmable data processing system which, at minimum, consists of an arithmetic logic unit, some registers, and some type of control. Microprocessors generally handle shorter words than other computers, usually from 4 to as many as 16 bits.

Nonrecurrent Congestion—Type of congestion resulting from the occurrence of random or unpredictable events (e.g., accident).

Objective—Statement of specific action that can be taken as a step toward achievement of a goal.

Pretimed Entrance Ramp Control—Regulation of access control to a freeway by a device which meters vehicles at a constant rate regardless of prevailing freeway traffic conditions.

Recurrent Congestion—Type of congestion routinely expected at predictable locations during specific time periods.

Responsive Entrance Ramp Control—Regulation of entrance ramp metering rates according to freeway traffic conditions. Implies local actuated or system control.

Saturation Flow—Traffic flow condition which exists when traffic demand exceeds capacity.

System Entrance Ramp Control—Regulation of access control to a freeway by a device which meters vehicles at a rate determined by freeway traffic conditions throughout a given study area.

Utility Analysis—An evaluation procedure used for analyzing the ability of a traffic control system to perform its function in comparison to its cost.

CHAPTER 2

DECISION PROCESS FOR ENTRANCE RAMP CONTROL

DEFINITION OF DECISION PROCESS

An idealized decision process for freeway entrance ramp control would involve four basic decisions. These basic decisions are identified as follows:

1. Decision that a serious level of freeway congestion exists or will soon exist and that improvements should be made to reduce this level of congestion.
2. Decision on the type (or types) of improvements that will be made to reduce freeway congestion.
3. If vehicle diversion (time or space) by entrance ramp control is a desired improvement alternative, decision that entrance ramp control is feasible.
4. Decision on a specific mode of entrance ramp control.

In general, these decisions would be made in a sequential manner starting with decision 1. In actual practice, however, the studies and resultant decisions might be grouped together. It is believed, however, that the four basic decisions provide a logical framework on which to build a set of guidelines for entrance ramp control. Thus these guidelines have been organized around the concept of a decision-making process that proceeds through these four decisions.

The consideration of the total decision process permits one to relate entrance ramp control to the overall considerations of freeway operation and control and transportation systems management. The process is broad in nature relative to decisions 1 and 2 and then focuses specifically on entrance ramp control through decisions 3 and 4. The following material will provide a brief overview of these decisions and their information requirements.

FREEWAY LEVEL OF SERVICE

The overall decision process starts with the assumption of the responsibility to monitor the operation of the freeway facilities in a given jurisdiction (city, county, highway district, etc.). The freeway system in this jurisdiction was designed to operate at a desired level of service. As traffic demands increase, however, this level of service may be reduced until it reaches a point where remedial action of some type is justified.

The freeway system to be monitored should be divided into manageable sections, and traffic evaluation studies should be conducted at periodic intervals to determine traffic flow conditions on each section. Three basic types of studies are pertinent, each of which requires an increased level of detail. The first type of study represents minimal freeway monitoring to determine typical operation and degree of congestion. The second type of study would concentrate on quantifying the magnitude of congestion, and the third type of study, when justified, would provide for detailed studies to evaluate all aspects of the freeway and corridor operation.

The foregoing studies would permit a thorough evaluation of the operation on each section of the freeway system. Each responsible agency should establish some basic objectives (such as level of service D) relative to the peak hour operation of the freeway system. This would then provide a means of determining if the freeway congestion on certain sections of the system had reached a level that could be termed serious or intolerable. This would then trigger the decision that some sort of corrective action is justified.

IMPROVEMENT ALTERNATIVES

Once the initial decision has been made that some type of corrective action is needed to improve the freeway level of service, then a decision must be made relative to what improvement alternative (or alternatives) should be implemented. The reduced level of service results from "bottleneck congestion" where the traffic demand exceeds the freeway capacity. The freeway bottlenecks may be permanent and fixed in location or they may be created by incidents and thus vary in time of occurrence and location.

The alternatives to reduce congestion can be classified into three broad categories. These categories are (1) demand-oriented alternatives where the basic objective is to reduce demand by some sort of freeway management technique, (2) capacity-oriented alternatives where the basic objective is to increase capacity by some type of construction or modification project, and (3) some combination of 1 and 2.

Entrance ramp control can be used to reduce demand to a given freeway section. Such control will divert vehicles either in time (ramp storage) or space (diversion of ramp vehicles to other routes). Entrance ramp control can also increase the level-of-service operation capacity by improving the efficiency of merging operations and overall freeway flow.

The decision process for selecting an improvement alternative will need to consider a rather wide range of possibilities. These possibilities would include the following:

1. *Demand-Oriented Alternatives*—reduction of overall travel; ride sharing (carpools, vanpools, etc.); public transportation; entrance ramp control (vehicle diversion); mainline control; freeway-to-freeway connector control; corridor control; and peak-period dispersion.
2. *Capacity-Oriented Alternatives*—construction of additional facilities; revision of entrance and exit ramp locations; expansion of existing facilities; temporary use of shoulders and narrow lanes; geometric modifications; incident detection and removal; incident management, including entrance ramp control for traffic flow improvement; and installation of accident investigation sites.

The decision to be made at this point relative to the improvement of freeway operation can range from construction (or modification) to traffic management. If traffic management or a combination of both construction and traffic management appears desirable, the feasibility of entrance ramp control should be examined in detail.

ENTRANCE RAMP CONTROL

Entrance ramp control may not always be feasible and a decision must be made in this regard before initiating studies to design the specific entrance ramp control treatment. Some basic questions that define the feasibility of entrance ramp control are as follows:

1. Does the freeway congestion problem lend itself to correction or improvement by entrance ramp control?
2. Do adequate diversion routes exist to handle the traffic that might be diverted by entrance ramp control?
3. Will geometric conditions on the ramps and freeway lanes permit entrance ramp control?
4. Is the introduction of entrance ramp controls a politically viable decision?
5. Will public acceptance permit entrance ramp control and can it be enforced? (The public is generally receptive if the control is reasonable and public information is provided to affected motorists prior to implementation.)
6. Are funds and manpower available for installing, operating, enforcing, and maintaining entrance ramp control; and would the use of the funds for entrance ramp control be cost-effective?

Answers to these and any other questions that might be pertinent for a given situation must be obtained through specific studies before making the decision to use entrance ramp control as a part of the freeway management process. If entrance ramp control is found to be feasible, a final decision must be made as to the specific type of control that will be used.

CONTROL MODE

The final decision that must be made (if entrance ramp control is feasible) is the selection of a specific mode of entrance ramp control. The three basic categories (or modes) of entrance ramp control are pretimed control, local actuated control, and system control.

Pretimed control represents a minimum level of control relative to initial cost, operation costs, and design complexity. This basic level of control would be used as a starting point and then a decision would be made relative to using local actuated or system control. This decision would be based on the incremental benefits (over pretimed control) to be realized versus the incremental cost of installing and operating the higher levels of control.

The benefits to be gained from local actuated or system control increase as the traffic management problems become more complex. Variables that can be expected to affect these benefits are identified as follows: traffic demand variability, incident rates, environmental variations, degree of variability of the entrance ramp volumes, and geometrics.

Additional costs are generally incurred with the increment to local actuated or system control. With local actuated control, the additional costs are due mainly to additional detectors and local actuated controller. System control, in addition to requiring additional detectors, introduces new categories of cost items such as data communications subsystem and control center subsystem.

The decision then as to what type of control would be used would consider these factors: traffic and geometric conditions for the specific freeway section under study; relative benefits, compared to pretimed control, to be obtained by using local actuated and system control; and costs incurred (relative to pretimed control) to install local actuated or system control.

SUMMARY

The total decision process that has been briefly described is shown in Figures E-1 and E-2. Figure E-1 depicts the global decision process and very briefly describes the activities within each decision level. In turn, Figure E-2 shows the decision process in detail and permits one to relate entrance ramp control to an overall consideration of freeway improvement techniques. It also permits one to focus on the studies relating to entrance ramp control and the need for detailed analyses regarding entrance ramp control feasibility and control mode selection.

The following sections of these guidelines expand on the decision process that has been defined and present a methodology for defining and selecting entrance ramp control.

CHAPTER 3

EVALUATION OF FREEWAY OPERATION

NEED FOR EVALUATION

The first step in a sequence of decisions that leads to the selection and installation of entrance ramp controls is the recognition that a significant congestion problem exists or will soon exist on a given freeway. This decision initiates a consideration of the various alternatives that can reduce the level of congestion. One such means of improving freeway operation may be entrance ramp control.

It is recognized that the various agencies that have the responsibility of maintaining and operating freeway systems will have different procedures for collecting data, conducting evaluations, and determining that a serious problem exists. However, a basic methodology for accomplishing these steps will be outlined as a guide to the initial study action that may lead to an entrance ramp control installation.

EVALUATION TECHNIQUES

There are three levels of evaluation that should be considered. These levels represent an increasing level of study detail, complexity, and cost. They are identified as follows:

Level 1—Freeway Monitoring. Minimum level of freeway operation studies to indicate basic levels of operation and degree of congestion.

Level 2—Operation Evaluation. Studies to quantify the magnitude of congestion.

Level 3—Operation Analysis. Detailed studies to quantify and evaluate all aspects of the freeway and corridor operation and congestion.

Freeway Monitoring

A freeway system in an urban area represents a tremendous public investment and has a daily impact on thousands of motorists. It is critical that such a system be continuously monitored to determine if it is providing the desired level of service. It is desirable that a set of objectives be established on which to evaluate the freeway operation. Examples of objectives that could be identified and defined are as follows:

1. *Level of Service*—An objective can be stated in terms of minimum level of service to be maintained (such as level of service D [LOS D]) or minimum speed (such as 40 mph) or both.
2. *Safety*—An objective can be stated in terms of a maximum allowable accident rate (such as 2.5 accidents/million vehicle-miles).
3. *Incident Impact*—An objective can be stated in terms of the minimum time (minutes) required to detect and remove an incident, and restore traffic to a normal level of operation.

The specific definition of a set of objectives for a given freeway system should be the responsibility of the operating agency. The objectives are important in that they become standards for the evaluation studies and provide a gauge for measuring the level of freeway operation deterioration.

Once objectives have been established, data should be collected periodically to permit an evaluation of freeway operation in light of the objectives. A preferred schedule would be to collect and analyze data every 3 to 6 months. If this is not feasible, a less frequent schedule should be implemented.

The basic data collection studies should include the following:

1. *Traffic Volume Counts*—Traffic counts should be made by direction at critical locations of the freeway at least once every 3 months. The counts can be made on an hourly basis, but shorter intervals, such as 15 min, are preferred in order to define the peak period. Permanent count stations should be used to correlate data taken on irregular intervals at other locations.
2. *Travel Time Studies*—Travel time data can be collected on an informal basis at any time during the year by taking note of speeds when traveling through the section. Travel time studies, however, should be conducted at least twice a year at 15-min time intervals during the peak period.
3. *Accident Analyses*—Accident statistics should be maintained for the total freeway system. Accident rates should be computed for the various segments that are experiencing traffic congestion, and high accident locations should be observed.

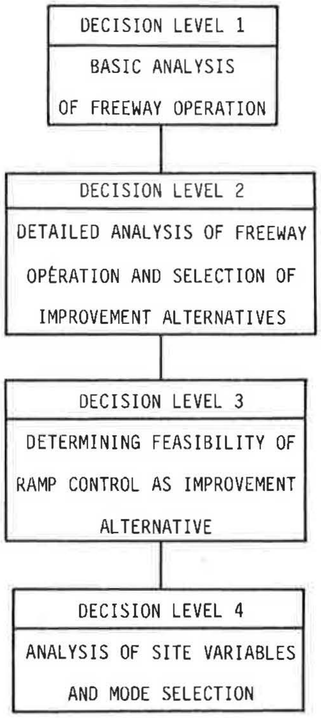


Figure E-1. Global flowchart of decision sequence.

The data collected during these studies, though relatively simple in nature, can provide the basic monitoring information that is needed. These data can be combined with the personal observations by the staff of the operating agency to provide a means of continuous monitoring that will establish trends and permit the first level decision ("Does a problem exist") to be made.

Operation Evaluation

If the data from the freeway monitoring system indicate a problem when compared with the basic objectives of operations, the magnitude of the problem should be quantified. In most cases, the freeway congestion problem will involve only a portion of the total freeway system. It is desirable to define these congested segments and to develop an estimate of the additional user costs created by the congestion.

Boundaries of Congested Segment

The first step is to define each congested segment in terms of its location on the freeway, the length of the congested segment, and the duration of the congestion. The monitoring studies for travel time data can provide a means of determining the location and length. That is, those sections of freeway that have average speeds less than the objective speed during the peak period can be identified. These findings should be quantified further by locating the downstream bottleneck of the congested segment (or segments). The downstream bottleneck will be defined by increased speeds downstream of the congestion. Peak hour observations of travel speeds should be made to establish the specific duration (minutes) of the congested period. The distances and times used to define the congested seg-

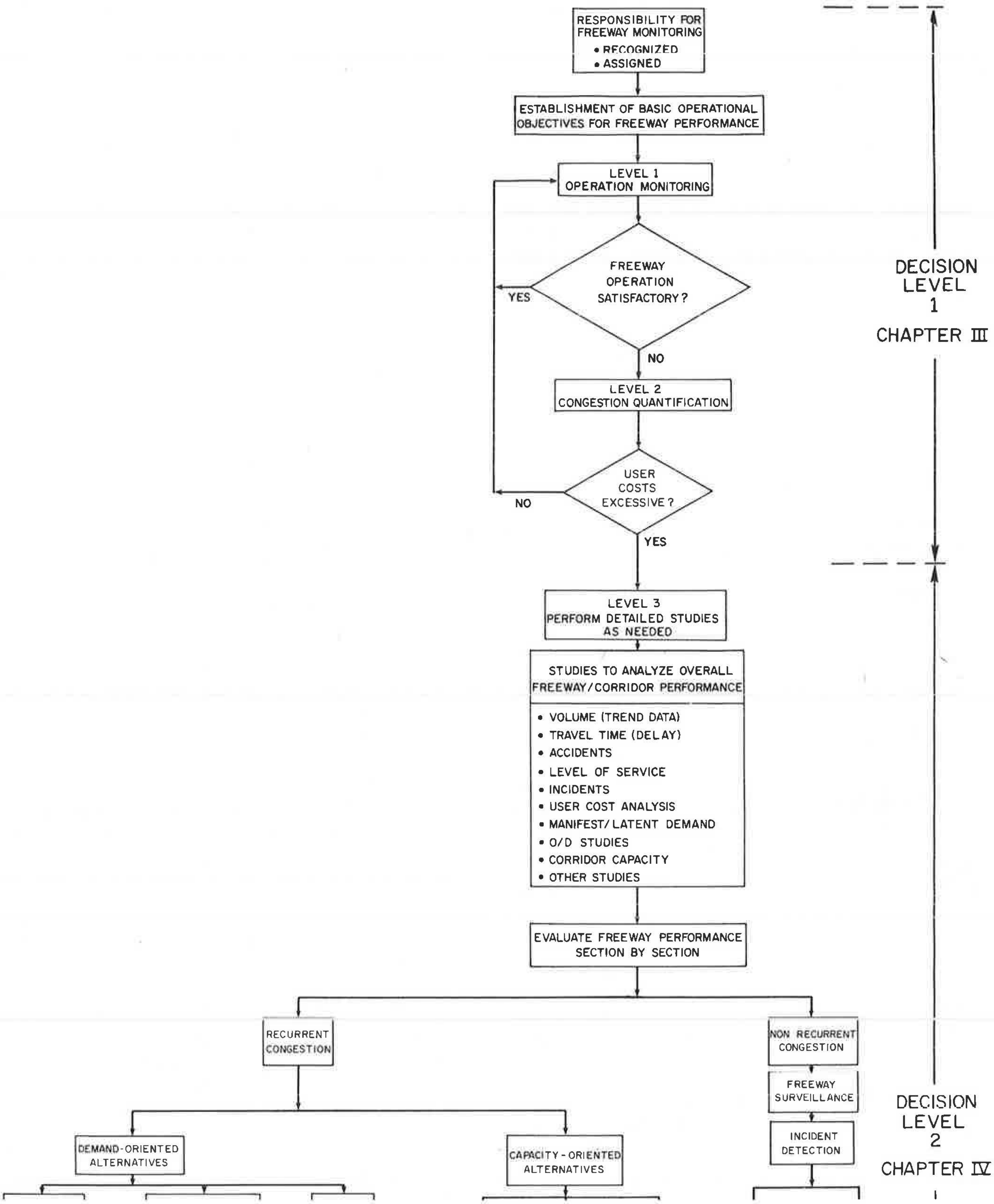
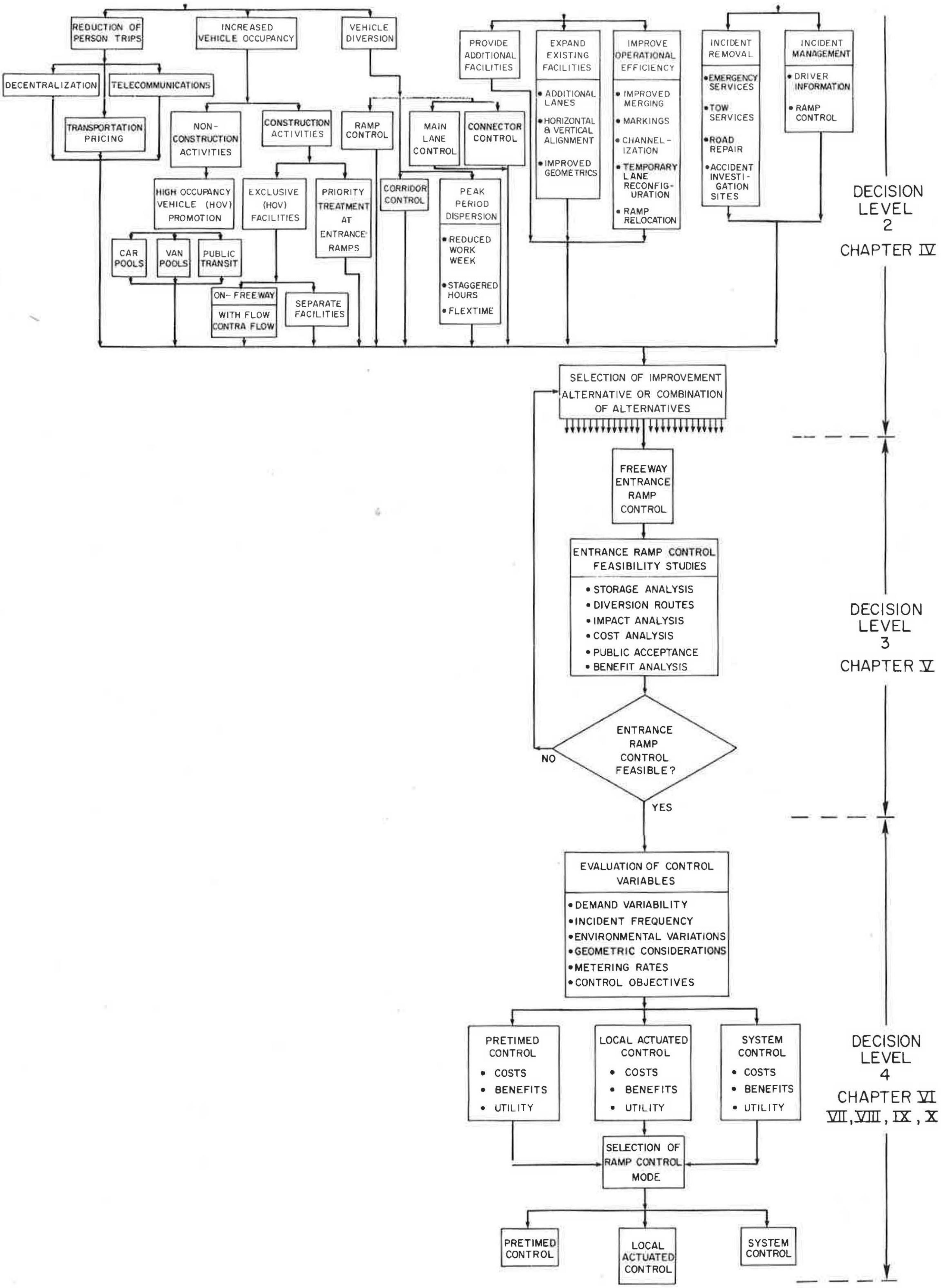


Figure E-2. Flowchart of freeway improvement techniques as related to entrance ramp control.


REDUCTION OF PERSON TRIPS
INCREASED VEHICLE OCCUPANCY
VEHICLE DIVERSION
DECENTRALIZATION
TELECOMMUNICATIONS
TRANSPORTATION PRICING
NON-CONSTRUCTION ACTIVITIES
CONSTRUCTION ACTIVITIES
HIGH OCCUPANCY VEHICLE (HOV) PROMOTION
EXCLUSIVE (HOV) FACILITIES
PRIORITY TREATMENT AT ENTRANCE RAMPS
CAR POOLS
VAN POOLS
PUBLIC TRANSIT
ON-FREEWAY
WITH FLOW CONTRA FLOW
SEPARATE FACILITIES
RAMP CONTROL
MAIN LANE CONTROL
CONNECTOR CONTROL
CORRIDOR CONTROL
PEAK PERIOD DISPERSION
• REDUCED WORK WEEK
• STAGGERED HOURS
• FLEXTIME
PROVIDE ADDITIONAL FACILITIES
EXPAND EXISTING FACILITIES
• ADDITIONAL LANES
• HORIZONTAL & VERTICAL ALIGNMENT
• IMPROVED GEOMETRICS
IMPROVE OPERATIONAL EFFICIENCY
• IMPROVED MERGING
• MARKINGS
• CHANNEL-IZATION
• TEMPORARY LANE RECONFIG-URATION
• RAMP RELOCATION
INCIDENT REMOVAL
• EMERGENCY SERVICES
• TOW SERVICES
• ROAD REPAIR
• ACCIDENT INVESTI-GATION SITES
INCIDENT MANAGEMENT
• DRIVER INFORMATION
• RAMP CONTROL
DECISION LEVEL 2
CHAPTER IV
SELECTION OF IMPROVEMENT ALTERNATIVE OR COMBINATION OF ALTERNATIVES
FREEWAY ENTRANCE RAMP CONTROL
ENTRANCE RAMP CONTROL FEASIBILITY STUDIES
• STORAGE ANALYSIS
• DIVERSION ROUTES
• IMPACT ANALYSIS
• COST ANALYSIS
• PUBLIC ACCEPTANCE
• BENEFIT ANALYSIS
ENTRANCE RAMP CONTROL FEASIBLE?
NO
YES
DECISION LEVEL 3
CHAPTER V
EVALUATION OF CONTROL VARIABLES
• DEMAND VARIABILITY
• INCIDENT FREQUENCY
• ENVIRONMENTAL VARIATIONS
• GEOMETRIC CONSIDERATIONS
• METERING RATES
• CONTROL OBJECTIVES
PRETIMED CONTROL
• COSTS
• BENEFITS
• UTILITY
LOCAL ACTUATED CONTROL
• COSTS
• BENEFITS
• UTILITY
SYSTEM CONTROL
• COSTS
• BENEFITS
• UTILITY
SELECTION OF RAMP CONTROL MODE
PRETIMED CONTROL
LOCAL ACTUATED CONTROL
SYSTEM CONTROL
DECISION LEVEL 4
CHAPTER VI VII, VIII, IX, X

ment should be as short as practical while still encompassing the entire peak conditions of the freeway.

Congestion Costs

As congestion develops on a freeway, the cost of operation as experienced by the freeway users will increase. Thus, the users experience "congestion costs." If the congestion costs are substantial, it becomes desirable to attempt to reduce these costs.

User costs that tend to increase as freeway congestion increases are as follows: travel time costs, vehicle operating costs, and accident costs.

A LOS D (average speeds 40 mph or greater) might be defined as a tolerable level of congestion and could be assumed to establish a base level of basic costs. As the LOS deteriorates to level E or F, the user costs will increase above those basic costs experienced at LOS D. The difference between the basic costs at LOS D and the actual costs at a greater level of congestion can then be used as a measure of the congestion costs. Stated another way, the congestion costs are potential benefits that could be obtained by improving the LOS on the congested segment of the freeway. An evaluation of these potential benefits can help the decision-maker to decide if a serious level of congestion exists and if some type of effort should be made to reduce the amount of congestion.

Basic Costs

Basic costs for freeway operation can be determined from procedures outlined in the publication *A Manual on User Benefit Analysis of Highway and Bus Transit Improvements 1977* (*E-1*). The assumptions associated with the LOS D are 1800 vehicles (passenger car equivalents) per hour per lane, 40-mph speed, and 0.9 V/C ratio. Unit costs are obtained either from Ref. (E-1), or from other sources that present updated values of costs to the current year.

The following cost figures were derived from tables in Chapter 13, which are taken from Buffington and Ritch (*E-2*); vehicle types are described in Table E-46:

$7.89 per vehicle-hour—based on an assumed vehicle occupancy of 1.25 persons per passenger vehicle (Chapter 13, Table E-47).

$0.0979 per vehicle-mile—passenger vehicle operating costs (Chapter 13, Table E-48).

$0.01482 per vehicle-mile—accident costs based on an accident rate of 2.60 accidents/MVM (Chapter 13, Table E-51).

Reference (E-1) indicates that the value of time may be a function of the amount of time saved per individual vehicle. If the amount of time saved exceeds 15 min, the value of time given in Table E-47 is appropriate. If the time saved is less than 15 min, the value of time given in Table E-47 should be reduced. In order to simplify the procedure of determining an acceptable value of time, the reduction factors given in Table E-1 are suggested.

To illustrate, assume an estimated time saving per individual vehicle in the 5 to 10-min range. The reduction factor would be 0.6, and the adjusted value of time would be $4.73 [$7.89 (from Table E-47) × 0.6 (from Table E-1)].

TABLE E-1

VALUE OF TIME-REDUCTION FACTORS

Estimated Time Savings (min.)	Reduction Factor
0 - 5	0.2
5 - 10	0.6
10 - 15	0.9
15 or more	1.0

Actual Costs

The actual costs of the congested segment are directly determined by conducting the required studies. Travel time studies are conducted to determine actual operating speeds. Estimates of the operating costs are obtained by using the average speed and obtaining a cents per vehicle-mile value from Table E-48 of Chapter 13. Accident costs are determined by evaluating the actual number of accidents and converting these to an accident rate (per million vehicle-miles).

An example is presented later to illustrate specific procedures to be followed in estimating basic and actual costs.

Operation Analysis

On the basis of the results of the level 2 evaluation analysis, it might be determined that a rather serious congestion problem exists and that some sort of improvement should be undertaken. At this point a more detailed operational analysis of the freeway should be conducted. The level 1 and level 2 studies should provide sufficient justification for the establishment of a properly funded study project to fulfill this need.

The objective of the level 3 study would be to define the basic cause of the problem and to develop a sufficient data base from which alternative freeway improvements could be evaluated. The types of studies to be conducted as needed are listed in the following; detailed descriptions for the study proceduers can be found in various publications (*E-3, E-4, E-5, E-6*):

1. *Bottleneck Analyses*—Speed and flow rate studies are used to define the location, cause, and capacity of bottleneck sections in the study area. Other studies, such as input-output analysis, aerial photography, and instrumented vehicle studies, are useful in determining the duration of congestion caused by the bottleneck.

2. *Volume Counts*—Volume counts at time intervals of 5 to 15 min should be made on all critical sections of the freeway and the ramps to determine short period flow rates, beginning and end of peak periods, and potential diversion and entrance ramp metering rates.

3. *Origin–Destination Studies*—It is helpful to determine the traffic flow patterns approaching and leaving the freeway if considerable volumes must be diverted from the

freeway as part of a control strategy. This information is useful in the analysis of the corridor.

4. *Corridor Analysis*—The same studies used to define the travel characteristics on the freeway lanes are used to evaluate the alternate routes to the freeway when traffic diversion is a possibility.

5. *Traffic Composition*—Volume counts by type of vehicle are conducted to determine the composition of the traffic stream.

6. *Geometric Analysis*—Geometric design deficiencies that affect the speed and capacity of the roadway are evaluated.

7. *Vehicle Occupancy*—The average passenger occupancy of the vehicles is determined for analysis of travel time and to indicate the potential for providing a high occupancy vehicle bypass.

The foregoing studies when completed would produce an excellent data base and permit a total knowledge of the freeway operation. This information would be useful in evaluating various improvement alternatives. These data would enable a more accurate calculation of the user costs and other measures of effectiveness described in this chapter.

EXAMPLE FREEWAY

To assist the user of these guidelines in following the procedures outlined in this and subsequent chapters, a typical freeway section with average peak hour traffic conditions will be described. The basis for the geometrics of this example freeway was the result of a questionnaire survey conducted in conjunction with the development of the guidelines. From 28 ramp control projects surveyed, it was found that the "typical" or "average" entrance ramp control system had the following characteristics:

5 entrance ramps
4 exit ramps
3 freeway lanes one direction
2.55 miles (7.65 lane-miles) segment length
Downstream "bottleneck" with average capacity of 5782 vehicles per hour (vph).

The ramp spacing and configuration for the example freeway are shown in Figure E-3. A capacity of 1900 vph per lane (5700 vph) with a LOS C was used for the example freeway.

Example—Level 1 Evaluation

In order to illustrate a simple level 1 evaluation, consider the example freeway shown in Figure E-3. Assume that manual or automatic counts are taken to obtain D_u (upstream demand) and V_d (downstream volume) and that an average speed through the section is measured or estimated. These data are as follows:

$$\begin{aligned} D_u &= 4{,}400 \text{ vph} \\ V_d &= 5{,}600 \text{ vph} \\ \text{Average speed} &= 30 \text{ mph} \end{aligned}$$

Considering these data, the following significant traffic parameters can be calculated for the peak hour:

- Total travel (TT) is a measure of productivity for a freeway. It is the product of the traffic estimated in several ways, and is expressed in vehicle-miles:

$$\begin{aligned} \text{Average volume} &= \frac{4{,}400 + 5{,}600}{2} = 5{,}000 \text{ vph} \\ \text{Total travel} &= 5{,}000 \text{ vph} \times 2.55 \text{ miles} \\ &= 12{,}750 \text{ veh-miles} \end{aligned}$$

- Total travel time (TTT) is the sum of the individual vehicle travel times along a specific freeway section, expressed in vehicle-hours. It too can be calculated or estimated in several ways; the one used in this example is TT divided by average speed of all vehicles:

$$\begin{aligned} \text{Total travel time} &= \frac{12{,}750 \text{ veh-miles}}{30 \text{ mph}} \\ &= 425 \text{ veh-hours} \end{aligned}$$

- Delay is the travel time over and above that required to travel a section of freeway at a desired speed. Assume desired speed is 40 mph, then:

$$\begin{aligned} \text{Travel time (40 mph)} &= \frac{12{,}750 \text{ veh-miles}}{40 \text{ mph}} \\ &= 318.75 \text{ veh-hours} \\ \text{Delay} = 425 - 318.75 &= 106.25 \text{ veh-hours} \end{aligned}$$

Simple studies and analyses of the type illustrated are satisfactory for the level 1 evaluation.

Example—Level 2 Evaluation

Basic Costs

The first step in the level 2 evaluation is to develop an estimate of the basic costs (i.e., the user costs incurred when the segment is operating at a LOS D). As indicated earlier, the following assumptions are associated with LOS D:

1800 vph per lane
40 mph speed
0.9 V/C ratio
$7.89/veh-hour travel time costs (1.25 persons/vehicle)
$0.0979/veh-mile operating costs
$0.01482/veh-mile accident costs

Slightly more detailed data would be developed for the level 2 evaluation. At least four travel time runs should be

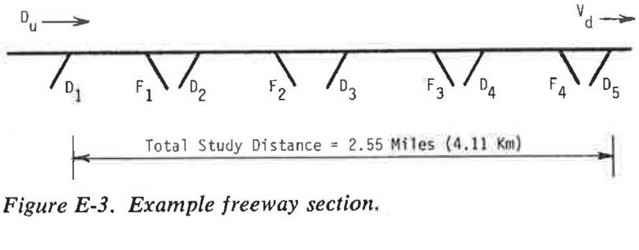


Figure E-3. Example freeway section.

TABLE E-2

TRAVEL TIME STUDIES

Travel Run No.	Travel Time (minutes)	Average Speed (mph)
1	3.83	40
2	7.65	20
3	7.65	20
4	3.83	40

Average travel time = 5.74 min. Average Speed = 26.6 mph

performed. Assume travel time runs produced the data given in Table E-2. Additional volume data including ramp volumes would be collected. These data would be tabulated as given in Table E-3.

Basic costs can now be estimated. The average individual time saving is the delay (106.25 veh-hours) divided by the volume (5000 veh). The average time saved (1.28 min) is in the range of 0 to 5 min. (Reference Table E-1 for value of time reduction factor.)

Total travel = 13,030 veh-miles

$$\text{Total travel time} = \frac{13{,}030 \text{ veh-miles}}{40 \text{ mph}}$$

= 325.75 veh-hours

Travel time costs = 325.75 veh-hours × 7.89 \$/veh-hour × 0.2

= \$540.03

Operating costs = 13,030 veh-miles × 0.0979 \$/veh-miles

= \$1275.64

Accident costs = 13,030 veh-miles × 0.01482 \$/veh-miles

= \$193.10

Total basic costs (LOS D) = \$514.03 + \$1275.64 + \$193.10

= \$1982.77 per peak hour

TABLE E-3

VOLUME AND TRAVEL TIME STUDIES

Count Location	Hourly Count (vph)	Freeway Demand (vph)	Distance (miles)	Total Travel (Veh-Miles)
D_u	4,400	4,400	0	0
D_1	600	5.000	0.35	1,750
F_1	300	4,700	0.25	1,175
D_2	500	5,200	0.35	1,820
F_2	300	4,900	0.35	1,715
D_3	400	5,300	0.40	2,120
F_3	300	5,000	0.25	1,250
D_4	500	5,500	0.35	1,925
F_4	400	5,100	0.25	1,275
V_d	5,600	5,600	0	0

Total Travel in System = 13,030 Vehicle-Miles

Actual Costs

The pertinent data that have already been tabulated are summarized as follows:

Total travel = 13,030 veh-miles
Average speed = 26.6 mph

$$\text{Total travel time} = \frac{13{,}030}{26.6} = 489.8 \text{ veh-hours}$$

Assume that studies of actual accident records indicate an accident rate of 3.0 accidents/million veh-miles. The actual costs can then be estimated as follows:

$$\begin{aligned}\text{Travel time costs} &= 489.8 \text{ veh-hours} \times 7.89 \text{ \$/veh-hour} \times 0.2\\ &= \$772.90\\ \text{Operating costs} &= 13{,}030 \text{ veh-miles} \times 0.0979 \text{ \$/veh-miles}\\ &= \$1275.64\\ \text{Accident costs} &= 13{,}030 \text{ veh-miles} \times \frac{3.0}{2.6} \times 0.01482 \text{ \$/veh-miles}\\ &= \$222.81\end{aligned}$$

$$\begin{aligned}\text{Total actual costs} &= \$772.90 + \$1275.64 + \$222.81\\ &= \underline{\$2271.35 \text{ per peak hour}}\end{aligned}$$

Congestion Costs

It is now possible to obtain an estimate of congestion costs by analyzing the difference between basic costs and actual costs. This difference is determined as follows:

$$\begin{aligned}\text{Actual costs} &= \$2{,}271.35\\ \text{Basic costs} &= \underline{\$1{,}982.77}\\ &\ \$\ \ 288.58\end{aligned}$$

The annual congestion cost for the segment used in the example is estimated, assuming 250 peak periods per year, as follows:

$$\begin{aligned}\text{Annual congestion cost} &= \$288.58 \times 250\\ &= \$72{,}145\end{aligned}$$

Thus, one can estimate an annual congestion cost (or potential improvement benefits) of $72,145 for the example freeway. This information could assist a decision-maker in determining if congestion is severe enough to warrant some sort of improvement action (decision 1).

