COST-EFFECTIVENESS ANALYSIS OF

FREEWAY RAMP CONTROL

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The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the Bureau of Public Roads.

SUMMARY

This report is concerned with the evaluation of alternative
freeway merging control systems from a cost-effectiveness stand-
point. Alternative systems that were evaluated include: 1) Analog
Satellite System, 2) Digital Satellite System, and 3) Digital Central
Control System.

The report also provides a methodology for evaluating the cost-
effectiveness of freeway control systems. This methodology is
consistent with a multilevel system design concept. The multilevel
approach is directed towards establishing a hierarchy of control that
results not only in an efficient system but one that can be implemented
in stages. Each succeeding stage results in increased system sophisti-
cation and consequently an increase in cost. The cost-effectiveness
of each of four stages (or levels) of control has been evaluated and
is reported herein.

Because of the complexity of the freeway phenomenon and the
relevancy of a variety of measures of effectiveness to the objectives
of freeway ramp control, several measures were used to evaluate the
alternatives. The systems costs and effectiveness of the alternatives
were determined for a section of the Gulf Freeway currently under surveil-
lance and control. The effectiveness reported constitute those achieved
during the morning peak period (7-8 a.m.). The capital investment as
related to the number of ramps controlled were also investigated.

The following findings may be drawn from the evaluation presented
in this report:

1. The Analog Satellite System appears to be the preferred alternative

for the 8-ramp system studied on the Gulf Freeway. It should be noted, however, that there has been considerable speculation that technological advances may drastically reduce the costs of digital equipment in the near future. If this occurs, the Digital Satellite System may represent the most economical system for the length of highway analyzed in this report.

2. When the number of controlled ramps increases to about 20, then the cost of implementing the Central Digital System becomes increasingly less than either the Analog Satellite or Digital Satellite Systems.

3. Implementation of control level 1, which constitutes the control level with the lowest sophistication and which is least expensive, results in a substantial improvement in freeway operations. In some cases implementation of a system at this level may be sufficient to alleviate freeway congestion in certain areas.

4. The multilevel system design concept provides a rational basis for evaluating the cost-effectiveness of alternative freeway ramp control systems.

Recommendations for Implementation

The following recommendations for implementation are offered:

1. The methodology of cost-effectiveness consistent with a multilevel system design concept may be adopted by the Highway Department as a means for evaluating control system alternatives for implementation on other freeways.

2. This report contains the capital investment costs and annual

operating costs of freeway ramp control system alternatives. This information will be useful in costing future systems. The results of the cost-effectiveness analysis will be useful for making decisions regarding the design of future systems.

3. Consideration should be given to the possibility of implementing systems at control level 1 as an immediate step to improving freeway operations where known major problems exist. Consideration should also be given to immediate application of control level 1 where accident experience on entrance ramps is high. This level of control constitutes a very basic system which can be increased in sophistication at a later date by adding more hardware and software if the need exists.

INTRODUCTION

Statement of the Problem

The administrator faced with the task of implementing and operating a freeway ramp control system must make certain decisions regarding the nature of the system that is needed. These decisions must be made in the face of constraints which affect his decisions. Generally, the most pressing constraint is that of limited monetary resources. If there were no limitations on money, then certainly the most elaborate and effective system could be installed, and there would be few decision problems. In the real world, however, it would be a rare occasion when he could work with an unlimited budget. The administrator should therefore strive to install the system which will provide the greatest returns in the form of user benefits with the available resources.

An attempt to analyze the effectiveness of alternative control systems is soon frustrated by the lack of information available. First of all, it is difficult to correlate the reported effectiveness of existing freeway control systems, since the measures of effectiveness reported are not consistent among systems. Furthermore these measures may not be compatible with the decision-maker's opinions or priorities with respect to user benefits. Secondly, the effectiveness of freeway control systems have generally been reported on the basis of total completed systems. The administrator interested in implementing a system may not have sufficient resources to install a complete system.

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He may, however, have the funds to install a partial system and plan
to expand the system capabilities as additional funds become
available. The pressing problem becomes a matter of where should
he start or what elements of the system could be installed and yet
be effective in improving freeway safety and operations. Because
of the interactional effects of individual system components, it may
be difficult for him to estimate their combined effects and thus it
may be difficult to systematically build a total freeway control system
that provides the greatest effectiveness for the least cost. In
this report, an attempt is made at providing the information required
for a systematic approach to assist the administrator in developing
a control system consistent with cost-effectiveness considerations.

Cost-Effectiveness

Cost-effectiveness analysis is a technique developed to assist
the decision-maker in identifying a preferred system from among several
possible alternatives. In the traffic engineering context, typical
analyses may tackle such problems as the best type of traffic con-
trollers to be purchased for intersection control, the type of con-
trol measures that should be applied to a particular arterial street,
or in light of this analysis, the type of control system that should be
installed on a freeway. A cost-effectiveness analysis is applied when
there are alternative ways of reaching an objective and each alterna-
tive produces a level of effectiveness for a given amount of resources.
The analysis is designed to systematically examine costs, effectiveness,
and risks of alternate ways of accomplishing an objective.

Cost-effectiveness analysis is specifically directed toward
problems in which the output cannot be totally evaluated in terms of
a dollar value, but in which the resource inputs can be appropriately
evaluated at market prices.[1] Road-user level-of-service factors such
as safety, comfort, convenience, and traffic impedances are typical
outputs of a highway system which currently are difficult to price.

Elements of Cost-Effectiveness Analyses[2, 3]

The essential elements of a cost-effectiveness analysis are:

- Objectives (functions to be accomplished).

- Alternatives (feasible ways or courses of action for
  attaining objectives).

- Costs (associated with each alternative).

- Models (A set of mathematical or logical relationships
  among the objectives, alternatives, environment and resources).

- Criteria (for choosing the preferred system).

Objectives are the aims that need to be accomplished with the
alternative systems. The selection of objectives is, therefore, a
basic part of defining the problem that the analysis is designed to
solve. Alternatives are the various proposed systems that are capable
of attaining the specified objectives. Each alternative has its own
price tag with respect to facilities, time, and men. The costs associated
with alternative systems are generally composed of four main categories:

- Research, Development, Test and Evaluation Costs.

- Initial Investment Costs.

- Annual Operating Costs.

- Attrition Costs.

Models are used in the analysis to cope with the variables that are inherent in problems of the future. Criteria are the tests used to make the selection between alternatives. Two criteria generally employed are:

- Equal Cost - This criterion is used when there is a fixed budget, and the analysis determines which alternative provides the greatest effectiveness for a given resource expenditure.

- Equal Effectiveness - This criterion assumes that a specified and measurable effectiveness (capability) is required and the analysis determines which alternative achieves this level of effectiveness at the least cost.

Figure 1 serves to illustrate the equal cost criterion. Notice that the level of effectiveness that can be provided at a fixed expenditure is determined for each alternative. It is clear that alternative B is the preferred system in this example since it provides the greatest level of effectiveness for the available budget. The equal effectiveness criterion is illustrated in Figure 2. In this case, it is apparent that alternative A is preferred over B since alternative A can produce the selected level of effectiveness at a lower cost.

It is imperative either to determine the absolute level of effectiveness for each alternative at a fixed cost if the first criterion is used, or to determine the absolute cost for each alternative at a given level of effectiveness if the second criterion is employed. However, in highway research, it may not always be meaningful to select either one of the above criteria. If one is concerned with a specific problem for a specific location, then it stands to reason that either of the criteria would apply. But, in most cases, it is the intent of the investigator to generalize the research results
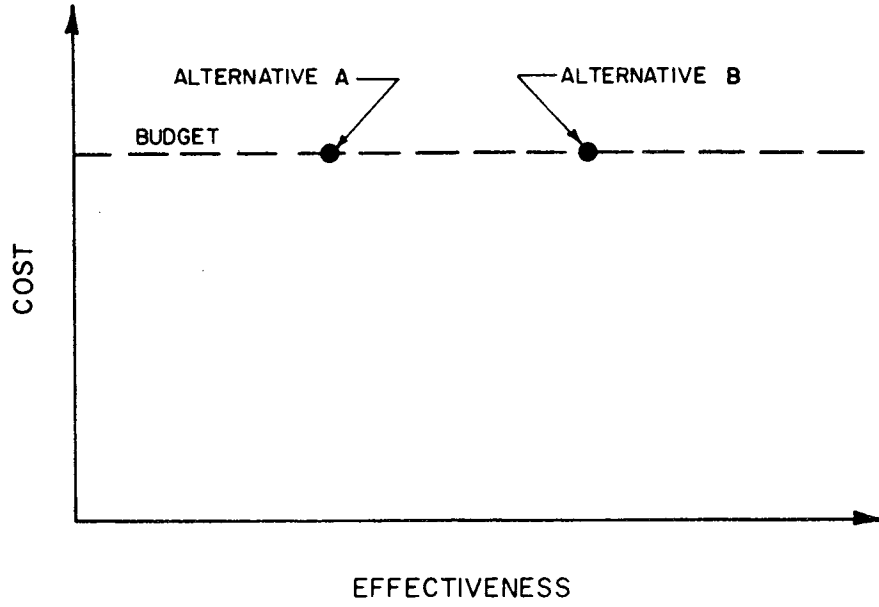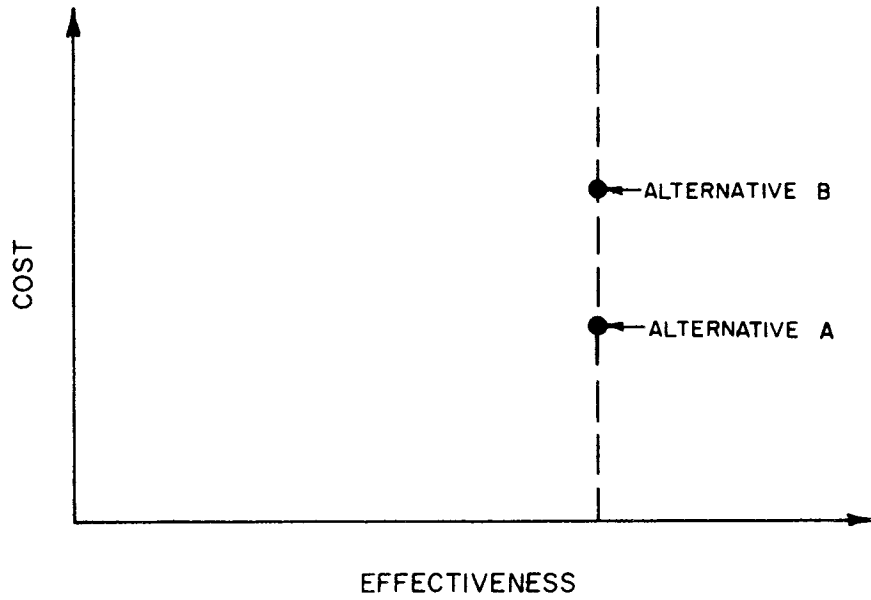
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FIG. I EXAMPLE OF EQUAL COST CRITERION

FIG. 2 EXAMPLE OF EQUAL EFFECTIVENESS
CRITERION

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toward a broader application so that several people from different locations might profit from the research.

