COST-EFFECTIVENESS OF FREEWAY MERGING CONTROL

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This report is concerned with the cost-effectiveness evaluation of alternate freeway merging control systems, including the analog satellite system, digital satellite system, and digital central control system. The methodology used was consistent with a multilevel system design concept that establishes a hierarchy of control that results not only in an efficient system but also in one that can be implemented in stages. Each succeeding stage results in increased system sophistication and consequently increased cost. The cost effectiveness of each of 4 control stages (or levels) has been evaluated. The costs and effectiveness of alternative control systems were determined for a section of the Gulf Freeway currently under surveillance and control. The measures of effectiveness reported constitute those achieved during the morning peak period from 7 to 8 a.m. The capital investment as related to the number of ramps controlled was also investigated. The analog system appears to be the preferred alternative for the 8-ramp system studied on the Gulf Freeway. However, when the number of controlled ramps increases, the cost of implementing the central digital system will eventually be less than the cost of either the analog satellite or the digital satellite systems.

•THE HIGHWAY administrator faced with the arduous task of implementing and operating a freeway ramp control system must make decisions regarding the nature of the system desired within certain constraints that affect his decisions. Generally, the principal constraint is that of limited monetary resources. If there were no monetary limitations, then certainly the most elaborate and effective system could be installed. In this situation, the administrator would have few decision problems. In the real world, however, it would be a rare occasion when he could work with an unlimited budget. He, therefore, strives to achieve a strategy that will allow him to provide the greatest benefits with available funds.

The administrator may have sufficient resources to install only a partial system but have funds available later for expanding the system capabilities. The pressing problem becomes a matter of where to start or what elements to install so that at any stage the system is effective in improving freeway operations and safety. In this paper, an attempt is made to provide information required for a systematic approach toward the development of a control system consistent with cost-effectiveness considerations.

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ANALYSIS OF FREEWAY MERGING CONTROL

Objectives of Freeway Merging Control

The objectives of a merging 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 reduces the probability of rear-end collisions in the merging areas due to false starts, reduces the tension on a merging driver, and 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 these requirements for merging and freeway control (1, 2). 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 that the ramp can move into the gap. Figure 1 shows 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 vehicle can probably enter it, a ramp vehicle is released so that it reaches 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.

Multilevel Design Approach

A multilevel approach to design has been introduced by Drew (3) 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, and the control law is split into several degrees or levels of sophistication. The multilevel approach is directed toward establishing a hierarchy of control that results not only in an efficient system but also in one that can be implemented in stages. The 4 levels of control, in ascending order of sophistication, are regulating, optimizing, adaptive, and self-organizing.

The regulating level as applied to freeway merging control accomplishes that which might be called the basic subgoal of the system, i.e., 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 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 2 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 or stalls), 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 3 levels. Decisions are based on the accumulated experience and understanding of the freeway system operation. 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 that will exceed this capacity.