CHAPTER 4

IMPROVEMENT ALTERNATIVES

DETAILED FREEWAY EVALUATION

If the freeway studies to evaluate operation described in Chapter 3 indicate that improvement is needed, one is faced with the decision of selecting the type of improvement to be made. The operation problems are the result of bottleneck congestion where the term "bottleneck" is used to define a point on the freeway where its physical or geometric features reduce the capacity (or ability to accommodate traffic flow) below that of other freeway locations in the same vicinity.

Two types of bottleneck congestion occur on freeways and they are termed (1) recurrent and (2) nonrecurrent. *Recurrent* bottleneck congestion is the term given to freeway congestion where both the location and time of occurrence can be predicted with a high degree of accuracy. *Nonrecurrent* bottleneck congestion is the term given to freeway congestion where either the location or time (or both) of occurrence is random in nature. This type of congestion results from incidents (accidents, stalled vehicles, spilled loads, etc.) that create a temporary bottleneck by blocking one or more lanes or in some way reducing the freeway capacity.

Both types of congestion present serious problems and merit special consideration. The approach to minimizing the effects of nonrecurrent congestion is one of detecting the incident and removing its effect on freeway capacty as soon as possible. This requires some type of freeway surveillance system for rapid incident detection and a response capability that can clear the incident and manage the freeway flow to minimize the effects of congestion while the bottleneck is being cleared.

Recurrent congestion is simply a case of freeway demand exceeding freeway capacity; two basic solutions exist for this problem. One can (1) reduce the demand, and/or (2) increase the capacity. Accordingly, the alternatives associated with this problem could be termed demand-oriented alternatives or capacity-oriented alternatives.

Thus, it can be seen that a first step in defining improvement alternatives would be to identify the prevalent type (recurrent or nonrecurrent) of congestion that is occurring. If the problem is one of nonrecurrent congestion, an approach involving surveillance and freeway management is needed. If the problem is one of recurrent congestion, both the capacity- and demand-oriented alternatives should be investigated. The most common situation is one where recurrent congestion is further compounded by nonrecurrent congestion; an approach that attacks both types of congestion is needed.

ALTERNATIVES FOR RECURRENT CONGESTION

As indicated earlier, two basic categories of improvement alternatives exist relative to recurrent congestion. These are demand-oriented alternatives and capacity-oriented alternatives. The alternatives available within each of these categories are identified and briefly discussed in the following material.

Demand-Oriented Alternatives

Alternatives in this category seek to reduce the traffic demand for movement through a bottleneck. These alternatives have a broad range and seek to accomplish one or more of the following objectives:

1. To decrease freeway demand by reducing the overall need to travel.
2. To decrease freeway demand by increasing the number of persons per vehicle.
3. To decrease peak period freeway demand by diverting trips in time or space.

The achievement of the first objective is long range in nature and requires the reduction of the need for people to travel. Basic approaches include the following:

1. *Decentralization*—This approach seeks to reduce the concentration of work centers and thus to reduce trip demand. It involves long-range land-use planning, and long-range socioeconomic changes.
2. *Telecommunications*—This approach seeks to reduce the need for direct, person-to-person contact (and thus travel demands) by using advanced communication techniques.
3. *Transportation Pricing*—This approach seeks to regulate demand through restrictive pricing of various transportation facilities.

The reduction of person-trips is a broad-based concept that has little immediate application. It will likely receive more attention in the future and may eventually become a more viable approach.

The achievement of the second objective has more immediate application and should receive serious attention. This approach seeks to increase vehicle occupancy and thus to reduce vehicle trips. Basic techniques for achieving this objective can be considered in two categories: (1) public promotion and (2) facility modification.

The public promotion approach uses an extensive public information program to encourage car pools, van pools, and the use of public transportation. Incentives for these types of programs include reduced commuting costs, reduced parking rates, preferential parking locations, and a sense of public improvement. Numerous programs have been developed and are available to promote car pooling, van pooling, and the use of public transit.

The facility modification approach seeks to encourage higher vehicle occupancy by providing a higher level of service to high occupancy vehicles (HOV). The modifications could include any of the following: separate HOV facilities, exclusive freeway lanes (with flow, contraflow), priority treatment (entrance ramps, toll facilities).

The third objective is achieved by diverting vehicles in time or space and thus reducing the demand at specific locations at certain points in time. Techniques for accomplishing this objective are indicated as follows:

1. *Entrance Ramp Control*—This technique seeks to divert vehicles in time or space (or both) by controlling the number of vehicles that can utilize an entrance ramp during a specific time period. Vehicles are either diverted in time (by storing on the ramp) or in space (by utilizing another route) and thus the demand at a specific bottleneck location can be reduced.
2. *Main Lane Metering*—This technique is similar to entrance ramp control except that the vehicle is controlled (stored or diverted) on the main lanes of the freeway. There has been very limited use of this technique in the past, but it is likely to receive more use in the future.
3. *Freeway-to-Freeway Connection Metering*—This technique is a form of metering similar to entrance ramp control where the metering occurs on the connections between freeways.
4. *Corridor Control*—This technique seeks to spread the traffic demand over all the facilities in a travel corridor and thus to reduce the demand on the freeway. The use of extensive driver information systems to advise drivers of the presence of congestion and the availability of alternate routes is a key element of this approach.
5. *Peak Period Dispersion*—This technique seeks to reduce peak period demand by spreading the time period during which persons must arrive or leave their work over a much larger base. Approaches to this type of dispersion include: reduced work week, staggered hours, and flextime.

Capacity-Oriented Alternatives

Alternatives in this category seek to increase the capacity available to serve the traffic demand. This is accomplished by one of three basic methods identified as follows:

1. Provide additional facilities.
2. Expand existing facilities.
3. Improve the efficiency of existing facilities.

The provision of additional facilities which might parallel overloaded freeway sections and service a similar origin–destination demand is a very capital-intensive and long-range approach. It should not be overlooked, however, as an alternative which may be necessary.

It is often possible to expand existing facilities to correct capacity deficiencies at bottleneck locations. Improvements could include one or more of the following: addition of one or more lanes; improvement of horizontal or vertical alignment. Measures to improve the capacity of parallel arteries should be considered as well. This would include upgrading and operational improvement of frontage roads.

A final technique for improving bottleneck capacity would be to make modifications or operational changes that improve the efficiency (and thus capacity) of existing facilities. Examples of this type of improvement include the following:

1. Entrance ramp control to improve merging efficiency.

2. Reduction of lane width and use of shoulders to increase the number of lanes.
3. Channelization to improve merging and weaving operations.
4. Improvement of geometric features (lateral clearances, acceleration lanes, etc.).
5. Reversal and/or relocation of entrance and exit ramps.

ALTERNATIVES FOR NONRECURRENT CONGESTION

Nonrecurrent congestion is created by the occurrence of some type of incident that has a capacity reducing effect on the main lanes of the freeway. The capacity reduction can range from minor, such as a "gapers block" created by an accident or police vehicles on the shoulder, to major when a spilled load or stalled vehicle may block a freeway lane, to total closure of the freeway by an overturned truck or major accident.

The proper response to incidents involves the following three major activities:

1. Rapid detection of the incident.
2. Rapid removal of the incident.
3. Traffic control to minimize the impact of the incident.

Major surveillance techniques that have been used to detect incidents include the following:

1. Electronic surveillance.
2. Closed circuit television.
3. Aerial surveillance.
4. Emergency call boxes.
5. Emergency telephones.
6. Cooperative motorist-aid systems.
7. Citizen band radio.
8. Police and service patrols.

Incident removal normally involves the provision of one or more of the following services: emergency services (police, fire, ambulance), tow services, and road repair services. These services need excellent communication and coordination to assure that the freeway is cleared of all capacity-reducing effects as soon as possible. It may be desirable to use accident investigation sites adjacent to the freeway to which accident-involved vehicles and persons may be removed.

If the incident creates a substantial blockage (one or more lanes), it is usually desirable to be able to use some form of freeway incident management. The basic concept of incident management is to use control strategies and driver information systems to minimize the impact of the incident. Components of incident management include development of traffic control plans, informing drivers of the blockage, suggesting alternate routes, and controlling the input to the freeway section where the incident has occurred.

Where incidents are frequent, it may be desirable to use entrance ramp control. Entrance ramps upstream of the incident can be metered to reduce traffic input to the congested area. The metering rates on entrance ramps downstream of the incident can be increased to accommodate traffic bypassing the incident.

SELECTION OF IMPROVEMENT ALTERNATIVE

The purpose of this chapter has been to identify the wide range of improvement alternatives that exist relative to freeways and to indicate the relationship of entrance ramp control to the numerous alternatives. It is obvious that a number of alternatives must be considered and that a wide range of studies must be conducted to evaluate the various alternatives. These guidelines are concerned only with the use of entrance ramp controls and will thus consider only those alternatives that involve entrance ramp control. The total spectrum of improvement alternatives has been presented, however, to provide a perspective of entrance ramp control in the total freeway improvement picture.

The decision to investigate the use of entrance ramp control as a means of improving freeway operation would be made in conjunction with an evaluation of the various improvement alternatives. If a decision is made to pursue the evaluation of an alternative involving entrance ramp control, specific studies can be conducted to determine the feasibility of entrance ramp control and select the mode of control. These studies are presented in following chapters.

CHAPTER 5

ENTRANCE RAMP CONTROL FEASIBILITY

INTRODUCTION

Although entrance ramp control is applicable to most freeways, one should not automatically assume that entrance ramp control will be desirable and feasible for all freeways. Thus, the next major decision involves conducting studies to evaluate the feasibility of entrance ramp control.

Although entrance ramp controls are useful in managing freeway traffic when incidents create nonrecurrent congestion, their major use is associated with recurrent congestion situations. Recurrent congestion is created at points on the freeway where traffic demand predictably exceeds the normal mainline capacity of the freeway. Traffic demand at this point may be reduced by the selective use of entrance ramp controls.

ENTRANCE RAMP CONTROL WARRANTS

It is difficult to specify any type of numerical warrants for entrance ramp control such as those that might be used to determine if an intersection should be signalized. Instead, the decision must be based on an engineering analysis of a number of factors that have a significant bearing on the desirability and feasibility of entrance ramp control.

The basic logic for the engineering analysis of entrance ramp control is expressed in the "Interim Warrants for Freeway Entrance Ramp Control Signals" incorporated in Section 4E-23 of the 1978 Edition of the *Manual on Uniform Traffic Control Devices* (*E-7*). These warrants state:

1. Installation of freeway entrance ramp control signals may be warranted when:
   a. The expected reduction in delay to freeway traffic exceeds the expected delay to ramp users and added travel time for diverted traffic and traffic on the alternate surface routes; and
   b. There is adequate storage space for the vehicles which will be delayed; and
   c. There are suitable alternate surface routes available having capacity for traffic diverted from the freeway ramps; and
      (1) there is recurring congestion on the freeway due to traffic demand in excess of the capacity, or
      (2) there is recurring congestion or a severe accident hazard at the freeway entrance ramp because of inadequate ramp merging area.
2. Installation of freeway entrance ramp control signals may be warranted to reduce sporadic congestion on isolated sections of freeway caused by short-period peak traffic loads from special events or from severe peak loads of recreational traffic. It should be noted that these are "Interim" warrants and that some disagreement exists in the transportation community relative to the use of these warrants.

Minimum volume warrants have been suggested. Table E-4 indicates one such set of volume warrants that are used by the Texas State Department of Highways and Public Transportation, and which could be used as a guideline.

ENTRANCE RAMP CONTROL PHILOSOPHY

There are some overall philosophies of entrance control that should be considered at this point. One philosophy of entrance ramp control maintains that such controls should be introduced prior to the occurrence of severe freeway congestion. Under this concept, the freeways would be carefully monitored and projections of the growth of peak hour traffic demand would be developed. By utilizing these projections, entrance ramp control would be planned and installed prior to the occurrence of severe peak hour congestion. In this manner, a desired level of service would be maintained on the freeway. Also, it is believed that the introduction of entrance ramp control at lower levels of congestion would be more acceptable to the public, bebecause it would be less restrictive (higher metering rates, less diversion) at this point. The use of warrant volumes as given in Table E-4 reflects this concept.

TABLE E-4

MINIMUM PEAK HOUR WARRANT VOLUMES (MAIN LANES PLUS RAMP) AT BOTTLENECK LOCATION IN METROPOLITAN AREA OF APPLICABLE SIZE SHOWN

Freeway Facility	Metropolitan Area Size <500,000	 500,000-1,000,000	 Over 1,000,000
Four lane freeway (Two lanes one direction)	2,600	2,850	3,050
Six lane freeway (Three lanes one direction)	3,850	4,200	4,550
Eight lane freeway (Four lanes one direction)	5,150	5,550	6,050
Each additional lane above four in one direction and one-lane ramp connections at interchanges.	1,300	1,350	1,500

"The above warrant volumes apply when traffic volumes are increasing."

Source: Texas State Department of Highways and Public Transportation

Although the concept of planning and introducing entrance ramp controls ahead of serious congestion is fundamentally sound, it will likely encounter a number of practical problems (lack of funds, official interest, etc.). It is a concept that is worthy of noting and using if possible.

Another philosophy of entrance ramp control relates the introduction of such control to any capacity improvements that are made to the freeway. For example, if a lane is added to a congested freeway section that has no entrance ramp control, entrance ramp control should be included as a part of the modification project. In this way, the improved level of service obtained by adding the freeway lane can be maintained by controlling the amount of entrance ramp traffic. If controls are not introduced, the latest demand will absorb the increased capacity (provided by the additional lane) and the freeway will quickly return to a congested state.

FEASIBILITY STUDIES

A consideration of the suggested warrants defines several types of studies that may be necessary to assemble the basic information needed to determine the feasibility of entrance ramp control. These studies can be defined as follows:

1. Bottleneck analyses (location, demand analyses, capacity analyses, metering rates).
2. Geometric analyses (ramp storage, merging areas).
3. Traffic diversion analyses (diversion estimate, diversion routes, diversion impact).
4. Accident analyses.
5. Enforcement analyses.
6. Public acceptance analyses.
7. Preliminary cost considerations and cost-effectiveness analyses.

The completion of the foregoing studies in a thorough manner will provide the decision-maker with a solid data base to use in determining the feasibility of entrance ramp control.

Bottleneck Analyses

The first step in evaluating entrance ramp control feasibility is to conduct an analysis of the freeway bottleneck (or bottlenecks). This study would determine the demand/capacity ratio at the bottleneck, and evaluate the means by which demand to the bottleneck section can be reduced or the capacity of the bottleneck increased.

Bottleneck Location

The identification of the location of the freeway bottleneck is a relatively easy task. A review of the main lane geometrics may point to locations where capacity reductions occur. These reductions may be due to lane reduction, horizontal or vertical curvature, or other physical features such as lane width, lateral clearance, or surface condition.

The location of bottlenecks can be further verified by travel time studies. The development of a speed profile along the freeway will indicate where speeds are low because of congestion as well as points where speeds increase as one passes through the bottleneck.

Aerial photography or aerial observation is also an excellent means for pinpointing freeway bottlenecks. Aerial observation during peak periods of flow will permit the rapid delineation of bottlenecks. Aerial photography can be used to document the characteristics and locations of bottleneck conditions.

Demand/Capacity Ratio

Once a bottleneck has been located, the next step is to determine both the capacity of the bottleneck as well as the demand for traffic to flow through the bottleneck. The capacity can best be determined by taking volume counts at the bottleneck section when traffic demand is at or above capacity. The mainline volumes should be observed and recorded at 5-min intervals. The volume count should start at least 30 min prior to the peak period and the traffic volumes should be recorded for each freeway lane if possible.

By initiating the count well in advance of the peak period, it is possible to observe maximum flow rates as the traffic builds up. The maximum throughput will usually occur just prior to the onset of congestion. Once stop and go conditions are initiated by the peak period congestion, the flow rate through the bottleneck will be reduced. By observing the traffic flow during the peak periods, it will be possible to establish a reasonable capacity value for the bottleneck section.

There are two types of demand that must be recognized in connection with freeway operation:

1. *Manifest Demand*—Number of vehicles actually using a freeway at a given point.
2. *Latent Demand*—Total number of vehicles that may desire to use a freeway at a given point.

Latent demand is very difficult to measure. Thus, in the case of freeway bottleneck studies, one usually measures manifest demand directly and uses this value to develop estimates of the latent demand.

Experience with urban freeways over a number of years has indicated that the peak hour demand ranges from 10 to 11 percent of the average daily traffic (ADT). However, today it is not uncommon to observe congested freeways where the peak period has been increased in time and the peak hour/ADT ratio has dropped to 7 percent. This indicates that the freeway users are starting their trips earlier or later (often at some personal inconvenience). It also indicates that there is a large latent peak hour demand that may exceed current freeway volumes by as much as 50 percent. Thus, if added capacity is provided to a freeway section, this capacity will quickly be consumed by the large amount of latent demand.

The use of input-output study techniques is recommended for recording demand. For such a study, the input count locations are selected upstream of all congestion. The mainline output boundary is selected just downstream of the bottleneck section. Input and output volumes are observed by 5-min intervals starting before the peak period and continuing past the peak period.

The input-output data can then be used to compute the demand-capacity relationship for the bottleneck section throughout the entire peak period.

Metering Rates

The demand-capacity study results can be used to estimate preliminary entrance ramp metering rates. The resultant metering rates provide a key value that can be used to judge the feasibility of entrance ramp metering.

Metering rates for entrance ramp control have upper and lower limits, and it is important to determine if the requisite metering rates fall within these limits. It is usually desirable to use single-entry metering, which is the type of metering where vehicles queue behind a ramp signal and are released one vehicle at a time. Two practical considerations thus govern the upper and lower limits of entrance ramp control.

If one considers the maximum metering rate, it is necessary to recognize that the ramp signal must remain on red long enough to give the next vehicle in line time to pull up to the signal. Thus, the minimum length for a full green-yellow-red cycle of the ramp signal is approximately 4 sec. This yields an hourly metering rate of $(3600/4) = 900$ vph.

If the ramp signals display a red for as long as 20 sec, there is high probability that the driver of the stopped vehicle will ignore the signal and enter against the red. A ramp metering rate of approximately $(3600/20) = 180$ vph is suggested as a lower limit of ramp metering rates. (At metering rates lower than 180 vph, it may be desirable to close the ramp entirely by the use of gates or other appropriate control techniques.) Thus, the range of acceptable metering rates is approximately 180 to 900 vph.

The results of the demand-capacity studies discussed earlier provide a basis for estimating the metering rates that would be necessary. The entrance ramp control would have to be capable of reducing the demand to a point at or below the bottleneck capacity. By determining the bottleneck capacity and the mainline demand, it is then possible to determine the maximum input from the entrance ramps upstream of the bottleneck section that can be permitted to maintain the total bottleneck demand at an acceptable level.

The preliminary metering rates are useful in two ways for evaluating the feasibility of entrance ramp control. First, the metering rates can be compared with the acceptable range of metering rates to determine if they fall within a feasible range. Second, the metering rates will be useful in estimating ramp queues and amount of diverted traffic. The use of these data (queue lengths, diversion) will be discussed in a later chapter. An example will also be presented to illustrate the development of a metering plan.

Geometric Analyses

The entrance ramps that are being considered for control should be analyzed from two geometric viewpoints. First, the placement of the entrance ramp control signals and the associated equipment should be studied. Once the signals are located according to adequate acceleration distances, it will be possible to evaluate the storage capacity of the individual entrance ramps. A storage requirement of 24 ft per vehicle can be used to estimate the number of vehicles that can be stored at a given entrance ramp without creating major operational problems. Then a comparison of the necessary entrance ramp metering rate and the traffic demand on the entrance ramp can be used to estimate the probable number of vehicles that will be queued at the entrance ramp. The number of queued vehicles can be adjusted to account for some diversion to nonfreeway routes.

The estimated queue length can be compared to the amount of ramp storage for each entrance ramp under question to determine if serious queueing problems will exist. Entrance ramp storage may be increased by the use of multiple approach lanes. If the predicted queues cannot be accommodated, the feasibility of applying entrance ramp control is questionable. One might also establish some maximum waiting time for use as a guideline of control feasibility (i.e., 5 min).

The second geometric consideration for entrance ramp control is that of the merging area geometrics. In general, it can be stated that entrance ramp control with single-entry metering will facilitate the merging maneuver. The more undesirable the merging area's geometric characteristics, the more desirable entrance ramp control will be.

Traffic Diversion Analyses

The results of the bottleneck analyses and the geometric analyses can be used to estimate probable traffic diversion that will be created by the introduction of entrance ramp controls. Three factors are critical in a diversion analysis and these are listed as follows:

1. Number of vehicles diverted at each entrance ramp.
2. The routes that will be taken by the diverted vehicles.
3. The impact of the diverted traffic on the alternate routes.

Diversion Estimate

The first step in the diversion analysis is to estimate the number of vehicles that may be diverted by the introduction of entrance ramp control. Such an estimate must be developed for each affected entrance ramp.

The amount of diverted traffic at a given ramp will be a function of the trip length, queue length, the amount of entry delay encountered, and the availability and efficiency of alternate routes. There are no specific methods for determining the amount of diverted traffic. A good set of data on entrance ramp demands, average delay, storage capabilities, and alternate routes must be used in conjunction with good engineering judgment to produce a reasonable estimate. A reasonable diversion level can be estimated by determining the difference in the allowable ramp volume (determined by the demand-capacity analyses) and the existing uncontrolled entrance ramp volume.

Diversion Routes

The next step is to identify and evaluate the alternate routes that would be followed by any diverted entrance ramp traffic. This can be accomplished by developing a good understanding of the potential destinations of the entrance ramp traffic and inventorying the potential diversion routes. In some cases, it may not be possible to find feasible alternate routes. For example, barriers such as railroads, drainage ditches, and major cross streets may limit the availability of alternate routes.

Once the alternate routes are identified, studies should be conducted to evaluate the routes. Travel time studies should be conducted to evaluate the travel time of diverted traffic to a number of potential destinations. Such studies would permit the determination of the additional delay (if any) that might be imposed on diverted entrance ramp traffic.

Bottleneck locations on the alternate routes should also be identified and capacity analyses should be conducted at these points. These data will be needed to conduct impact analyses.

Diversion Impact

The third step is to evaluate the potential impact that the diverted traffic may have on the alternate routes. If the alternate routes are operating at or near capacity, the addition of significant numbers of diverted vehicles to the routes may create some very undesirable congestion problems.

To accomplish this analysis, a majority of the predicted number of vehicles that are diverted at each ramp must be assigned to a specific alternate route. This assignment is usually based on one's best engineering judgment. This diverted traffic must then be considered in conjunction with existing traffic at bottleneck locations along the alternate routes.

Demand-capacity analyses must then be conducted to evaluate the congestion impact of the diverted traffic.

Summary

The final step in the diversion analysis is to evaluate all aspects of the traffic diversion. This will include a consideration of the additional travel time that may be encountered by the diverted traffic as well as an evaluation of the impact of the diverted traffic on the alternate routes. These considerations will then provide another factor that can be used to evaluate the feasibility of entrance ramp control.

Accident Analyses

Although entrance ramp controls are not usually installed as a safety measure, they contribute to smoother traffic flow which results in safer operation. As another factor to be considered, an accident analysis should be conducted to determine the frequency, severity, and types of accident experiences.

Conventional accident analyses techniques can be used to determine the frequency and rates of accidents on the mainline as well as the entrance ramps. These rates can then be compared to other freeways that are operating with entrance ramp controls or that have demand/capacity ratios and average speeds that approximate those to be achieved with ramp control. To determine the potential improvement in safety only the time periods of control should be used in the accident analysis.

Experience indicates that entrance ramp control impacts the accident experience through the reduction of rear-end accidents. Figures reported indicate accident reductions ranging from 10 to 35 perecnt. In general, the experience with severe injury and fatal accidents is not significantly changed by the introduction of entrance ramp controls. A reduction of numerous minor accidents and their resultant impact on freeway flow is a significant benefit, however.

Conventional accident analysis techniques can be used to develop the accident study. This might include plotting individual accident locations on a freeway layout and indicating the type of collision, time of occurrence, severity, and any other pertinent data. This will facilitate an analysis of the pattern of accidents. It will then be possible to study the entrance ramp operations in terms of accidents to determine if a large number of entrance ramp-related accidents are occurring. If a peak period pattern of rear-end accidents on the ramps and/or accidents in the ramp merging areas is evident, this will give additional weight to the desirability of introducing entrance ramp control.

Enforcement

The success of entrance ramp control is largely dependent on the degree of compliance that is obtained from the drivers. The introduction of entrance ramp controls represents a departure from the high degree of driver freedom normally associated with freeway operations. When metering rates are set in the range of 180 to 360 vph and long queues are created, there must be concern that the drivers will not obey the ramp control system because they will encounter rather significant delays in entering the freeway.

Therefore, a good climate of traffic control enforcement is essential. Coordination and cooperation should exist between the traffic control agency and the law enforcement agency. A high level enforcement activity is necessary during the initial entrance ramp control operation. Continuing enforcement efforts throughout the life of the control operation will be required to keep control violations at a reasonable level (5 to 10 percent).

Thus, another factor that must be considered in evaluating the feasibility of entrance ramp control is enforcement. A special study of entrance ramp control enforcement, therefore, should be conducted as a part of the feasibility studies. This study should evaluate potential enforcement problems and estimate the cost and problems associated with providing low, medium, and high levels of enforcement surveillance.

Public Acceptance

Another area of concern relative to ramp control feasibility is the public acceptance of entrance ramp control. Although entrance ramp control may offer significant overall benefits to the public, it is difficult to relate these benefits to individual freeway users.

A majority of the users who will be impacted by entrance ramp control will only see the delay caused by the entrance ramp control signals. Although specific benefits may be produced by the entrance ramp controls (reduced delay, reduced accidents, and the like) and can be demonstrated statistically, they may not be recognized by individual motorists. However, an average 2 or 3 min wait in an entrance ramp queue is very real and easily recognized by all motorists.

In announcing the beginning of an entrance ramp control system, it is important to convey three main items to the public:

1. The basic reasons for initiating the control (severe congestion, inefficient freeway operation, etc.).
2. A realistic expectation of the benefits of the control (reduced delays and user costs).
3. The alternate choices that are available to users of the system.

It is evident that a good working relationship with the news media is essential so that announcements and the necessary information can be transmitted to the public. The operating agency should be prepared to transmit factual and current information to the news media both before and after the installation of the controls.

At frequent intervals, it is desirable to provide a brief update on the control project. On an annual basis, a review of the accident experience and the cost effectiveness of the project should be provided.

Strong support of the control project by pertinent public officials is essential. This support should be obtained through good technical briefings which show the value of the control project. To date, only one operational control system has been removed because of public reaction. Public complaints relative to any aspect of the system should be properly investigated. It is not advisable, however, to placate public complaints by unwarranted adjustments of metering rates. If metering rates are set too high to effectively control demand, the total concept of the entrance ramp control is circumvented.

Cost Considerations

A final factor that should receive consideration in the feasibility is the preliminary cost estimate of the ramp controls. The need at this point is not for highly refined cost analyses but for general "ballpark" figures on the overall costs of introducing ramp control.

Two basic costs must be recognized at this point. These costs are (1) initial capital costs and (2) operating and maintenance costs. The initial costs provide for purchasing and installing the necessary entrance ramp control equipment, and the operating and maintenance costs provide for keeping the control system operating over time. The need for these expenditures must be recognized at this point so that this information can become a part of the total data base of the feasibility study. Information on control system costs and how they may be estimated is provided in Chapter 7.

FEASIBILITY DECISION

It should now be apparent that a considerable amount of information must be collected, analyzed, and summarized to provide a total data base for making the decision to install entrance ramp controls. It should also be evident that specific numerical warrants may not be desirable and that a considerable amount of engineering and managerial judgment must be applied in determining the feasibility of entrance ramp control.

The material in this chapter is intended to provide a straightforward and logical process for conducting a feasibility study and focusing on the decision of entrance ramp control feasibility.

CHAPTER 6

CONTROL MODES

ENTRANCE RAMP CONTROL MODE DEFINITION

An entrance ramp control system's mode is defined as the particular arrangement that is used for determining when its ramp signals are in operation and how its metering rates are resolved. Entrance ramp control modes can be organized into three basic categories: pretimed, local actuated, and system. The majority of entrance ramp control systems in operation can be placed readily in one of these three categories.

PRETIMED CONTROL MODE

Any form of entrance ramp metering that is not directly influenced by mainline traffic conditions is called pretimed control. This term does not necessarily imply the absence of vehicle detectors. In many applications, both demand and passage detectors are used to actuate and terminate each metering cycle. These detectors, however, are used to detect entrance ramp vehicles rather than mainline vehicles, and cause an entrance ramp signal to cycle during the control period only when vehicles are present.

The individual metering rates used with pretimed control are solely a function of past traffic observations, which may include origin–destination studies that determine the particular ramps affected by the freeway travel patterns. When the set of rates has been established through a metering plan, metering operation is subsequently independent of all factors other than time-of-day, day-of-week, or special events. Pretimed control can apply, of course, to any number of entrance ramps—from a single ramp to many ramps. No interconnection with other entrance ramps is used. A further discussion on the pretimed control hardware configuration occurs later in this chapter.

LOCAL ACTUATED CONTROL MODE

Local actuated control, in contrast to pretimed control, is directly influenced by the mainline traffic conditions during the metering period. For example, a local actuated controller may implement progressively more restrictive metering as occupancy levels on the mainline increase. The decision-making mechanism is based primarily on real-time, locally measured traffic conditions based on mainline detectors in the immediate vicinity of the ramp. No interconnection with other ramps is used and no attempt at global optimization is possible, except whatever the combined effect of individual entrance ramp controls may be. A further discussion on the local actuated control hardware configuration is given later in this chapter.

SYSTEM CONTROL MODE

System control is the form of entrance ramp metering in which real-time information on total freeway traffic conditions is used for control of a system of entrance ramps. Although such metering is typically imposed by a central, computer-controlled system, the control intelligence may also be distributed among the individual entrance ramps. A significant feature of this class of metering is the interconnection that permits conditions at one location to affect the metering rate imposed at one or more other locations. Freeway traffic conditions as reflected by detectors throughout the system are analyzed at a central location and metering rates for all ramps are established according to a real-time metering plan. A further discussion on the system control hardware configuration is given later in this chapter.

HARDWARE OVERVIEW

The hardware for implementing pretimed and local actuated modes of entrance ramp control is generally similar, but with different functional capabilities of some of the components. The system mode of entrance ramp control, on the other hand, introduces considerably more hardware to the system requirements. Figure E-4 shows the basic hardware requirements for the three modes. Various combinations of these components may be configured. The principal components necessary for entrance ramp control system operation are discussed in the following.

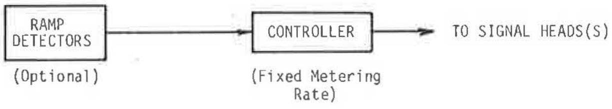
Detectors (*E-8*)

The 1980 state of the art of vehicle sensors clearly favors the use of discrete detectors. Of the many types of discrete detectors that could be used, three have received widespread acceptance and use: ultrasonic, magnetometer, and inductive-loop. Of these three, the inductive-loop detector is widely acclaimed as the most flexible, reliable, and accurate. Therefore, the inductive-loop detector appears more frequently in freeway applications, especially at the on-ramp where special lengths or shapes may be required for a broad area of coverage. At least one loop detector manufacturer claims satisfactory performance with a 1000-ft lead-in. Where very long lead-ins are needed, magnetometer detectors are desirable. For both main lane counting and speed-trap applications, magnetometer detectors are performance and cost competitive with loop detectors, and can be installed more quickly. For applications where pavement cutting is not possible, or where unsettled pavement exists, ultrasonic, radar, or television may be considered. Too, the selection of detector type depends on the needs imposed by the choice of control strategy. Guidelines for locating freeway detectors are given in Koble et al. (*E-9*).

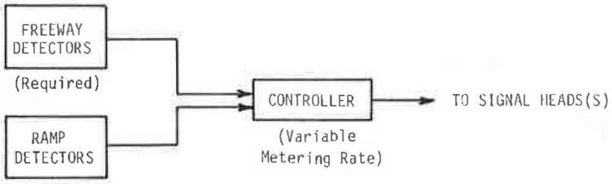
Discrete detectors provide the basic data source for any control or surveillance system, and also represent the weakest link in the entire chain. Advances and improvements made in detectors over the years have not removed the need for additional improvement. For example, uniformity of loop detectors from unit to unit is difficult to achieve and not generally obtained. Generally speaking, false calls, lockups, nondetection, and complete failures can be expected and should be a consideration in system design and operation. It is difficult to positively confirm detector operation without 24-hour computer monitoring.

Controllers

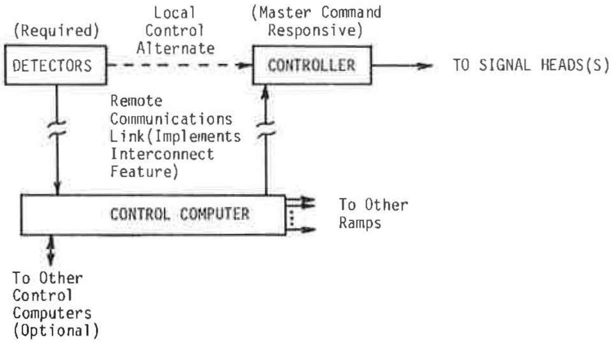
The controller is the control element that provides the functions given in Table E-5.



a. Pretimed



b. Local Actuated



c. System

Figure E-4. Basic hardware requirements for three modes of entrance ramp control.

TABLE E-5

CONTROLLER FUNCTIONS BY MODE

Mode	Receives Detector Inputs?	Accepts Master Commands?	Directs Signal States?
Pretimed	Possibly	No	Yes
Local Actuated	Yes	No	Yes
System	Possibly*	Yes	Yes

*Isolated control may be possible.

Controllers provide the switching outputs to the ramp signal, with detector inputs utilized according to mode. In the case of system mode, the controller interfaces to a communication link for the interconnect capability. In terms of the amount of control logic required at the entrance ramp, a pretimed controller requires a minimum amount of logic to implement time dependent activities, a local actuated controller requires a respectable amount of logic to make control decisions based on detector inputs, and a system controller may require only a small amount of logic to implement master commands. The low cost of the microcomputer has made the amount of logic in the controller relatively incidental.