If the investigator reports on a cost-effectiveness analysis of a particular system using the equal cost criterion, this information may not be useful to a decision-maker with the problem of implementing a system in another location. For example, he may not have the resources to implement a system as sophisticated as the one analyzed in the report. Or perhaps, he has greater resources and he needs information relative to benefits to be expected from the additional expenditures. A comparable problem could arise when an analysis is made from the standpoint of the equal effectiveness criterion. A solution to the problem would be to develop a cost-effectiveness curve (or points) for each alternative, similar to that shown in Figure 3, from which decisions can be made.
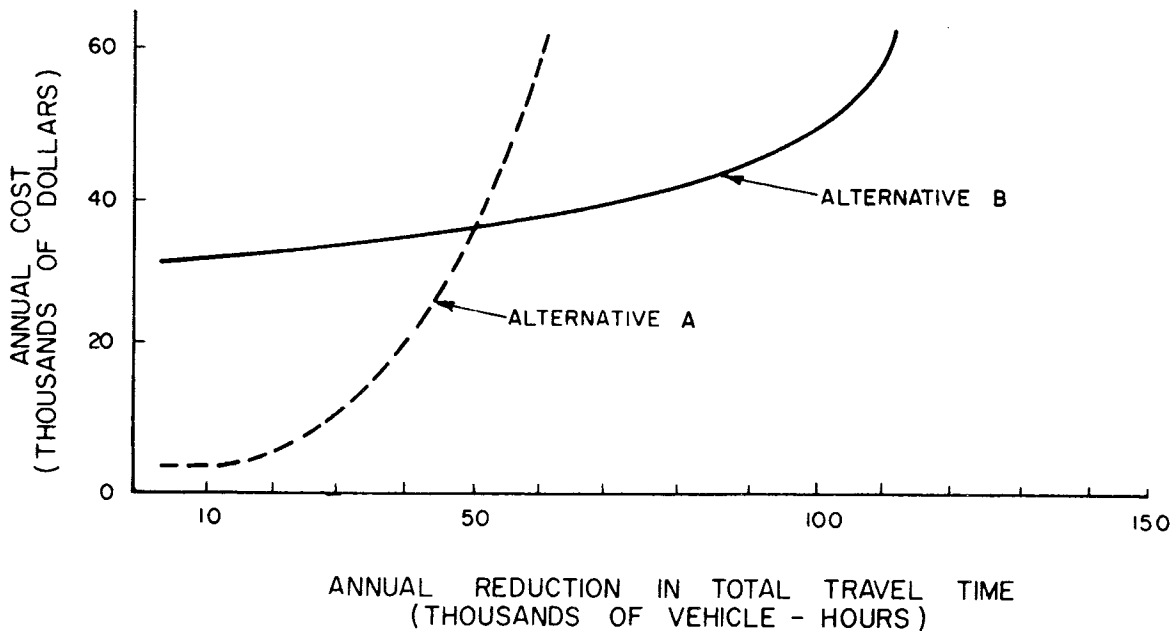

FIG. 3 ALTERNATIVES FOR REDUCING TOTAL TRAVEL TIME

Importance of Analyzing Absolute Size of Gain or Cost

Figure 3 also serves to illustrate the importance of analyzing an absolute level of effectiveness or cost (depending upon which criterion is used). Hypothetical cost-effectiveness curves are presented for two alternative traffic control systems. The measure of effectiveness is assumed to be the reduction of total travel time. The question becomes a matter of deciding which of the two alternatives should be selected. A study of Figure 3 will show that the selection will depend upon which alternative will have the lowest cost for a given absolute level of effectiveness, or which alternative will provide the greatest benefits at a given absolute level of resources (depending upon the criterion used). From the standpoint of selecting an alternative for a given level of effectiveness, it is evident in this situation that alternative A would be preferred at selected levels of effectiveness below 50,000 vehicle-hours; at higher levels of effectiveness (50,000 - 110,000), alternative B would be preferred. It is also evident that neither alternative A nor B would be acceptable if the reduction in total travel time required is greater than 110,000.

At times, studies ignore the absolute size of effectiveness or the absolute size of cost and use effectiveness-to-cost ratios. The flaw in the use of such ratios is the absence of any specified level of effectiveness required or resources available as previously discussed. If the level of activity (either cost or effectiveness) is fixed, a ratio may be useful in ranking among alternative systems. However, the effectiveness-to-cost ratio criterion is often applied when the level of activity is not fixed. Therefore, care should be

exercised in interpreting this type of analysis because it can be
misleading. For example, if the cost-effectiveness curves shown
in Figure 1 were not available for alternatives A and B, but a benefit-
to-cost ratio for each alternative could be obtained through studies,
then it is probable that the results might be as illustrated in Figure
4. It is observed from Figure 4 that alternative A can reduce total
travel time by 30,000 vehicle hours at an annual cost of $10,000
yielding a ratio of 3:1. At a cost of $50,000, alternative B can
reduce total travel time by 100,000 vehicle hours, a ratio of 2:1.
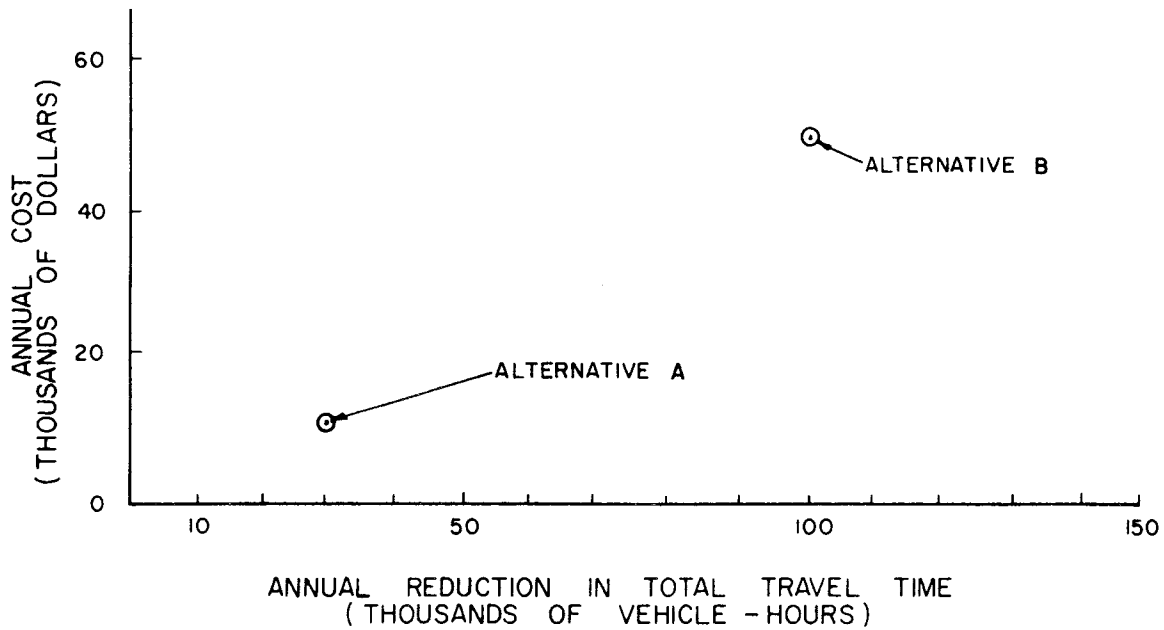
FIG. 4   ALTERNATIVES   FOR   REDUCING   TOTAL
TRAVEL   TIME

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A comparison of the ratios would lead one to select alternative A over B. Unfortunately, this selection is obviously wrong when the system is required to reduce total travel time by more than 50,000 vehicle hours.

Maximizing the ratio of effectiveness-to-cost outwardly appears to be a reasonable criterion, but it allows the absolute magnitude of the cost or the level of effectiveness to roam. This does not imply that the ratio is not a useful criterion; it can be successfully used when the level of effectiveness is fixed or when the available resources are fixed. The ratio may then be useful in ranking among alternative systems. However, the ratio reduces itself to an analysis of maximum effectiveness for a given amount of resources, or a specified level of effectiveness at minimum cost, and might have been considered in that context initially.

ANALYSIS OF FREEWAY RAMP CONTROL

General

When the terminology "freeway ramp control" is used, at least the following modes of control are brought to mind: (1) ramp closure, (2) fixed time ramp metering, (3) dynamic ramp metering, and (4) ramp merging control. Although each of the above constitutes a different control philosophy, it is safe to say that in essence one of the primary objectives of each mode is to optimize freeway operation. It is not the intent of this report to analyze the differences between each of these modes. Rather, the objectives are to provide a methodology for evaluating alternative freeway control systems and to assist the decision-maker in establishing a framework for implementation of a system. With this in mind, a comprehensive cost-effectiveness analysis was made of alternative ramp merging control systems, and is reported in the remaining sections of this report.

Objectives of Freeway Merging Control

The objectives of a merging and freeway control system are to achieve optimum freeway operations and to optimize the use of acceptable freeway gaps in the merging maneuver. The underlying philosophy of the second objective is that minimizing intervehicular interference at entrance ramps (1) reduces the probability of rear-end collisions in the merging areas due to false starts, (2) reduces the tension on a merging driver, and (3) prevents shock waves from developing on the freeway in the vicinity of entrance ramps.

A control criterion referred to as "gap acceptance" has emerged in recent years in recognition of the above requirements for merging and freeway control.[4] This philosophy of control is based on the measurement and projection of gaps (the time interval between the arrival of successive vehicles) in the outside freeway lane upstream of the entrance ramp and the release of a ramp vehicle when an acceptable gap is detected, so as to fit the ramp vehicle into the gap. Figure 5 illustrates this mode of ramp control. A detector, placed upstream of the merge area, measures gaps and the speed of traffic in the outside freeway lane. Whenever a gap is measured to be large enough so that a ramp driver will probably enter it, a ramp vehicle is released so as to reach the merging area at the same time as the "acceptable" gap. It is this gap acceptance concept that forms the basis for the development of the cost-effectiveness analysis.