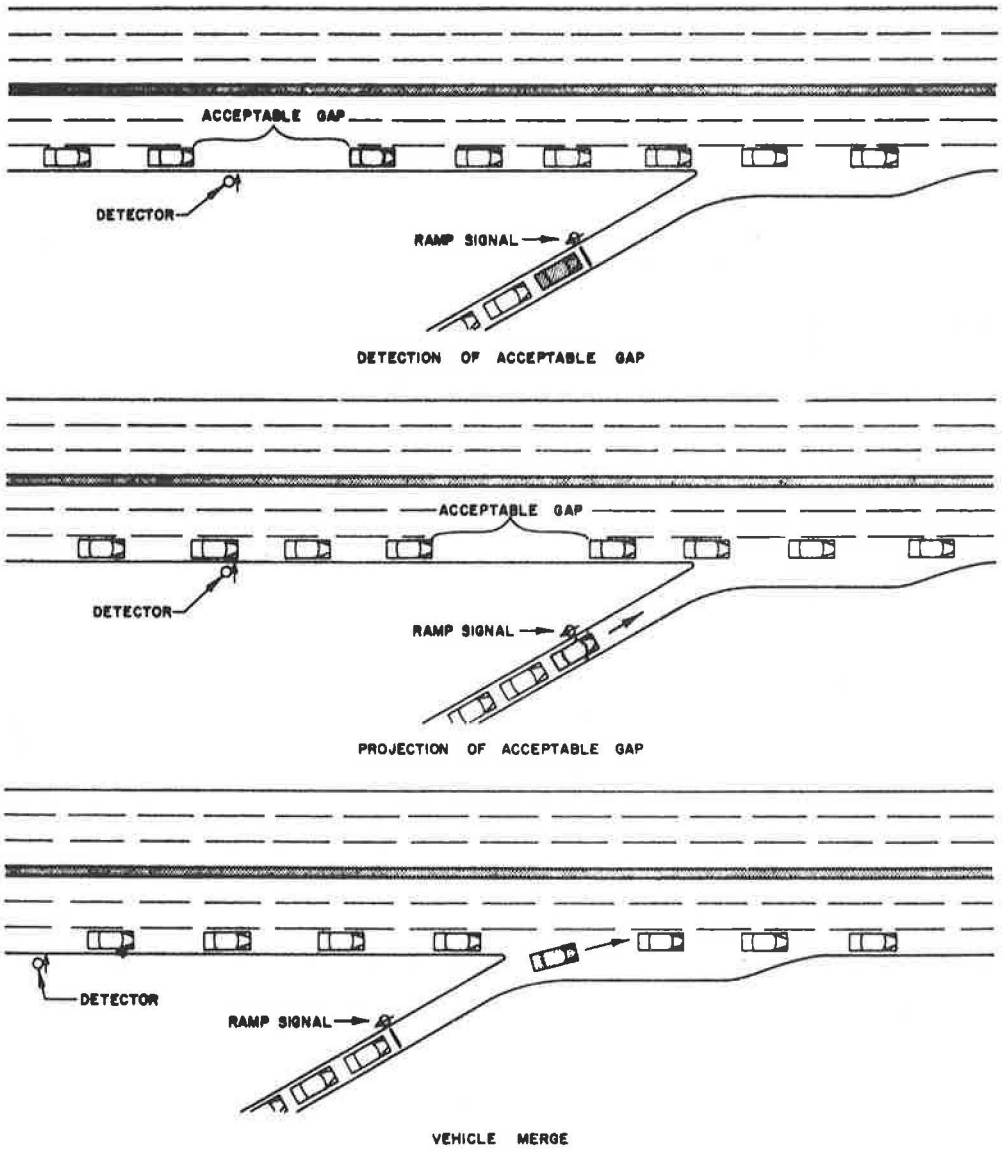


Figure 1. Gap-acceptance mode of ramp control.

Each level of control represents an increase in sophistication that raises the cost of the system and provides a separate level of effectiveness. The multilevel approach, therefore, provides a rational 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 control systems under consideration. The cost and effectiveness of each alternative, discussed later in this paper, were analyzed at each of the 4 levels of control and are reported here.

Study Site

The Gulf Freeway in Houston was selected as the proving grounds for the development of a prototype freeway merging 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-ft lanes in each direction, separated by a 4-ft concrete median with a 6-in. barrier curb. The study area extends about 2½ miles on the inbound freeway from Texas-225 to Dumble Street interchange. Between these interchanges defining the study area are 8 interchanges and 10 entrance ramps; 8 of the entrance ramps are under control. Frontage roads are one-way and continuous except at 2 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 overpasses.

Candidate Freeway Merging Control Systems

Three candidate merging control systems that utilize the gap-acceptance control criterion were analyzed. For distribution, these systems are designated in this paper as follows: system 1, analog satellite; system 2, digital satellite; and system 3, digital central control.