Data Communications

Communication of data beyond the immediate vicinity of an individual entrance ramp becomes necessary with the forwarding of detector data and the linking of controllers to a central point for the system control mode. Such an interconnection is usually implemented by private or leased lines. Private lines are owned and maintained by the operating agency, while leased line services are generally provided by the local telephone company. Although private lines cost more initially and present a continuing maintenance overhead, they are nevertheless becoming more attractive in view of leased line cost increases in the past few years. The solution tò this problem varies, but the services of a qualified communications consultant should be employed for assistance in analyzing specific cases. This involves not only the communication lines, but also the electronic equipment at either end to transmit/receive data. Other techniques besides a hard wire link can be employed.

Control Computer

Only the system control mode requires the use of a supervisory control computer. Generally, this function is satisfied by a minicomputer, with a choice of many brands available. Memory sizes can be quite large if needed, and a variety of peripheral units such as disk drives, printers, keyboards, cathode ray tube (CRT) terminals, etc., can be attached. Very large entrance ramp control systems might require a medium scale computer, while smaller systems might require only a microcomputer.

Source: RIO-6, 2B-35; Manual On Uniform Traffic Control Devices, U.S. Department of Transportation, Federal Highway Administration, 1971.

Figure E-5. Entrance ramp signal sign.

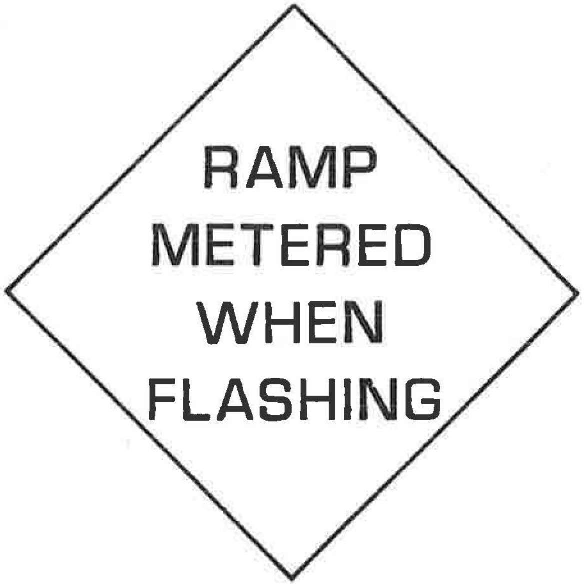


Figure E-6. Advisory sign for controlled entrance ramps.

Signal Heads

Signal heads are the standard single head design, with either 2-color or 3-color displays. Consideration here is given primarily to single vehicle metering. Multivehicle metering is a simple extension of single vehicle metering, requiring revised signal timing and/or geometrics. Head heights are generally low because of close proximity viewing by the waiting driver. A sign mounted on the signal stand to encourage vehicles to approach the stop line (and actuate the demand detector) is shown in Figure E-5.

Advance Flashers

Advance flashers may be placed upstream of a controlled ramp, either on the ramp itself or on the servicing frontage road. During ramp signal operation, the flashers are activated to inform the driver of the control situation. An information sign may be associated with the flashers, depicting a message such as the one in Figure E-6.

TYPICAL SYSTEM CONFIGURATIONS

The three types of systems described herein are pretimed, local actuated, and system. Although each field installation varies in detail from the idealized description, the basic features of each type of system follow.

Pretimed Mode Configuration

The principal components of a pretimed mode configuration are the controller, signal head, cabinet, wiring, and possibly detectors. A diagram of these components is shown in Figure E-7.

An entrance ramp metering system to be installed at the very lowest cost would use no detectors at all. In such a system, metering would necessarily be performed by some pretimed controller. The most obvious choice of hardware would be the dial-and-stepped-cam controller, still used in large numbers for street intersections. Although far from representative of the latest technology, it is low in cost, can be effective, and does not require specialized maintenance skills. The dial can be turned on and off with a time clock, so that metering intervals correspond only to recurrent patterns. By using multidial assemblies, simple forms of rate selection may be implemented.

Whether an electromechanical dial or solid state unit is chosen, the functional operation of the ramp is much the same. Simple cycling of the red, yellow, and green intervals occurs, the red interval being lengthened or shortened to control the metering rate. The use of a yellow interval can be used to prevent sudden stops that give rise to rear-end collisions. Using a 3-color head, typical display times are a 1.5 sec green, followed by a 2-sec yellow and a minimum 0.5-sec red. With this cycle time of 4 sec, a full 900 vph may be metered, even with a pretimed controller. In actual practice, however, the full 900 vph may not be achieved. The major objection to pretimed metering is that it is not responsive to actual freeway congestion or to real-time demand. Turn-on and turn-off times are according to time-of-day. An advance flasher unit (if used) is activated when the entrance ramp signal is being operated.

Local Actuated Mode Configuration

The principal components of a local actuated mode configuration are the controller, signal head, cabinet, detectors, and wiring. A diagram of these components is shown in Figure E-8.

Main lane freeway detector information is furnished to the controller by the detector amplifier units in the control cabinet. This information is used to implement a specific metering rate according to presettable parameters. Volume, speed, or occupancy levels are typical parameters that can be keyed to metering rates. The entrance ramp is operated strictly on the basis of the information that is supplied by its freeway detectors, plus the mechanical control functions dictated by the ramp detectors. Turn-on and turn-off times can be a function of freeway traffic conditions. An advance flasher unit (if used) is activated when the entrance ramp signal is being operated.

Note that the merge, output, and queue detectors are shown as optional in Figure E-8. A merge detector is used as a feedback mechanism to prevent additional metering while vehicles are stopped in the merge area. The output detector can be used in conjunction with the merge detector to further refine the logic of detecting vehicles waiting to merge, by performing a simple input-output study of the section between the output and merge detectors. Additionally, the output detector is an accurate counting detector for the number of vehicles metered. The queue detector is used at locations where backup of traffic is critical to other operations, such as an intersection. This discussion also applies to the system mode configuration described in the following section.

System Configuration

The principal components of a system mode configuration are the controller, signal head(s), cabinet, detectors, wiring, data communications subsystem, communications medium, and control computer. A diagram of these components is shown in Figure E-9.

Freeway status information is furnished to the control computer via the detector amplifier units in the control cabinet. This information is transmitted through the data communication subsystem. All of the freeway status information is available to the control computer for systematic evaluation. Metering rates are issued by the control computer to the respective entrance ramps, based not only on traffic conditions in the immediate vicinity of the ramps but well upstream and downstream of particular ramps. This is the basic concept of system control; the

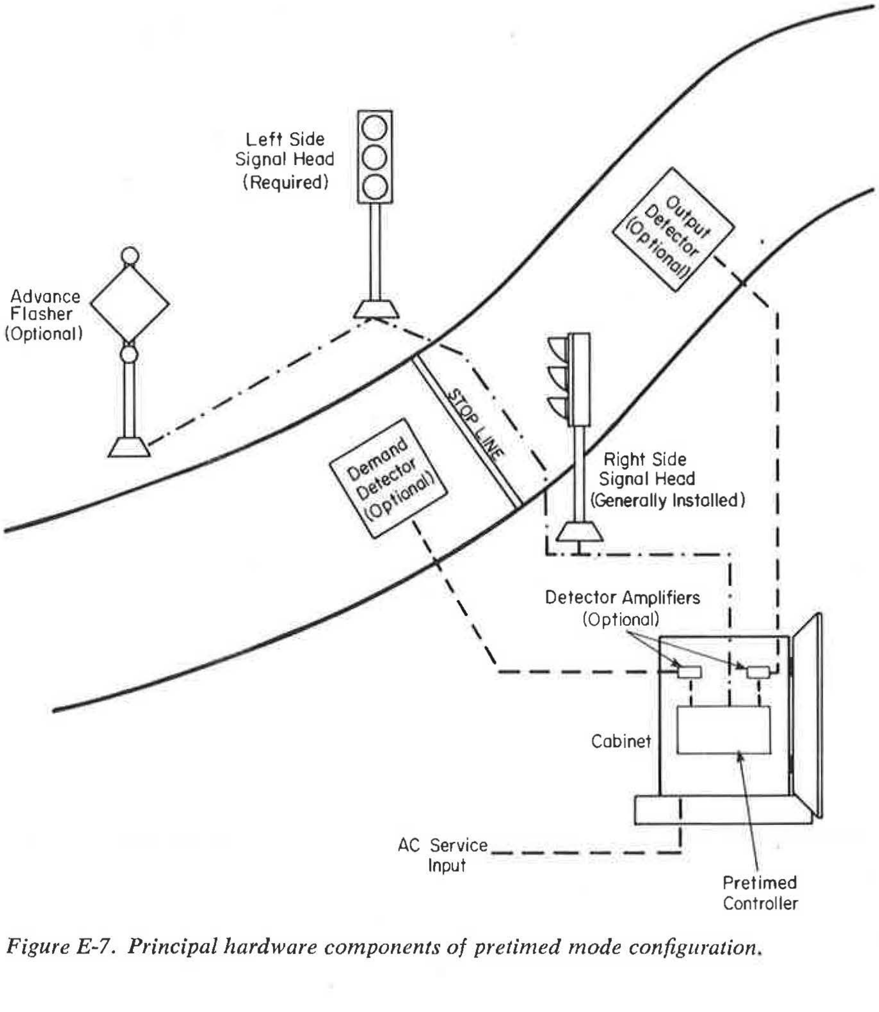


Figure E-7. Principal hardware components of pretimed mode configuration.

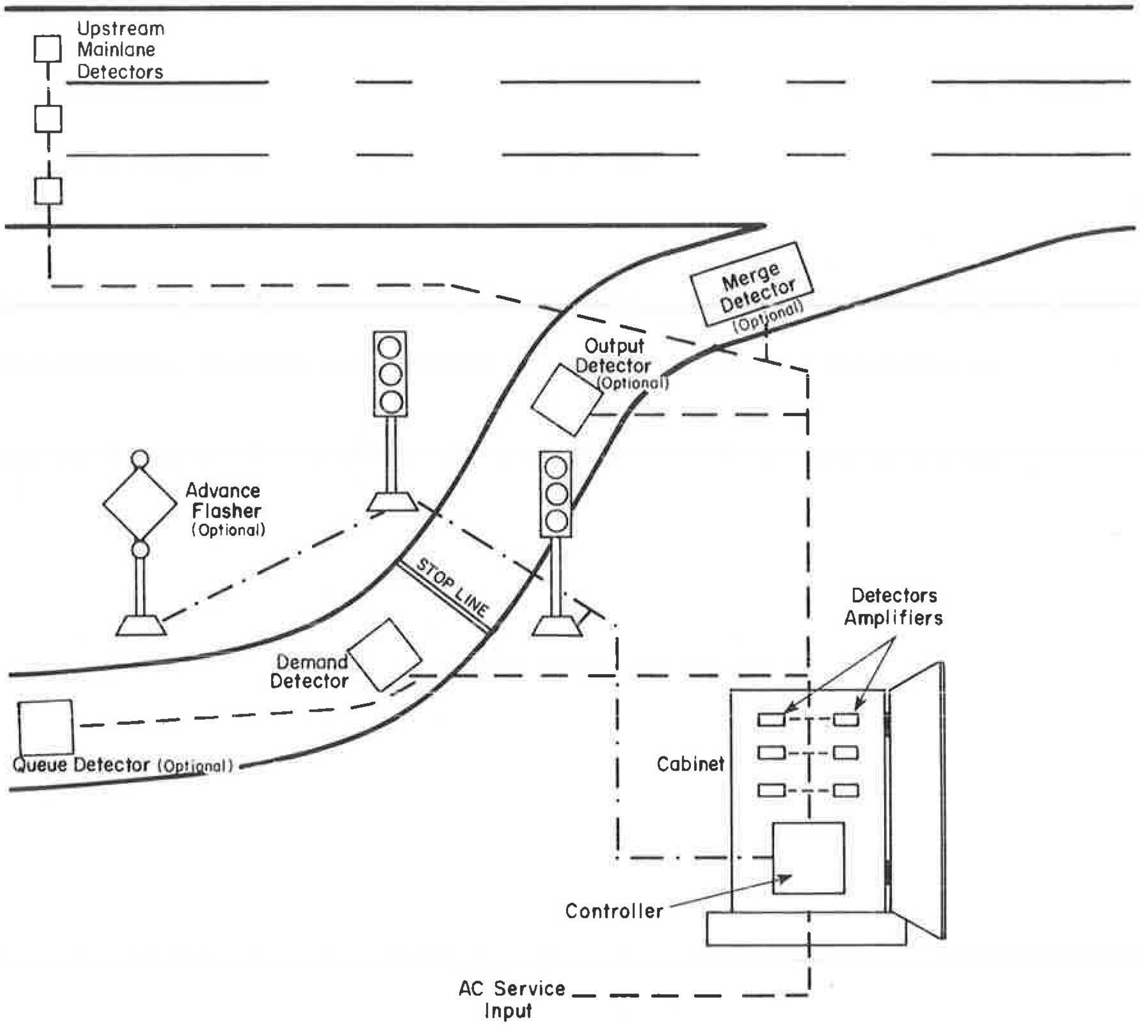


Figure E-8. Principal hardware components of local actuated mode configuration.

entire freeway section under control is treated as a unit in real-time. Pretimed and local actuated have as their objective the control of a freeway section as a unit. The pretimed mode accomplishes this task without the benefit of information on freeway conditions, while the local actuated mode manages the situation by piecemeal control of isolated subsections.

The function provided by the controller can be an extension of the control computer or merely a unit for implementing direct control commands. In the former case, the controller functions as a memory unit and implements a commanded metering rate until commanded to change that metering rate. In the latter case, the control computer issues timing commands for the duration of each color displayed during each cycle. Turn-on and turn-off times can be a function of freeway conditions. An advance flasher unit (if used) is activated when the ramp signal is being operated.

CONTROL STRATEGIES

The control strategies are the algorithms followed in developing the rates at which the ramp signals are cycled. Considering single vehicle metering, this translates into the number of vehicles that are admitted to the freeway per unit of time. A typical rate is 10 vpm or 600 vph.

Pretimed Control Strategies

If N is the number of different time intervals that a metering rate can be specified during a control period, an N dial pretimed controller is required to implement the strategy. Turn-on and turn-off times are initiated by the time-of-day.

A pretimed strategy is based on matching uniform demands with control measures that reduce freeway congestion. A preliminary control plan is developed which limits access by the desired amount, based on current traffic data. When the system becomes operational, traffic data are collected which reflect the operational characteristics of the freeway when it is under control. These data are then used as feedback to revise the metering rates for continuing control. Queue lengths and motorist response are factors in the revision of metering rates, but sufficient time must be

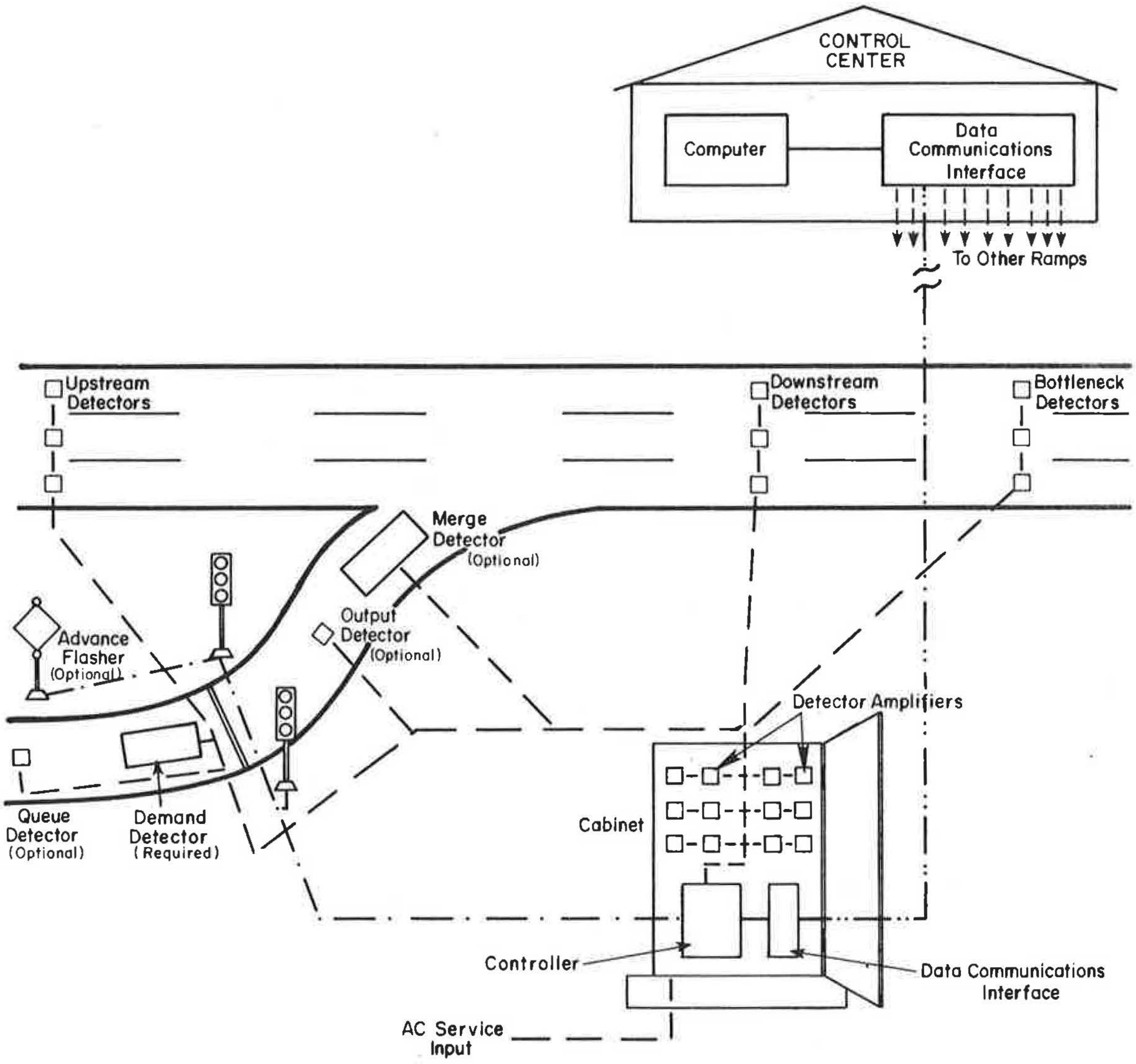


Figure E-9. Principal hardware components of system mode configuration.

given for the system to stabilize with each change. Small increments of change are desirable to gradually reshape traffic patterns.

Local Actuated Control Strategies

Local actuated control, because it is influenced by mainline traffic conditions, can respond to traffic conditions in the subsystem comprised by the freeway subsection in the immediate vicinity of the ramp. Freeway speed, volume, density or occupancy can be used as a measure of the quality of flow. Generally speaking, the metering rate is proportional to the quality of freeway flow—low quality, low metering rate; high quality, high metering rate.

A typical local actuated strategy limits the entrance ramp volume to a desired value by correlation with the occupancy level of the adjacent mainline traffic. This occupancy level would be determined by measuring the percent of time that vehicles were over a point of detection. Table E-6 is an example of occupancy levels with corresponding metering rates.

TABLE E-6

LOCAL ACTUATED METERING RATES AS A FUNCTION OF MAINLINE OCCUPANCY

Occupancy (%)	Metering Rate (Vehicles/Min.)
≤10	12
11-16	10
17-22	8
23-28	6
29-34	4
>34	3

System Control Strategies

The system mode of control is the only control mode that can truly have a control strategy. Pretimed and local actuated modes can be more accurately described as operating according to a control plan rather than a control strategy.

Assume a control system with across-all-lanes detector count stations at regular intervals and speed detectors at critical bottleneck locations. Any given entrance ramp would have a count station both upstream and downstream of the ramp, together with a speed measurement at a critical downstream bottleneck. The strategy would compare each of these three parameter measurements against a table of threshold volumes, and preassigned metering rates would be obtained for each of these measurements. A simple strategy is then to pick the smallest of the determined metering rates.

For example, assume a 3-lane freeway section with a 1-min upstream flow of 95 vehicles, downstream flow of 85 vehicles, and critical downstream bottleneck speed of 25 mph. The associated parameters are given in Table E-7, and the metering rates for upstream, downstream, and bottleneck locations, respectively, are 3, 6, and 9. Selecting the minimum metering rate of 3 would dictate that the entrance ramp would meter 3 vpm over the next minute, at which time the parameter movements would again be evaluated for the following minute's metering rate, and so on. Many other combinations of analytic procedures could be applied to achieve a strategy for assigning metering rates.

Common Elements of Strategies

The main difference between the three mode strategies is time. The pretimed strategy is computed on the basis of a forecast of the average traffic conditions that will be occurring during a specific time period. A dial is associated with the time period. Freeway operation resulting from the effects of metering during this time period is the consequence of this strategy.

The local actuated mode operates in real-time in response to freeway traffic conditions as they occur in the vicinity of each ramp. The effect of this mode of control is that the freeway is divided into subsections delineated by the locations of mainline detectors. The monitoring of local conditions is essentially continuous because the response to occupancy changeover levels is immediate. The operation within each subsection is highly dependent on the operation of the immediate upstream and downstream subsections. The effectiveness of total system operation under local actuated control is a function of (1) the propagation speeds of congestive and clearing conditions of the downstream subsystem and (2) the output of the upstream subsystem.

The system mode is an on-line real-time process that calculates a new metering strategy regularly according to existing traffic conditions. If, for example, the update interval is 1 min, a calculation is made each minute to determine the metering strategy for the next minute. As a result, feedback from the metering strategy is for all practical purposes a continuous operation. Given this capability, a control algorithm is structured to provide a metering strategy that is compatible with the virtually continuous method of updating metering rates systemwide in real time.

Detailed discussions of various control strategies are given in Everall (*E-6*), Masher et al. (*E-8*), and Carroll et al. (*E-10*).

TABLE E-7
CONTROL STRATEGY PARAMETERS

Upstream		Downstream		Bottleneck	
1 Min. Vol.	Metering Rate	1 Min. Vol.	Metering Rate	Speed	Metering Rate
91-100	3	91-100	3	41-50	15
81-90	6	81-90	6	31-40	12
71-80	9	71-80	9	21-30	9
61-70	12	61-70	12	11-20	6
<61	15	<61	15	0-10	3

CHAPTER 7

CONTROL SYSTEM COSTS

AVERAGE COST OF A CONTROL SYSTEM *(E-11)*

This chapter deals with the costs of an entrance ramp control system and warrants a qualified introduction. Nothing is a clearer indication of an outdated document than cost figures that are not current. This document was produced in 1980 and, as such, reflects costs in terms of 1980 dollars. But even so, costs vary in every part of the country and are the result of various economic forces that are present in a particular locality. If inaccuracies exist in this document, they are most likely to surface when the user estimates his system costs and compares them to the figures in this chapter.

Based on average costs of installed systems, if a pretimed mode installation costs X dollars per ramp, a local actuated mode installation will cost 1.25 X dollars per ramp, and a system mode installation will cost 2.0 X dollars. These ratios, of course, are subject to change over time.

A good estimate for X is $16,000 in 1980. Thus, for a pretimed configuration costing $16,000/ramp, a local actuated configuration would cost $20,000/ramp and a system configuration would cost $32,000/ramp (this figure is exclusive of the cost of the communications medium, i.e., leased or private lines). Generally, though, these prices are meaningless without detailed qualification of what is and what is not included in the configuration.

EXAMINING THE COST PROCESS

The steps involved in deriving the cost of an entrance ramp control system should be no different from those followed in costing out any traffic control system. All direct and indirect costs should be considered, and the amount of experience that the user has had in design, procurement, operation, and salvage will be a factor in the accuracy of the cost estimate. This chapter is intended to provide a checklist for the components of an entrance ramp control system, as well as to explore some of the operational and maintenance issues.

PREPARATION FOR THE COST ESTIMATE

After selecting an entrance ramp control system configuration, the limits of the freeway control section should be established. Detectors, signals, and advance flashers should be located on the plans. It is appropriate to cluster detector amplifiers and controllers in a minimum number of control cabinets, consistent with the detector maximum lead-in length limitation. As control cabinets are located on the plans, electrical service should be planned to each of the control cabinets, as well as conduit paths for detector lead-in, signal head, and advance flasher wiring.

In implementing the system control mode, it is necessary to coordinate the technique of cabinet entry with termination equipment inside the cabinet (leased lines), or locate conduit/overhead paths for a private communication system. After selecting a central control center site, conduit runs should be planned for communications system entry if using a private wire system. Sufficient electrical service and outlets for the computer system and displays, plus adequate air conditioning/ventilation, are necessary for the control center.

RAMP CONTROL CONFIGURATION COSTS

This section gives general cost information on all three ramp control modes and lists most of the items that are generally required in an entrance ramp control system installation. These items may vary according to local convention, but the functional categories should provide substitution for specialized components. Subsystems are listed for each control mode, followed by a listing of the typical components that comprise each subsystem.

Pretimed Mode Configuration

The following are the subsystems that are required in a pretimed mode installation:

Subsystem	Percent of Total Cost	1980 $ Estimate
• Detector (Optional)	10	1600
• Traffic Signal	40	6400
• Advance Flasher	10	1600
• Control Cabinet	40	6400
Equipment and Installation (E&I) Subtotal	100%	$16,000
Annual Maintenance	10% of E&I/year*	
Annual Operation	6% of E&I/year*	
Operation and Maintenance (O&M) Subtotal	16%*	

* These are first year costs, subject to increase over the life of the project. Use of a solid state controller (lower maintenance cost) is presumed.

Local Actuated Mode Configuration

The following subsystems are required in a local actuated mode installation:

Subsystem	Relative Cost (%)
• Detector	25
• Traffic Signal	32
• Advance Flasher	8
• Control Cabinet	35
Equipment and Installation (E&I) Subtotal	100%
Annual Maintenance	12% of E&I/year*
Annual Operation	6% of E&I/year*
Operation and Maintenance (O&M) Subtotal	18%*

* These are first year costs, subject to increase over the life of the project.

System Mode Configuration

The following subsystems are required in a system mode installation:

Subsystem	Relative Cost (%)
• Detector	20
• Traffic Signal	20
• Advance Flasher	5
• Control Cabinet	20
• Data Communications *	6
• Computer	24
• Control Center	5
Equipment and Installation (E&I) Subtotal	100%
Annual Maintenance	15% of E&I **
Annual Operation	15% of E&I **
Operation and Maintenance (O&M) Subtotal	30% **

* Exclusive of communications medium, such as leased or private lines.
** These are first year costs with leased lines, subject to increase over the life of the project.

SUBSYSTEM COMPONENTS

This section addresses the individual items that are components of the various subsystems. Approximate percentage costs of the subsystem, relative to total installation cost, are given in parentheses in the following order: (pretimed; local actuated; system).

- Detector Subsystem (10%; 25%; 20%)
    - Detector lead-in cable
    - Detector sensing element
    - Detector amplifier (as required)
    - Conduit
    - Trenching, boring, and jacking
    - Pull boxes
    - Drip T's
    - Splicing
    - Saw cuts
    - Channelization fixtures (wide ramps)
- Traffic Signal Subsystem (40%; 32%; 20%)
    - Signal head
    - Pole
    - Base
    - Fittings
    - Advisory sign
    - Foundation—concrete and reinforcing
    - Anchor bolts
    - Ground rod
    - Wire and cable
    - Trenching, boring, and jacking
- Advance Flasher Subsystem (10%; 8%; 5%)
    - Signal head
    - Pole
    - Base
    - Fittings
    - Advisory sign
    - Foundation—concrete and reinforcing
    - Anchor bolts
    - Ground rod
    - Wire and cable
    - Trenching, boring, and jacking
- Control Cabinet Subsystem (40%; 35%; 20%)
    - Control cabinet
    - Shelves
    - Ventilation fan
    - Foundation—concrete and reinforcing
    - Anchor bolts
    - Ground rod
    - Cabinet wiring
    - Communications service conduit (system mode only)
    - Signal conduit
    - Detector conduit
    - Terminal blocks
    - Ground bus
    - Circuit protectors
    - Fuses
    - Trouble lamp
    - Outlet receptacle
    - Special paint
    - Manual operating circuit
    - Controller
    - Flash unit (for advance flasher)
- Data Communications Subsystem (0%; 0%; 6%) (Exclusive of communications medium, such as leased or private lines. If user-owned lines are provided, this item will increase considerably (possibly up to 50% of project cost) and operating costs (detailed in following section) would be expected to decrease due to absence of leased line charges. The components of the data communications subsystem can vary widely according to the technique employed. Major items which can be included are as follows.)
    - Modems
    - Multiplexers
    - Tone transmitters and receivers
    - Line drivers
    - Decoders/encoders
    - Power supplies

  - Lightning protection
  - Test mode features
  - Voice equipment for maintenance
  - Communications concentrator or front end-control center only
  - Cabinets—control center only
- Computer Subsystem (0%; 0%; 24%) (The computer configuration and costs can vary widely among installations and are highly dependent on the number of ramps. Major items which can be included are as follows.)
  - Computer mainframe and memory
  - Card reader
  - Line printer
  - CRT terminals
  - Printing terminals
  - Multiplexer
  - Parallel input/output ports
  - Hard disk drive(s)—fixed and/or removable
  - Magnetic tape unit(s)
  - Cassette tape unit(s)
  - Flexible disk drive(s)
  - Paper tape reader/punch
  - Software (This item can exceed the cost of all other system components combined. The pricing of the computer subsystem assumes the software does not have to be developed from scratch, but rather it is an adaptation of existing software to this particular system. Further, it is assumed that the software adaptation is performed by experienced traffic control system programmers.)
  - Computer options
    - Real-time clock
    - Power fail/auto restart
- Control Center Subsystem (0%; 0%; 5%)
  - Air conditioning
  - AC power service
  - AC receptacles
  - Disk storage cabinets
  - Card cabinets
  - Keypunch
  - Paper tape storage
  - Magnetic tape storage
  - Wiring terminals
- Maintenance (10%; 12%; 15%)
  - Field maintenance
    - One traffic system electronic technician, helper, and service vehicle per 25 ramp signals and 25 detectors
    - Replacement parts
    - One communication system technician and service vehicle per 25 ramp signals (system control mode only)
  - Control center maintenance (system control mode only)
    - Computer and peripherals (suggest use of maintenance contract with manufacturers or independent service organizations; limited maintenance may be accomplished through the use of rental/loaner boards)
    - Software (one systems analyst/programmer per 30 ramps)
- Operation (6%; 6%; 15%)
  - Data acquisition
    - Manual counts
    - Travel time studies
    - Field observers
  - Electricity
  - Updating of control plan
  - Control center (system control mode only)
    - Computer operator
    - Computer systems analyst(s) and/or programmers
    - Traffic engineer
  - Leased line charges (system control mode only)
  - Control center rent and supplies (system control mode only)
- Initial Operation (10%; 10%; 8%)
  - Before study (immediately prior to turn-on)
    - Field observation
    - Analysis
  - After study (after traffic pattern stabilization)
    - Field observation
    - Analysis
  - Publicity

EXAMPLE SYSTEM COSTS

The example freeway introduced in Chapter 3 consists of 5 entrance ramps and 4 exit ramps. Table E-8 gives the estimated costs for the example freeway according to control mode.

TABLE E-8
EXAMPLE FREEWAY COSTS ACCORDING TO CONTROL MODE

Note: These figures are based on $16,000/ramp for Pretimed configurations, $20,000/ramp for Local Actuated configurations, and $32,000/ramp for System configurations.

CAPITAL COSTS FOR FIVE RAMPS

ITEM	PRETIMED	LOCAL ACTUATED	SYSTEM
Detector subsystem	8,000	25,000	32,000
Traffic signal subsystem	32,000	32,000	32,000
Advance flasher subsystem	8,000	8,000	8,000
Control Cabinet subsystem	32,000	35,000	32,000
Data communications subsystem*	0	0	9,600
Computer subsystem	0	0	38,400
Control center subsystem	0	0	8,000
Total capital costs	$80,000	$100,000	$160,000

CONTINUING COSTS FOR FIVE RAMPS

ITEM	PRETIMED	LOCAL ACTUATED	SYSTEM
Annual maintenance	8,000	12,000	24,000
Annual operation	4,800	6,000	24,000
Total annual maintenance and operation	$12,800	$18,000	$48,000

*Exclusive of communications medium, such as leased or private lines.

CHAPTER 8

FACTORS AFFECTING CONTROL MODE CHOICE

MODE SELECTION CONCEPT

The basic concept of entrance ramp control can be illustrated by considering Figure E-10. In this simple example, the goal is to maintain a V/C ratio (volume to capacity) at or less than 1.0. In order to obtain a V/C ratio of 1.0, the ramp volume would have to be restricted to 420 vph or 7 vpm (5400 − 4980 = 420).

It is reasonable to assume that the desired entrance ramp control for this example problem could be implemented effectively with a pretimed controller if the following four conditions exist:

1. The basic freeway volume upstream of the ramp does not change and is spread uniformly over the peak period.
2. The basic entrance ramp volume does not change and is spread uniformly over the peak period.
3. The freeway capacity does not change.
4. There is no need to alter the control plan at this entrance ramp because of conditions occurring at locations upstream or downstream of the example ramp.

The foregoing conditions cannot be expected to exist. In fact, one would expect significant variations in demand and capacity. This knowledge provides the basis for the mode selection methodology that is presented in Chapter 9. This methodology seeks to evaluate the changes in demand and capacity and the relative ability (compared to pretimed) of local actuated or system control to cope with these changes. The following basic steps are the framework of this methodology:

1. The selection of pretimed control as the minimum mode of control and the estimation of certain user costs for operation of the system under this mode of control.
2. The evaluation of expected variations in freeway and ramp demands and the comparative ability of local actuated or system control to treat these *demand* variations relative to pretimed control.
3. The evaluation of expected variations in freeway capacity and the comparative ability of local actuated or system control to treat these *capacity* variations relative to pretimed control.

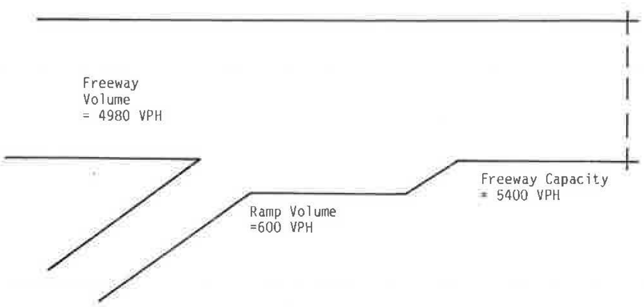


Figure E-10. Entrance ramp diagram.

4. The evaluation of the overall freeway management problem and need for total system control and surveillance.
5. On the basis of the data assembled in steps 2, 3, and 4, the estimation of expected incremental benefits (relative to a base of pretimed control) for local actuated and system control.
6. The estimation of incremental costs (relative to a base of pretimed control) for the installation of local actuated and system control.
7. The comparison of incremental benefits and costs and the selection of a ramp control mode (pretimed, local actuated, system).

DEMAND VARIATIONS

The evaluation of the amount of demand variation on a given freeway is a basic step in the mode selection procedure. Thus, a discussion of demand variations is presented here to define basic considerations in this regard.

The demand variations discussed are those that occur during peak periods of flow when freeway entrance ramp control finds its maximum application. The two major considerations relative to demand variations are:

1. Variations in the ratio of mainline to entrance ramp demand.
2. Variations in the overall demand pattern.

Mainline Versus Ramp Demand

A major consideration in the use of responsive ramp controls is the "controllability" of a given freeway. This "controllability" depends on the relationship between mainline demand and entrance ramp demand. As the mainline demand becomes larger, the maximum allowable metering rates become smaller. Accordingly, the permissible metering rates for the responsive modes become more and more constrained and the entrance ramp metering functions more and more like pretimed control regardless of the mode of control used.