Defining A System

The importance of analyzing the absolute increases in gain or cost for the alternative systems has been emphasized. To develop cost-effectiveness curves, the analyst must be able to recognize and distinguish between those factors which characterize one system from another in contrast with those factors which represent absolute increases in cost for the same system. For example, the addition of a series of environmental detectors to a freeway control system does not necessarily mean that this composite system is a new alternative but instead it represents an absolute increase in cost for the same system from which a different level of effectiveness might be expected. Analysis of the cost and effectiveness at this new level of sophistication would merely

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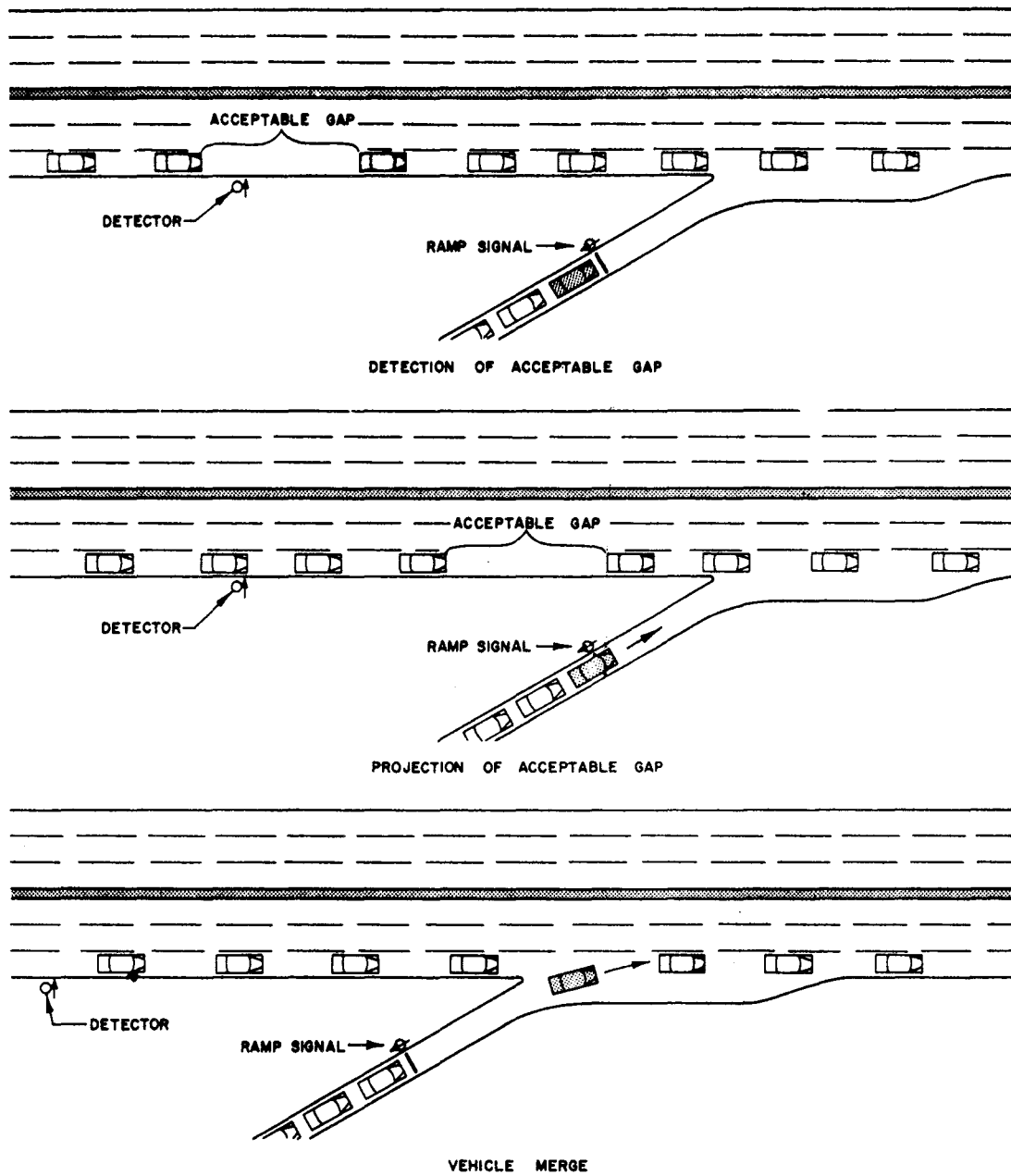
ACCEPTABLE GAP

DETECTOR

RAMP SIGNAL →

DETECTION OF ACCEPTABLE GAP

ACCEPTABLE GAP

DETECTOR

RAMP SIGNAL →

PROJECTION OF ACCEPTABLE GAP

DETECTOR

RAMP SIGNAL →

VEHICLE MERGE

FIG. 5   ILLUSTRATION OF GAP ACCEPTANCE MODE OF RAMP CONTROL

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represent an additional point on the cost-effectiveness curve for
the same system. It is imperative that an acceptable criterion be
used to distinguish these differences so that proper distinction
can be made between alternative systems. A rational method of system
design is therefore necessary for both developing and analyzing a system.

Multilevel Design Approach

A multilevel approach to design has been introduced by Drew[5,15]
as a rational means for developing a complex freeway control system.
This approach, described as the decomposition of the control function,
applies a relatively comprehensive control system to the operation
of the entire facility. The freeway system is viewed as a single
entity with the control law being split into several degrees or levels
of sophistication. The multilevel approach is directed towards
establishing a hierarchy of control that results not only in an
efficient system but one that can be implemented in stages. The four
levels of control, in ascending order of sophistication, are as follows:
(1) regulating, (2) optimizing, (3) adaptive, and (4) self-organizing
levels.

The regulating level as applied to freeway merging control accom-
plishes what might be called the basic "subgoal" of the system which
is the optimal use of available gaps in the shoulder lane of the freeway
by the timely release of ramp vehicles. The optimizing level dynamically
adjusts the gap setting of the first level regulating controller in
response to the outside freeway lane operation so as to maximize the
ramp service volume. For example, if the gap setting on the regulating

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controller is too high, many gaps are left unfilled; if the setting is too low, many metered vehicles will reject the gaps and be forced to stop in the merging area. The optimum gap setting therefore is somewhere between "too high" and "too low."

Whereas, the first two levels of control apply to individual ramps, both the adaptive and self-organizing levels involve system considerations. The function of the adaptive level is to handle the unexpected environmental factors, such as ambient conditions and temporary capacity reducing conditions (vehicular accidents, stalls, etc.), by adjusting the lower level controllers when these environmental conditions are detected.

The fundamental property of the self-organizing (learning) control level is its ability to increase its performance efficiency as time progresses. This level is programmed to automatically update the control parameters used in the lower three levels. Decisions are based on the accumulated experience and understanding of the freeway system operation. For example, the capacity of the freeway at geometric bottlenecks, or when the pavement is wet or icy, can be "learned" by a computer which retains information of attainable operational characteristics during these conditions. Once the capacity profile of the freeway has been "learned," the self-organizing level will not allow the lower levels to meter ramp traffic at a rate which will exceed this capacity. The reader is referred to Reference 5 and 6 for a more detailed discussion of the four control levels.

Each level of control represents an increase in sophistication which raises the cost of the system and provides a separate level of effectiveness. The multilevel approach therefore provides a rational

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means of distinguishing between different levels of control for a given system. This approach provided the framework for determining the cost-effectiveness of the alternative systems under consideration. The cost and effectiveness of every alternative system, discussed later in this report, were analyzed at each of the above four levels of control and are reported herein.

Study Site

The Gulf Freeway in Houston, Texas was selected as the proving grounds for the development of a prototype merging and freeway control system. Operation on this facility is typical of many urban freeways that have been suffering severe congestion and high accident rates. The Gulf Freeway has three 12-foot lanes in each direction separated by a 4-foot concrete median with a 6-inch barrier-type curb. The study area extends about 2½ miles on the inbound freeway from State Highway 225 to Dumble Street interchange. Between these interchanges defining the study area are eight interchanges and ten entrance ramps. Eight of the entrance ramps are under control. Frontage roads are one-way and continuous except at two railroad crossings. The through lanes of the Gulf Freeway pass over the intersecting streets at the interchanges with the effect that this grade line tends to produce bottlenecks at the over-passes.

System Hardware

The hardware required to implement a multilevel freeway control system can be categorized into six basic subsystems: detectors, control-lers, traffic signals, transmission, digital computer, and displays.

Briefly, detectors are devices embedded in or placed above the roadway to detect the presence and location of vehicles. Electrical pulses from the detectors are transmitted to the digital computer where the information is accumulated and analyzed. Decisions are then made and commands are sent up and down the four-level hierarchy. Controllers transform the computer commands into controls for the signals on the entrance ramps. The traffic signals simply present the traffic control indications to the ramp drivers. The transmission or communication subsystem provides the means of transferring information from the detectors and controllers to the computer and transferring command information from the computer to the ramp controllers (if local controllers are used). Displays are incorporated so that observers can monitor the status of the overall freeway operation.