In the analog satellite system, analog controllers are used at each entrance ramp to perform the first 2 levels of functional control, independent of any central control unit. At these 2 levels, each controller regulates and optimizes the operation at its own particular ramp area, independent 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 2 levels of functional control. A central processing unit is required to integrate these controllers and to effect 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; therefore, the need for analog or digital controllers at the ramps is negated.

The digital central control system has a central digital computer perform all 4 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 unit costs of the capital investment for each system and is based on experience gained with freeway merging control systems. The estimates reflect the labor and installation costs associated with the Texas area and will, therefore, vary among locations. The costs for each system are divided into estimates for each of the 4 functional levels, consistent with the multilevel system-design approach, for control in 1 direction of freeway flow. These costs represent the initial amount that would be required to install any 1 of the 4 levels. For example, the costs at the second functional level are associated with a system that is designed to operate at the second level.

A control system designed for both directions of freeway flow can conceivably take one of the following 2 forms: (a) a system capable of control in only 1 direction at a time or (b) a system 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 1 direction in the morning and in the opposite direction during the evening. This type of control feature minimizes the cost because equipment required for unidirectional control can be electronically interconnected to serve both directions

TABLE 1

UNIT COSTS OF CAPITAL INVESTMENT, INCLUDING PURCHASE AND INSTALLATION, FOR 4 SYSTEMS

System	Level	Comment	Equipment	Cost ($)
Analog satellite	Regulating	Each ramp has analog controller, ramp signal, gap and speed detector, merge detector, and check-in detector.	Detectors, signals, and cabinets, per ramp Controller, per ramp	2,500 4,000
	Optimizing	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 are in addition to those for the regulating level.	Detectors, per ramp Controller, per ramp	500 1,000
	Adaptive	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 Per ramp Additional for system Local controller, per ramp Central controller, for system Telemetry, per foot	 2,000 1,000 1,000 10,000 1.20
	Self-organizing	In addition to the equipment at the adaptive level, electronic memory (digital), interface equipment, and a more sophisticated central controller are required. Costs given are additional to the costs at the adaptive level.	Memory, for system Interface, for system Central controller, for system	8,000 3,000 1,000
Digital satellite	Regulating	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, and cabinets, per ramp Computer, per ramp	2,500 8,500
	Optimizing	A queue detector is necessary in addition to the equipment for the regulating level. The controller does not change. Costs given are additional to the regulating level.	Detectors, per ramp	500
	Adaptive	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 are additional to the costs of the optimizing level.	Detectors Per ramp Additional, for system Local controllers, per ramp Central computer, for system Telemetry, per foot	 2,000 1,000 500 10,000 1.20
	Self-organizing	Central computer requires some additional hardware to that of the adaptive level. The cost given is additional to the cost for the adaptive level.	Central computer, per ramp	2,000
Digital system control	Regulating	This system involves a single central computer. Telemetry is required with the first level. Cost is for a 50 pair direct cable.	Detectors, signals, and cabinets, per ramp Computer, for system Telemetry, per foot	2,000 105,000 1.60
	Optimizing	In addition to the equipment for the regulating level, queue detectors are required at each ramp at the additional cost given.	Detector, per ramp	500
	Adaptive	The computer is expanded to 2 disk drives with an additional data channel. The costs given represent the additional cost above the optimizing level.	Detectors Per ramp Additional, for system Computer, for system	 2,000 1,000 5,500
	Self-organizing	The computer is expanded from 16K to 24K core. The costs given represent the additional cost above the adaptive level.	Computer, for system	18,000

on a time-sharing basis. The cost of a system capable of 2-directional control would be less than twice the cost of a unidirectional control system because certain costs are fixed, regardless of the number of directions controlled. In this report, only unidirectional systems are considered. It should be kept in mind, however, that a 2-directional control system would be more cost effective.