Conversely, as the mainline demand becomes smaller, more traffic can be allowed onto the freeway from the entrance ramps. In this condition, the entrance ramp control has more flexibility and can exert a greater degree of impact on the quality of freeway flow and thus produce greater benefits.

A technique has been developed to evaluate the controllability of a given section of freeway. This technique involves the computation of a "controllability index" which is defined as follows:

$$\text{Controllability index} = \frac{\begin{pmatrix}\text{Total metered input}\\ \text{with pretimed}\\ \text{control}\end{pmatrix} - \begin{pmatrix}\text{Total metered input when}\\ \text{min. metering rates}\\ \text{are used}\end{pmatrix}}{\begin{pmatrix}\text{Total metered input when}\\ \text{min. metering rates are used}\end{pmatrix}}$$

This index is a normalized measure that indicates the degree to which responsive control can vary metering rates.

It is desirable to establish a minimum metering rate for any entrance ramp under control. This minimum metering rate is usually 180 vph. The difference between the input with pretimed control and the minimum metering rate provides an indication of the metering flexibility (or controllability) of the freeway section. This difference is then normalized by dividing it by the total metered input when minimum metering rates are used. The result is the controllability index. The index would range from approximately 0.5 (very low controllability), to 1.0 (medium controllability), to 2.0 (very high controllability).

An example of determination of a Controllability Index is provided by the pretimed metering plan developed in a later section of this chapter.

Variations In The Overall Demand Pattern

The basic patterns of freeway and entrance ramp demand are shown in Figures E-11 and E-12. Figure E-11 shows a typical pattern of freeway mainline input demand, and Figure E-12 shows a typical pattern of entrance ramp demand.

Two basic variations in the demand pattern (freeway or entrance ramp) would include:

1. Shift of the demand level. This shift could be either up or down. Figure E-13 shows this type of demand variation.
2. Temporal demand variations. Short-term fluctuations in the demand pattern. Figure E-14 shows this type of demand variation.

With significant amounts of these two basic types of demand variation, the potential for incremental benefits from responsive ramp control is increased.

CAPACITY REDUCTIONS

Mainline freeway capacity reductions can be discussed in two basic categories: (1) incidents and (2) system reduction. Incidents such as accidents, stalled vehicles, spilled loads, or other occurrences create a reduction of the mainline freeway capacity at a specific point on the freeway.

System reduction situations are created by rain, snow, fog, or other environmental conditions that reduce the mainline freeway capacity over the entire system. Both types of capacity reductions (incidents and system reduction), if relatively frequent in nature, can create the need for a responsive entrance ramp control system to cope with the variations in available capacity.

Incidents

Incidents can create a sudden and unpredictable change in the mainline freeway capacity. Response to incidents cannot be preprogrammed in a pretimed control system, and, thus, the occurrence of a number of incidents introduces the potential for considerable benefits from responsive control (i.e., local actuated or system control).

The potential benefits from responsive control will vary depending on the following conditions relative to the occurrence of the incident:

1. Time of occurrence of the incident within the peak period.
2. Duration of the incident.
3. Location of the incident.
4. Severity of the capacity reduction caused by the incident.

A methodology for evaluating the potential benefits of responsive control relative to incidents is presented in the next chapter.

System Reduction

Weather conditions such as rain, ice, or snow or environmental conditions (such as smoke or fog) can reduce the mainline freeway capacity on the entire section under consideration. Thus, a freeway section in an area where there are frequent inclement weather or environmental conditions would have a greater potential to achieve additional benefits from responsive ramp control.

Capacity reductions due to weather or environmental conditions should be evaluated in terms of the following:

1. Magnitude of the capacity reduction.
2. Duration of the capacity reduction.
3. Time of occurrence within the peak period.
4. Annual frequency.

A methodology for evaluating responsive control relative to reduced capacity situations will be provided in the following material. It is also possible to encounter the combined effect of these two types of capacity reductions (incident and system reduction). This results when an incident occurs during a peak period in which an overall system capacity reduction has developed because of rain, fog, or other adverse weather conditions.

INCREMENTAL BENEFITS

The responsive ramp control modes (local actuated and system) will be evaluated in terms of the incremental benefits they produce when compared to pretimed control. The incremental benefits will be measured in terms of the following three items:

1. *Travel-Time*—Total travel-time (vehicle-hours) savings for the entire freeway corridor (freeway section, ramps, and alternate routes) for the entire peak period.
2. *Fuel Consumption*—Savings in fuel consumption for the entire corridor for the peak period.
3. *Vehicle Emissions*—Reductions in vehicle emissions (HC, CO, and NO_x) for the entire corridor for the peak period.

These measures of effectiveness were chosen because of their compatibility with the simulation analysis that was used as the basis for the overall mode selection evaluation. There are obviously other potential benefits such as reduced accidents, reduced operating costs, and the like, but these were difficult to incorporate into the simulation analysis.

EVALUATION OF DEMAND-CAPACITY VARIATIONS

The selection of a responsive ramp control mode (local

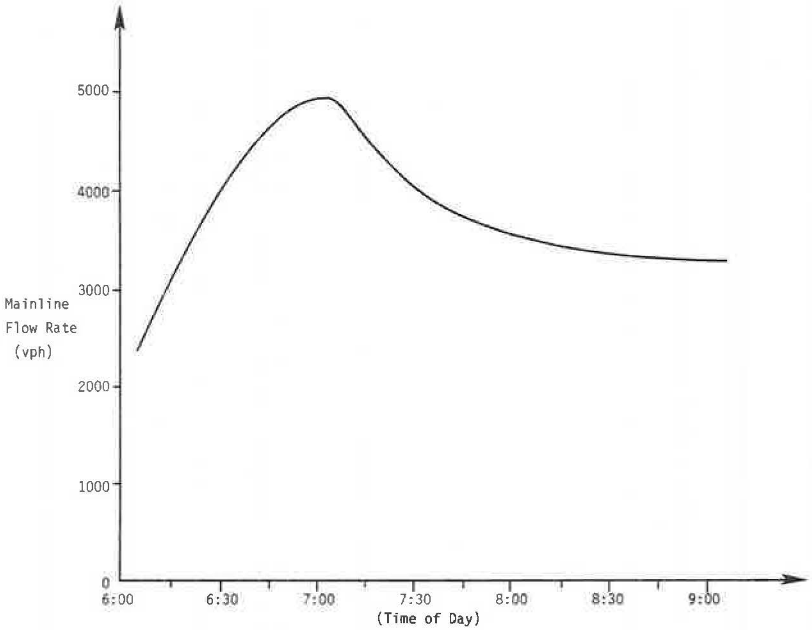


Figure E-11. Typical pattern of freeway mainline input demand.

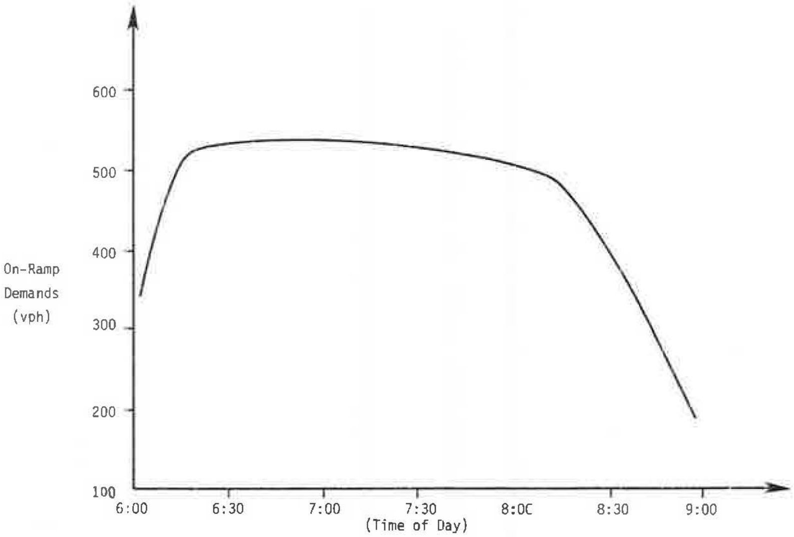


Figure E-12. Typical pattern of entrance ramp demand.

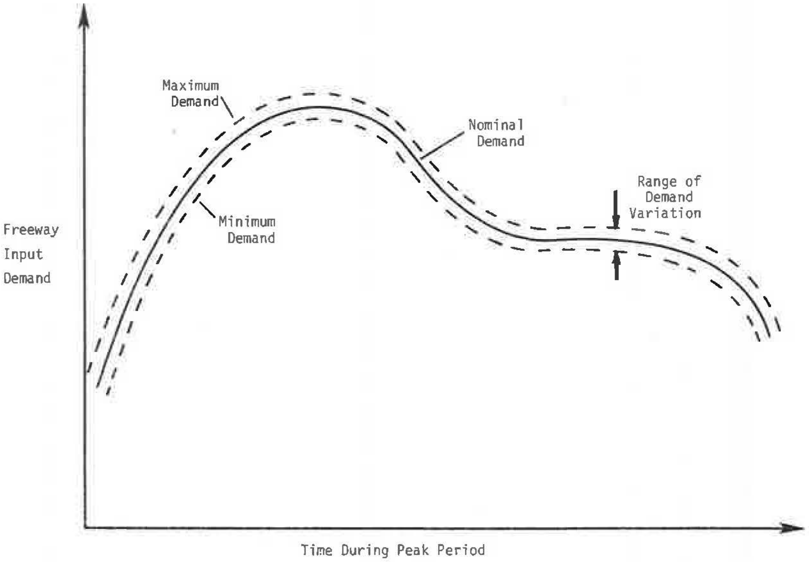


Figure E-13. Entrance ramp demand pattern variation due to shift of demand level.

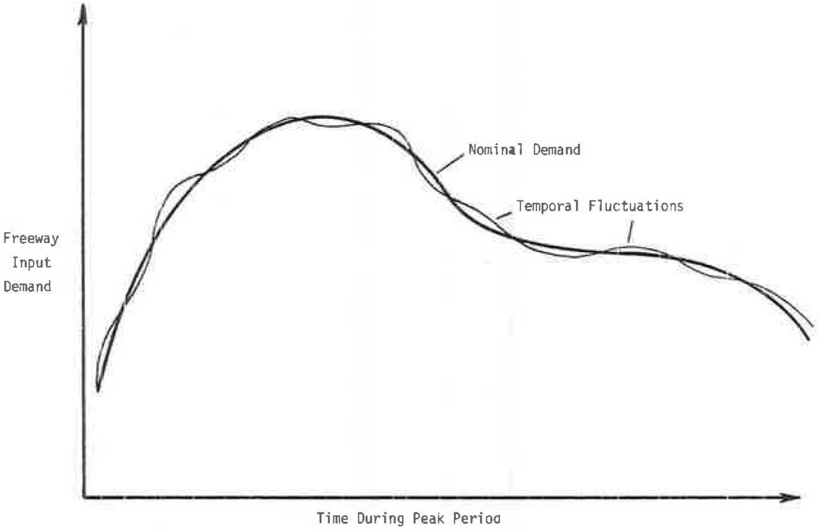


Figure E-14. Entrance ramp demand pattern temporal variations.

actuated or system) is highly dependent on the degree of the capacity and demand variations that are experienced. Thus, as a part of the mode selection process for a given section of freeway, a thorough evaluation of potential demand-capacity variations should be conducted. The studies and data that will be needed are discussed in the following. The basic information that must be assembled in order to conduct a mode selection analysis includes the following items:

1. Geometric data.
2. Peak period demand and O-D patterns.
3. Pretimed metering plan.
4. Demand variation analysis.
5. Incident analysis.
6. Environmental analysis.

Geometric Data

A first step would be to define the boundaries (beginning and end) of the specific freeway section for which entrance ramp control is to be considered. Once the study section is defined, maps and drawings should be assembled that describe and illustrate the geometrics of this section.

General geometric data that should be made available would include:

- Number of freeway lanes.
- Number and location of entrance ramps and exit ramps.
- Freeway grades.
- Ramp geometrics.
- Ramp storage capability.
- Availability of freeway shoulders.
- Total lane-miles.

Peak Period Demand and O-D Patterns

Once the freeway section to be studied is defined, it comprises a system. A typical system is shown in Figure E-15. The mainline input to the system occurs at point A and entrance ramp input occurs at each of the entrance ramps. Traffic departs the system at each of the exit ramps and at the downstream mainline terminal (point B). If a basic origin–destination (O-D) pattern can be established for each of the input demands (point A plus entrance ramps), movement of vehicles through the system and point demands can be estimated.

Thus, two basic data items are needed to determine traffic demand:

1. System input from mainline entry and each entrance ramp plus exit ramp volumes.
2. Data on the destination of the traffic demand as a percent of system input. For example, 4 percent of mainline input exits at exit ramp 1, 3.5 percent at exit ramp 2, and so on.

The data on input and output volumes should be collected at 5-min intervals through the peak period. The O-D data can be obtained directly from license plate observations or questionnaire surveys, or it can be estimated from field data.

Pretimed Metering Plan

Once the input demand data and the O-D data are developed, it will then be possible to prepare a pretimed metering plan. Each entrance ramp in the system will be analyzed to determine a metering rate for each ramp. This rate will be based on achieving a desired demand/capacity ratio downstream of the ramp. Considerations would include mainline demand upstream of the entrance ramp, mainline capacity downstream of the entrance ramp, and any constraints at the ramp such as minimum metering rates.

The pretimed metering plan provides a basis for estimating baseline user costs when pretimed control is used. These

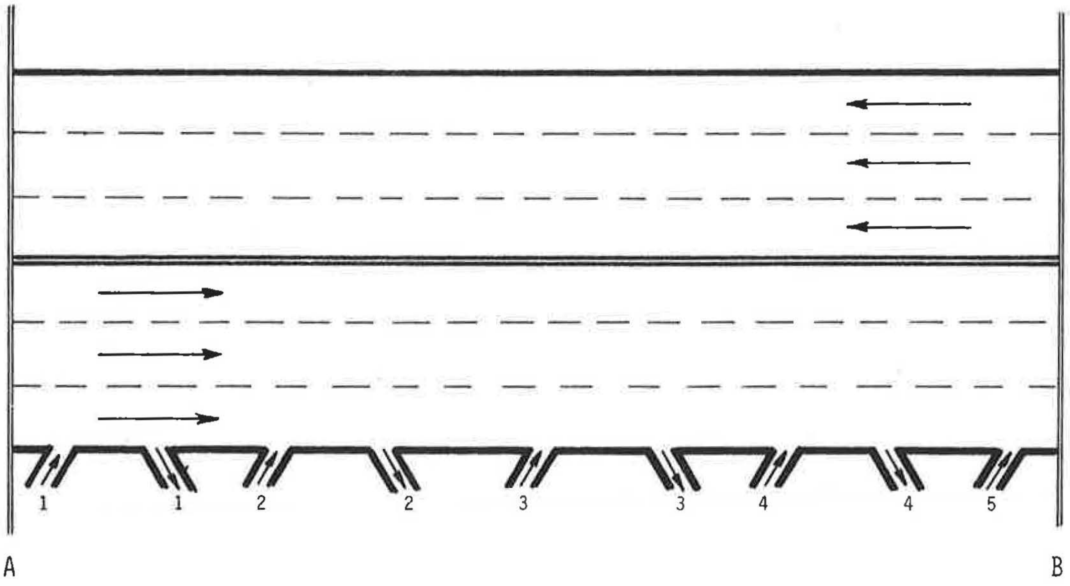


Figure E-15. Typical freeway section.

user costs will serve as a reference for evaluating the relative benefits of local actuated or system control. From the pretimed metering plan, a controllability index can be determined for the freeway section under study. This controllability index is an essential part of the mode selection methodology presented in Chapter 9.

Demand Variation Analysis

The evaluation methodology to be presented later utilizes an evaluation of demand variation. This demand variation will be defined in terms of (1) demand increases, (2) demand decreases, and (3) fluctuating demand (short term).

Incident Analysis

Incidents have a major impact on freeway operation, and because of their unpredictability it is not possible to handle their effects with a pretimed control system. Thus the greater the number of incidents expected during a peak period, the greater the benefits derived from a responsive control system. It is therefore necessary to estimate the number of peak period incidents as a part of the mode selection methodology.

As stated earlier, the impact of an incident is greatly influenced by: time of occurrence within peak period, duration of the incident, location along metered freeway, and severity of the capacity reduction. The evaluation methodology presented in Chapter 9 has been developed in such a manner as to account for these factors.

Environmental Analysis

The reduction of freeway capacity because of various environmental conditions, such as rain, ice, snow, fog, is a major consideration. Such reductions are random in nature and their frequency of occurrence depends on the geographic area and the attendant weather conditions in that area.

In areas where environmental variations are substantial, the benefits from responsive control may increase. Thus, a part of the mode selection requires an analysis of environmental conditions for the specific freeway section being studied. This analysis should investigate the frequency with which inclement environmental conditions occur and their impact on freeway capacity.

FREEWAY/CORRIDOR MANAGEMENT

As indicated in Chapter 4, freeway/corridor management can include a wide range of activities such as corridor control, high occupancy vehicle (HOV) promotion, driver information systems, and mainline metering. The development of these activities may require the installation of a Control Center together with an extensive data collection and communication system.

If an extensive freeway/corridor management project is contemplated that requires a data collection and communication system, the installation of the system mode of entrance ramp control can be accomplished at a greatly reduced incremental cost. This reduced cost results from a sharing of the cost of expensive data collection, data transmission, and data handling facilities as well as control center costs among a number of project activities (freeway surveillance, driver information, corridor management, etc.).

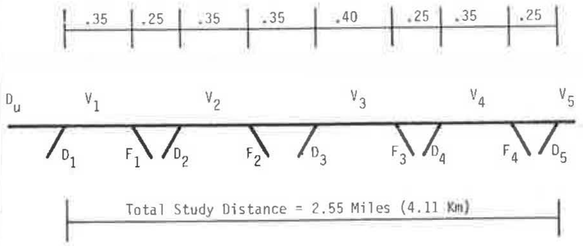
Thus, in evaluating the system mode of control, there are two other considerations in addition to the incremental benefits (as compared to pretimed control). These considerations are:

1. Freeway/corridor control activities may require (and help justify) a data collection and communication system. If this is the case, the incremental cost of system control (as compared to local actuated control) may be negligible.
2. There are additional benefits that result from system control such as equipment surveillance and continuous data collection. It is difficult to assign a dollar value to these benefits, but they are substantial and should receive consideration in the overall mode selection process.

EXAMPLE—PRETIMED METERING PLAN

In Chapter 3, an example of a typical congested freeway segment was developed to illustrate the estimation of congestion costs. This example considered a 1-hour peak period and illustrated basic procedures for estimating basic costs (for level of service D), actual costs and congestion costs.

To illustrate the methodology in the remainder of these guidelines, a slightly revised version of the example freeway will be used. In this example, the same freeway geometrics will be used, but it will be assumed that the peak period extends over a 2-hour period. The conditions for the second example are shown in Figure E-16.



INPUT - OUTPUT DEMANDS (VPH)

Location-D_u		D_1	F_1	D_2	F_2	D_3	F_3	D_4	F_4	D_5	D_d	V_d
Time (min.)												
0-60	4900	700	350	600	350	450	350	600	450	700	6450	(5700)
60-120	4400	350	200	300	200	200	200	300	200	350	5100	(5850)

Volume	Distance (miles)	Vehicle-Miles
4900 + 4400 + 700 + 350 = 10350	.35	3622.5
10350 - 350 - 200 = 9800	.25	2450
9800 + 600 + 300 = 10700	.35	3745
10700 - 350 - 200 = 10150	.35	3552.5
10150 + 450 + 200 = 10800	.40	4320
10800 - 350 - 200 = 10250	.25	2562.5
10250 + 600 + 300 = 11150	.35	3902.5
11150 - 450 - 200 = 10500	.25	2625
	Total Travel	26,780 Vehicle-Miles

Figure E-16. Example freeway—two-hour peak period.

Actual Conditions

For the 2-hour demands given in Figure E-16, the total travel on the freeway is determined to be 26,780 veh-miles. Demand and capacity flow rates are plotted with respect to time for the bottleneck in Figure E-17. The vehicle delay, which is the area between the two curves, is calculated to be 825 veh-hours.

To determine the total travel time for the peak period, an average speed of 38 mph is assumed for the freeway operating at a capacity of 5700 vph. This speed is based on an average density of 50 vehicels per lane which corresponds to the low range of level of service D (*E-4*). If all the vehicle-miles of travel could be accommodated at this speed, the travel time would be:

$$\frac{26{,}780\text{-veh-miles}}{38\text{ mph}} = 705\text{ veh-hours}$$

The total travel time is the sum of this value and the delay caused by the excess demand, or:

$$705 + 825 = 1{,}530\text{ veh-hours}$$

The average speed for the vehicles using the freeway under these conditions of no control and no diversion would be:

$$\frac{26{,}780\text{ veh-miles}}{1{,}530\text{ veh-hours}} = 17.5\text{ mph}$$

Basic Procedure—Pretimed Metering Plan

The objective of a ramp metering plan is to eliminate freeway delay by maintaining the traffic demands at a level less than the freeway capacity. There are several techniques used to develop a metering plan, and each plan may have several options. The option selected would be based on the decision of which traffic is to be delayed and/or diverted from the freeway.

One procedure for calculating metering rates along a freeway is the integrated demand-capacity calculation (*E-8*). Ramp flows and possibly upstream freeway flows are adjusted as required to keep the volume below the section capacity. Figure E-18 is a diagram of a freeway section for illustrating the demand-capacity calculation.

The index $i = 0, 1, 2, 3, 4, 5$ represents the points of entry to sections $j = 1, 2, 3, 4, 5, 6$; and index $k = 1, 2, 3, 4, 5$ represents the points of exit from the sections. The notation D_i represents the demand for input i, whereas R_i represents the allowable volume input at i, on the basis of the demand-capacity calculations. F_k represents the demand for exit ramp k. In this example, the demands for the exit ramps are held constant. Other procedures may use a variable origin–destination matrix to determine the exit demands as a function of the upstream input volumes. C_j represents the capacity at freeway section j; V_j represents the section volume at section j.

The procedure begins at the section farthest upstream and works downstream. For section j, the entrance ramp demand, D_j, is used to calculate the section volume, V_j. If V_j is less than the section capacity, C_j, the allowable entrance ramp volume R_j is set equal to the entrance ramp demand D_j. If V_j is greater than the section capacity, C_j, the allowable entrance ramp volume R_j is chosen so that $V_j = C_j$. If $V_j > C_j$ even for $R_j = 0$, the entrance ramp volumes previously calculated upstream must be readjusted. The integrated demand-capacity calculations are illustrated by the following example. (Additional examples and techniques for obtaining metering plans can be reviewed in detail in Masher et al. (*E-8*).)

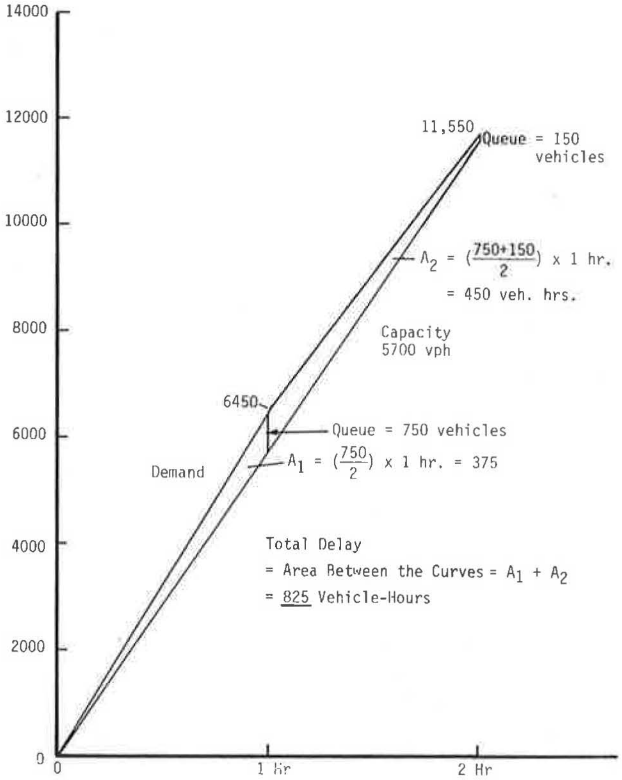


Figure E-17. Demand versus capacity at bottleneck location of example freeway.

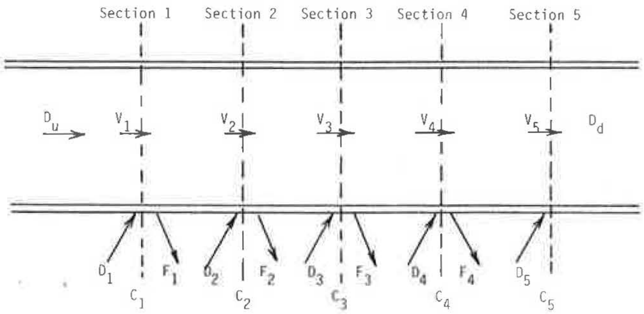


Figure E-18. Freeway section for illustrating demand-capacity calculation.

In the example freeway, calculations for the pretimed metering plan are subject to the following conditions:

1. Maxamum metering rate = 600 vph. This is the maximum *desirable* rate for one-by-one metering with a

pretimed control. If a higher demand must be accommodated at one ramp, the rate can be extended to 900 vph, or the type of metering can be changed to platoon metering or two-lane metering. See "Metering Rates" section, Chapter 5.

2. Minimum metering rate = 180 vph. This is the minimum desirable rate. For low volume ramps, the minimum rate can be lowered to 120 vph. See "Metering Rates" section, Chapter 5.

3. Diversion is based on a maximum queue length of 25 vehicles. (This condition could be expressed in maximum waiting time.)

4. Diversion will be to an alternate route that is assumed to be 0.5 miles longer than the freeway trip, has an operating speed of 20 mph, and has adequate capacity for handling diverted traffic.

5. Ramp 3 does not have access to an acceptable alternate route. (This is to illustrate the condition of a barrier such as a railroad or drainage facility.)

6. One metering rate is assumed for the total peak period. Metering plans with several rates ranging from the maximum to the minimum rates could be developed when the variations in main lane volumes are known. In this example, a second set of metering rates could be established for the second hour of the peak period using the same procedures.

7. When ramp demands are less than the allowable ramp volume, an average queue length of three vehicles is assumed in the calculation of the vehicle waiting time.

Compute the allowable entrance ramp values, R$_i$'s, *for the first hour:*

- Set $D_0 = R_0 = 4900$ vph.
- $V_i = R_0 + D_1 = 4900 + 700 = 5600$ vph $< C_1 = 5700$ vph; thus $R_1 = 700$ vph. This exceeds the maximum metering rate.
- Set $R_1 = 600$ vph.
- $V_2 = V_1 - F_1 + D_2 = 5500 - 350 + 600 = 5750$ vph $> C_2 = 5700$ vph; thus $R_2 = 550$ vph.
- $V_3 = V_2 - F_2 + D_3 = 5700 - 350 + 450 = 5800$ vph $> C_3 = 5700$ vph; thus $R_3 = 350$ vph.
- $V_4 = V_3 - F_3 + D_4 = 5700 - 350 + 600 = 5950$ vph $> C_4 = 5700$ vph; thus $R_4 = 350$ vph.
- $V_5 = V_4 - F_4 + D_5 = 5700 - 450 + 700 = 5950$ vph $> C_5 = 5700$ vph; thus $R_5 = 450$ vph.

The results of the metering plan for the first hour are given in Table E-9.

TABLE E-9

EXAMPLE SYSTEM VOLUMES

Section	Entrance Ramp Demand (D_i)(VPH)	Entrance Ramp Volume (R_k)(VPH)	Freeway Volume (V_j)(VPH)	Diverted or Stored in Ramp Queue(VEH)
1	700	600	5500	100
2	600	550	5700	50
3	450	350	5700	100
4	600	350	5700	250
5	700	450	5700	250

This metering plan results in the maximum use of the freeway because all sections, with the exception of section 1, operate at capacity. Because ramp 3 cannot have diversion, there are two options to be considered:

1. Adjust an upstream ramp volume to permit a higher volume at ramp 3. The results are given in Table E-10. This results in lower use of the freeway, but accommodates the metering restrictions.

2. Allow the ramp queues to form, and wait for the lower demand in the second hour to reduce the queue length and ramp waiting time. This is the technique that is used in the following example.

These variations, or options, of the control plan will depend on the availability of alternate routes, ramp storage space, and other technical as well as political considerations. In this example the traffic demands for the second hour are less than the capacity of the freeway. Therefore, it is possible for a portion of the ramp diversion from the first hour to be made in time rather than in space. The maximum queue length of 25 vehicles for ramps 1, 2, 4, and 5, and 100 vehicles for ramp 3, is carried over to the second hour and becomes added demand for the ramp.

Compute the allowable ramp volumes, R$_i$'s, *for the second hour:*

- Set $D_0 = R_0 = 4400$ vph.
- $V_1 = R_0 + D_1 = 4400 + (350 + 25\,{*}) = 4775$ vph $< C_1 = 5700$ vph; $R_1 = 375$ vph.
- $V_2 = V_1 - F_1 + D_2 = 4775 - 200 + (300 + 25\,{*}) = 4900$ vph $< C_2 = 5700$ vph; R$_2$ = 325 vph.
- $V_3 = V_2 - F_2 + D_3 = 4900 - 200 + (200 + 100\,{*}) = 5000$ vph $< C_4 = 5700$ vph; R$_3$ = 300 vph.
- $V_4 = V_3 - F_3 + D_4 = 5000 - 200 + (300 + 25\,{*}) = 5700$ vph; R$_4$ = 325 vph.
- $V_5 = V_4 - F_4 + D_5 = 5125 - 200 + (350 + 25\,{*}) = 5300$ vph; R$_5$ = 375 vph.

* Demands for the second hour are increased by the queue length remaining after the first hour.

Measurement of Parameters

Now that the basic pretimed metering plan is established, the parameters for evaluating the system performance can be calculated.

Total Travel Time

The total travel time is the sum of the time spent travel-

TABLE E-10

EXAMPLE SYSTEM VOLUMES—REVISED

Section	Entrance Ramp Demand (D_i)(VPH)	Entrance Ramp Volume (R_k)(VPH)	Freeway Volume (V_j)(VPH)	Total Traffic Diverted or Stored in Ramp Queue (VEH)
1	700	600	5500	100
2	600	450	5600	150
3	450	450	5700	0

ing through the 2.55-mile freeway section, the time waiting to enter at all of the metered ramps, and the time for the diverted traffic to travel the alternate routes. For the example freeway, these values are:

- Freeway total travel time = 625.7 veh-hours.
- Ramp waiting time = 193.7 veh-hours.
- Diversion travel time = 32.5 veh-hours.

Total Travel Time = 851.9 veh-hours.

The discussion and calculations for these results follow.

Freeway Total Travel Time. The total travel time for the main lanes of the freeway is calculated by dividing the total travel in vehicle miles by the average speed. From Table E-11 the total travel is calculated to be 14,005 veh-miles for the first hour. The calculations must be done by time interval because the average speed changes. The average speed for the first hour is 40 mph. This is derived from the freeway operating at volume/capacity (V/C) ratios of 0.9 to 1.0 in LOS D. Therefore, the total travel time for the first hour is:

$$\frac{14{,}005 \text{ veh-miles}}{40 \text{ mph}} = 350.1 \text{ veh-hours}$$

For the second hour, the total travel is 12,400 veh-miles and the average speed for V/C ratios that vary from 0.8 to 0.9 is assumed to be 45 mph. Therefore, total travel time for the second hour is:

$$\frac{12{,}400 \text{ veh-miles}}{45 \text{ mph}} = 275.6 \text{ veh-hours}$$

and the total for the two hours is 625.7 veh-hours for the freeway lanes.

Entrance Ramp Waiting Time. Entrance ramp waiting time is the same as entrance ramp delay and is calculated by using the demand-capacity curve relation, where the capacity is equal to the allowable entrance ramp volume, R_i. The demand curve is altered by the queue which forms at the ramp meter station and by the diversion volume of traffic to the alternate route. In Figure E-19, the capacity for ramp 1 is 600 vph for the first hour and 375 for the second hour. The demand for ramp 1 for the two hours is 700 vph and 350 vph, respectively. At the end of the first hour, 600 vehicles have entered the freeway, 25 are waiting in the queue on the ramp, and 75 vehicles have diverted to the alternate route.

In the second hour, the 25-vehicle queue is allowed to dissipate and the ramp operates at an average queue level of 3 vehicles for the remainder of the peak period. A total of 375 vehicles enter the freeway, and 0 vehicles are diverted. The entrance ramp waiting time is the area between the two corrected curves, with the diverted traffic removed from the demand curve.

This area between the curves can be calculated in the following manner:

- First Hour:

$$A_1 + A_2 = \left(\frac{25 \text{ veh}}{(700 - 600) \text{ vph}}\right)\left(\frac{25 \text{ veh}}{2}\right) + 1 \text{ hr} - \frac{25 \text{ veh}}{(700 - 600) \text{ vph}} 25 \text{ veh}$$

$$= 3.125 + 25 - 6.25 = 21.9 \text{ veh-hours}$$

TABLE E-11

EXAMPLE FREEWAY TOTAL TRAVEL TIME

Count Location	First Hour Volume(VPH)	Freeway Vol(VPH)	Distance (Miles)	Total Travel (Veh-Miles)
D_0	4900			
R_1	600			
		5500	.35	1925.0
F_1	350			
		5150	.25	1287.5
R_2	550			
		5700	.35	1995.0
F_2	350			
		5350	.35	1872.5
R_3	350			
		5700	.40	2280.0
F_3	350			
		5350	.25	1337.5
R_4	350			
		5700	.35	1995.0
F_4	450			
		5250	.25	1312.5
R_5	450			
		5700		
			2.55	14,005.0

$$\text{Total Travel Time} = \frac{14{,}005.0}{40} = 350.125$$

Count Location	Second Hour Volume(VPH)	Freeway Vol(VPH)	Distance (Miles)	Total Travel (Veh Miles)
D_0	4400			
R_1	375			
		4775	.35	1671.25
F_1	200			
		4575	.25	1143.75
R_2	325			
		4900	.35	1715.00
F_2	200			
		4700	.35	1645.00
R_3	300			
		5000	.40	2000.00
F_3	200			
		4800	.25	1200.00
R_4	325			
		5125	.35	1793.75
F_4	200			
		4925	.25	1231.25
R_5	375			
		5300		
			2.55	12,400.00

$$\text{Total Travel Time} = \frac{12{,}400.0}{45} = 275.6$$

- Second Hour:

$$A_3 + A_4 = \left(\frac{25 \text{ veh}}{(600 - 350) \text{ vph}}\right)\left(\frac{25 \text{ veh}}{2}\right) + 1 \text{ hr} - \frac{25 \text{ veh}}{(600 - 350) \text{ vph}} 3 \text{ veh}$$

$$= 1.25 + 3.00 - 0.30 = 4.0 \text{ veh-hours}$$

- Therefore, the total ramp waiting time for ramp 1 is:

$= 21.9 + 4.0$

$= 25.9$ veh-hours

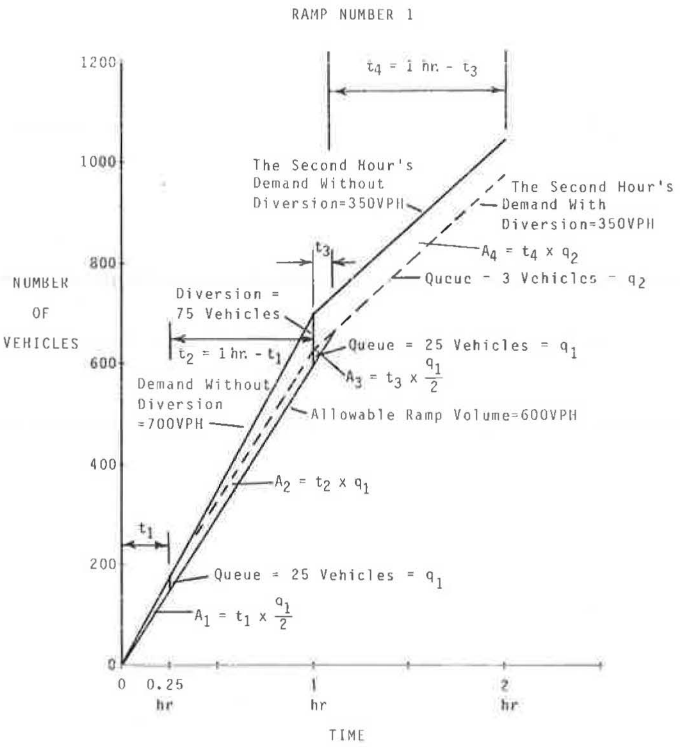


Figure E-19. Example freeway—entrance ramp 1 waiting time.