The Gulf Freeway prototype surveillance and control system is shown on the schematic in Figure 6. Analog and digital computers now installed and operating in the Surveillance and Control Center, permit a wide range of control measures from the simplest to the most sophisticated to be affected on the inbound Gulf Freeway. This redundancy of computers is not recommended for operational projects; but in a research project, flexibility is needed to compare various control system configurations, to establish control warrants, and to perform cost-effectiveness analyses. The above instrumentation, in conjunction with a closed circuit television system, provided the means for measuring the figures of merit which were used in this cost-effectiveness analysis. The reader is referred to References 6,7 and 8 for a more complete
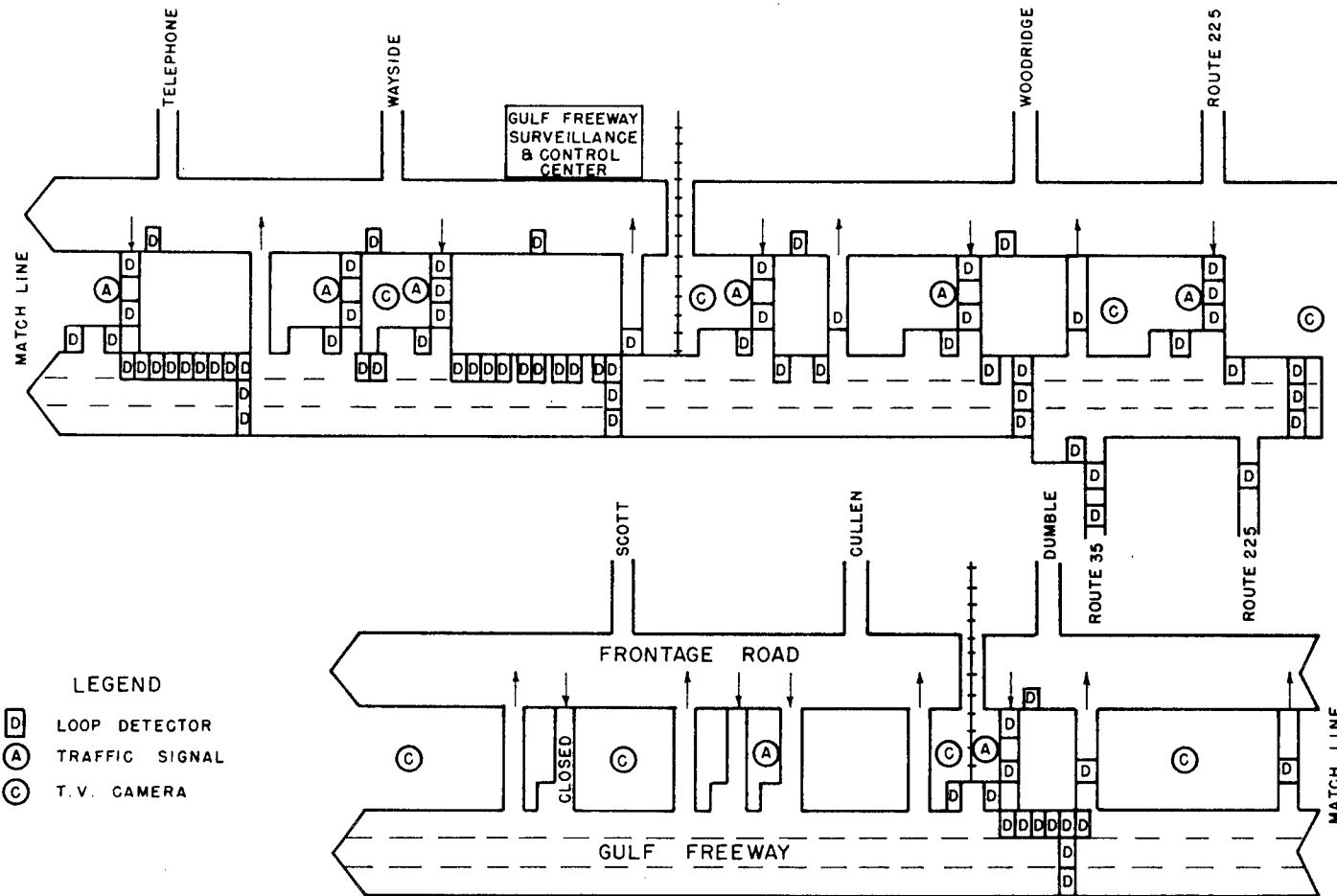
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FIG. 6   SCHEMATIC OF GULF FREEWAY PROTOTYPE SURVEILLANCE & CONTROL SYSTEM (INBOUND)

LEGEND

D LOOP DETECTOR
A TRAFFIC SIGNAL
C T.V. CAMERA

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description and discussion of the equipment.

Candidate Freeway Merging Control Systems

Three candidate systems for freeway merging control which utilize the gap acceptance control criterion were analyzed. For distinction, these systems will be designated to in this report as:

- Analog Satellite (System I).
- Digital Satellite (System II).
- Digital Central Control (System III).

In the Analog Satellite System, analog controllers are used at each entrance ramp to perform the first two levels of functional control independent of any central control unit. At these two levels of control, each controller regulates and optimizes the operation at its own particular ramp area independently of adjacent analog controllers. When the system is expanded to the third and fourth levels, a central processing unit integrates the control functions of the local analog controllers for total system optimization.

The Digital Satellite System follows the same pattern of development except that, local digital controllers, instead of analog controllers, are used at each ramp for the first two levels of functional control. A central processing unit is required to integrate these controllers and to affect the third and fourth levels of control.

A central digital computer of sufficient size can simulate the performance of the local digital controllers and thus can directly accept the inputs from detectors in the field, process the information, and regulate the ramp signals thereby negating the need for analog or digital controllers at the ramps. The third alternative, referred to in this

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report as Digital Central Control, is a system in which a central
digital computer performs all four levels of control as a central
controller. As one develops the system from the first to the fourth
level, the capabilities of the computer would be increased by purchasing
additional computer storage.

Alternative System Costs

Table 1 gives the estimated capital investment unit costs for
each alternative system based on experience gained with freeway control
systems. The estimates reflect the labor and installation costs associated
with the Texas area and will therefore vary from one location to
another. The costs for each system have been broken down into estimates
for each of the four functional levels of control, consistent with the
multilevel system-design approach, for control in one direction of
freeway flow. These costs represent the initial amount that would
be required to install any one of the four levels. For example, the
tabulated costs at the second functional level are associated with a
system that is designed to operate at the second level. This assumes
that the decision was made to by-pass the first level of control
completely. In other words, the costs in Table 1 do not represent
incremental costs associated with the stage development of a total
system since the many variables associated with stage construction
would further complicate the analysis and tend to confuse the issue.
For example, suppose an engineer had intentions of developing a system
to operate at the fourth level of control; assume also, that his
resources dictated that he could initially install a system at the

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TABLE I

CAPITAL INVESTMENT UNIT COSTS — ONE DIRECTION OF CONTROL
(PURCHASE & INSTALLATION)

I. ANALOG SATELLITE SYSTEM

    (1) Regulating Level

        Each ramp has: Analog controller, ramp signal, gap and speed detector, merge detector, check-in detector.

Detectors, signals & cabinets	$2,500 per ramp
Controller	$4,000 per ramp

    (2) Optimizing Level

        A queue detector is necessary in addition to the equipment for the Regulating Level. Also, the controller needs to be somewhat more sophisticated. Costs given below are additional to that of the Regulating Level.

Detectors	$500 per ramp
Controller	$1,000 per ramp

    (3) Adaptive Level

        In addition to the equipment necessary for the Optimizing Level, the following is required: a central controller with telemetry to each local controller, 3 freeway detectors with telemetry to the central controller and 1 ramp detector tied to the local controller, plus environmental sensors tied to the central controller. Costs are in addition to the costs for the Optimizing Level. Telemetry consists of 15 pair direct cable.

Detectors	$2,000 per ramp + $1,000 for system
Local Controller	$1,000 per ramp
Central Controller	$10,000 for system
Telemetry	$1.20 per foot

    (4) Self-Organizing Level

        In addition to the equipment at the Adaptive Level, electronic memory (digital), interface equipment and a more sophisticated central controller are required. Costs given below are additional to the costs at the Adaptive Level.

Memory	$8,000 for system
Interface	$3,000 for system
Central Controller	$1,000 for system

II. DIGITAL SATELLITE SYSTEM

    (1) Regulating Level

        The equipment is the same as that of the Regulating Level for the Analog Satellite System except that the controller is a small digital computer.

Detectors, signals & cabinets	$2,500 per ramp
Computer	$8,500 per ramp

    (2) Optimizing Level

        A queue detector is necessary in addition to the equipment for the Regulating Level. The controller does not change. Costs given below are additional to the Regulating Level.

Detectors	$500 per ramp

TABLE I   (continued)

(3) Adaptive Level

In addition to the equipment at the Optimizing Level, a small central computer is added. Extra sensors and telemetry are also required comparable to system 1. Local computers require some additional hardware. The costs below are additional to the costs of the Optimizing Level.

Detectors	$2,000 per ramp + $1,000 for system
Local Controllers	$500 per ramp
Central Computers	$10,000 for system
Telemetry	$1.20 per foot

(4) Self-Organizing Level

Central Computer requires some additional hardware to that of the Adaptive Level. The cost given below is additional to the cost for the Adaptive Level.

Central Computer	$2,000 per ramp

III.   CENTRAL DIGITAL SYSTEM

(1) Regulating Level

This system involves a single central computer. Telemetry is required with the first level. Cost is for a 50 pair direct cable.

Detectors, signals & cabinets	$2,000 per ramp
Computer	$105,000 per system
Telemetry	$1.60 per foot

(2) Optimizing Level

In addition to the equipment for the Regulating Level, queue detectors are required at each ramp at the following additional cost:

Detectors	$500 per ramp

(3) Adaptive Level

The computer is expanded to 2 disk drives with an additional data channel. The following represents the additional cost above the Optimizing Level.

Detectors	$2,000 per ramp + $1,000 per system
Computer	$5,500 per system

(4) Self-Organizing Level

The computer is expanded from 16K to 24K core. The following represents the additional cost above the Adaptive Level.

Computer	$18,000 per system

first level and later add the extra sophistication of the other levels as resources become available. Naturally, he would want to add equipment at the early stages of development, over and above the actual requirements for that level, so that the cost of moving to the higher levels would be minimized. If his intentions were to develop a system to the third level, his actions in the lower stages might be somewhat different than if he were planning a fourth level system. In addition, each organization might consider different actions at the lower levels of control in the process of stage construction. There are, therefore, too many possible permutations of stage development to consider them all in this report.

A control system designed for both directions of freeway flow can conceivably take one of the following two forms: (1) a system capable of control in only one direction at a time, or, (2) a system which is capable of simultaneous control in both directions. The former would be a system designed basically for peak period control where the system would be operational in one direction in the morning and in the opposite direction during the evening. This type of control feature minimizes the cost because equipment required for uni-directional control can be electronically interconnected to serve both directions on a time-sharing basis. The cost of a system capable of two-directional control would be less than twice the cost of a uni-directional control system, because certain costs are fixed regardless of the number of directions controlled. In this report, only uni-directional systems are considered. It should be kept in mind, however, that a two-directional control system will be more cost-effective.

The cost estimate of the digital satellite system is biased
on the high side because of the lack of experience with such a system.
It is known that controlling two ramps with a digital computer re-
quires only a relatively small increase in investment above that
required for the control of a single ramp. It is therefore felt
that a small digital computer, designed to control up to four or six
ramps, may well prove to be the most cost-effective for the lower
levels of control. The cost estimates in this report, however, allow
for one small digital computer at each ramp.

Table 2 is a tabulation of the estimated capital investment costs
of the three alternative operational systems for the section of
freeway considered. The estimated direct annual costs for each alter-
native system are presented in Table 3.