The cost estimate of the digital satellite system is biased toward the high side because of the lack of experience with such a system. It is known that controlling 2 ramps with a digital computer requires 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 as many as 4 or 6 ramps, may well prove to be the most cost effective for the lower levels of control. The cost estimates in this paper, however, allow for 1 small digital controller at each ramp.

Table 2 gives the estimated capital investment costs of the 3 operational systems for the section of freeway considered. The estimated direct annual costs for each system are given in Table 3.

TABLE 2

SUMMARY OF CAPITAL INVESTMENT COSTS FOR 2½-MILE SECTION OF FREEWAY IN 1 DIRECTION WITH 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

Measure of Effectiveness

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, several measures should be employed in the design and evaluation. Although it would have been desirable to actually measure the figures of merit at all levels of control, the development of the prototype system on the Gulf Freeway has not yet progressed beyond the second level of control. Consequently, the evaluations of the system at the first 2 levels of control, in comparison with no control at all, are substantiated with actual field measurements. The effectiveness of the systems at the 2 higher levels of control are speculative and represent the best judgment of the project staff on the basis of their close association with merging control systems during a 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 one of the prime techniques used for the analysis 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 in the past to evaluate freeway flow (4). These techniques provide the following measures of system effectiveness: total travel, total travel time, average speed, and kinetic energy.

In addition, 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. Average speeds and the average number of speed changes were calculated, and based on the knowledge of the volume and the dis-

TABLE 3

DIRECT ANNUAL COSTS

Item	Level of Control	System 1	System 2	System 3
Maintenance	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
Wages[a]				15,500[b]
Power and transmission[a]				10,000
Miscellaneous[a]				
Office rental				6,000
Contingencies				10,000

[a]Same for all 3 systems at all levels of control.
[b]One engineer and one technician on a 50 percent basis.

tribution of traffic, motor vehicle running costs were calculated by using Winfrey's (5) cost tabulations.

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 represents 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 during the past 4 years via the closed-circuit television surveillance system and has been documented in the literature (6). These data formed the basis for relating the effectiveness of the alternative freeway merging 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 that reflect the efficiency of the merge were also included in the analysis. Special ramp studies were performed to measure the acceleration noise of ramp vehicles, the delays to ramp vehicles, and 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 noise (7). 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 acceleration characteristics, whereas values approaching zero reflect a smooth flow. Acceleration noise is related to factors such as comfort and driver anxiety 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 restriction 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 the matching of 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 2 shows the basic relationship between total travel and total travel time on the 2½-mile Gulf Freeway study section and also shows the manner and degree in which flow on a freeway can be improved by implementing a ramp merging control system consistent with 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 is to reduce total travel time and increase total travel time in a manner that achieves operations at or near the vertex. Figure 2 shows