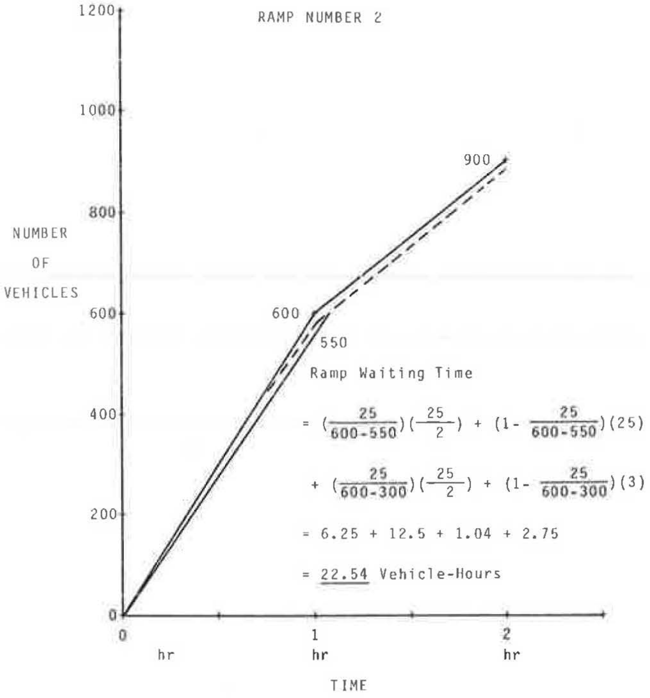


Figure E-20. Example freeway—entrance ramp 2 waiting time.

Similar calculations are shown on Figures E-20 through E-23 for the other 4 ramps, and the total waiting time for all ramps is:

$$25.9 + 22.5 + 84.3 + 31.5 + 29.1 = 193.3 \text{ veh-hours}$$

or 11,598 veh-min in vehicle idling time.

In the example ramp, ramp 3 is designed for a maximum queue length of 100 vehicles. From Figure E-21, the maximum waiting time is determined to be 17.1 min. Unless ramp traffic develops a new arrival rate, the waiting time may be too severe. An alternate plan, such as the one given in Table E-10, may be implemented to provide for a more equitable distribution of travel delays.

Diversion Travel Time. The total travel time for the diverted traffic traveling over the alternate route is calculated by dividing the total travel in vehicle-miles by the average speed. In the assumptions for alternate route, an average speed of 20 mph was selected, and the route length was estimated to be 0.5 miles longer than the freeway trip. Therefore, the total travel time for each ramp can be determined by the following calculations:

- Ramp 1
  75 vehicles are diverted over a distance equal to (2.55 + 0.50) or 3.05 miles at an average speed of 20 mph:

$$\text{Total travel time} = \frac{75 \text{ veh} \times 3.05 \text{ miles}}{20 \text{ mph}} = 11.4 \text{ veh-hours}$$

- Ramp 2
  25 vehicles are diverted a distance of 1.95 + 0.50 = 2.45 miles:

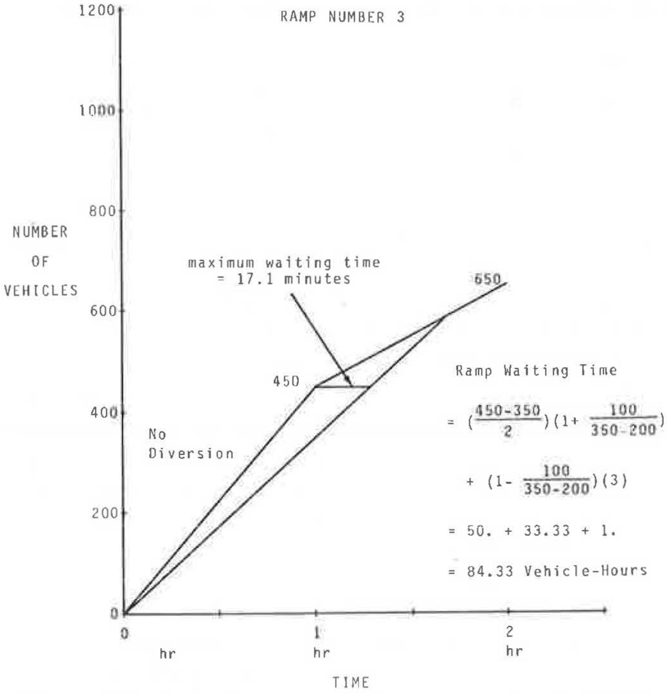


Figure E-21. Example freeway—entrance ramp 3 waiting time.

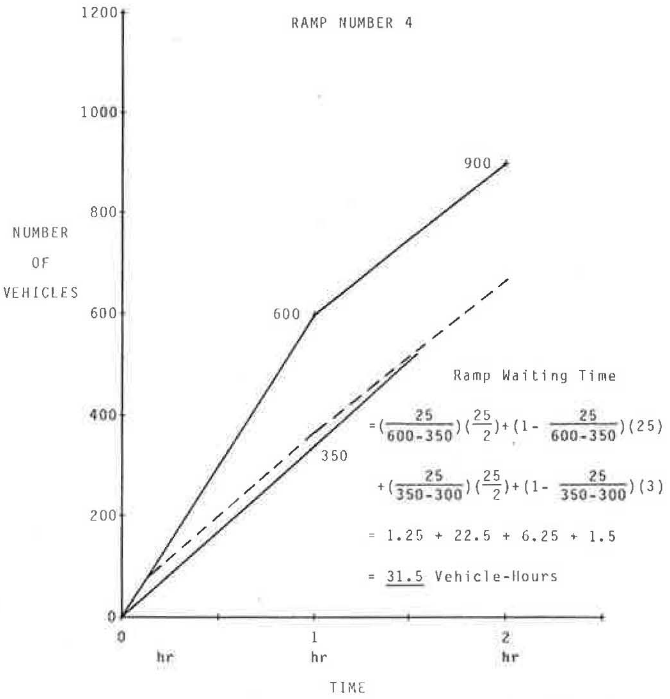


Figure E-22. Example freeway—entrance ramp 4 waiting time.

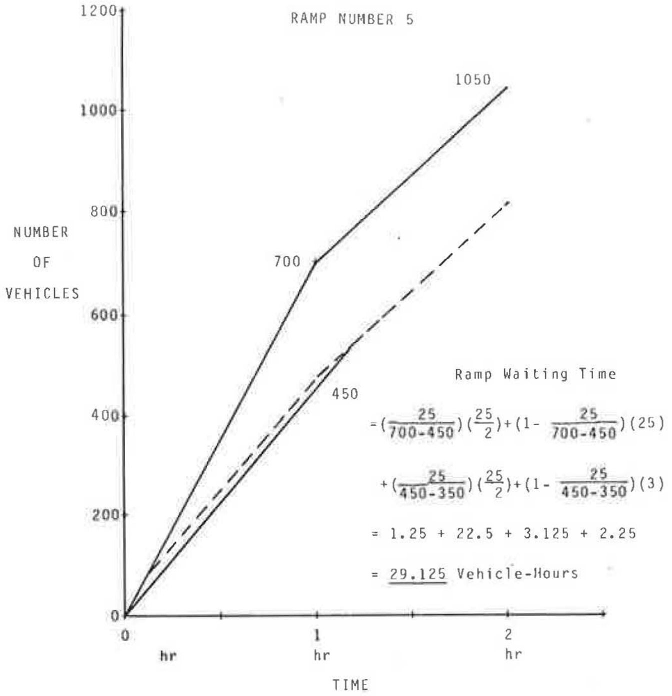


Figure E-23. Example freeway—entrance ramp 5 waiting time.

$$\text{Total travel time} = \frac{25 \text{ veh} \times 2.45 \text{ miles}}{20 \text{ mph}} = 3.1 \text{ veh-hours}$$

- Ramp 3
  No diversion.
- Ramp 4
  225 vehicles are diverted a distance of 0.6 + 0.50 = 1.1 miles:

$$\text{Total travel time} = \frac{225 \text{ veh} \times 1.1 \text{ miles}}{20 \text{ mph}} = 12.4 \text{ veh-hours}$$

- Ramp 5
  225 vehicles are diverted a distance of 0.5 miles:

$$\text{Total travel time} = \frac{225 \text{ veh} \times 0.5 \text{ miles}}{20 \text{ mph}} = 5.6 \text{ veh-hours}$$

The total travel time for the diverted vehicles is equal to 32.5 veh-hours.

Fuel Consumption

Fuel consumption is based on the number of vehicle-miles of travel at a specific speed for a given level of service. The fuel consumption rates used in the example are taken from tables updated for 1980 conditions, but are derived from rates reported in Winfrey's *Economic Analysis For Highways* (*E-12*). For the sake of simplicity, the assumption is made that the freeway traffic stream is made up of 100 percent passenger vehicles (Type 1 vehicles; see Table E-57 in Chapter 13). Rates for other types of vehicles are given in the Tables E-58 and E-59 (Chapter 13).

The fuel consumption is calculated for the two freeway speeds, the alternate route speed, and for the idling time at the entrance ramps. The results are as follows:

- Freeway travel at 40 mph = 718.5 gal
- Freeway travel at 45 mph = 657.2 gal
- Ramp idling = 71.5 gal
- Diversion travel at 20 mph = 29.9 gal *

Total Fuel Consumption = 1477.1 Gallons

* This calculation was made by reference to Table E-61 in Chapter 13, for passenger cars at a uniform speed. Tables E-62, E-63, and E-64 are included in Chapter 13 for the user who wishes to incorporate the effect of speed cycle changes on traffic along the diversion route.

The calculations involved in determining these values are given in Table E-12.

Exhaust Emissions

The emission rates for the 3 types of pollutants were derived from factors published in the U.S. Environmental Protection Agency, *Supplement No. 5 for Compilation of Air Pollutant Emission Factors* (*E-13*), for passenger cars only. The estimates of the vehicle emissions for the two peak-hour period are as follows:

- Carbon monoxide = 772.0 kg
- Hydrocarbons = 80 kg
- Nitrogen oxides = 126.5 kg

TABLE E-12

FUEL CONSUMPTION CALCULATIONS (PASSENGER CARS ONLY)

Freeway

First Hour: Speed = 40 mph LOS D
Total Travel = 14,005 vehicle-miles
Fuel Consumption Rate = 0.0513 gal/veh-mile (From Table A-12, Appendix A)
Total Gallons Consumed = 718.5 gallons

Second Hour: Speed = 45 mph LOS C
Total Travel = 12,400 vehicle-miles
Fuel Consumption Rate = 0.0530 gal/veh-mile (From Table A-12, Appendix A)
Total Gallons Consumed = 657.2 gallons

TOTAL FUEL CONSUMPTION ON FREEWAY = 1375.7 gallons/peak period

Entrance Ramp

Waiting Time on Entrance Ramp = 193.3 vehicle-hours
Idling Fuel Consumption Rate = .370 gallon per veh-hr (From Table A-15, Appendix A)

TOTAL FUEL CONSUMPTION ON ENTRANCE RAMP = 71.5 gallons/peak period

Diversion Route

Average Speed = 20 mph
Total Travel on Alternate Routes = 650 vehicle-miles
Fuel Consumption Rate = 0.0460 (From Table A-16, Appendix A)

TOTAL FUEL CONSUMED BY DIVERTED TRAFFIC = 29.9 gallons/peak period

\>>>>>>>>>TOTAL 1477.1 GALLONS<<<<<<<<<<

The calculations used for determining these values are given in Table E-13.

Freeway Controllability

One parameter that has been previously defined in these guidelines as a measure on which to determine the benefits of control is called the "controllability index." For the example freeway, this expression would be:

$$\text{Controllability index} = \frac{4000\text{ veh} - 1800\text{ veh}}{1800\text{ veh}} = 1.22$$

where 4000 veh is the pretimed metered input to the freeway, and 1800 veh is the minimum metered input to the freeway. This level of controllability would be considered to be in the midrange or medium controllability.

Summary

The basic results of the pretimed metering plan are summarized in Tables E-14 and E-15. The pretimed metering plan provides a basis for estimating the incremental benefits of local actuated or system entrance ramp control. This estimation methodology is described in the followrig chapter.

TABLE E-13

EXAMPLE FREEWAY EXHAUST EMISSIONS

Average Speed (mph)	Travel (veh-miles)	Rate* (Gms/Veh.Mile)		Total (kg)
Carbon Monoxide				
40	14,005	22.62	=	316.8
45	12,400	20.46	=	253.7
20	650	46.40	=	30.2
Idling	11,598**	14.74**	=	171.0
		TOTAL		771.7
Hydrocarbons				
40	14,005	2.63	=	36.8
45	12,400	2.48	=	30.8
20	650	4.38	=	2.8
Idling	11,598**	0.83**	=	9.6
		TOTAL		80.0
Nitrogen Oxides				
40	14,005	4.57	=	64.0
45	12,400	4.72	=	58.5
20	650	3.95	=	2.6
Idling	11,598**	0.12**	=	1.4
		TOTAL		126.5

* These rates are from Tables E-65 and E-68 in Chapter 13.

** Idling quantities and rates expressed in vehicle minutes and gms/vehicle minute.

TABLE E-14

SUMARY OF METERING PLAN

Demand for Inputs

	D_u	D_1	D_2	D_3	D_4	D_5	D_d
1st. Hour	4900	700	600	450	600	700	6450
2nd. Hour	4400	350	300	200	300	350	5850

Volume for Inputs

	V_u	R_1	R_2	R_3	R_4	R_5	V_d
1st. Hour	4900	600	550	350	350	450	5700
2nd. Hour	4400	375	325	300	325	375	5300

Diversion Volumes

Ramp Number	1	2	3	4	5
1st. Hour	75	25	0	225	225
2nd. Hour	0	0	0	0	0

TABLE E-15

SUMMARY OF PARAMETERS FOR DESIGN PEAK PERIOD

	Pretimed Metering Plan	
Parameter	Total for Two Hour Peak Period	No Control
Total Travel	27055 vehicle-miles	26780
Total Travel Time	851.9 vehicle-hours	1530
Total Fuel Consumption	1487.2 gallons	2435
HC Emissions	80.0 kilograms	132
CO Emissions	772.0 kilograms	1439
NO_x Emissions	126.5 kilograms	105
Pretimed Metered Input	4000 vehicles	4550
Minimum Input	1800 vehicles	
Controllability Index	1.22	

CHAPTER 9

MODE SELECTION METHODOLOGY

BASIS OF METHODOLOGY

It is now possible to present a step-by-step methodology that permits one to estimate the incremental benefits of either local actuated or system control relative to pretimed control. The estimated benefits can then be used to conduct a benefit-cost analysis and to choose the ramp control mode (pretimed, local actuated, or system control) with the most desirable benefit/cost ratio.

The study procedures used to develop the mode selection methodology are presented in other sections of this report. The basic steps that were followed are shown in Figure E-24.

OVERALL EVALUATION PROCEDURE

The overall mode evaluation procedure is shown in Figure E-25. The following material describes each step of this methodology and explains the procedure to be followed. The evaluation methodology is also illustrated by example, utilizing the example freeway material covered in Chapters 3 and 8.

Step 1—Tabulate Pretimed Control Results for the Design Peak Period

The methods presented in this chapter assume that the user of these guidelines has analyzed the proposed entrance ramp control system to the point that a pretimed metering plan has been developed for a nominal or "design" peak period as discussed in Chapter 8. Once the demand pattern of the design peak period is specified and the pretimed metering plan is developed, the pretimed performance is estimated. Namely, the user costs methodology discussed in Chapter 8 is applied to estimate the absolute magnitude of travel time, fuel consumption, and vehicle emissions that accumulate over the entire design peak period. The percent savings in travel time, fuel consumption, and vehicle emissions that result from the use of local actuated or system control will then be used with the baseline (or pretimed) costs to estimate the incremental benefits of responsive ramp control.

Example—Step 1

The example freeway section shown in Figure E-3 is used to illustrate the methodology. The analysis of the pretimed metering plan given in Chapter 8 produced the results tabulated in Table E-15.

Step 2—Estimate Freeway Controllability

The incremental benefits that are produced by the responsive modes of control are greatly dependent on the degree of control that is possible. It is, therefore, necessary to compute a "controllability index" for the freeway section being studied.

Example—Step 2

The "controllability index" is computed as follows for the example freeway:

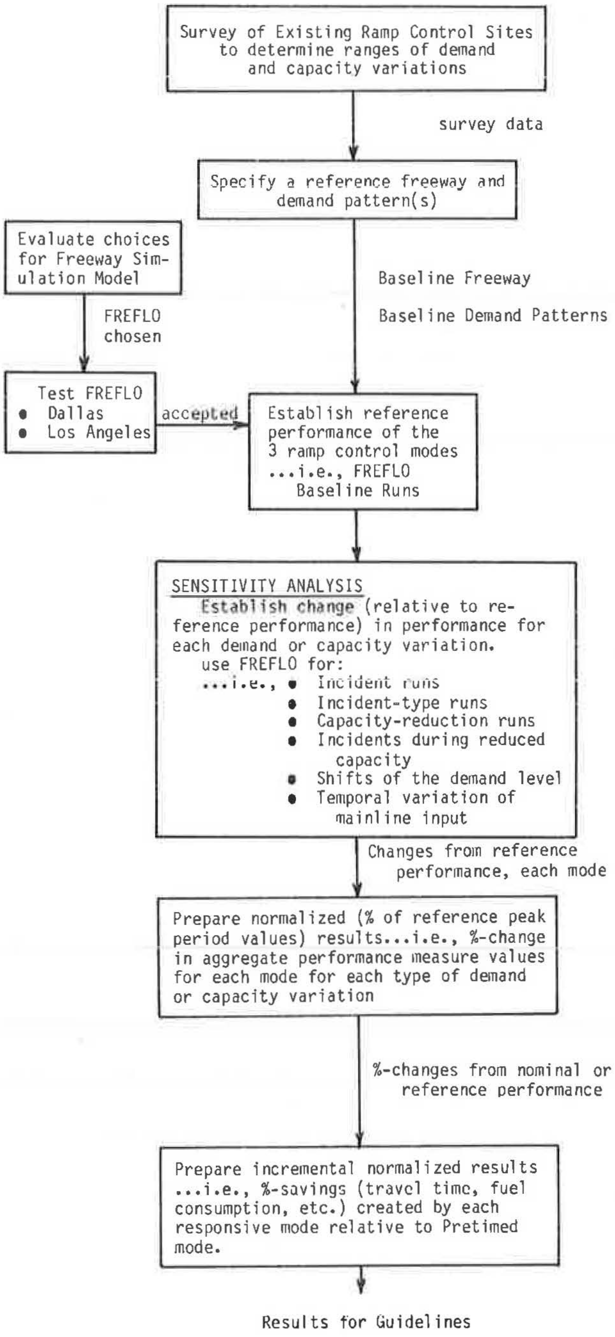


Figure E-24. Overall sensitivity analysis methodology.

$$\text{Controllability index (C.I.)} = \frac{\begin{array}{c}\text{Total metered}\\ \text{input with}\\ \text{pretimed control}\end{array} - \begin{array}{c}\text{Total metered}\\ \text{input with}\\ \text{min. metering rates}\end{array}}{\begin{array}{c}\text{Total metered input}\\ \text{with min. metering rates}\end{array}}$$

In Chapter 8, Table E-11 gives the allowable ramp volumes. If these volumes are totaled for the 2-hour peak period the following results:

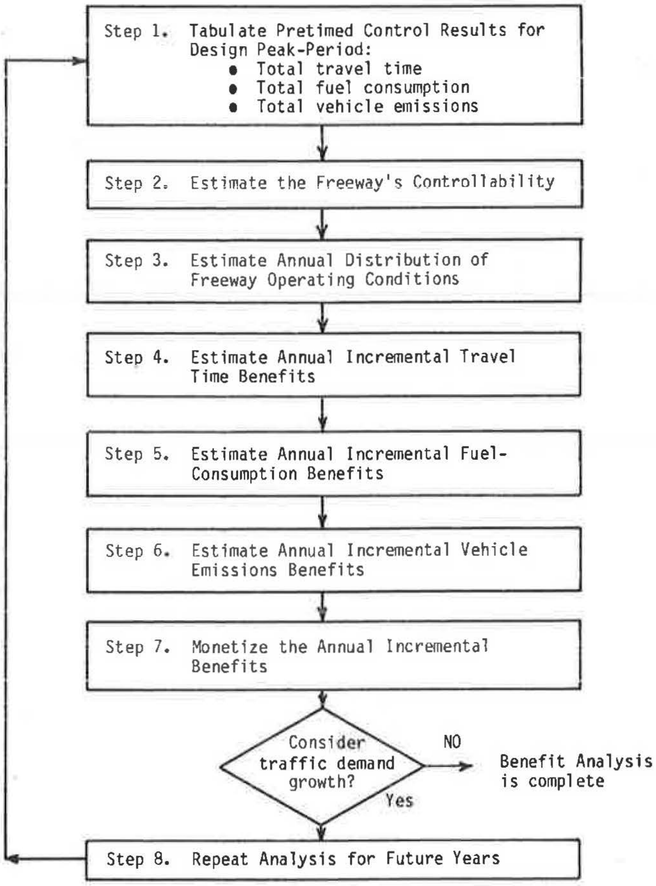


Figure E-25. Procedure for estimating annual incremental benefits of responsive ramp control modes.

R_1 $600 + 375 = 975$
R_2 $550 + 325 = 875$
R_3 $350 + 300 = 650$
R_4 $350 + 325 = 675$
R_5 $450 + 375 = 825$
$\overline{4000}$ = Total metered input for 2-hour peak period

Thus:

Total metered input with pretimed control = 4000 veh

In Chapter 5, it was indicated that a maximum desired duration of a red indication on a ramp control signal was 20 sec. A minimum metering rate then would be 3600/20 or 180 vph. With five ramps:

$$\begin{aligned}\text{Total metered input}&\\ \text{with min. metering rate} &= 5 \text{ (ramps)} \times 180 \times 2 \text{ (hours)}\\ &= 1800 \text{ veh}\end{aligned}$$

Thus:

$$\text{C.I.} = \frac{4000 - 1800}{1800} = 1.22$$

Step 3—Estimate Annual Distribution of Freeway Operating Conditions

When the "unexpected" occurs, responsive control (either local actuated or system control) has the potential to reduce travel time, fuel consumption, or emissions below what they would be in the same circumstances for pretimed control. The unexpected creates departures of freeway demand or capacity from nominal conditions, and creates a need to modify the entering ramp volumes from those required under normal conditions.

The research methodology (briefly discussed at the beginning of this chapter) identified six basic types of peak periods that can occur. These peak period types are given in Table E-16. When these types of peak periods occur, responsive control can produce incremental benefits (as compared to pretimed control) by adapting metering rates to the actual freeway condition. Thus, to determine the annual incremental benefits of responsive control (local actuated or system), one must estimate the annual distribution of freeway operating conditions over the peak period types shown in Table E-16.

One can establish the annual distribution of peak period types as follows:

1. First, consult local weather records to determine the expected number of peak periods in a year that have very poor weather conditions (very heavy rain, snowstorms, ice storms, etc.). Assume that ramp metering will be turned off on those days due to the abnormal operating conditions. If there are X such peak periods per year, considering weekdays only, this leaves (260 — X) peak periods during which entrance ramp control will be used.

2. Again, using local weather records for guidance, estimate the split of the remaining days into those for which freeway capacity is reduced (due to rain, fog or other adverse conditions) and those for which it is not.

3. Estimate the number of incidents per year and the number that are likely to occur within the set of system reduction peak periods and those that are likely to occur during the remaining peak periods. The operational ramp control installations surveyed reported the annual frequency of incidents given in Table E-17. The last column, giving the annual number of incidents per lane-mile per hour of peak period, can be used as a guide in estimating the total number of incidents. The mean reported frequency of incident occurrences (of all types) was 5.18 per year per lane-mile per hour of the peak period. The standard deviation was ±3.58 per year per peak period hour per lane-mile. From the survey data, the relative likelihood of incident occurrences in poor (such as rain or fog) versus normal operating conditions was also computed. These results are given in Table E-18. It is seen that for nearly half of the systems, poor operating conditions are not a factor. The mean computed relative likelihood was 2.19, with a standard deviation of +1.84, meaning that the national frequency of incident occurrences during poor op-

TABLE E-16

TYPES OF PEAK PERIODS THAT MAY OCCUR DURING A YEAR

Peak Period Type	Description
Incident	Peak periods that are at nominal conditions--except that one or more incident(s) occur(s).
System Reduction	Peak periods for which the freeway operates at reduced capacity throughout the system (as during rain or fog conditions)--and without incidents.
Incident Plus System Reduction	Peak periods for which the freeway operates at Reduced capacity throughout the system and one or more incident(s) occur(s).
Demand Increase	Peak periods for which traffic demand is greater than usual (an upward shift in the demand level).
Demand Decrease	Peak periods for which traffic demand is less than usual (a downward shift in the demand level).
Fluctuating Demand	Peak periods for which traffic demand fluctuates with high frequency.

NOTE: Incidents are considered only with Incident and Incident Plus System Reduction peak periods. To simplify the analysis, incidents were not considered with the last three types of peak periods listed above. This omission leads to only a slight understatement of the incremental benefits.

TABLE E-17

ANNUAL FREQUENCY OF INCIDENTS DURING METERED OPERATIONS

System Location		Annual Number Incidents During Metered Hours	Peak Period (hrs.)	Lane-Miles	Annual Number per Lane-Mile per Peak Hour
Chicago	a)	100	3.25	12.3	2.75
Milwaukee	a)	400*	----	----	----
	b)	350*	----	----	----
	c)	250*	----	----	----
Minneapolis	a)	67	1.25	16.6	3.23
	b)	134	3.25	11.7	3.53
	c)	92	3.25	10.7	2.65
Toronto	a)	95	1.83	11.3	4.59
Dallas	a)	216	1.50	20.5	7.02
San Antonio	a)	45	2.00	1.9	11.78
Houston	a)	311	2.33	40.2	3.32
Ft. Worth	a)	195	1.00	17.1	11.40
San Jose	a)	---	----	----	----
	b)	---	----	----	----
San Francisco	a)	N.A.	----	----	----
Los Angeles	a)	130	2.67	19.5	2.50
	b)	---	----	----	----

*These values seem unusually large.

TABLE E-18

RELATIVE LIKELIHOOD OF INCIDENT OCCURRENCE—POOR OPERATING CONDITIONS RELATIVE TO NORMAL OPERATING CONDITIONS

System Location		Relative Likelihood of Incident Occurrences; Poor vs. Normal Operating Conditions
Chicago	a)	1.00
Milwaukee	a)	1.00
	b)	1.00
	c)	1.00
Minneapolis	a)	3.92
	b)	1.84
	c)	2.69
	d)	1.54
Dallas	a)	----
San Antonio	a)	----
Houston	a)	1.00
Ft. Worth	a)	----
San Jose	a)	----
	b)	----
San Francisco	a)	7.00
Los Angeles	a)	2.11
	b)	----

erating conditions may average about twice the frequency under good operating conditions. Using Table E-18 for guidance, estimate the split of incidents as follows:

$$\begin{matrix}\text{Probability of}\\ \text{incidents under}\\ \text{poor conditions}\end{matrix} = \left(\begin{matrix}\text{Relative}\\ \text{likelihood}\end{matrix}\right) \times \frac{\begin{matrix}\text{(No. peak periods}\\ \text{with system}\\ \text{reduction)}\end{matrix}}{\begin{matrix}\text{(No. peak periods}\\ \text{with normal}\\ \text{conditions)}\end{matrix}}$$

4. Having estimated the split of incidents between peak periods of poor operating conditions and peak periods of normal operating conditions, compute the annual number of incidents for each operating condition.

5. Now estimate the annual number of (see Table E-16 for definitions):

- Incident peak periods.
- Reduced capacity peak periods.
- Incident plus system reduction peak periods.

Subtract the number of incident plus system reduction peak periods from the number of system reduction peak periods, and no system reduction peak periods.

6. Now estimate the annual number of (see Table E-16 for definitions):

- Demand increase peak periods.
- Demand decrease peak periods.
- Fluctuating demand peak periods.

It is recommended that every peak period be considered one with fluctuating demand, and that the demand level be considered evenly distributed among demand increase, demand decrease, and nominal demand-level peak periods.

7. Finally, consolidate the estimates of peak period types into a summary of the annual distribution of freeway operating conditions. Also specify the average number of incidents per peak period.

Example—Step 3

The seven substeps of step 3 are illustrated in the following with the example freeway.

Estimate Severe Weather Periods. Assume that after reviewing past weather records, it is determined that very severe weather conditions (rain, fog, snow, etc.) will exist during 10 peak periods each year. Entrance ramp controls will not be operated during these severe weather periods. Thus, the entrance ramp controls would operate during (260 — 10) = 250 peak periods each year.

Estimate Periods of System Reduction. Also assume that the past weather records indicate that freeway capacity will be reduced because of rain, fog, or other adverse conditions an average of 20 days per year. Thus, of the 250 peak periods when the entrance ramp controls would be operational, 20 peak periods would have a system reduction condition and 230 peak periods would occur under near-normal conditions.

Incident Analysis. Assume that after an analysis of incident occurrence relative to poor operating conditions, it is feasible to use a relative likelihood factor of 2.0. Using this assumption, the probability of incidents occurring during poor operating conditions is estimated as follows:

$$\begin{matrix}\text{Probability of}\\ \text{incidents under}\\ \text{system}\\ \text{reduction}\end{matrix} = (2.0)\,\frac{\begin{matrix}\text{No. peak periods with}\\ \text{system reduction}\end{matrix}}{\begin{matrix}\text{No. peak periods with}\\ \text{normal conditions}\end{matrix}}$$

$$= 2.0\,\frac{20}{230} = 0.174$$

Estimate Total Incidents. As previously indicated, the example freeway is metered 2-hours per peak period and contains 7.65 (3 × 2.55) lane-miles of freeway.

Assume for the freeway in question that an estimate of the frequency of incidents is 6.75 per peak period hour per lane-mile per year. The total annual incidents would then be distributed as follows:

Total incidents = (6.75) (7.65) (2) = 103 per year
Incidents under system reduction = (103) (0.174) = 18 per year
Incidents under normal freeway conditions = 103 — 18 = 85 per year

Peak Period Type. The example freeway is estimated to have 20 system reduction peak periods per year. Also, 18 incidents under system reduction conditions are expected. Therefore assume all system reduction peak periods also contain an incident.

A summary of the peak period types is given in Table E-19.

TABLE E-19

SUMMARY OF EXAMPLE FREEWAY PEAK PERIOD TYPES

Peak Period Type	Annual Number
Incident	85
System Reduction Only	0*
Incident Plus System Reduction	20

*All System Reduction Peak Periods are assumed to also contain an incident, thus this category is zero to avoid double counting.

Demand Analysis. The example freeway has a total of 250 peak periods under control. Assume all 250 peak periods have demand fluctuations equally distributed around peaks with (1) demand increase, (2) demand decrease, and (3) normal demand. Thus, there are 250/3 or 83 of each of these types.

Summarize Annual Operating Conditions. From the previous substeps it is possible to develop the summary of annual operating conditions given in Table E-20.

TABLE E-20

ANNUAL DISTRIBUTION OF EXAMPLE FREEWAY OPERATING CONDITIONS

Peak Period Type	Annual Number	Incidents Per Peak Period
Incident	85	1.00
System Reduction	0	N.A.
Incident Plus System Reduction	20	1.00
Demand Increase	83	N.A.
Demand Decrease	83	N.A.
Fluctuating Demand	250	N.A.

Step 4—Estimate Annual Incremental Travel Time Benefits

The procedure for estimating annual incremental travel time benefits consists of the following five substeps:

1. The incremental benefits of either local actuated control or system control are estimated for each of the six types of peak periods. These six types of peak periods are those defined in Table E-16. The incremental benefits for each type of peak period are found from graphs.
2. The incremental benefits found for each one of the six peak period types are then multiplied by the number of times that particular type of peak period is expected to occur annually.
3. The annual incremental benefits, computed in step 2, are multiplied by the expected number of incidents per peak period if the peak period type involves incident(s).
4. The annual incremental benefits, as computed in steps 2 and 3, are then summed over all types of peak periods. The sum is equal to the total annual incremental benefits in vehicle-hours saved per year.
5. The annual vehicle-hours saved are converted into traveler-hours saved by multiplying vehicle-hours saved by the average vehicle occupancy during peak periods.

A discussion of the procedure for estimating the incremental benefits for each of the six types of peak periods follows.

Incident Peak Periods

The incremental travel time benefits of responsive control during peak periods that contain an incident can be estimated from Figure E-26. This graph provides an estimate of the travel-time savings (over that for a nominal peak period) for both local actuated and system control.

Example—Incident Peak Periods. The example freeway has 85 incident peak periods annually, a total travel time of 851.9 veh-hours in a nominal peak period, and a controllability index of 1.22. Using Figure E-26, one finds an average 2.0 percent incremental benefit for local actuated control and a 5.2 percent incremental benefit for system control. Thus, the annual incremental benefits that can be attributed to the incident peak periods are estimated as follows:

Annual reduction in travel time due to local actuated control = (85) (851.9) (0.020)

= 1448 veh-hours

Annual reduction in travel time due to system control = (85) (851.9) (0.052)

= 3765 veh-hours

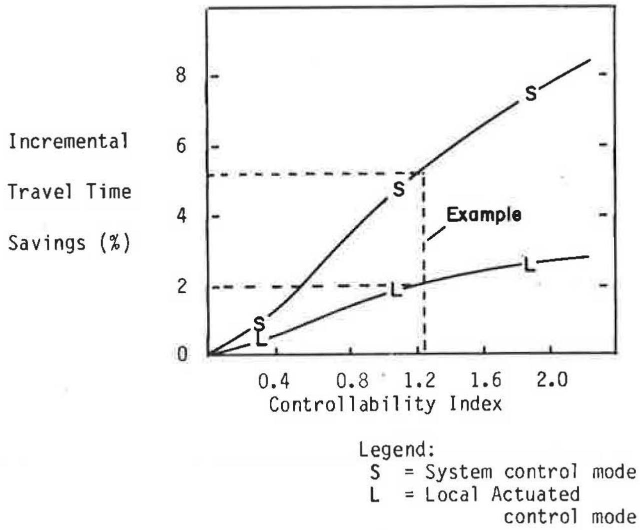


Figure E-26. Incremental travel-time benefits—incident peak periods.