Measures of Effectiveness

Various figures of merit have been proposed in the past to
evaluate freeway operations. To some extent, they can be categorized
according to whether they are: (1) macroscopic or microscopic in
nature, (2) rational or empirical, and (3) designer- or user-oriented.
Further considerations relate to their sensitivity and capability of
automatic measurement.

The traffic variables easiest to measure are volume and speed--
both are capable of automatic detection. Volume is a macroscopic,
designer-oriented measure of effectiveness. Although the number of
vehicles passing a point on a freeway is useful to the designer, it
is meaningless to the driver. On the other hand, speed is a microscopic,

TABLE 2

SUMMARY OF CAPITAL INVESTMENT COSTS FOR A 2 1/2 MILE
SECTION OF FREEWAY (ONE DIRECTION, 8 RAMPS)

Level of Control	SYSTEM 1	SYSTEM 2	SYSTEM 3
1	$ 52,000	$ 88,000	$134,200
2	64,000	92,000	138,200
3	114,700	138,700	160,700
4	126,700	140,700	178,700

TABLE 3

DIRECT ANNUAL COSTS

I. MAINTENANCE

Level of Control	SYSTEM 1	SYSTEM 2	SYSTEM 3
1	$1,500	$1,500	$3,000
2	2,500	1,800	3,300
3	3,800	4,000	4,000
4	4,200	4,200	4,200

II. WAGES** $15,000*

III. POWER AND TRANSMISSION**   10,000

IV. MISCELLANEOUS**

   a. Office Rental   6,000
   b. Contingencies   10,000

*One engineer and one technician on a 50% time basis.
**Same for all three systems at all levels of control.

user-oriented figure of merit.

Total travel time in the system is a popular measure of effective-ness analyses. Yet, travel time is rather insensitive--much more so than, say, acceleration noise, since two trips over a route can exhibit the same travel time with one trip described by a constant average speed and the other trip by stop-and-go driving.[9] In addition, a minor travel time savings per vehicle can result in a very significant savings when the total system is considered. This savings would look very appealing to the designer, although the minor reduction in travel time perhaps may not even be noticed by the highway user. It is necessary to be cognizant of the differences of viewpoint between the designer and the road user when evaluating the measures of effectiveness.

Other figures of merit are such factors as accidents, motor-vehicle running costs, driver anxiety, and delay on the ramp. Because of the complexity of the freeway phenomenon and the relevancy of a variety of measures of effectiveness to the objectives of freeway control systems, not one, but several measures should be employed in the design and evaluation of freeway control systems.

Although it would have been desirable to actually measure the figures of merit at all levels of control, the development of the prototype Gulf Freeway system has not yet progressed beyond the second level of control. Consequently, the evaluations of the system at the first two levels of control, in comparison to no control at all, are substantiated with actual field measurements. The effectiveness of the systems at the two higher levels of control are speculative, representing

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the best judgment of the Project staff on the basis of their close
association with merging control systems over the period of several
years. Future work in this area will provide more accurate field
measurements at the higher levels of control. In addition, the
measures of effectiveness used in this analysis relate to the user
benefits only during the morning peak hour of control.

System Measurements

System input-output study techniques, using the electronic sensing
and processing equipment, were considered to be one of the essential
techniques for the analysis of the effectiveness of the alternative
systems. The positioning of the vehicle detectors coupled with the
digital computer provided a means for automatic data collection on a
regular schedule. Data collected on several days were used to evaluate
the figures of merit on a system basis. These data were obtained from
measurements made between 7 and 8 a.m. and reflect the system efficiency
during the morning peak traffic period.

System input-output studies have been used successfully on several
occasions in the past to evaluate freeway flow. The methodology for
these studies are discussed in Reference 10. System input-output tech-
niques provide the following measures of system effectiveness: (1) Total
Travel, (2) Total Travel Time, (3) Average Speed, and (4) Kinetic Energy.

In addition to the above, moving vehicle studies were conducted
to determine motor vehicle operating costs. A test vehicle equipped
with a speed recorder was driven in traffic on several days to record
individual vehicle performance during the morning peak period. Speed
contour maps were plotted which provided information in a form suitable

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for analysis. Average speeds and the average number of speed changes were calculated from these contours, and with the knowledge of the volume and the distribution of traffic, motor vehicle running costs were calculated using Winfrey's[11] cost tabulations. This method has been used in the past and provides a convenient and relatively easy way of determining average vehicle costs associated with freeway flow.[12]

Another measure of the efficiency of a control system is its ability to reduce vehicular accidents on the freeway and ramp proper. Reduction of accidents represent another marketable measure because it can be evaluated in terms of a dollar value. Accident experience on the Gulf Freeway study section has been observed daily over the last three years via the closed circuit television surveillance system and has been documented in the literature.[13] These data formed the basis of relating the effectiveness of the alternative merging and freeway control systems with respect to accident reduction.

Ramp Measurements

Consistent with one of the objectives of merging control--i.e., to assist motorists in the merging maneuver--measures of effectiveness which reflect the efficiency of the merge were also included in the analysis. Special ramp studies were performed to measure (1) the acceleration noise of ramp vehicles, (2) the delays to ramp vehicles, and (3) the potential conflicts in the merge area, as represented by vehicles not matched with acceptable gaps.

A measure of the "jerkiness" of the vehicle on a roadway is the standard deviation of the acceleration of a vehicle, called acceleration

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noise. This traffic parameter measures the manner in which a vehicle deviates from a uniform speed. High acceleration noise values are indicative of violent braking and accelerating characteristics; whereas, values approaching zero reflect a smooth flow. Acceleration noise is related to factors of comfort, driver anxiety, etc. and is a useful measure of effectiveness to reflect the "smoothness" of the merging maneuver.

Delay of vehicular progress very frequently is used for performance evaluation. Freeway control does impose some restrictions of ramp movement and as such causes delay at entrance ramps. Typical measurements for ramp delay are total delay, average delay per vehicle, and maximum delay for a vehicle.

One aspect of freeway merging control is to match the ramp vehicles with acceptable gaps in the freeway merging lane. The ability of the system to efficiently accomplish this task is reflected in the probability of both a ramp vehicle and an acceptable gap arriving in the merge area at the same time. Potential conflicts arise when the system fails to match the vehicle with the gap.

RESULTS

Throughput and Travel Time Characteristics

Figure 7 illustrates the basic relationship between total travel and total travel time for the 2½-mile Gulf Freeway study section and serves to demonstrate the manner and degree in which flow on a freeway can be improved by implementing a ramp merging control system consistent to the multilevel system-design concept. Maximum throughput is achieved when the freeway is operating under conditions coincident with those at the vertex of the curve.

The section to the right of the vertex represents congested flow. The congestion becomes more severe and the system less efficient at points to the right of the vertex. Operations to the left of the vertex delineate good operating conditions and higher levels of service. Although the total travel time is reduced, it should be noted that total throughput is also reduced simply because the demand for the freeway is below capacity.

One function of a control system would be to reduce total travel time and increase total travel in a manner which would achieve operations at or near the vertex. Figure 7 shows that prior to the implementation of controls, the productivity of the freeway in terms of vehicle-miles of travel was relatively low while the total travel time was relatively high during the morning peak hour. It also illustrates how the application of control level 1 through 3 incrementally increases the productivity of the freeway and reduces total system travel time. Control level 4 further increases the level of service of the freeway but it is important to understand that although total travel time is reduced, the reduction
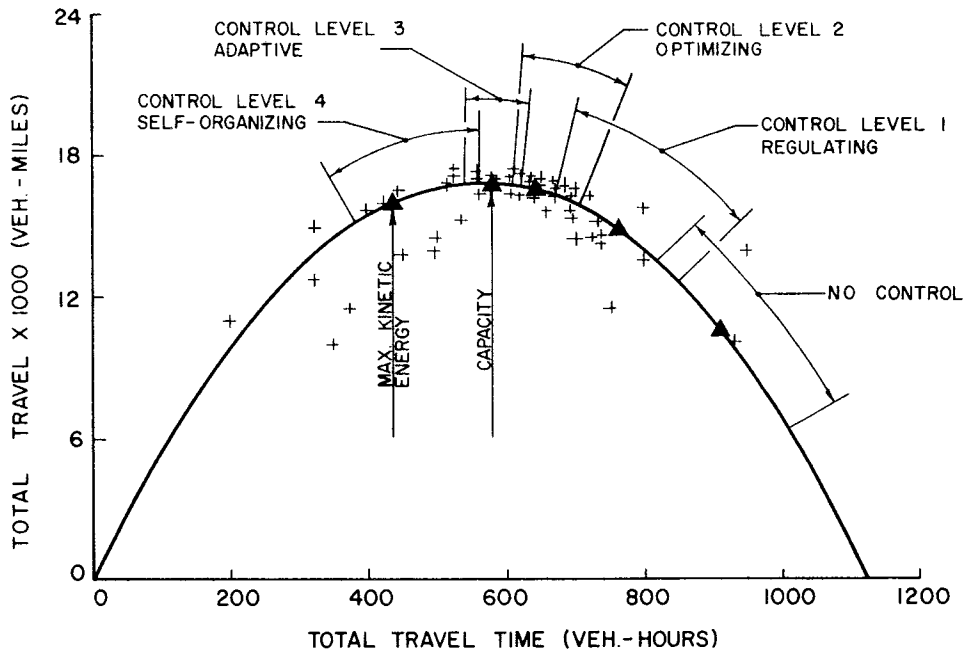
FIG. 7 OPERATING CHARACTERISTIC FOR A 2½ MILE SECTION OF THE GULF FREEWAY CONTROL SYSTEM

is at the expense of a more restricted ramp control policy. By reducing the ramp inputs, the total throughput (total travel) in terms of vehicle miles of travel is reduced. That is, the freeway will operate at volumes below capacity and at speeds above the critical speed. This fourth level of control allows a range of operating conditions which tends to minimize acceleration noise (or maximize kinetic energy) and maintain a more uniform speed on the freeway.

The operating points indicated in Figure 7 for each level of control have been identified by the authors as the locations on the total travel and total travel time curve at which the highest expectation of operation would occur for the study section of the Gulf Freeway. These points

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have been isolated for analysis purposes only in order to compare
the three alternative systems under investigation. It should be
recognized that a wide range of operation does occur for each of the
control levels due to random variation of traffic. These points,
however, provide realistic estimates of operation relative to the
multilevel design approach and were used to develop a portion of the
cost-effectiveness relationships used in this study.