If the average vehicle occupancy during the peak periods is 1.25 persons/vehicle, the person-hours are computed as follows:

Incremental benefits
local actuated control
= (1448) (1.25) = 1810 person hours
Incremental benefits
system control
= (3765) (1.25) = 4706 person-hours

System Reduction Peak Period

The incremental travel-time benefits of responsive control during peak periods that have system reduction can be estimated from Figure E-27.

Example—System Reduction. For the example freeway, it was assumed that there would be no system reduction peak periods without incidents. Thus no incremental benefits are estimated for this peak period type for the example freeway.

Incident Plus System Reduction

The incremental travel time benefits of responsive control during peak periods that contain an incident plus system reduction situation can be estimated from Figure E-28.

Example—Incident Plus System Reduction. The example freeway is assumed to have 20 incident plus system reduction peak periods annually. The total travel time for a nominal peak period is 851.9 veh-hours and the controllability index is 1.22. Figure E-28 indicates an average 15.3 percent incremental benefit for local actuated control and a 17.0 percent incremental benefit for system control. If the average vehicle occupancy is assumed to be 1.25 persons/vehicle, the annual incremental travel time benefits are estimated as follows:

Incremental benefits local actuated control = (20) (851.9) (1.00) (0.153) (1.25)
= 3259 person-hours
Incremental benefits system control = (20) (851.9) (1.00) (0.17) (1.25)
= 3621 person-hours

Demand Increase

The incremental travel time benefits of responsive control during peak periods that experience a demand increase can be estimated from Figure E-29.

Example—Demand Increase. The example freeway has 83 demand increase peak periods annually, a total travel time of 851.9 veh-hours in a nominal peak period, and a controllability index of 1.22. Figure E-29 indicates that there is an average 0.9 percent incremental benefit for each peak period for either mode of control. Assuming a vehicle occupancy of 1.25 persons/vehicle, the annual incremental benefits are estimated as follows:

Incremental benefits local actuated or system control = (83) (851.9) (0.009) (1.25)
= 796 person-hours

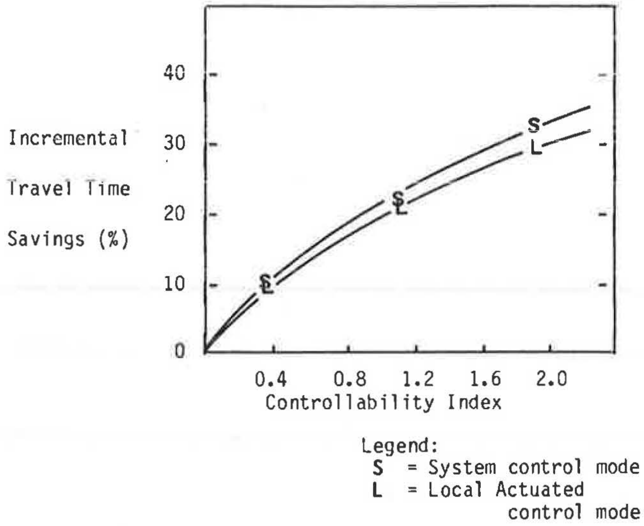


Figure E-27. Incremental travel-time benefits—system reduction peak period.

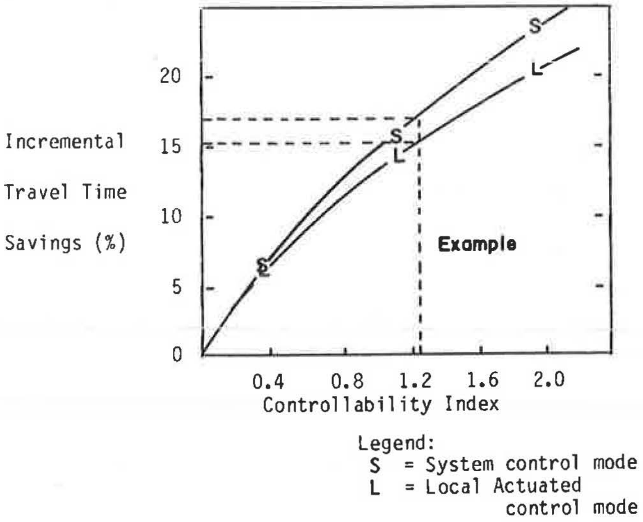


Figure E-28. Incremental travel-time benefits—incident plus system reduction.

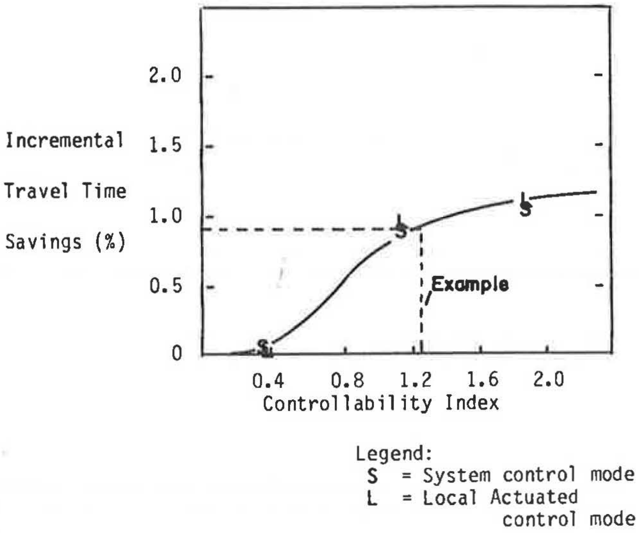


Figure E-29. Incremental travel-time benefits—demand increase.

Demand Decrease

The incremental travel time benefits of responsive control during peak periods that experience a demand decrease can be estimated from Figure E-30.

Example—Demand Decrease. The example freeway has 83 demand decrease peak periods annually. Figure E-30 indicates an average annual 2.6 percent incremental benefit for local actuated control and 1.8 percent for system control. The total benefits are estimated as follows:

$$\begin{aligned}\text{Incremental benefits local actuated control} &= (83)\ (851.9)\ (0.026)\ (1.25)\\ &= 2298 \text{ person-hours}\\ \text{Incremental benefits system control} &= (83)\ (851.9)\ (0.018)\ (1.25)\\ &= 1591 \text{ person-hours}\end{aligned}$$

Fluctuating Demand

The incremental travel time benefits of responsive control during peak periods that experience short-term demand fluctuation can be estimated from Figure E-31. Each peak period in which entrance ramp control is used is expected to experience fluctuating demand.

Example—Fluctuating Demand. The incremental benefits from responsive control (local actuated or system) are very small. These benefits could be estimated, but in the interest of deriving a conservative total estimate of benefits they will be considered to be zero for the example freeway.

Total Annual Travel-Time Benefits—All Peak Period Types

The total annual incremental travel-time benefits for each responsive control mode is the sum of the benefits resulting from evaluating the various types of peak periods.

Example—Total-Travel Time Benefits. The total annual incremental travel-time benefits for the example freeway are given in Table E-21.

Step 5—Estimate Annual Incremental Fuel-Consumption Benefits

The procedure for estimating annual incremental fuel-consumption benefits is very similar to that already described for the travel-time benefits. Each of the various types of peak periods is considered and the appropriate incremental benefits are estimated. The various types of peak periods and the estimate of fuel-consumption benefits due to responsive control are discussed and illustrated in Chapter 11.

Step 6—Estimate Annual Incremental Vehicle Emissions Benefits

The basic procedure for estimating annual incremental vehicle emissions benefits is the same as that used to estimate the travel-time and fuel-consumption benefits. Chapter 12 discusses each of the peak period types and provides examples of the methodology. It may be noted from the example in Chapter 12 that the consideration of vehicle

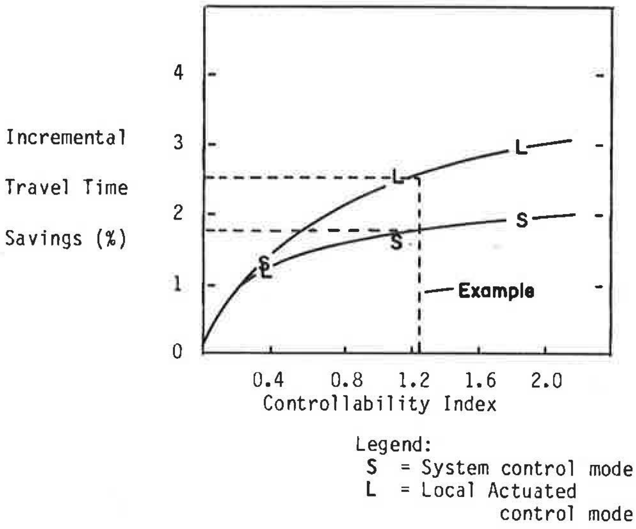


Figure E-30. Incremental travel-time benefits—demand decrease.

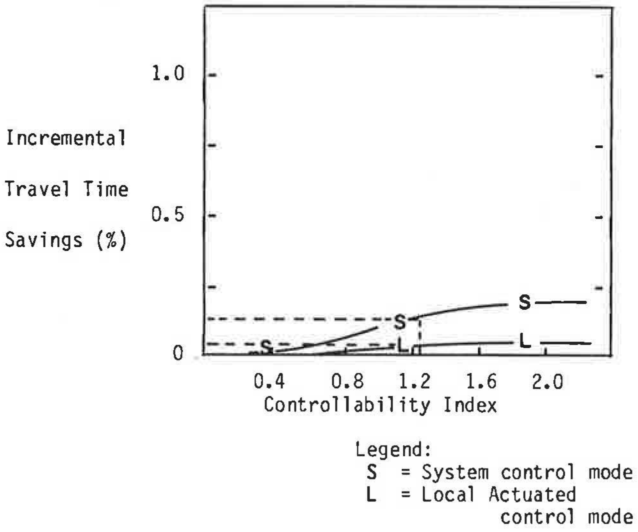


Figure E-31. Incremental travel-time benefits—fluctuating demand.

TABLE E-21

ANNUAL INCREMENTAL TRAVEL TIME BENEFITS OF RESPONSIVE CONTROL MODES—EXAMPLE FREEWAY

		Annual Incremental Benefits (Person-Hrs)	
	Period Types	Local Actuated Control	System Control
1.	Incident	1810	4706
2.	System Reduction	0	0
3.	Incident Plus System Reduction	3259	3621
4.	Demand Increase	796	796
5.	Demand Decrease	2298	1591
6.	Fluctuating Demand	0	0
	Annual Totals	8,163	10,714

emissions for peak periods results in relatively small values. Thus, it may not be desirable to analyze the incremental benefit for vehicle emissions. A methodology is presented, however, in the event such an evaluation is deemed desirable.

Step 7—Monetize Annual Incremental Benefits

The previous steps presented a methodology for estimating incremental benefits for travel time reductions, fuel consumption reductions, and vehicle emissions reductions. Only the first two items can be monetized with current economic procedures. The next sections present the procedures to be followed in monetizing travel-time and fuel-consumption benefits.

Monetizing Travel-Time Benefits

Chapter 3 discussed procedures for monetizing travel-time savings and these same basic procedures are used in this chapter.

Example—Travel-Time Benefits. The incremental travel-time benefits for local actuated and system control are estimated as follows:

Local actuated control = 8,163 person-hours of incremental travel-time benefits
System control = 10,714 person-hours of incremental travel time benefits

If an individual time saving per vehicle in the range of 5 to 10 min is assumed, a reduction factor of 0.6 can be obtained from Table E-1 and a value of time of $6.31 per hour (for driver and passengers of automobiles) can be obtained from Table E-47. If the average vehicle occupancy is assumed to be 1.25, the travel-time reductions can be monetized as follows:

Travel time benefits (local actuated control) = ($6.31) (1.25) (0.6) (8,163)
= $38,631.00 per year
Travel time benefits (system control) = ($6.31) (1.25) (0.6) (10,714)
= $50,704.00 per year

Monetizing Fuel-Consumption Benefits

The gallons of fuel saved by the responsive control modes (relative to pretimed control) can be monetized at the prevailing price per gallon of fuel for automobiles. As of mid-1980, a value of $1.25 per gallon was appropriate.

Example—Fuel-Consumption Benefits. The incremental fuel consumption benefits for local actuated over system control are estimated as follows:

Local actuated control = 2067 gal/year incremental fuel-consumption benefit
System control = 2246 gal/year incremental fuel-consumption benefit

Thus the annual value of fuel-consumption benefits are as follows:

Fuel-consumption benefits (local actuated control) = ($1.25) (2067)
= $2584.00 per year
Fuel-consumption benefits (system control) = ($1.25) (2246)
= $2808.00 per year

Step 8—Repeat Analysis for Future years

Thus far, this report has only considered the problem of estimating the incremental benefits for a single year in the lifetime of the proposed entrance ramp control installation. Of course, a new installation will have a lifetime of many years. If the traffic demand pattern was not to change over the project lifetime, the annual benefits determined for one year would apply to each year of the project lifetime.

The graphs of (normalized) incremental benefits are generally nonlinear. More precisely, the benefits are nonlinear functions of the freeway controllability. The implication of this is that if traffic demand grows substantially over the lifetime of the project, the controllability of the freeway will become smaller and smaller. Because the benefits are nonlinearly related to the controllability, it is possible that the benefits could decrease faster than the growth rate of demand. This, in turn, could substantially decrease the present value of benefits accrued over the lifetime of the project. For this reason, it is recommended that the user of these guidelines repeat his analysis for two or more years throughout the project lifetime. The projected demand growth should be factored into these analyses. If several "snapshots" are obtained of the annual benefits at different points in the project lifetime, the entire time stream of benefits can be estimated by interpolating between the snapshot-year benefits.

In summary, when substantial demand growth is expected over the project lifetime (a 10- to 15-year service life is suggested), it is recommended that the demand projections be used to estimate the benefits in several "snapshot" years of the project lifetime. From these snapshot benefit values, one can estimate the benefits in other years through interpolation. Three snapshot years are advisable: the first year of operation, the last year of operation, and a year at project midlife.

CHAPTER 10

MODE SELECTION

BENEFIT-COST ANALYSIS

A last step in the mode selection process is that of using the data on costs (Chapter 7) and benefits (Chapter 9) to make a final decision. A simple benefit-cost analysis should be used as input to this decision. The following material presents a benefit-cost analysis for the example freeway that has been utilized throughout these guidelines.

Benefit-Cost Method

An accepted method for deciding on the economic justification of an entrance ramp control project is to compute the benefit-cost (B/C) ratio. This ratio may be expressed as

$$\mathrm{B/C} = \frac{\text{Equivalent benefit to the motorist}}{\text{Equivalent cost to the agency}} \qquad \text{(E-1)}$$

where the benefits and costs are present or equivalent annual amounts computed using the cost of money. Thus, the B/C ratio reflects the user's equivalent dollar cost. If the ratio is 1, the equivalent benefits and the equivalent costs are equal. This represents the minimum justification for an expenditure by an operating agency.

Incremental Benefit-Cost Technique

The incremental benefits and costs of responsive control modes have been developed. The incremental benefit-cost ratio, $\mathrm{B/C_I}$, is now defined as

$$\mathrm{B/C_I} = \frac{B_I}{C_I + O_I} \qquad \text{(E-2)}$$

where

B_I = incremental net equivalent benefits to the motorist;
C_I = incremental net equivalent capital invested by the agency; and
O_I = incremental net equivalent annual operation and maintenance costs to the agency.

The incremental benefits to the motorist, B_I, are the summation of travel-time savings, fuel-consumption savings, and vehicle emissions reductions. Because vehicle emissions reductions are generally unquantifiable for economic analysis, the incremental benefits become

B_I = Travel-time savings + fuel-consumption savings

The incremental capital cost to the agency is based on the figures developed in Chapter 7, i.e.,

Pretimed installation = $16,000 per ramp
Local actuated installation = $20,000 per ramp
System installation = $32,000 per ramp

These figures are based on averages, so they apply to all systems in general, but none in particular. The user should develop his site-specific cost figures for improved accuracy in benefit-cost calculations. Using the foregoing figures, the incremental costs per ramp are

Pretimed-to-local actuated incremental capital cost = 20,000 − 16,000
= $4,000 per ramp

and

Pretimed-to-system incremental capital cost = 32,000 − 16,000
= $16,000 per ramp

Similarly, the incremental annual cost to the agency is based on the figures developed in Chapter 7, i.e.,

Pretimed annual cost = 16% of capital cost
= (0.16) (16,000)
= $2,560 per ramp
Local actuated annual cost = 18% of capital cost
= (0.18) (20,000)
= $3,600 per ramp
System annual cost = 30% of capital cost
= (0.30) (32,000)
= $9,600 per ramp

Thus, the incremental annual costs per ramp are

Pretimed-to-local actuated incremental annual cost = 3,600 − 2,560
= 1,040 per ramp
Pretimed-to-system incremental annual cost = $9,600 − 2,560
= $7,040 per ramp

Two additional figures must be developed for the incremental benefit-cost calculations. These are in conjunction with the value of money invested for a specified time period (both capital and annual operating and maintenance cost) and must be expressed on a net equivalent annual basis for comparison. (The incremental benefits for the example freeway are expressed on an annual basis in Tables E-21, E-36, and E-45.) The following calculations assume an annual interest rate of 10 percent and a 10-year life of the installation.

An equal-payment-series capital-recovery factor is needed to determine the net annual equivalent of the capital cost of the installation. This can be obtained from a table in an engineering economics textbook such as Theusen et al. (*E-15*), or can be calculated by the following formula:

$$F_{CR} = \frac{i(i+1)^n}{(1+i)^n - 1} \qquad \text{(E-3)}$$

where

F_{CR} = equal-payment-series capital-recovery factor;
i = interest rate; and
n = life of installation in years.

The capital cost of the installation is multiplied by the capital-recovery factor to obtain the net annual equivalent of the capital cost of the installation.

A uniform gradient-series factor is needed to determine a net annual equivalent of annually escalating operating and maintenance costs of the installation. Again, this may be obtained from tables or derived from the following formula:

$$F_{GS} = \frac{1}{i} - \frac{n}{i}\left(\frac{i}{(i+1)^n - 1}\right) \qquad \text{(E 4)}$$

where

F_{GS} = uniform gradient series factor;
i = interest rate; and
n = life of installation in years.

The net annual equivalent of the operating and maintenance costs of the installation is obtained by adding the first year maintenance cost to the product of the gradient amount and the gradient factor. The gradient amount is the dollar amount that the operating and maintenance costs will increase annually.

Incremental Benefit-Cost Analysis of Example Freeway

The incremental benefit/cost ratios of mode differences can now be calculated. First, the incremental benefit/cost ratio from pretimed to local actuated mode is

$$\text{Pretimed-to-local actuated B/C}_\text{I} = \frac{\text{Incremental savings in travel time and fuel consumption}}{\text{Incremental capital and annual costs}} \qquad \text{(E-5)}$$

The component calculations are:

Incremental savings in travel time = 8,163 traveler-hours (from Table E-21)
× $6.31 value per traveler-hour (from Table E-47, Chapter 13)
× 0.6 reduction factor (from Table E-1)
= $30,905

Incremental savings in fuel consumption = 2,067 gal (from Table E-36)
× $1.25 per gal
= $2,584

Incremental capital costs = 5 (ramps)
× $4,000 (pretimed-to-local actuated incremental capital cost per ramp from this chapter's incremental benefit-cost technique section)
× 0.1628 (capital-recovery factor of 10 years at 10%)
= $3,256

Incremental annual costs = 5 (ramps)
× $1,040 (pretimed-to-local actuated incremental annual cost per ramp, from this chapter's incremental benefit-cost technique section)
× 0.18 (percent of capital cost for first year operating and maintenance, from local actuated mode configuration section of Chapter 7)
+ 5 (ramps)
× $1,040 (pretimed-to-local actuated incremental cost, from this chapter's incremental benefit-cost technique section)
× 0.05 (annual percent increase of operating and maintenance costs)
× 4.0991 (uniform gradient-series factor of 10 years at 10%, from this chapter's benefit-cost technique-section)
= $936 + $1,066
= $2,002

Finally,

$$\text{Pretimed-to-local actuated B/C}_\text{I} = \frac{\$30{,}905 + \$2{,}584}{\$3{,}256 + \$2{,}002} = 6.4$$

Similarly, the incremental benefit/cost ratio from pretimed-to-system mode is

$$\text{Pretimed-to-system B/C}_\text{I} = \frac{\text{Incremental savings in travel time and fuel consumption}}{\text{Incremental capital and annual costs}}$$

$$= \frac{(10714)(6.31)(0.6) + (2246)(1.25)}{(5)(16000)(0.1628) + (5)(7040)(0.30) + (5)(7040)(0.05)(4.0991)}$$

$$= \frac{\$40{,}563 + \$2{,}808}{\$13{,}024 + \$10{,}560 + \$7{,}214}$$

$$= 1.4$$

Mode Selection Decision

The incremental benefit-cost ratios for local actuated (6.4) and system control (1.4) aid in quantifying a decision on the selection of an entrance ramp control mode. The use of local actuated control seems warranted when one considers the relatively high B/C$_\text{I}$ of 6.4. The system control B/C$_\text{I}$ of 1.4 is more marginal.

It should be noted that the example problem has only used the incremental benefits for the initial year of operation. These benefits could decrease over time because of increased traffic demand if the increase was accompanied by a lower level of controllability. Incremental benefits should be estimated for both midpoint and final years and combined with the initial year estimates to obtain a more conservative average value for these benefits.

One should also consider intangible benefits in addition to the monetary benefits previously estimated. A method for the evaluation of intangible benefits follows.

UTILITY-COST ANALYSIS *(E-3, E-16)*

The decision to install a freeway control system involves explicit considerations of numerous variables *(E-17)*. A consideration of the tangible traffic operation variables has been used to evaluate the application of criteria for a particular ramp control mode. An assessment of the direct benefits associated with the costs yields the values shown in the previous section.

At the same time, there are numerous benefits *(E-17)*, particularly with system control, that are intangible and thus defy the application of a dollar benefit or cost. To further complicate the issue, each agency is likely to assign different weights to many intangible variables. Clearly, the transition from pretimed to local actuated to system control modes is represented by nonlinearly increasing costs —but without a similar scale of increasing benefits. The intangible benefits, on the other hand, may justify the selection of a higher level of control. To deal with this situation, a cost utility evaluation can be made. The result of the utility analysis is a relative effectiveness value for each control mode. The utility or effectiveness values are then related to the respective total costs to provide cost effectiveness indications. The control modes are compared on the basis of these indicators, and the incremental difference between indicators is compared to determine the most likely candidate for implementation. The analysis should be tempered by engineering judgment to be sure that a rational decision is made.

Steps In A Utility-Cost Analysis

The process of system evaluation by the utility-cost technique can be stated as a series of finite steps that are ordinarily performed at the committee level. These are

- Definition of goals and subgoals.
- Weighting of goals.
- Weighting of subgoals.
- Utility rating.
- Utility-cost analysis.

These steps are explained and individually applied to the example freeway.

Define Goals

Goal definition is the selection of broad categories that reflect long-range overall management desires for a ramp control system. These goals should be stated in such a manner that they are *(E-16)*:

1. Distinct (i.e., one not implying any of the others).
2. Independent (i.e., the achievement of one not influencing or affecting the achievement of any of the others).
3. Noncontradictory (i.e., the achievement of any combination of objectives not being impossible).
4. Additive (i.e., the achievement of each objective adding to the total desirability regardless of the achievement of other objectives).

When formulating the goals, it is not important that they be listed in any particular order of importance because this will be done later. A set of goals which could be applied to the example freeway is listed as follows; other goals could also be applicable. It is noted that each agency would be expected to have a different set of goals that specifically applies to its particular needs. The following goals are typical of a set that would be applicable to a ramp control installation, but are not necessarily applicable to all situations.

Goal 1—Traffic Operations. The primary goal of the ramp control system for the example freeway is to improve traffic operations. This includes the following considerations: (1) reduce total delay to the motorist; (2) maintain level-of-service D, or better; and reduce stop-and-go congestion.

Goal 2—Safety. A goal is to improve safety on the example freeway, which has a high accident rate on both the main lanes and ramps. This seems to be due to the given combination of congestion and geometrics. The introduction of ramp control will reduce the likelihood of certain accident scenarios.

Goal 3—Implementation. A goal is to minimize the perturbations associated with the implementation of a freeway ramp control system. Factors that are of concern for the example freeway are:

- Disruption of traffic—The state of congestion is such that even minor construction activities would severely affect peak operation.
- Time frame—Operational improvement is needed now. A short installation period is desirable.
- Training of operational personnel—It is desirable to train existing personnel to operate and maintain the ramp control system. A training program will be required.

Goal 4—Operating Factors.—A goal is to meet the needs of daily operating requirements. It is recognized that the installation of a ramp control system on the example freeway represents a definite operating commitment each weekday. Similarly, a commitment of service personnel will be required to provide maintenance. The factor of equipment maintainability is of major concern, as is the relationship of timely outage response which is linked to the freeway management goal. A capable, responsible, and continuing maintenance program is vital to the success of the operation.

Goal 5—Freeway Management. A goal is to provide management of the freeway system. The ramp control system for the example freeway will be the first one under the jurisdiction of the operating agency. It is felt that the highly congestive state could have been better anticipated if a better freeway management plan had been in effect. With this new installation, the agency plans to implement a new management procedure that will better serve operational needs. Additionally, the system should have a good capability for expansion.

Goal 6—Operational Efficiency. A goal is to achieve an operationally efficient traffic handling capability. The proposed ramp control system should handle existing traffic patterns and traffic fluctuations of the example freeway in an efficient manner. An inventory of traffic operation has produced detailed information on the congestion problem, and any corrective measures should, at a minimum, handle existing needs.

Assign Weight to Goals

The next step is to develop a numerical weighting of the goals, generally accomplished in a group session attended by representatives of all system phases, such as management, design, construction monitoring, acceptance testing, operation, and maintenance. The session should be characterized by an open discussion of the goals so as to clearly impart the full meaning of each goal definition. Each participant is asked to assign an importance rating to each of the goals on a scale of 1 to 100, where the most important goal would have a weight of 100 and decreasing values are assigned to the other goals based on an estimate of their relative importance to each other. This can be accomplished by ballot or round-table voting on each goal. The chairman tallies the votes (including his own) and averages the weights.

With a single weight (still on a scale of 1 to 100) now achieved for each goal, the goals can be listed in order of highest to lowest weight. The list should be reviewed for reasonableness of relative weights. The weights should be refined as appropriate, with a conversion of the final weights to percentages by totaling the weights, dividing each rating by the total, and multiplying each by 100.

For the example freeway, the goal weights given in Table E-22 were initially established.

The goals for the example freeway were reordered by descending numerical weight as given in Table E-23.

In reviewing Table E-23, it quickly became apparent that the tendency had been to assign weights too high for all but the most important goal. The percentage rating for goal 1, Traffic Operations, was only 31 and this pointed out the problem. At the same time, however, it was felt that the relative ordering of the goals was correct.

At this point it was necessary to apply the technique mentioned in Barish (*E-16*) for improving the reliability of the ratings. This technique is a method for refining goal weights by measuring the importance of each goal relative to the combined importance of all succeeding goals. The results given in Table E-24 were obtained after reassigning the goal weights.

TABLE E-22

EXAMPLE FREEWAY INITIAL GOAL WEIGHT ASSIGNMENT

Goal	Weight
1. Traffic Operations	100
2. Safety	30
3. Implementation	10
4. Operating Factors	40
5. Freeway Management	60
6. Operational Efficiency	80

TABLE E-23

EXAMPLE FREEWAY GOALS ORDERED BY WEIGHT

Goal	Weight	Percentage
A. Traffic Operations	100	31
B. Operational Efficiency	80	25
C. Freeway Management	60	19
D. Operating Factors	40	13
E. Safety	30	9
F. Implementation	10	3
Totals	320	100

TABLE E-24

EXAMPLE FREEWAY REVISED GOAL WEIGHT ASSIGNMENTS

Goal	Weight	Percentage
A. Traffic Operations (<<80+60+40+30+10)	150	34
B. Operational Efficiency (<60+40+30+10)	100	23
C. Freeway Management (>40+30+10)	100	23
D. Operating Factors (>30+10)	60	14
E. Safety (>10)	20	4
F. Implementation	10	2
Totals	440	100

Assign Weight to Subgoals

The subgoals provide a clarification of what is included in each goal and thus form a specific definition of each goal. A weighting of subgoals provides an indication of the percentage contribution of each subgoal to its respective goal.

For each established goal, a list of subgoals should be developed. Subgoals should be directly applicable to their respective goals, and represented by a qualitative rating according to control mode. Such a representation of subgoals for the example freeway is given in Table E-25.

The next step is identical to that of weighting the goals, except that it is successively applied to each group of subgoals. Subgoal weights for the example freeway were established as shown in parenthesis to the right of each subgoal in Table E-25.

Because the subgoal ratings are achieved independently as a group relating to a specific goal, there is the possibility of losing sight of the relative rating of the entire body of subgoals to one another. This final corrective measure is effected by developing an ordered list of all the subgoals by normalized weight. The normalized weights are achieved by multiplying 100 times the percentage weight of the subgoal by the percentage weight of its respective goal. Such an ordered list for the example freeway is given in Table E-26. At this stage the fundamental components of the decision process are documented by relative importance and can be reviewed on a global basis. Final adjustment of the subgoal ratings is made from this list and updates are applied accordingly.

Utility Rating

This step evaluates the relative ability of each control mode to satisfy the subgoals established by the agency. The previous steps have been involved in establishing the definition and relative importance of the goals and subgoals, and now it is time to link the subgoals with the candidate control modes. This is accomplished on a subgoal by subgoal basis by asking the following question: On a scale of 1 to 10, how well does the candidate mode meet this subgoal? The total result is an internal rating of the relative ability of the three control modes to meet the agency's needs. From this, the total utility can be derived.

Tables E-27 through E-32 give the weighted utility values for each of the goals for the example freeway, and the overall utility values for each of the control modes are given in Table E-33.

Utility-Cost Analysis

A method that relates utility versus cost completes the utility analysis. The utility-cost ratios for the candidate modes are given in Table E-34, and incremental utility-cost ratios are given in Table E-35. Figure E-32 graphically depicts the comparison of cost with utility for each of the candidate modes. The utility cost ratio is represented as the slope of a line from the origin to the utility cost intersection. Kay (*E-17*) suggests the enclosure of the point of intersection with a box to illustrate the degree of accuracy of the utility measurement. The utility cost ratio increases as the slope of the line approaches the utility axis.

From Table E-34, the utility-cost ratios for pretimed, local actuated, and system configurations are 0.48, 0.60, and 0.33, respectively. From Table E-35, the incremental utility cost ratios are 0.92 from pretimed to local actuated, and 0.26 from pretimed to system. This indicates that a local actuated configuration is appropriate for the example freeway, because its respective utility-cost ratio is the highest (0.60) of the three choices. The incremental utility cost ratio from pretimed to local actuated approaches unity, which is desirable. Because the pretimed configuration has a utility-cost ratio of 0.48, the incremental investment required to go from pretimed to local actuated is twice as desirable (0.92/0.48) of that of investment in the pretimed configuration.

TABLE E-25

EXAMPLE FREEWAY GOALS AND SUBGOALS

	Weight	Percentage
1. Traffic Operations (34%)		
• Reduce freeway delay to the motorist	(70)	44
• Maintain Level of Service D	(50)	31
• Reduce stop and go congestion	(40)	25
		100
2. Safety (4%)		
• Reduce freeway accidents	(100)	57
• Reduce ramp/merging accidents	(75)	43
		100
3. Implementation (2%)		
• Disruption of traffic during construction	(60)	46
• Time frame of installation	(30)	23
• Training of operational personnel	(40)	31
		100
4. Operating Factors (14%)		
• Equipment simplicity	(60)	38
• Level of equipment maintenance	(100)	62
		100
5. Freeway Management (23%)		
• Provide management mechanism	(50)	9
• Accommodate future demands (expansion capability of equipment)	(80)	14
• Redistribute delay/demand	(30)	6
• Defer capital improvement	(35)	6
• Provide traffic operation surveillance	(60)	11
• Improve accident/incident response	(40)	7
• Facilitate data collection	(80)	14
• Provide equipment surveillance	(75)	13
• Provide driver information	(40)	7
• Coordinate with corridor signal systems	(75)	13
		100
6. Operational Efficiency (23%)		
• Responsiveness to flow instability	(60)	16
• Responsiveness to incidents	(50)	14
• Variation of peak start/end times	(50)	14
• Responsiveness to fluctuating demand	(30)	8
• Adjustment of metering rates	(100)	27
• Responsiveness to traffic pattern changes	(75)	21
		100

Note that the introduction of intangible benefits through the utility-cost analysis did improve the relative desirability of a system versus local actuated configuration. Using incremental benefit-cost ratios, it is seen that a local actuated configuration is 4.6 times (6.4/1.4, from incremental benefit-cost analysis of example freeway section) more desirable than a system configuration. Using incremental utility-cost ratios, a local actuated configuration is 3.5 times

TABLE E-26

ORDERED LIST OF EXAMPLE FREEWAY SUBGOALS

Subgoal	Normalized Weight
1. Reduce freeway delay to the motorist	15.0
2. Maintain Level of Service D	10.5
3. Level of equipment maintenance	8.7
4. Reduce stop and go congestion	8.5
5. Adjustment of metering rates	6.2
6. Equipment simplicity	5.3
7. Responsiveness to traffic pattern changes	4.9
8. Responsiveness to flow instability	3.7
9. Accommodate future demands	3.2
10. Responsiveness to incidents	3.2
11. Variation of peak start/end times	3.2
12. Facilitate data collection	3.2
13. Coordinate with corridor signal systems	3.0
14. Provide equipment surveillance	3.0
15. Provide traffic operation surveillance	2.5
16. Reduce freeway accidents	2.3
17. Provide management mechanism	2.1
18. Responsiveness to fluctutating demand	1.8
19. Reduce ramp/merging accidents	1.7
20. Improve accident/incident response	1.6
21. Provide driver information	1.6
22. Redistribute delay/demand	1.4
23. Defer capital improvement	1.4
24. Traffic disruption during construction	0.9
25. Training of operating personnel	0.6
26. Time frame of installation	0.5

(0.92/0.26) more desirable than a system configuration. Why then does the system configuration not fare better when intangibles are being considered? The answer is that the utility-cost analysis is most appropriate when trying to decide between alternatives that have generally similar characteristics, such as between the pretimed and local actuated configurations. When the system configuration is considered, however, many features are introduced that are not present in either of the other two configurations. The penalty for absence of a feature is not significant in the evaluation process. For example, consider the feature of being able to monitor equipment failure. The system configuration would have this feature by default, while the penalty for not having this feature would be a zero utility for that subgoal category, which would affect the overall utility-cost ratio very little. If this feature is absolutely required, the control system specifications would be used

TABLE E-27

GOAL 1 UTILITY RATINGS—TRAFFIC OPERATION

SUBGOAL	SUBGOAL WEIGHT	PRETIMED		LOCAL ACTUATED		SYSTEM	
		RATING	UTILITY*	RATING	UTILITY*	RATING	UTILITY*
Reduce freeway delay to the motorist	44	6	264	8	352	9	396
Maintain Level of Service D	31	5	155	7	217	8	248
Reduce stop and go congestion	25	6	150	8	200	9	225
TOTAL UTILITY OF SUBGOALS			569		769		869
GOAL WEIGHT			.34		.34		.34
GOAL UTILITY			193		261		295

*Subgoal weight times subgoal rating.

TABLE E-28

GOAL 2 UTILITY RATINGS—SAFETY

SUBGOAL	SUBGOAL WEIGHT	PRETIMED		LOCAL ACTUATED		SYSTEM	
		RATING	UTILITY*	RATING	UTILITY*	RATING	UTILITY*
Reduce freeway accidents	57	2	114	4	228	6	342
Reduce ramp/merging accidents	43	1	43	2	86	3	129
TOTAL UTILITY OF SUBGOALS			157		314		471
GOAL WEIGHT			.04		.04		.04
GOAL UTILITY			6		13		19

* Subgoal weight times subgoal rating

TABLE E-29

GOAL 3 UTILITY RATINGS—IMPLEMENTATION

SUBGOAL	SUBGOAL WEIGHT	PRETIMED		LOCAL ACTUATED		SYSTEM	
		RATING	UTILITY*	RATING	UTILITY*	RATING	UTILITY*
Disruption of traffic during construction	46	8	368	6	276	5	230
Time frame of installation	23	10	230	9	207	5	115
Level of operational personnel	31	10	310	10	310	5	155
TOTAL UTILITY OF SUBGOALS			908		793		500
GOAL WEIGHT			.02		.02		.02
GOAL UTILITY			18		16		10

* Subgoal weight times subgoal rating

TABLE E-30

GOAL 4 UTILITY RATINGS—OPERATING FACTORS

SUBGOAL	SUBGOAL WEIGHT	PRETIMED		LOCAL ACTUATED		SYSTEM	
		RATING	UTILITY*	RATING	UTILITY*	RATING	UTILITY*
Equipment complexity	38	9	342	9	342	5	190
Level of equipment maintenance	62	9	558	8	496	4	248
TOTAL UTILITY OF SUBGOALS			900		838		438
GOAL WEIGHT			.14		.14		.14
GOAL UTILITY			126		117		61

* Subgoal weight times subgoal rating

as the method for obtaining particular equipment or performance characteristics. The sponsoring agency has this option to assure the inclusion of specific features. These guidelines, however, are presumed to be used as a prespecification decision mechanism, the results of which will be used to choose a suitable control mode.

SUMMARY

The benefit-cost technique provides an objective assessment of costs versus tangible benefits of the three ramp control modes. The measurable differences in control modes are tangible, by definition. Based on cost differences alone, the system mode of control fails to receive credit for the many intangible benefits provided. As cited by Bulman (*E-19*), the cost utility technique bridges this gap and provides a theoretically superior analysis by virtue of the fact that it takes all factors into account, not just the ones easily transformable to monetary units. To ensure the success of a cost utility analysis, it is essential that the users of the process be well informed regarding the advantages and disadvantages of the three control modes, that they understand the meaning of the utility measures, and that they are willing to base a recommendation on the structured process involved in the cost utility procedure. The agency is responsible for setting pertinent goals in the public interest and using good engineering judgment to apply sound analysis techniques to evaluate a system which best meets these goals. This chapter completes the entrance ramp control guidelines. The evaluation and selection of an entrance ramp control mode is a process that will vary for each freeway site and will involve a considerable amount of engineering judgment. These guidelines present a logical framework for the evaluation and decision process and outline a methodology that will be very useful in guiding and quantifying the mode selection process.

TABLE E-31

GOAL 5 UTILITY RATINGS—FREEWAY MANAGEMENT

SUBGOAL	SUBGOAL	PRETIMED		LOCAL ACTUATED		SYSTEM	
	WEIGHT	RATING	UTILITY*	RATING	UTILITY*	RATING	UTILITY*
Provide management mechanism	9	5	45	8	72	9	81
Accommodate future demands	14	1	14	6	84	8	112
Redistribute delay/ demand	6	4	24	5	30	6	36
Defer capital improvement	6	1	6	2	12	3	18
Provide traffic operation surv.	11	0	0	0	0	10	110
Improve accident/ incident response	7	0	0	0	0	8	56
Facilitate data collection	14	0	0	2	28	9	126
Provide equipment surveillance	13	0	0	0	0	10	130
Provide driver information	7	0	0	0	0	10	70
Coordination w/ corridor signals	13	0	0	0	0	10	130
TOTAL UTILITY OF SUBGOALS			89		226		869
GOAL WEIGHT			.23		.23		.23
GOAL UTILITY			20		52		200

* Subgoal weight times subgoal rating

TABLE E-32

GOAL 6 UTILITY RATINGS—OPERATIONAL EFFICIENCY

SUBGOAL	SUBGOAL	PRETIMED		LOCAL ACTUATED		SYSTEM	
	WEIGHT	RATING	UTILITY*	RATING	UTILITY*	RATING	UTILITY*
Responsiveness to flow instability	16	0	0	8	128	10	160
Responsiveness to incidents	14	0	0	7	98	10	140
Variation of peak start/end times	14	0	0	10	140	10	140
Responsiveness to fluctuating demand	8	0	0	9	72	10	80
Adjustment of metering rates	27	4	108	8	216	10	270
Responsiveness to pattern changes	21	0	0	7	147	10	210
TOTAL UTILITY OF SUBGOALS			108		801		1000
GOAL WEIGHT			.23		.23		.23
GOAL UTILITY			25		184		230

* Subgoal weight times subgoal rating

TABLE E-33

EXAMPLE FREEWAY UTILITY BY CONTROL MODE

GOAL	CONTROL MODE		
	PRETIMED	LOCAL ACTUATED	SYSTEM
1. TRAFFIC OPERATIONS	193	261	295
2. SAFETY	6	13	19
3. IMPLEMENTATION	18	16	10
4. OPERATING FACTORS	126	117	61
5. FREEWAY MANAGEMENT	20	52	200
6. OPERATIONAL EFFICIENCY	25	184	230
TOTAL UTILITY VALUES	388	643	815

TABLE E-34

EXAMPLE FREEWAY COST AND UTILITY SUMMARY BY CONTROL MODE

	COST*	PRESENT WORTH**	UTILITY	UTILITY/ COST (Relative)
PRETIMED	208,000	80,193	388	.48
LOCAL ACTUATED	280,000	107,952	643	.60
SYSTEM	640,000	246,748	815	.33

*Ten year cost including maintenance and operation, from Table E-8.

**Ten year period at 10%.

TABLE E-35

EXAMPLE FREEWAY INCREMENTAL COST AND UTILITY SUMMARY

	INCREMENTAL COST	INCREMENTAL UTILITY	INCREMENTAL UTILITY/COST RATIO (Relative)
PRETIMED TO LOCAL ACTUATED	27,759	255	.92
PRETIMED TO SYSTEM	166,555	427	.26

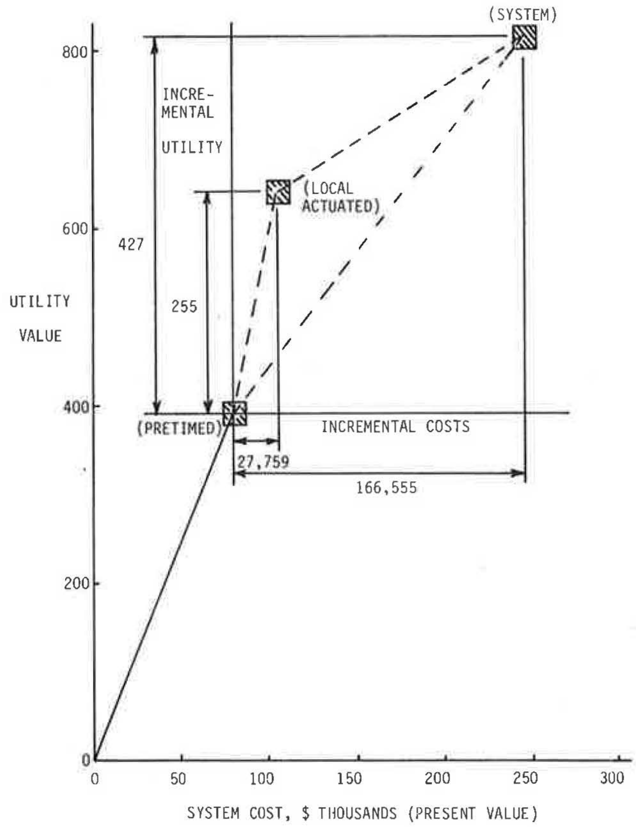


Figure E-32. Example freeway utility cost comparisons by control mode.

CHAPTER 11

PROCEDURE FOR ESTIMATING INCREMENTAL FUEL-CONSUMPTION BENEFITS

INCIDENT PEAK PERIODS

Figure E-33 provides a graph that can be used to estimate the fuel-consumption benefits produced by responsive control during an incident peak period. One will note from this figure that these benefits are very minor and can actually be negative (disbenefits) for a low level of controllability. Thus, it is recommended that no incremental fuel-consumption benefits be estimated for this type of peak period.

SYSTEM REDUCTION PEAK PERIODS

Figure E-34 provides a graph that can be used to estimate the annual incremental fuel-consumption benefits from responsive control for system reduction peak periods.

Example—System Reduction Peak Periods. In the example freeway used, there were no system reduction peak periods. Thus, no estimate of incremental benefits will be made for this type of peak period.

INCIDENT PLUS SYSTEM REDUCTION

Figure E-35 provides a graph that can be used to estimate the annual incremental fuel-consumption benefits for incident plus system reduction peak periods.

Example—Incident Plus System Reduction. The example freeway has 20 incident plus system reduction peak periods annually. Also the example freeway has a total fuel consumption of 1251.7 gal in a nominal peak period, a controllability index of 1.22, and 1.00 incidents per peak period. Figure E-35 indicates for each incident plus system reduction there is an average 0.7 percent incremental benefit for local actuated control and a 1.3 percent incremental benefit for system control. The annual fuel-consumption benefits for either mode are thus estimated as follows:

$$\begin{aligned}\begin{array}{l}\text{Incremental benefits}\\ \text{local actuated control}\end{array} &= (20)\ (1487.2)\ (1.00)\ (0.007)\\ &= 208 \text{ gal per year}\end{aligned}$$

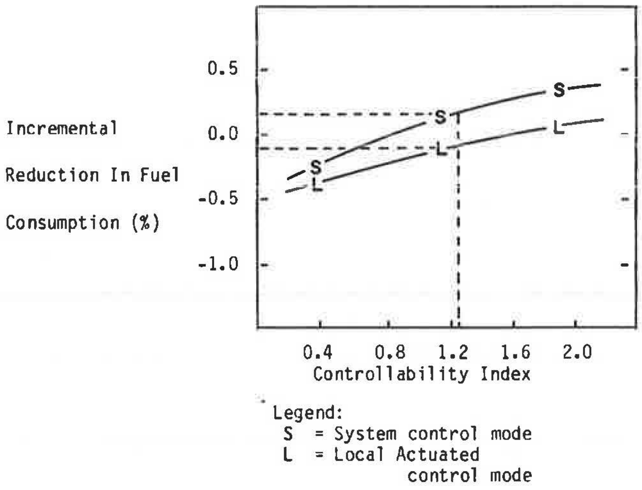


Figure E-33. Incremental reduction in fuel consumption—incident peak period.

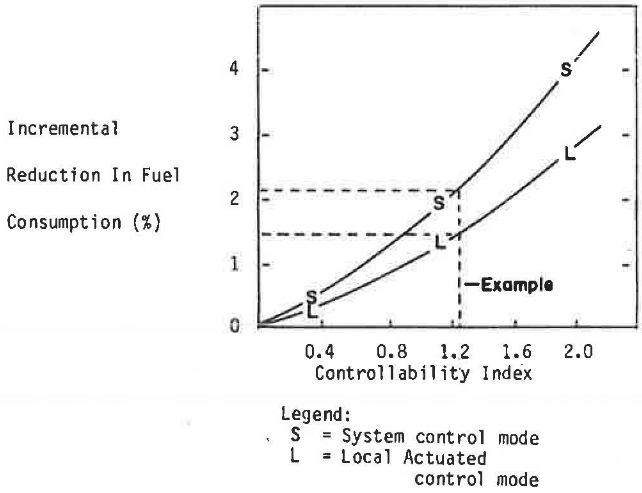


Figure E-34. Incremental reduction in fuel consumption—system reduction peak period.

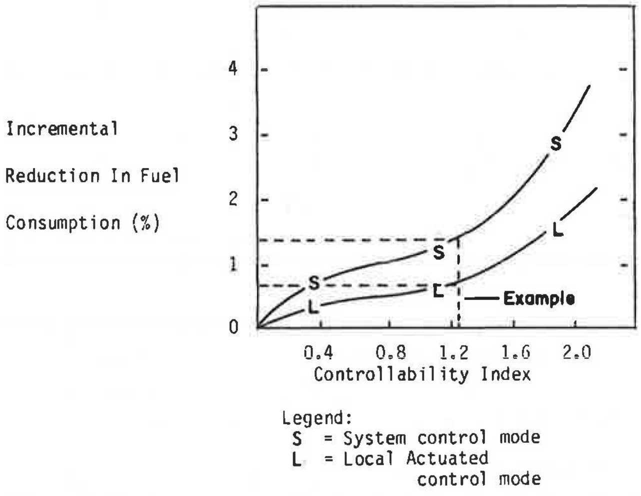


Figure E-35. Incremental reduction in fuel consumption—incident plus system reduction peak period.

Incremental benefits system control = (20) (1487.2) (1.00) (0.013)

= 387 gal per year

DEMAND INCREASE/DECREASE

Figure E-36 provides a graph that can be used to estimate the annual benefits for demand increase peak periods. One will note that these benefits are negative, leading to the conclusion that there will actually be increased fuel consumption with the responsive modes.

Figure E-37 provides a graph that can be used to estimate the annual benefits for demand decrease peak periods. These benefits roughly offset the disbenefits that result from a demand increase peak period. Because there will usually be as many demand increase peak periods as demand decrease peak periods, these benefits/disbenefits offset each other and so are eliminated from consideration.

FLUCTUATING DEMAND

Figure E-38 provides a graph that can be used to estimate the annual benefits for fluctuating demand peak periods.

Example—Fluctuating Demand. In the example freeway, every peak period when control is used is expected to have a fluctuating demand. Thus, 250 peak periods per year will be used. Figure E-38 indicates a 0.05 percent incremental benefit for either mode of control. The annual benefits for either mode are thus as follows:

Annual benefits—reduced fuel consumption (local actuated or system) = (250) (1487.2) (0.005)

= 1859 gal per year

TOTAL ANNUAL FUEL-CONSUMPTION BENEFIT—ALL PEAK TYPES

The total annual incremental fuel-consumption benefit of each responsive control mode can be estimated by summing the benefits estimated for each of the peak types.

Example—Total Benefits. Table E-36 summarizes the fuel-consumption benefits from responsive control for the various peak types.

TABLE E-36

ANNUAL INCREMENTAL FUEL-CONSUMPTION BENEFITS OF RESPONSIVE CONTROL MODES—EXAMPLE FREEWAY

	Annual Incremental Benefits (gal)	
Peak Period Types	Local Actuated Control	System Control
1. Incident	-	-
2. System Reduction	0	0
3. Incident Plus System Reduction	208	387
4. Demand Increase	-	-
5. Demand Decrease	-	-
6. Fluctuating Demand	1859	1859
Annual Totals:	2067	2246

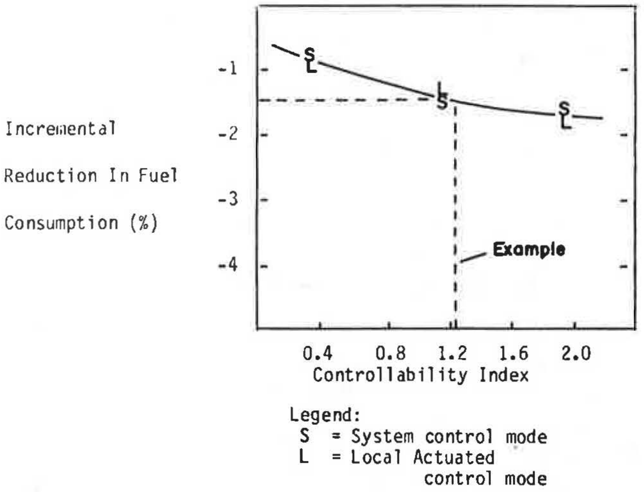


Figure E-36. Incremental reduction in fuel consumption—demand increase.

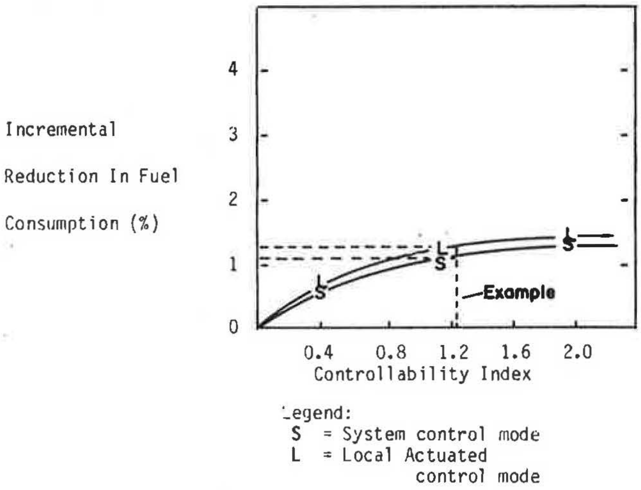


Figure E-37. Incremental reduction in fuel consumption—demand decrease.

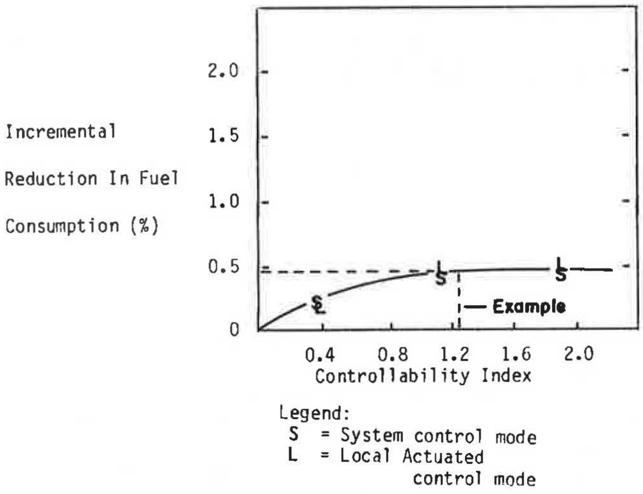


Figure E-38. Incremental reduction in fuel consumption—fluctuating demand.

CHAPTER 12

PROCEDURE FOR ESTIMATING INCREMENTAL VEHICLE EMISSIONS BENEFITS

INCIDENT PEAK PERIODS

Figures E-39, E-40, and E-41 provide graphs that can be used to estimate the annual benefits of responsive control during incident peak periods. Note that separate graphs are provided for hydrocarbon (HC), carbon dioxide (CO), and nitrogen oxide (NO_x) emissions. Note also that one may encounter negative benefits (or disbenefits). This is especially true for NO_x emissions which are increased by the use of responsive control.

Example—Incident Peak Periods. Using the example freeway with a controllability index of 1.22, the percent benefits for emissions during incident peak periods are given in Table E-37.

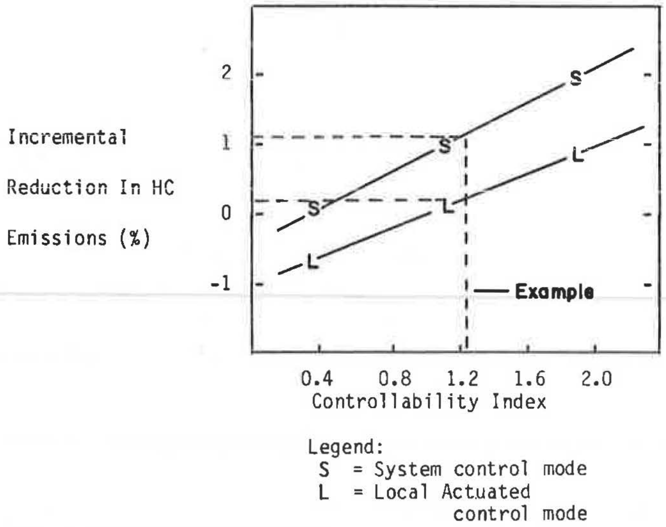


Figure E-39. Incremental reduction in HC emissions—incident peak period.

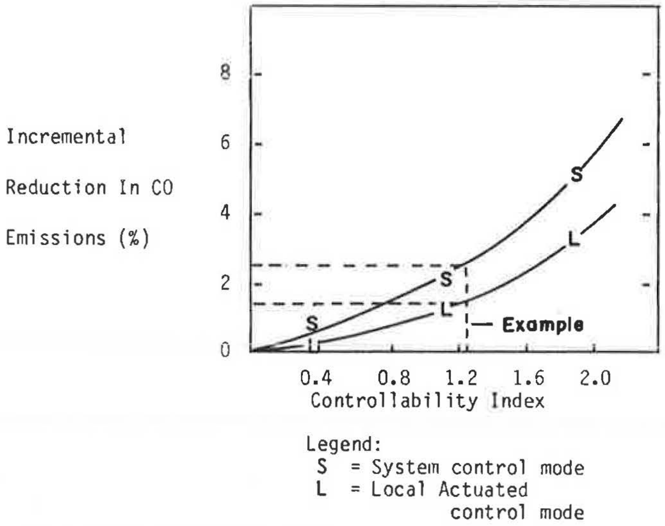


Figure E-40. Incremental reduction in CO emissions—incident peak period.

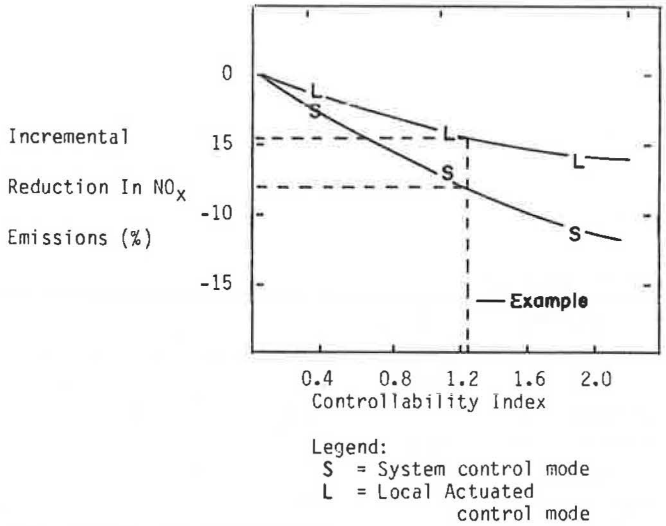


Figure E-41. Incremental reduction in NO_x emissions—incident peak period.

The example freeway has 82 incident peak periods per year and the nominal peak period emissions are HC: 80 kg, CO: 772 kg, and NO_x: 127 kg. The annual benefits can be calculated as follows:

$$HC = (85)\ (80)\ (0.002) = 13.6 \text{ kg annually}$$

Using this procedure, estimates for each emission component are made and the results are given in Table E-38.

SYSTEM REDUCTION PEAK PERIODS

Figures E-42, E-43, and E-44 provide graphs that can be used to estimate the emission benefits of responsive control during a system reduction peak period.

Example—System Reduction Peak Periods. The example freeway has no periods of this type and thus these benefits are not estimated.

INCIDENT PLUS SYSTEM REDUCTION

Figures E-45, E-46, and E-47 provide graphs that can be used to estimate the emission benefits of responsive control during an incident plus system reduction peak period.

Example—Incident Plus System Reduction. The graphs in Figures E-45, E-46, and E-47 can be used to obtain the values given in Table E-39.

TABLE E-37

EXAMPLE FREEWAY EMISSIONS PERCENT INCREMENTAL BENEFITS—INCIDENT PEAK PERIODS

	Percent Incremental Benefits	
Emissions Component	Local Actuated Control	System Control
HC	0.2	1.1
CO	1.3	2.4
NO_x	-4.9	8.0

TABLE E-38

EXAMPLE FREEWAY EMISSIONS ANNUAL INCREMENTAL BENEFITS—INCIDENT PEAK PERIODS

	Annual Incremental Benefits(kg)	
Emissions Component	Local Actuated Control	System Control
HC	13.6	74.8
CO	853.0	1574.9
NO_x	-528.9	-863.6

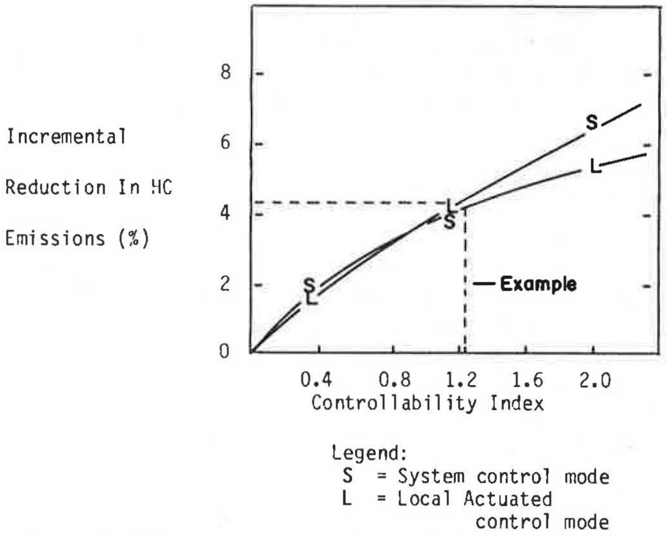


Figure E-42. Incremental reduction in HC emissions—system reduction peak period.

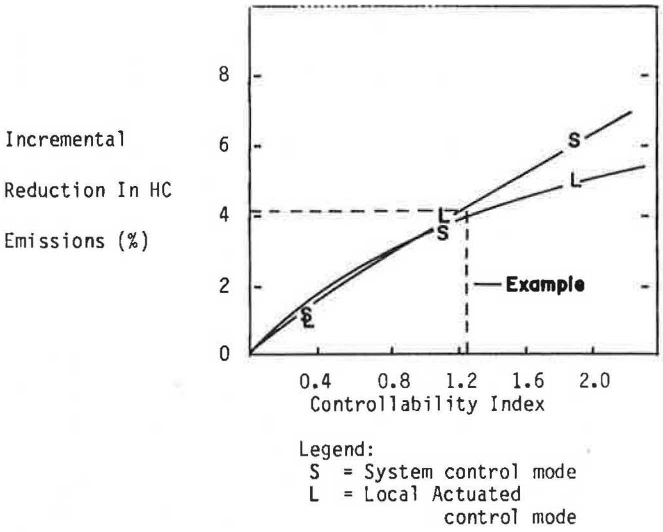


Figure E-45. Incremental reduction in HC emissions—incident plus system reduction.

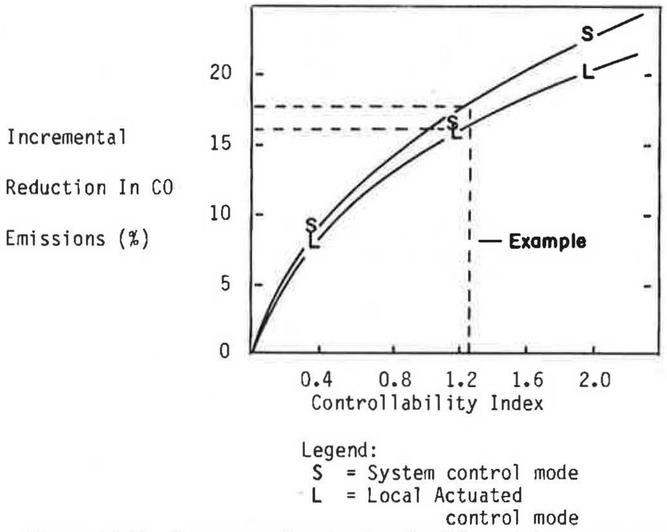


Figure E-43. Incremental reduction in CO emissions—system reduction peak period.

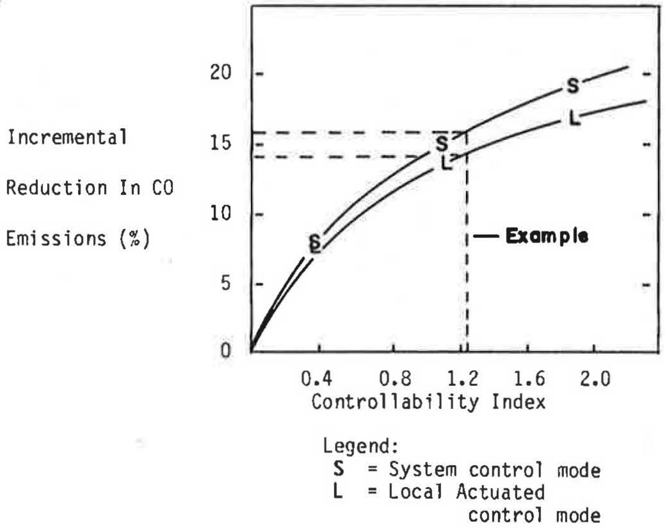


Figure E-46. Incremental reduction in CO emissions—incident plus system reduction.

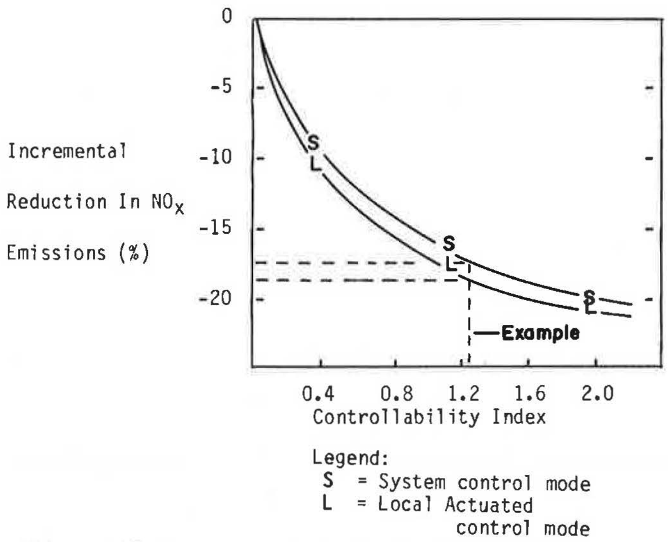


Figure E-44. Incremental reduction in NO_x emissions—system reduction peak period.

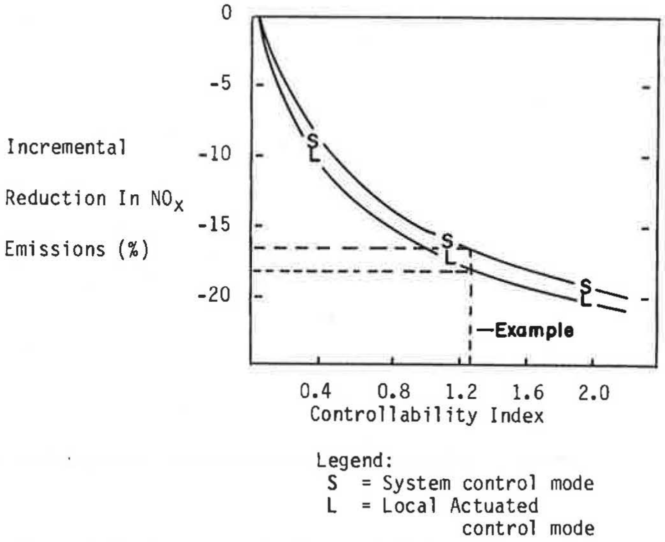


Figure E-47. Incremental reduction in NO_x emissions—incident plus system reduction.

The example freeway has 20 incident plus system reduction peak periods per year with 1.00 incidents per peak period. The annual incremental benefits are calculated as follows:

$$HC = (80)\ (20)\ (1.00)\ (0.039) = 62.4 \text{ kg annually (local actuated)}$$

Using this computational procedure, the annual incremental benefits were estimated as given in Table E-40.

DEMAND INCREASE

Figures E-48, E-49, and E-50 provide graphs that can be used to estimate the annual emission benefits from the use of responsive control during demand increase peak periods.

Example—Demand Increase. The example freeway has 83 demand increase peak periods per year. The percent incremental benefits are given in Table E-41. Annual incremental benefits were estimated as given in Table E-42.

DEMAND DECREASE

Figures E-51, E-52, and E-53 provide graphs that can be used to estimate the annual emission benefits from the use of responsive control during demand decrease peak periods.

Example—Demand Decrease. The example freeway has 83 demand decrease peak periods per year. Using Figures E-51, E-52, and E-53 with the basic computational procedure, emission benefits were estimated as given in Table E-43.

FLUCTUATING DEMAND

Figures E-54, E-55, and E-56 provide graphs that can be used to estimate the annual emission benefits for the use of responsive control during fluctuating demand peak periods.

Example—Fluctuating Demand. For the example freeway, it is estimated that every peak period in which control is used will also be a fluctuating demand peak period. Thus, there are 250 such periods per year. Using Figures E-54, E-55, and E-56, emissions benefits were estimated as given in Table E-44.

TOTAL ANNUAL VEHICLE EMISSIONS BENEFITS

The total annual vehicle emission benefits are the sum of the benefits resulting from the use of responsive control during each of the peak period types.

Example—Total Benefits. Table E-45 summarizes the emission benefits for the example freeway:

TABLE E-39

EXAMPLE FREEWAY EMISSIONS PERCENT INCREMENTAL BENEFITS—INCIDENT PLUS SYSTEM REDUCTION

	Percent Incremental Benefits	
Emissions Component	Local Actuated Control	System Control
HC	3.9	4.1
CO	14.0	15.9
NO_x	-18.0	-16.5

TABLE E-40

EXAMPLE FREEWAY EMISSIONS ANNUAL INCREMENTAL BENEFITS—INCIDENT PLUS SYSTEM REDUCTION

	Annual Incremental Benefits(kg)	
Emissions Component	Local Actuated Control	Systems Control
HC	62.4	65.6
CO	2161.6	2455.0
NO_x	-457.2	-419.1

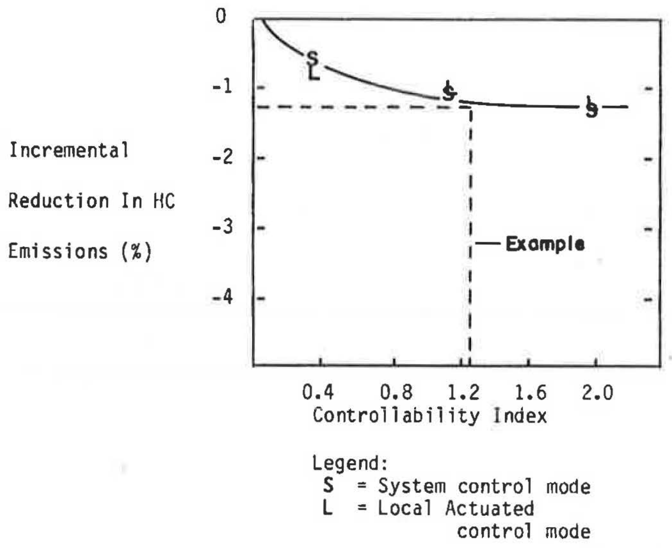


Figure E-48. Incremental reduction in HC emissions—demand increase.