Cost-effectiveness curves for the alternative control systems
are presented in Figure 8. The analysis assumes a 5 percent vestcharge
rate and a 10-year amortization period for all the equipment. It
also assumes that the computer software package which is used to control
the system would be available to the operating engineer. Any modifi-
cation requirements of the software are considered to be performed by
the personnel assigned to the system, and the costs for the modifica-
tions are included within the wages of these personnel. The measures
of effectiveness in Figure 8 relate to user benefits accrued during
the morning peak hour only; off-peak considerations have not been included.
The cost and effectiveness of each alternative were determined at each
of the four levels of control.

A study of Figure 8 reveals that the Analog Satellite System is
most cost-effective in comparison to the other alternatives. This
system can provide absolute levels of effectiveness at a cost lower
than either the Digital Satellite or the Central Digital Systems. For
example, based upon the effectiveness in reducing total travel time
with a system capable of operation at the first level of control, it
is observed that the annual cost to reduce total travel time by

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I FREEWAY
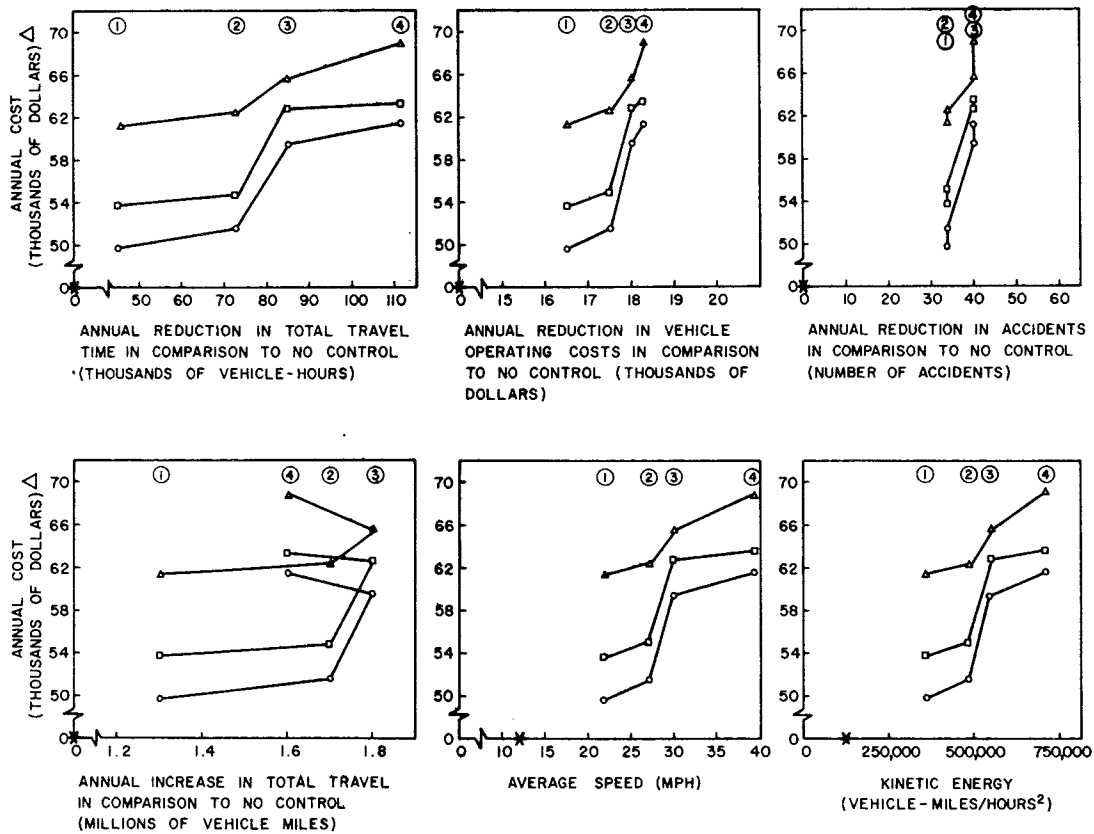
II RAMPS
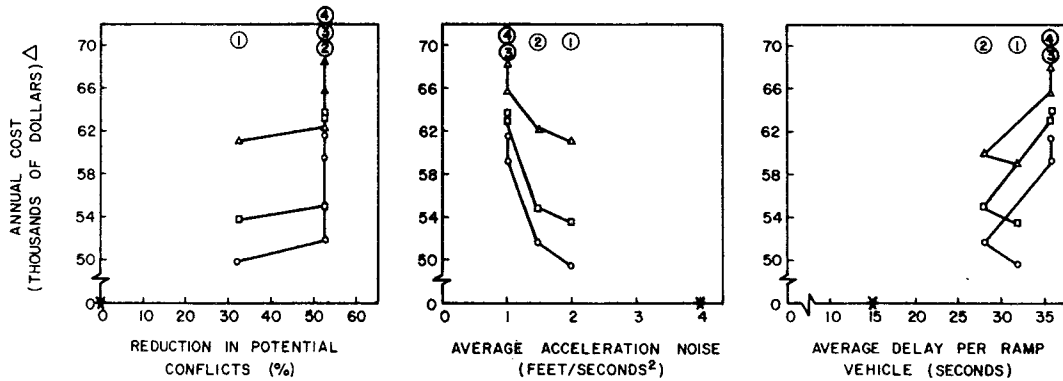
△ CENTRAL DIGITAL
□ DIGITAL SATELLITE
○ ANALOG SATELLITE
① CONTROL LEVEL

✱ REPRESENTS COST-EFFECTIVENESS WITH NO MERGING CONTROL

△ ASSUMES A IO-YEAR AMORTIZATION PERIOD AND A VEST-CHARGE RATE OF 5 PERCENT

FIG. 8   COST-EFFECTIVENESS   RESULTS

42,000 vehicle hours per year is about $49,000 for the Analog

Satellite System compared with $53,500 for the Digital Satellite

and $61,000 for the Central Digital Systems. The tendency of the

Analog Satellite System to be more cost-effective than the other

two alternatives is consistent for each measure of effectiveness

and applies throughout the total range of each measure of

effectiveness indicated in Figure 8.

The asterisk located on the abscissa of each graph represents

freeway characteristics when no control is applied to the ramps. The

points of the curves which lie below the symbols ①, ②, ③, and ④

represent the operating conditions of the freeway at control level

1, 2, 3, and 4, respectively. Inspection of each graph in Figure 8

indicates that the greatest incremental increase in effectiveness will

occur between the condition of no control and that of control level

1 which is the simplest form of merging control. This important

finding is discussed in greater detail later in this report.

Incremental Analysis

From the standpoint of the multi-level approach to the design of

a freeway merging control system, it is of importance to know if the

increase in system sophistication can be justified, that is, whether

the installation of a system that operates at control level 2, or

level 3, or level 4 is worth the added expenditure over the next

lowest acceptable level. An incremental analysis was therefore performed

to give some insight to this type of decision. Only System 1 (Analog

Satellite System) was selected for this phase of the analysis since

it proved to be the preferred system for the number of ramps under investigation on the Gulf Freeway.

Although several measures of effectiveness were used to evaluate the three alternative systems, not all are priceable. Presently, economic coefficients can be safely assigned to only travel time, accidents and motor vehicle operating costs. The monetary benefits due to these three measures of effectiveness can be combined to compute a cost-benefit ratio. In addition to this ratio, the remaining non-market factors can be assessed among the various levels of control.

The results of an earlier Project report, in which benefits of traffic surveillance and control on the Gulf Freeway were evaluated,[14] were used to derive a value of time for an average vehicle operating on the Gulf Freeway during the 7-8 a.m. peak period. A five-day count of different types of vehicles was made and the proportions of vehicles of different types given by these counts were used with values of time from two recent studies to derive a composite value of time. Since the precise amount of time saved by different vehicle types was not known, it was assumed that the proportion of total time saved by vehicles of a particular type was the same as the proportion of such vehicles as given by the five-day count.

For purposes of vehicle counts, vehicles were divided into four types, each of which was assigned a different value of time. The first type, "Autos and Pick-ups," included all automobiles, pick-ups apparently used for the same purpose as automobiles, campers, and compact, non-commercial panels. "Delivery Vehicles" included panel trucks not included in the first vehicle type, stake-bed pick-ups, light, two-

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axle, four-tire trucks, pick-ups apparently used commercially (with load or tools), pick-ups with trailers, and school buses. "Trucks" included single-unit trucks with dual tires and truck-trailer combinations. "Commercial Buses" included buses identified as commercial and other full-size buses.

A value of time of $2.82 per vehicle hour was used for the first type of vehicles, "Autos and Pick-ups." This figure was based upon a recent Stanford Research Institute study[16] which recommends $2.82 per passenger per hour as a value of time. This value of $2.82 was used as the value of time per vehicle hour in this study, although it represents a conservative estimate since the average number of passengers per vehicle was greater than one. The values of time for the other three types of vehicles were taken from a recent Texas Transportation Institute study.[17] Table 4 gives the derivation of the "average" value of time, $2.92 per vehicle hour, which is used in this paper.

Since no information was readily available on the cost of motor vehicle accidents occurring on and near the inbound Gulf Freeway, a value of $600 per accident was assumed for the cost of property damage, medical expenses, and loss of output due to injury and death. This cost per accident is based on a National Safety Council memorandum.[18]

The results of the incremental analysis for the Analog Satellite System are presented in Table 5. The incremental benefit-cost ratio is the economic assessment of the benefits accrued through savings in travel time, accidents and motor vehicle operating costs as the sophistication of the control system is increased by one level. The

TABLE 4

DERIVATION OF AVERAGE VALUE
OF TIME PER VEHICLE HOUR

Types of Vehicles	Proportion of Vehicles of This Type[1]		Value of Time Per Vehicle Hour		
Autos, Pick-ups	.9445	x	$2.82[2]	=	2.6635
Delivery Vehicles	.0371	x	3.68[3]	=	.1365
Trucks	.0165	x	6.56[3]	=	.1082
Buses	.0019	x	7.43[3]	=	.0142
	Value of Time Per Vehicle Hour			=	2.92

[1] Based on a five-day survey, made during control on the Gulf Freeway, of peak-period inbound traffic.

[2] Based on Stanford Research Institute, The Value of Time for Passenger Cars, Vol. I by Dan G. Haney et al. and Vol. II by Thomas C. Thomas (Menlo Park, California: Stanford Research Institute, May, 1967).

[3] Based on William G. Adkins, Allan W. Ward, and William F. McFarland, Values of Time Savings of Commercial Vehicles, National Cooperative Highway Research Program Report 33 (Washington, D. C.: Highway Research Board, 1967).

TABLE 5

INCREMENTAL ANALYSIS
—ANALOG SATELLITE SYSTEM—

Base Alternative	Proposed Alternative	Incremental Net Annual Benefits*	Incremental Net Annual Costs	Incremental Benefit-Cost Ratio	Annual Increase In Total Travel (Million Veh.-Mi.)	Increase In Average Speed (MPH)	Increase In Kinetic Energy (Veh.-Mi./Hr^2)	Reduction In Potential Ramp Conflicts (%)	Reduction In Ave. Ramp Acceleration Noise (Ft/Sec^2)
No Control	Level 1-Regulating	$186,000	$53,000	3.9	1.3	10	215,000	32	1.9
Level 1-Regulating	Level 2-Optimizing	27,600	13,000	2.1	0.4	5	140,000	21	0.6
Level 2-Optimizing	Level 3-Adaptive	14,100	52,000	0.3	0.1	3	50,000	0	0.4
Level 3-Adaptive	Level 4-Self-Organizing	26,900	12,400	2.2	–0.2	9	140,000	0	0.0

*Based on savings in travel time, accidents and motor vehicle operating costs only.

Base Alternative is assumed to be the current system. The Proposed Alternative is the alternative at one higher level of control. For example, in the first line of the Table, the Base Alternative of the first analysis is that of no control. The Proposed Alternative is that of implementing a ramp control system at control level 1. The remaining information represent the costs and benefits resulting from implementing control level 1.* In addition to the aforementioned benefits which can be priced, the annual increase in total travel as well as factors relating to driver comfort and anxiety in terms of increase in average speed, increase in kinetic energy, reduction in average ramp acceleration noise and reduction in potential ramp conflicts are presented.

The first question of interest is whether the benefits of implementing a system at control level 1 are sufficient to warrant the $53,000 annual expenditure. A review of Table 5 illustrates that implementation of control level 1 (regulating) in comparison to no control at all would be highly cost-effective. The annual road user savings in travel time, accident and motor vehicle operating costs would be $186,000 from an annual investment of $53,000, thus yielding a benefit-cost ratio of 3.9. In addition, the following level of service improvements could be expected during the morning peak hour:

· A ten-mile per hour increase in average speed.

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*The reader should be aware that the use of the benefit-to-cost ratio in this context is different from the use discussed on pages 5 and 6 of this report. Here we are looking at the same system, a single curve on the cost-effectiveness plane, and analyzing the justification of incrementally moving up the curve in terms of costs and benefits. This is in contrast to utilizing the ratio to compare two distinct systems.

- Annual increase in total travel of 1,300,000 vehicle-miles.

- Increase in kinetic energy of 215,000 vehicle miles/hour^2.

- A 32 percent reduction in potention ramp conflicts.

- A reduction in average ramp acceleration noise of 1.9 feet/second^2.

The second question of importance is whether the additional annual expenditure of $13,000 would justify increasing the sophistication of the system from control level 1 to control level 2 (optimizing). The results in Table 5 show that a benefit-to-cost ratio of 2.1 results from the increased level of control sophistication. In addition, significant level of service improvements would result in terms of increased speed, reduction of potential ramp conflicts, increase in kinetic energy, etc.

The incremental analysis between control level 2 and control level 3 (adaptive) yielded results that are somewhat different in nature. The benefit-to-cost ratio for this analysis was only 0.3 which means that the annual increase in investment of $52,000 cannot be justified in terms of savings in cost to the road user. However, it is important to recognize that, although sufficient monetary returns would not be expected, implementation of control level 3 would result in an increase in the level of service afforded the road user. An increase of average freeway speed of 3 mph, an increase in kinetic energy of 50,000 vehicle-miles/hr.^{2} and an annual increase of 100,000 vehicle-miles of travel would result from peak hour control. The decision-maker must therefore decide whether this increase in level of service justifies the added expenditure.

A review of Figure 7 will help clarify the difference in operation between control levels 2 and 3. It can be seen that the reduction in total travel time between control level 2 and 3 is relatively small. Travel time is a highly sensitive parameter in terms of road user costs and benefits since the highest monetary road user benefits are reflected by the reduction in this parameter. It is understandable why the benefit-cost ratio between levels 2 and 3 is less than 1.0.

The last phase of the incremental analysis examines the cost-effectiveness of implementing control level 4 (self-organizing) assuming that level 3 is an acceptable alternative because of the level of service improvements over and above that of level 2.* The results of the analysis presented in Table 5 show a benefit-to-cost ratio of 2.2. In addition, an increase in freeway speed of 9 mph and increase in kinetic energy of 140,000 vehicle-miles/hr.^{2} results. It is important to note, however, that these improvements are accompanied by an annual <u>reduction</u> of total travel during the peak hour of 200,000 vehicle-hours. This occurrence can be fully understood by a careful study of Figure 2.

It is observed from Figure 7 that control level 4 places the oper-

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*According to acceptable practice, when considering the monetary benefits and costs, the next step in the analysis would be to use control level 2 as the base alternative and control level 4 as the proposed alternative since the incremental analysis between levels 2 and 3 yielded a benefit-to-cost ratio less than 1.0. However, in this cost-effectiveness analysis, importance is being given to non-priceable road user level of service factors. It was assumed in this analysis for illustrative purposes that the added increase in the level of service justifies the expenditure of implementing control level 3.

ation of the freeway in a range that falls to the left of the vertex of the curve. The operating characteristics to the left of the vertex are indicative of a higher level of service with the speeds above the critical speed and the volumes and densities below capacity levels. In other words, the freeway volumes are maintained at levels below capacity resulting in an increase in speed and reduction in density and travel time. The resultant effect will be a reduction in total travel (vehicle miles of travel) during the peak period.

Interpretation of Results

Although the results illustrated in Figure 8 indicate that the Analog Satellite System is a better system than either the Digital Satellite or the Central Digital Control Systems, careful interpretation is necessary before these results can be generalized. First of all, it should be noted that the estimated costs are based on current prices. There has been considerable speculation that technological advances will drastically reduce the costs of digital equipment in the near future. When this occurs, the Digital Satellite System may represent the most economical system for the length of highway analyzed in this report. Secondly, the magnitude of the system under control greatly affects the cost of the systems and will therefore alter the choice of system. Figure 9 shows the relationship between the capital investment of each alternative and the number of entrance ramps controlled, at each level of control, for a 10-mile system. It is clear from the figure that the cost of the Central Digital system for a
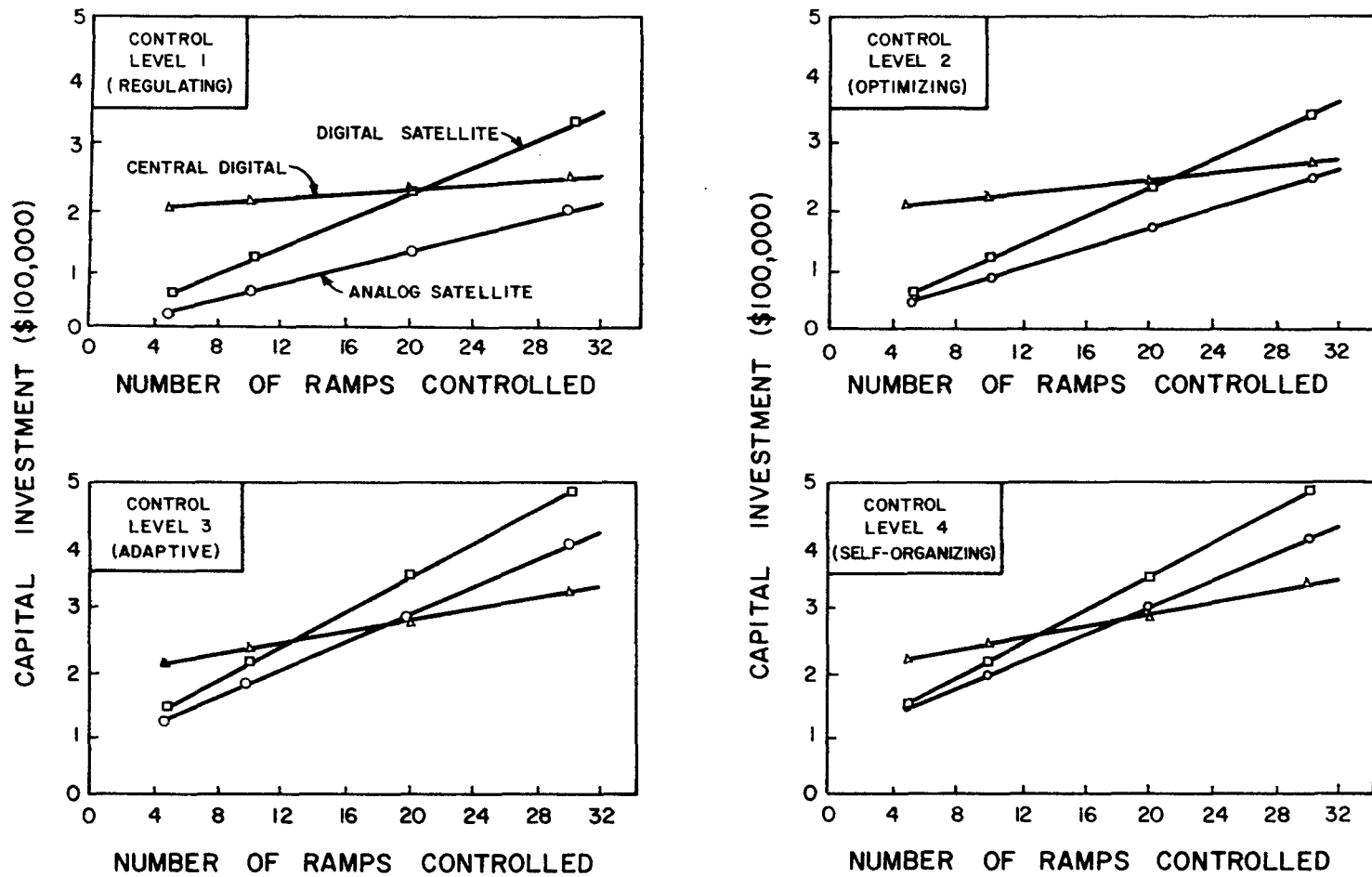
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FIG. 9   COMPARISON OF CAPITAL INVESTMENT AND THE NUMBER OF RAMPS CONTROLLED — TEN MILES OF FREEWAY — ONE DIRECTION

nineteen-ramp system is less than that of the other two systems at the third and fourth levels of control. The preference of the Central Digital system for a large number of ramps should be apparent. Thirdly, the benefits shown in Figure 3 represent the benefits accrued from only one hour of control per day and in only one direction. As the system is expanded to include both directions and longer periods of control, it is evident that its cost-effectiveness will continue to improve.