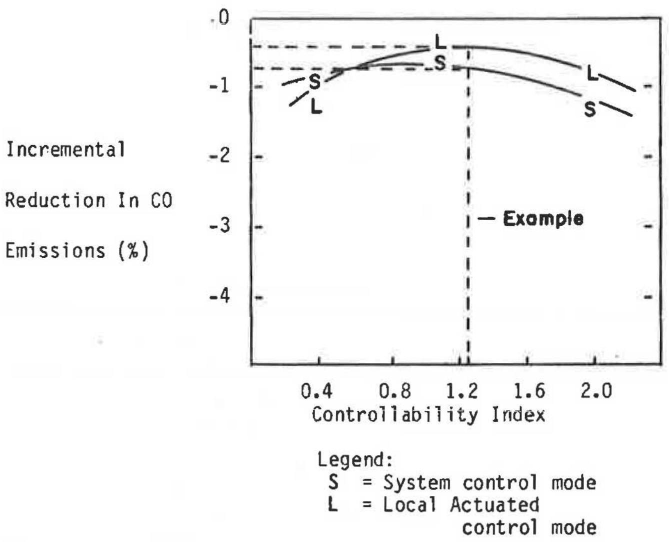


Figure E-49. Incremental reduction in CO emissions—demand increase.

TABLE E-41

EXAMPLE FREEWAY PERCENT INCREMENTAL BENEFITS—DEMAND INCREASE

	Percent Incremental Benefits	
Emissions Component	Local Actuated Control	Systems Control
HC	-1.3	-1.3
CO	-0.5	-0.9
NO_x	-5.5	-5.0

TABLE E-42

EXAMPLE FREEWAY ANNUAL INCREMENTAL BENEFITS—DEMAND INCREASE

	Annual Incremental Benefits(kg)	
Emissions Component	Local Actuated Control	System Control
HC	-86.3	-86.3
CO	-320.4	-576.7
NO_x	-579.8	-527.1

TABLE E-43

EXAMPLE FREEWAY INCREMENTAL BENEFITS—DEMAND DECREASE

	Percent Incremental Benefits	
Emissions Component	Local Actuated Control	Systems Control
HC	1.6	1.4
CO	2.5	1.8
NO_x	1.0	2.5
	Annual Incremental Benefits(kg)	
Emissions Component	Local Actuated Control	System Control
HC	126.2	93.0
CO	1601.9	1153.4
NO_x	105.4	263.5

TABLE E-44

EXAMPLE FREEWAY INCREMENTAL BENEFITS—FLUCTUATING DEMAND

	Percent Incremental Benefits	
Emissions Component	Local Actuated Control	System Control
HC	0.4	0.4
CO	0.5	0.4
NO_x	0.5	0.6
	Annual Incremental Benefits(kg)	
Emissions Component	Local Actuated Control	System Control
HC	80.	80.
CO	965.	772.
NO_x	158.8	190.5

TABLE E-45

ANNUAL INCREMENTAL EMISSION BENEFITS OF RESPONSIVE CONTROL MODES—EXAMPLE FREEWAY

	ANNUAL INCREMENTAL BENEFITS (KG)					
	Local Actuated Control			System Control		
Peak Period Types	HC	CO	NO_x	HC	CO	NO_x
Incident	13.6	853.0	-528.9	74.8	1574.9	-863.6
System Reduction	-	-	-	-	-	-
Incident Plus System Reduction	62.4	2161.6	-457.2	65.6	2455.0	-419.1
Demand Increase	-86.3	-320.4	-579.8	-86.3	-576.7	-527.1
Fluctuating Demand	80.0	965.0	158.8	80.0	772.0	190.5
Annual Totals	69.7	3659.2	-1407.1	134.1	4225.2	-1619.3

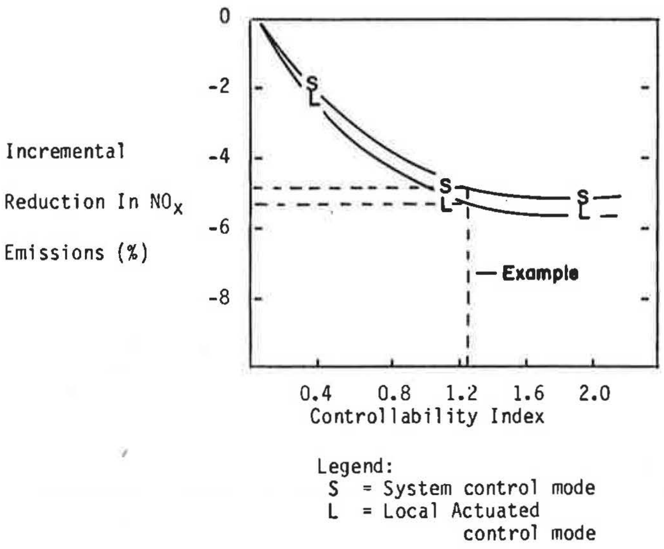


Figure E-50. Incremental reduction in NO_x emissions—demand increase.

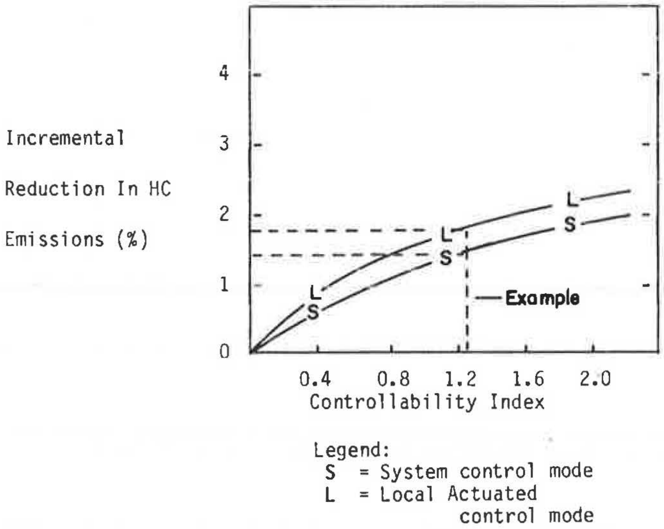


Figure E-51. Incremental reduction in HC emissions—demand decrease.

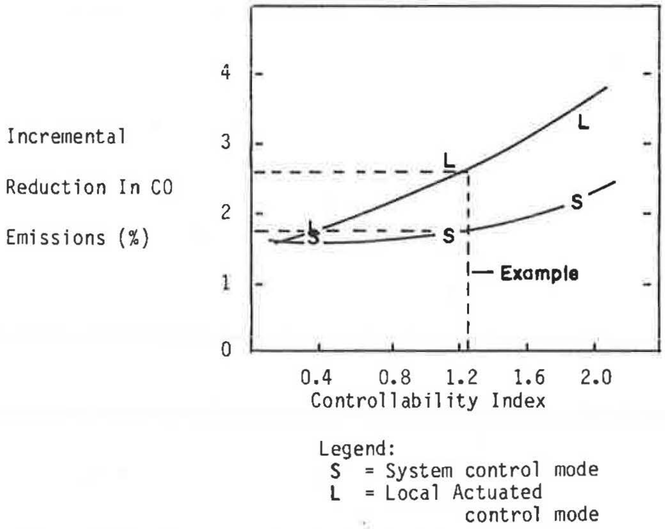


Figure E-52. Incremental reduction in CO emissions—demand decrease.

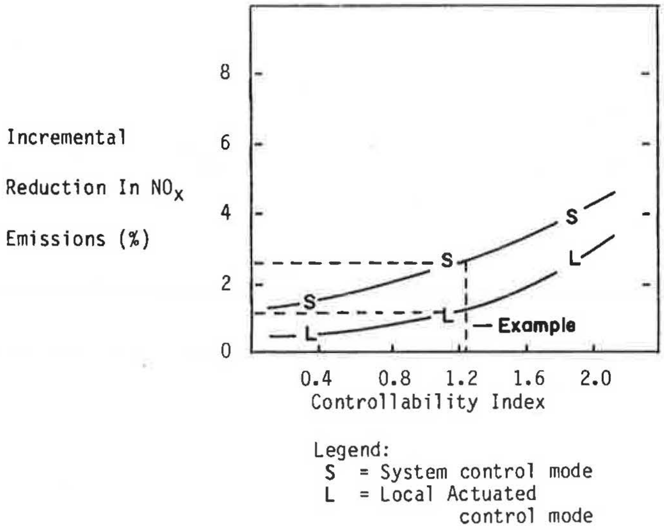


Figure E-53. Incremental reduction in NO_x emissions—demand decrease.

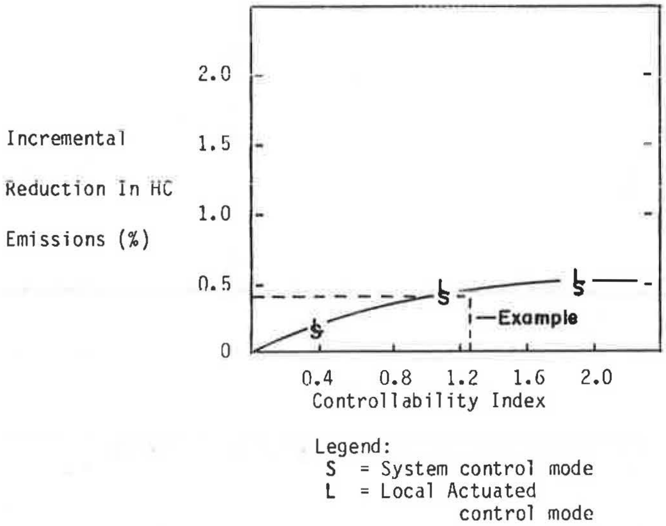


Figure E-54. Incremental reduction in HC emissions—fluctuating demand.

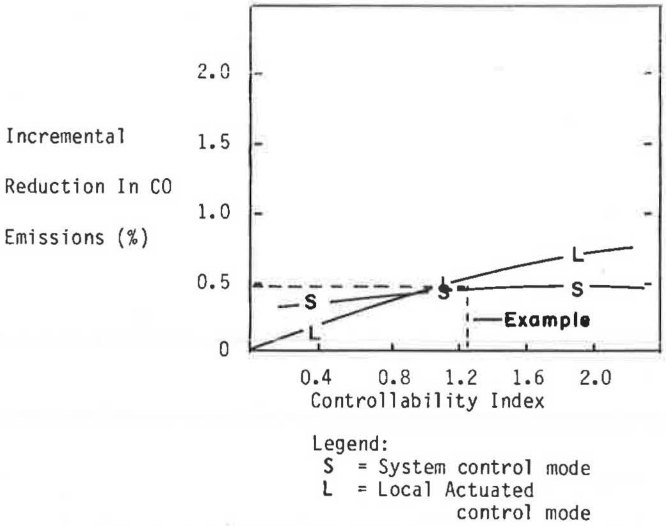


Figure E-55. Incremental reduction in CO emissions—fluctuating demand.

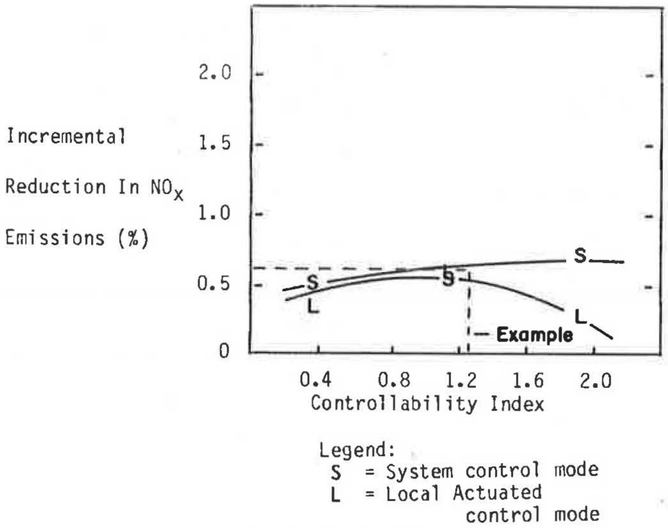


Figure E-56. Incremental reduction in NO_x emissions—fluctuating demand.

CHAPTER 13

VARIOUS TABLES

Tables E-46 through E-70 provide additional information that should facilitate use of these guidelines. For convenience of the user they are listed by title as follows:

TABLE E-46

VEHICLE TYPES

Vehicle Type Number	Vehicle Type Description
1	Automobiles, pickups, and panel trucks (2-axle, 4-tire)
2	Single-unit trucks (other than 2-axle, 4-tire)
3	Truck-tractor-semitrailer or trailer combinations
4	Buses

TABLE E-47

VALUE OF TIME BY VEHICLE TYPE AND DRIVING MODE[a]

Vehicle	In Moving Vehicle[a]		In Stopped Vehicle[b]	
Type	Driver	Passenger	Driver	Passenger
	- - - - - - - -Dollars Per Hour-		- - - - - - -	
1	6.31	6.31	9.47	9.47
2	11.72	6.31	18.21	9.47
3	16.36	6.31	24.54	9.47
4	17.66	6.31	26.49	9.47

[a] Update of values of time reported by Buffington and McFarland in Texas Transportation Institute Research Report 202-2 (E-20) to January 1980.

[b] Represents 1.5 times the in vehicle values of time, and is based on waiting data reported in the 1977 AASHTO Redbook (E-1).

TABLE E-48

RUNNING COSTS FOR VEHICLE TYPE 1 ON FREEWAYS, BY LEVEL OF SERVICE AND AVERAGE SPEED[a]

	LEVEL OF SERVICE					
Average Speed	A	B	C	D	E	F
Miles Per Hour[b]	- - - - - - Cents Per Vehicle Mile- - - - - -					
5						40.693
10						23.010
15						17.360
20						14.725
25						13.189
30					9.571	12.413
35				9.512	9.708	9.758
40			9.694	9.787	9.977	
45		9.713	10.033	10.200	10.537	
50	9.706	10.056	10.451	10.770		
55	10.647	10.504	11.077			
60	10.563	11.081				
65	11.268					

[a] Update of costs reported by Buffington and McFarland in Texas Transportation Institute Research Report 202-2(E-20) to January 1980.

[b] To convert from miles per hour to kilometers per hour, multiply by 1.609344.

[c] To convert from cents per mile to cents per kilometer, multiply by 0.6214.

TABLE E-49

RUNNING COSTS FOR VEHICLE TYPES 2 AND 4 ON FREEWAYS, BY LEVEL OF SERVICE AND AVERAGE SPEED[a]

	LEVEL OF SERVICE					
Average Speed	A	B	C	D	E	F
Miles Per Hour[b]	- - - - - - Cents Per Vehicle Mile[c]- - - - - -					
5						113.307
10						57.891
15						41.223
20						33.982
25						30.653
30					21.362	28.945
35				22.413	22.970	23.652
40			23.208	23.512	24.359	
45		23.834	24.596	25.087	25.809	
50	24.956	25.239	26.238	27.067		
55	25.883	27.067	23.388			
60	27.812	29.065				
65	30.081					

[a] Update of costs reported by Buffington and McFarland in Texas Transportation Institute Research Report 202-2(E-20) to January 1980.

[b] To convert from miles per hour to kilometers per hour, multiply by 1.609344.

[c] To convert from cents per mile to cents per kilometer, multiply by 0.6214.

TABLE E-50

RUNNING COSTS FOR VEHICLE TYPE 3 ON FREEWAYS, BY LEVEL OF SERVICE AND RUNNING SPEED[a]

	LEVEL OF SERVICE					
Average Speed	A	B	C	D	E	F
Miles Per Hour[b]	- - - - - - Cents Per Vehicle Mile[c]- - - - - -					
5						306.167
10						132.349
15						84.947
20						65.049
25						56.442
30					31.980	49.898
35				32.305	33.366	34.730
40			33.594	34.415	36.177	
45		35.301	36.668	37.685	38.185	
50	37.711	38.402	40.294	41.845		
55	40.299	42.651	45.283			
60	44.472	46.901				
65	49.283					

[a] Update of costs reported by Buffington and McFarland in Texas Transportation Institute Research Report 202-2(E-20) to January 1980.

[b] To convert from miles per hour to kilometers per hour, multiply by 1.609344.

[c] To convert from cents per mile to cents per kilometer, multiply by 0.6214.

TABLE E-51

DERIVATION OF ACCIDENT COST PER VEHICLE-MILE

1. From Table A-25, an accident rate of 2.6 accidents per million vehicle-miles is noted for a 6-lane freeway.
2. The following percentage distribution by accident severity is used (E-2):

.4% - Fatal
14.6% - Injury
85.0% - Property Damage Only.

3. From Table A-24, the unit costs per reported accident by severity are

\$446,503 - Fatal
\$ 21,551 - Injury
\$ 904 - Property Damage Only.

4. Thus, the average accident cost is

= [\$446,503(.004) + \$21,551(.146) + \$904(.85)]
= \$1786 + \$3146 + \$768
= \$5700.

5. The average accident cost per vehicle mile at a rate of 2.6 accidents/MVM is

$$= (2.6)\ \frac{\$5700}{1,000,000}$$

= \$.01482.

TABLE E-52

IDLING COSTS, BY TYPE OF VEHICLE [a]

Vehicle Type	Idling Costs
	Cents Per Hour
1	37.540
2 & 4	78.214
3	80.218

[a] Update of Costs reported by Buffington and McFarland in Texas Transportation Institute Research Report 202-2(E-20) to January 1980.

TABLE E-53

RUNNING COSTS ON CITY STREETS, BY VEHICLE TYPE AND UNIFORM SPEED [a]

Uniform Speed	Vehicle Type		
	1	2 & 4	3
Miles Per Hour[b]	Cents Per Vehicle Mile[c]		
5	19.202	36.497	66.960
10	14.556	28.608	46.590
15	12.866	25.627	39.345
20	12.022	24.275	36.051
25	11.534	23.834	34.718
30	11.292	23.969	34.581
35	11.276	24.528	35.273
40	11.345	25.357	36.896
45	11.544	26.458	39.073
50	11.858	27.829	41.951

[a] Update of Costs reported by Buffington and McFarland in Texas Transportation Institute Research Report 202-2(E-20) to January 1980.

[b] To convert from miles per hour to kilometers per hour, multiply by 1.609344.

[c] To convert from cents per mile to cents per kilometer, multiply by 0.6214.

TABLE E-54

EXCESS RUNNING COSTS OF SPEED CYCLE CHANGES ON CITY STREETS FOR VEHICLE TYPE 1, BY INITIAL SPEED [a]

Initial Speed	Speed Reduced to and Returned From (MPH)				
	Stop	10	20	30	40
Miles Per Hour[b]	Cents Per Cycle Change				
5	0.250				
10	0.545				
15	0.956	0.353			
20	1.457	0.768			
25	2.031	1.355	0.516		
30	2.738	2.032	1.178		
35	3.580	2.886	2.017	0.794	
40	4.611	3.888	3.003	1.795	
45	5.864	5.125	4.211	3.001	1.191
50	7.453	6.627	5.681	4.442	2.616

[a] Update of Costs reported by Buffington and McFarland in Texas Transportation Institute Research Report 202-2(E-20) to January 1980.

[b] To convert from miles per hour to kilometers per hour, multiply by 1.609344.

TABLE E-55

EXCESS RUNNING COSTS OF SPEED CYCLE CHANGES ON CITY STREETS FOR VEHICLE TYPES 2 & 4, BY INITIAL SPEED [a]

Initial Speed	Speed Reduced to and Returned From (MPH)				
	Stop	10	20	30	40
Miles Per Hour[b]	Cents Per Cycle Change				
5	0.680				
10	1.668				
15	2.930	1.036			
20	4.420	2.440			
25	6.232	4.145	1.602		
30	8.369	6.232	3.627		
35	10.927	8.758	6.119	2.395	
40	14.051	11.833	9.098	5.358	
45	17.775	15.492	12.708	8.904	3.545
50	22.227	19.879	17.014	13.161	7.754

[a] Update of Costs reported by Buffington and McFarland in Texas Transportation Institute Research Report 202-2(E-20) to January 1980.

[b] To convert from miles per hour to kilometers per hour, multiply by 1.609344.

TABLE E-56

EXCESS RUNNING COSTS OF SPEED CYCLE CHANGES ON CITY STREETS FOR VEHICLE TYPE 3, BY INITIAL SPEED[a]

Initial Speed	Speed Reduced to and Returned From (MPH) Stop	10	20	30	40
Miles Per Hour[b]	------------Cents Per Cycle Change----------				
5	3.001				
10	6.822				
15	11.256	6.576			
20	17.151	11.601			
25	24.456	17.208	7.038		
30	33.491	26.075	15.789		
35	44.599	37.019	26.598	10.847	
40	65.305	50.630	39.955	24.129	
45	75.125	67.157	56.342	40.209	16.371
50	95.601	87.425	76.325	60.093	35.965

[a] Update of Costs reported by Buffington and McFarland in Texas Transportation Institute Research Report 202-2(E-20) to January 1980.

[b] To convert from miles per hour to kilometers per hour, multiply by 1.609344.

TABLE E-57

FUEL CONSUMPTION RATES FOR VEHICLE TYPE 1 ON FREEWAYS, BY LEVEL OF SERVICE AND AVERAGE SPEED[a]

Average Speed	LEVEL OF SERVICE A	B	C	D	E	F
Miles Per Hour[b]	- - - - - - Gallons Per Vehicle Mile[c] - - - - - -					
5						.3970
10						.1649
15						.1028
20						.0772
25						.0641
30					.0433	.0574
35				.0420	.0428	.0431
40			.0426	.0429	.0444	
45		.0427	.0443	.0450	.0465	
50	.0438	.0454	.0471	.0486		
55	.0468	.0489	.0512			
60	.0494	.0519				
65	.0567					

[a] Based on proportion of fuel cost to total cost at various speeds as reported in the 1977 AASHTO Redbook(E-1) and applied to total costs as reported in the Texas Transportation Research Institute Report 202-2 (E-20) for vehicle types 1 and 2 in .97 and .03 proportions, and then converted to fuel consumption rates by using the appropriate cost per gallon. The fuel costs of the latter report were originally based on the fuel consumption rates reported in NCHRP Report 111, Highway Research Board, 1971 by Paul Claffey and Associates and in Reference (E-12).

[b] To convert from miles per hour to kilometers per hour, multiply by 1.609344.

[c] To convert from gallons per mile to liters per kilometer, multiply by 2.351.

TABLE E-58

FUEL CONSUMPTION RATES FOR VEHICLE TYPES 2 & 4 ON FREEWAYS, BY LEVEL OF SERVICE AND AVERAGE SPEED[a]

Average Speed	LEVEL OF SERVICE A	B	C	D	E	F
Miles Per Hour[b]	- - - - - - Gallons Per Vehicle Mile[c] - - - - - -					
5						.6765
10						.3491
15						.2249
20						.1772
25						.1635
30					.1139	.1577
35				.1250	.1281	.1319
40			.1329	.1346	.1395	
45		.1412	.1457	.1486	.1528	
50	.1486	.1542	.1603	.1634		
55	.1613	.1687	.1769			
60	.1782	.1862				
65						

[a] Based on Fuel Consumption rates and fuel costs as a proportion of total costs as reported in the 1977 AASHTO Redbook(E-1) and on total costs reported by Buffington and McFarland in Texas Transportation Research Report 202(E-20) for Vehicle Types 3 and 6.

[b] To convert from miles per hour to kilometers per hour, multiply by 1.609344.

[c] To convert from gallons per mile to liters per kilometer, multiply by 2.351.

TABLE E-59

FUEL CONSUMPTION RATES FOR VEHICLE TYPE 3 ON FREEWAYS, BY LEVEL OF SERVICE AND AVERAGE SPEED[a]

Average Speed	LEVEL OF SERVICE A	B	C	D	E	F
Miles Per Hour[b]	- - - - - - Gallons Per Vehicle Mile[c] - - - -					
5						3.1346
10						1.5550
15						.5660
20						.3786
25						.2963
30					.1567	.2445
35				.1503	.1552	.1613
40			.1529	.1566	.1646	
45		.1613	.1676	.1722	.1745	
50	.1778	.1860	.1951	.2026		
55	.1928	.2041	.2167			
60	.2017	.2128				
65	.2208					

[a] Based on Fuel Consumption rates and fuel costs as a proportion of total costs as reported in the 1977 AASHTO Redbook(E-1) and on total costs reported by Buffington and McFarland in Texas Transportation Research Report 202(E-20) after combining vehicle types 4 and 5 in .26 and .74 proportions, respectively.

[b] To convert from miles per hour to kilometers per hour, multiply by 1.609344.

[c] To convert from gallons per mile to liters per kilometer, multiply by 2.351.

TABLE E-60

IDLING FUEL CONSUMPTION, BY VEHICLE TYPE[a]

Vehicle Type	Idling Fuel Consumption Rate
	Gallons Per Hour(E-12)
1	.370
2 & 4	.650
3	.400

[a] To convert gallons per hour to liters per hour, multiply by 3.7854.

TABLE E-61

FUEL CONSUMPTION RATES ON CITY STREETS, BY VEHICLE TYPE AND UNIFORM SPEED

Uniform Speed	Vehicle Type		
	Type 1	Types 2&4	Type 3
Miles Per Hour[b]	------Gallons Per Mile[c]-----		
5	.1025	.1096	.5099
10	.0634	.1273	.2648
15	.0511	.1075	.1861
20	.0460	.0988	.1558
25	.0436	.0947	.1300
30	.0429	.0932	.1205
35	.0434	.0936	.1125
40	.0449	.0954	.1195
45	.0460	.0988	.1271
50	.0499	.1040	.1452

[a] Fuel consumption rates are based on those reported in Reference(E-12). Passenger cars and commercial vehicles, in proportions of .97 and .03 respectively, make up Type 1 vehicles. The 2-S2 gasoline trucks and 3-S2 diesel trucks, in proportions of .26 and .74 respectively, make up Type 3 vehicles.

[b] To convert miles per hour to kilometers per hour, multiply by 1.609344.

[c] To convert gallons per mile to liters per kilometer, multiply by 2.351.

TABLE E-62

EXCESS FUEL CONSUMPTION RATES FOR SPEED CYCLE CHANGES OF VEHICLE TYPE 1 ON CITY STREETS, BY INITIAL SPEED

	Speed Reduced to and Returned From (MPH)				
Initial Speed	Stop	10	20	30	40
Miles Per Hour[a]	------------Gallons Per Cycle Change[bc]-----				
5	.00025				
10	.00101				
15	.00268	.00078			
20	.000438	.00202			
25	.00613	.00378	.00135		
30	.00792	.00565	.00311		
35	.00980	.00766	.00524	.00198	
40	.01180	.00986	.00753	.00474	
45	.01399	.01228	.01005	.00750	.00277
50	.01647	.01511	.01287	.01046	.00601

[a] To convert from miles per hour to kilometers per hour, multiply by 1.609344.

[b] To convert from miles per hour to kilometers per hour, multiply by 3.7854.

[c] Fuel consumption rates are based on those reported in Reference (E-12). Passenger cars and commercial vehicles, in proportions of .97 and .03 respectively make up Type 1 vehicles.

TABLE E-63

EXCESS FUEL CONSUMPTION RATES FOR SPEED CYCLE CHANGES OF VEHICLE TYPE 2 & 4 ON CITY STREETS, BY INITIAL SPEED

	Speed Reduced to and Returned From (MPH)				
Initial Speed	Stop	10	20	30	40
Miles Per Hour[a]	------------Gallons Per Cycle Change[bc]-----				
5	-				
10	.00333				
15	.00756	.00206			
20	.01179	.00554			
25	.01602	.00972	.00333		
30	.02025	.01389	.00750		
35	.02448	.01805	.01170	.00447	
40	.02871	.02220	.01587	.00887	
45	.03294	.02635	.01989	.01300	.00508
50	.03717	.03050	.02389	.01697	.00945

[a] To convert from miles per hour to kilometers per hour, multiply by 1.609344.

[b] To convert from gallons per cycle to liters per cycle, multiply by 3.7854.

[c] Fuel consumption rates are those reported 12-kip single unit trucks in Reference (E-12).

TABLE E-64

EXCESS FUEL CONSUMPTION RATES FOR SPEED CYCLE CHANGES OF VEHICLE TYPE 3 ON CITY STREETS, BY INITIAL SPEED

	Speed Reduced to and Returned From (MPH)				
Initial Speed	Stop	10	20	30	40
Miles Per Hour[a]	------------Gallons Per Cycle Change[bc]-----				
5	.00112				
10	.00708				
15	.01735	.00722			
20	.02866	.01820			
25	.04097	.03094	.01360		
30	.05430	.04440	.02843		
35	.06860	.05865	.04349	.01929	
40	.08381	.07301	.05839	.03694	
45	.09990	.08821	.07341	.05336	.02376
50	.11682	.10429	.08867	.06916	.04312

[a] To convert from miles per hour to kilometers per hour, multiply by 1.609344.

[b] To convert from gallons per cycle to liters per cycle, multiply by 3.7854.

[c] Fuel consumption rates are based on those reported in Reference (E-12). Vehicle Type 3 rates represent gasoline trucks and 3-S2 diesel trucks combined in .26 and .74 proportions, respectively.

TABLE E-65

POLLUTION EMISSION RATES OF VEHICLE TYPE 1, BY TYPE OF POLLUTANT AND AVERAGE SPEED[a]

	Type of Pollutant		
Average Speed	Carbon Monoxide	Hydro-Carbons	Nitrogen Oxides
Miles Per Hour[b]	------------Grams Per Mile[c]-----------		
5	176.37	12.07	4.46
10	95.29	7.07	4.06
15	59.96	5.35	3.80
20	46.40	4.38	3.95
25	36.84	3.69	4.10
30	30.35	3.21	4.25
35	25.80	2.86	4.41
40	22.62	2.63	4.57
45	20.46	2.48	4.72
50	19.10	2.42	4.77
55	18.40	2.42	5.02
60	18.23	2.49	5.18

[a] Light duty gasoline automobiles and trucks are combined in .97 and .03 proportions, respectively.

[b] To convert from miles/hour to kilometers/hour, multiply by 1.609344.

[c] To convert from grams/mile to grams/kilometer, multiply by 0.6214.

TABLE E-66

POLLUTION EMISSION RATES OF VEHICLES TYPE 2 & 4, BY TYPE OF POLLUTANT AND AVERAGE SPEED[a]

	Type of Pollutant		
Average Speed	Carbon Monoxide	Hydro-Carbons	Nitrogen Oxides
Miles Per Hour[b]	------------Grams Per Mile[c]-----------		
5	572.82	54.35	11.49
10	328.02	29.63	11.03
15	237.16	24.30	10.64
20	191.42	19.65	11.00
25	159.16	16.37	11.35
30	136.32	14.05	11.70
35	120.28	12.42	12.06
40	109.32	11.31	12.41
45	102.36	10.61	12.76
50	98.72	10.25	13.11
55	98.07	10.20	13.47
60	100.37	10.45	13.82

[a] Represents heavy duty gasoline single-unit trucks and buses.

[b] To convert from miles/hour to kilometers/hour, multiply by 1.609344.

[c] To convert from grams/mile to grams/kilometer, multiply by 0.6214.

TABLE E-67

POLLUTION EMISSION RATES OF VEHICLE TYPE 3, BY TYPE OF POLLUTANT AND AVERAGE SPEED[a]

	Type of Pollutant		
Average Speed	Carbon Monoxide	Hydro-Carbons	Nitrogen Oxides
Miles Per Hour[b]	------------Grams Per Mile[c]-----------		
5	34.25	7.37	29.83
10	30.41	5.45	23.65
15	29.13	4.81	21.59
20	25.37	4.26	21.92
25	19.38	3.66	23.85
30	15.39	3.26	25.14
35	12.53	2.97	26.03
40	10.40	2.76	26.70
45	8.73	2.59	27.23
50	7.40	2.45	27.66
55	6.31	2.34	28.00
60	5.40	2.25	28.30

[a] Represents heavy duty diesel trucks and buses.

[b] To convert from miles/hour to kilometers/hour, multiply by 1.609344.

[c] To convert from grams/mile to grams/kilometer, multiply by 0.6214.

TABLE E-68

IDLING POLLUTION RATES, BY VEHICLE TYPE AND TYPE OF POLLUTANT

Vehicle Type	Type of Pollutant		
	Carbon Monoxide	Hydro-Carbons	Nitrogen Oxides
	------------Grams Per Mile--------------		
1[a]	14.74	0.83	0.12
2[b]	61.72	3.68	0.33
3[c]	00.64	0.32	1.03

[a] Based on light duty vehicles and light duty gasoline trucks combined in proportions of .97 and .03, respectively.

[b] Represents heavy duty gasoline trucks and buses and is based on the ratio of Vehicle Type 2 to Vehicle Type 1 moving vehicle emission rates.

[c] Represents heavy duty diesel trucks and buses.

TABLE E-69

MOTOR VEHICLE ACCIDENT UNIT COSTS PER REPORTED ACCIDENT

Severity of Accident	Location of Accident		
	Rural	Suburban	Urban
	-----------Dollars Per Accident[a]--------		
Fatal[b]	566,103	506,304	446,503
Injury[c]	27,709	24,630	21,551
Property Damage Only	1,264	1,084	904

[a] Based on NHTSA accident costs adjusted for location using CALTRANS accident cost data and then updated to January 1980.

[b] Includes direct accident costs and discounted gross future earnings which include future maintenance costs of the decedent.

[c] Includes direct accident costs as well as costs for pain and suffering, loss of earnings, and loss of services to home and family in partial or total disability accidents.

Source: American Association of State Highway and Transportation Officials, A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements (new Redbook), 444 North Capital Street, N.W. Suite 225, Washington, D.C., 1977.

TABLE E-70

MOTOR VEHICLE ACCIDENT RATES, BY HIGHWAY TYPE AND LOCATION OF ACCIDENT

Highway Type	Location of Accident		
	Rural	Urban	Urban Metered
	--Per Million Vehicle-Miles--		
Freeways			
4-lane	1.4	2.8	2.5
6-lane	1.3	2.6	2.3
8-lane	1.2	2.4	2.2
10-lane	1.1	2.2	2.0
12-lane	1.0	2.0	1.8
14-lane	-	1.8	1.6
16-lane	-	1.6	1.4
Expressways			
2-lane	3.0	6.0	-
4-lane	2.8	5.6	-
6-lane	2.6	5.2	-
Conventional Highways			
Undivided			
2-lane	6.0	12.0	-
4-lane	5.6	11.2	-
6-lane	5.2	10.4	-
Divided			
4-lane	2.8	-	-
6-lane	2.6	-	-

Source: Texas Department of Highways and Public Transportation, Guide to the Highway Economic Evaluation Model, Austin, Texas, February 1976.

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