The authors feel that further discussion is necessary regarding the total travel-total travel time characteristic curve illustrated in Figure 2 in relation to the implementation of a ramp control system consistent with the multi-level design concept. The reader should be aware that the characteristic curve in Figure 7 represents the operating characteristics for the case study section of the Gulf Freeway. The illustrated relationships will vary from freeway to freeway and between specific sections and lengths of a freeway.

The changes in the operating characteristics shown in Figure 7 resulting from each level of control are for the Gulf Freeway study section only. The improvements resulting from the implementation of the four levels of control will differ on other freeways and on other sections of the freeway and therefore each would require a separate analysis. It is probable for example, that the congestion on another freeway may not be as severe as that on the Gulf Freeway. If this is the case, then it may be possible to improve the operation of the facility to a range near the vertex of the characteristic curve or perhaps to the left of the vertex by merely implementing a control system at control level 1.

APPLICATION

The administrator who is considering implementation of freeway
ramp controls for a total freeway system within a city is confronted
with the problems of (1) identifying the freeways that must be controlled,
(2) the sections of each freeway that must be controlled, and (3) the
order of implementation. Order of implementation is important because
sufficient resources will not be available, in most cases, to immediately
install a complete system throughout the city. The preceding sections
of this report provide some methodology for cost-effectiveness analysis
and delineates the cost-effectiveness of four specific levels of control
which range from a simple type ramp control installation (level 1) to
a highly sophisticated type of control involving the use of a centralized
digital computer and having the abilities to increase its performance
efficiency as time progresses (level 4).

It has been pointed out that each level of control requires a
set expenditure that yields a given amount of effectiveness. As the
level of control is increased, additional hardware is required and
therefore the cost increases. The added hardware, however, can result
in some change in effectiveness. One should fully understand that
the basic hardware system of a given level of control is not discarded
when a higher level of control is implemented. The basic hardware
remains intact; hardware is added to the basic system without removing
the original components. Each component, both old and new, function
as the total hardware system for the new level of control. In other
words, the succeeding higher levels of control can be implemented in

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stages as **greater** sophistication in control is needed and desired.
It should be understood that implementation of the first level of
control can be highly cost-effective, and, in some cases, this level
might be sufficient to alleviate freeway congestion in certain areas.
Also, ramp control at the first level can significantly reduce rear-
end collisions on the ramps.

To provide a manual for the implementation of ramp merging control
for a total freeway system within a large city is beyond the scope
of this report. Certain guidelines and recommendations, however,
are feasible with the use of cost-effectiveness in evaluating alternatives.

Analysis of the Problem Situation

One of the first activities that must be accomplished before
implementation of hardware is to define the problem. Since a problem
is an outward expression of an unsatisfied need, the task is to define
the need. This means gathering and analyzing data to describe the
operational situation, economic considerations, policy, etc. Problem
definition is accomplished by activities variously called making a
systems survey, characterizing the situation, data gathering, environmental
research, and understanding the problem.[19]

The individual in charge of freeway operational improvements may
find himself in a situation in which he has a vague objective, a need
to satisfy, and many doubts on how to pursue it. A good starting place,
of course, would be to locate the general areas on the freeway system
on which operational problems exist. One way of accomplishing this
without expensive studies is to visually inspect the freeway system

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from the air. If the organization does not have a small fixed winged plane or a helicopter, a craft can be rented. Flights can be scheduled to coincide with the morning and afternoon peak periods for an on the spot inspection tour.

A better approach would be to take aerial photographs of the entire system and to use these photographs to develop mosaics of the freeway system. The mosaics would then provide visual representations of where the problem areas are for the entire freeway system. Therefore, these particular areas would be the locations where more detailed analyses could be made at a later date. The mosaics then would provide a starting place from which one can abstract general information relative to specific problem areas. Techniques of aerial photography and their application in analyzing freeway traffic operations have been described in previous TTI reports. See References 20, 21, 22 and 23 for example.

In addition to the mosaics, accident data could be obtained from accident records and accident frequency data could be developed and appropriately referenced to specific locations. Also, travel time runs and volume counts on each of the freeways during the peak periods can provide some valuable insight and information relative to the problem areas. The accident, volume and travel time data would be used as inputs for a more comprehensive cost-effectiveness evaluation during later stages in the planning phase. Once the general problem areas and their limits have been identified, more detailed studies can be made as required in order to define the problem situation more completely. The types of studies that can be made are described in other publications of this Project.

Setting Objectives

Selecting objectives is the logical end of problem definition. Once the objectives are chosen, the search for alternatives can begin. Setting objectives includes the selection of the measures of effectiveness which will be used to evaluate the alternative systems. A value system must be established to evaluate the merits of the alternatives.

The evaluation of the several measures of effectiveness have been reported on earlier in this report and should be helpful in assessing the relative changes of each individual factor in respect to the four levels of control which have been suggested in the multi-level design concept. The decision-maker must decide upon the measure of effectiveness which, when optimized, constitutes maximum efficiency.

It should be recognized that when more than one measure of effectiveness is selected, maximizing one of the figures of merit may result in what is termed "suboptimization." Optimization of one of the measures of effectiveness could have a negative effect with respect to the other measures of effectiveness. For example, in order to maximize freeway speed, a more respective ramp control policy would be imposed, thus increasing the delay on the ramp. This condition is referred to as suboptimization. Tradeoffs must therefore be made so that an optimal mix might be selected.

The appropriate measures of effectiveness should have two characteristics: First, it must be relevant; secondly, it should be measurable. These objectives are often conflicting to the extent that the most relevant are often very difficult to measure.

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Alternatives

After the problem has been analyzed and the objectives and measures of effectiveness established, alternative hardware systems can be listed and analyzed. Thorough examination of the functional needs usually brings insight into the problem and leads to generating alternatives that can satisfy the desired goals. The alternatives will depend upon the objectives selected. For example, if the prime objective was to minimize accidents on the on-ramps, then the level of control and ramps selected to be controlled might be different than if the objective were to reduce travel time in the freeway corridor.

System Costs

Costs are the resources expended in the introduction and continued operation of the alternative systems. In order to estimate the system costs, the systems should be described in terms of their cost generating properties. This includes information on (1) equipment description, (2) operational concepts and objectives, and (3) location of facilities. In other words, the systems should be described in specific terms.

Another step in costing the system is to define the ground rules to be used in the evaluation. The ground rules, if effect, represent the assumptions underlying the cost analysis. Examples of study ground rules are as follows:

   (1) Type of cost index to be used. (Example: Investment and 10
       years of operating cost).

   (2) Rules regarding amortization or discounting to present value.

(3) Rules regarding costs of other agencies or departments.

(4) Special rules regarding costs which may be shared by other
    groups. (Example: Use of the computer for data processing
    not related to freeway control).

Once the system is fully described and the study ground rules set,

the process of estimating resource requirements and costs can proceed.

The cost of implementating each of the alternative systems cannot

always be exactly ascertained to the dollar. However, using cost

data provided earlier in this report, it is possible to develop cost

estimates which should be reasonably close. The cost estimates pre-

sented in Tables 1, 2 and 3 of this report provide sufficient documen-

tation for analyst to estimate the cost of alternative systems that

have been generated for analysis. Some of the cost elements may differ

for future applications but basic cost items are available that should

be useful.

Benefits of Control

It would be ideal if the performance of the alternative control

systems for a specific freeway system could actually be measured. But

from a practical standpoint, it is not feasible to implement each hard-

ware system at every location in order to measure their effects. Thus,

if the systems cannot be evaluated under real world conditions, a model

of the system would be useful for evaluation. If a model could be

developed that would abstractly represent the operational system, then

this model could be manipulated to assist in estimating the effects of

the control systems. Figure 7 of this report is representative of the

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type of model which could be used to evaluate alternative systems from which several measures of effectiveness could be evaluated.

The amount of data required to determine the effectiveness of the alternative systems would depend upon the nature of the study. In some cases it might be sufficient to utilize results of other studies, such as the one reported here, and to extrapolate these results to the situation under study. Careful interpretation of the results would be necessary so that proper utilization would evolve. For example, Figure 8 of this report indicates that an annual reduction of about 42,000 vehicle-hours of total travel time could be realized on the 2 1/2 mile section of freeway under study by implementing control level 1 using the Analog Satellite System. This does not imply that a reduction of 84,000 vehicle-hours would result if the control system was extended another 2 1/2 miles upstream. It is apparent that if the upstream section were currently operating at a high level of service, ramp controls would not material change the operating conditions within this area. Benefits, therefore, are not necessarily linearly related to length of freeway controlled.

Criteria

Earlier in this report, two criteria were set forth for the evaluation of alternatives. The first criterion presumes that a fixed budget is specified. The effectiveness of each alternative system under the budgetary restraint is then determined. The system that has the highest level of effectiveness is the most efficient of the alternatives and therefore is the preferred system. The second criterion presumes that

the objective is specified. The cost of each alternative system in attaining the objective is then determined. The system that attains the objective at the lowest cost is the most economical of the alternatives and therefore is the preferred system. Note that in both of these general methods of approach to the problem, either the cost of the alternatives or the objective to be attained is held constant so as to have a common basis for comparison.

Cost-effectiveness curves were developed in this report in order to generalize the results of the investigation. Neither the Equal Cost nor the Equal Effectiveness criteria applied in this case because the authors were concerned with presenting the data in a form which would be usable over a wide range of cost and effectiveness. It is therefore possible to evaluate the results from the standpoint of any given cost or any given level of effectiveness within the ranges reported.

If the exact budget is known, then it would be convenient to select the Equal Cost criterion to evaluate the alternatives. Similarly, if a level of effectiveness is established, then the Equal Effectiveness criterion should be selected. The preferred system can then be chosen.

In the early stages of planning, however, it is conceivable that neither the amount of the available monetary resources not the desirable level of effectiveness have been decided upon. It would therefore be desirable to construct cost-effectiveness curves from which management could abstract data to make decisions regarding the program development. The concept of multi-level design (stage development), described and analyzed from a cost-effectiveness standpoint in this report, would be useful in the development of these curves. The cost-effectiveness

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curves for the alternative systems would be a valuable aid to management

who make the decision regarding resource allocation.

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