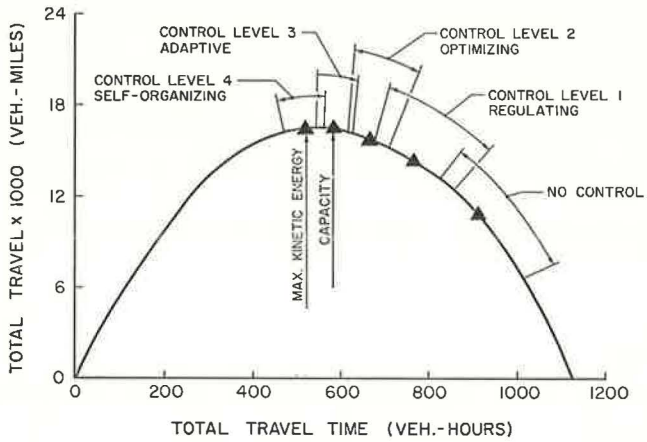


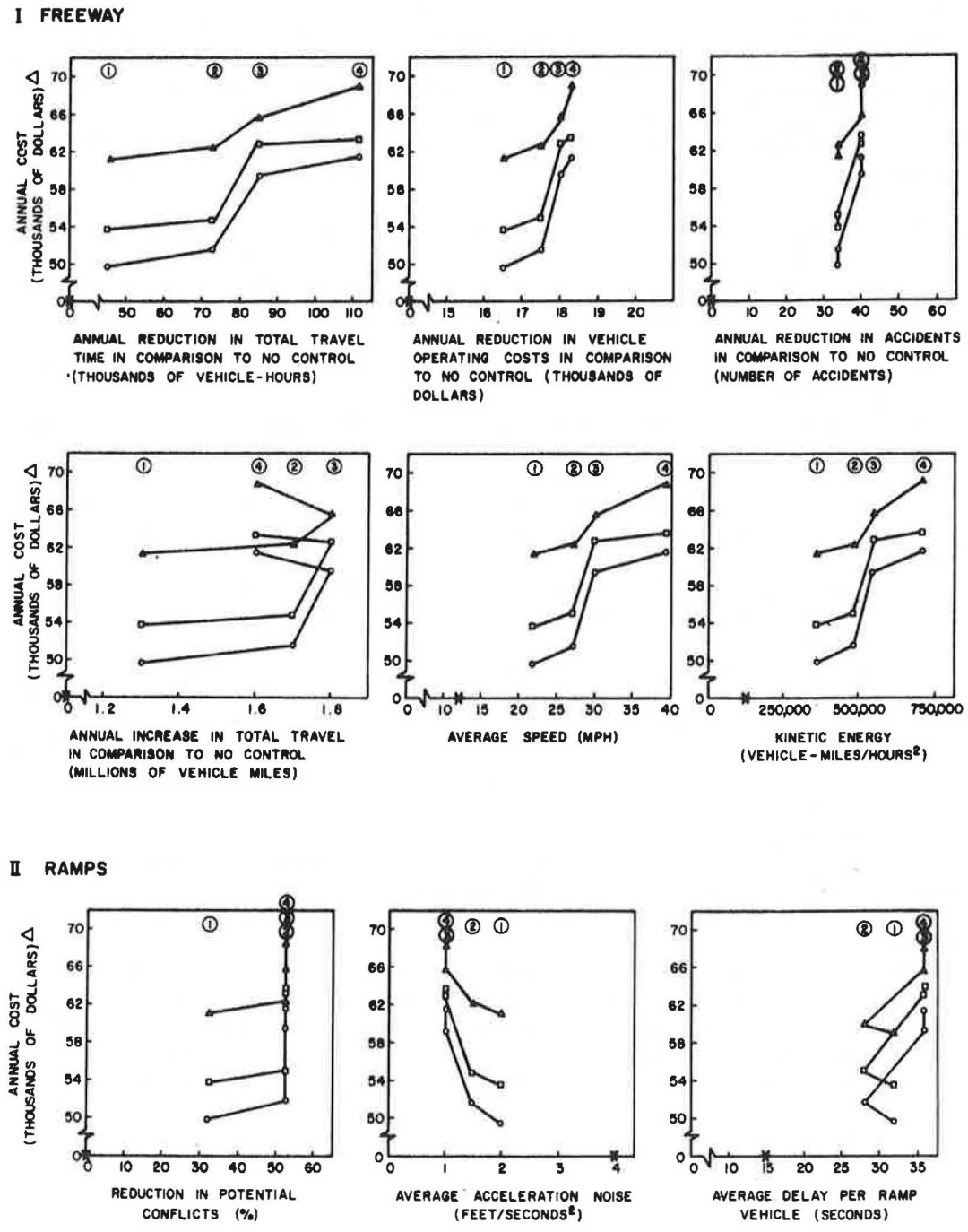
Figure 2. Operating characteristics for a 2½-mile section of the Gulf Freeway control system.

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 shows how the application of control levels 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 is at the expense of reduced throughput (total travel) in terms of vehicle-miles of travel. 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 that tends to maximize kinetic energy or minimize acceleration noise and maintain a more uniform speed on the freeway.

The operating points shown in Figure 2 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 on the Gulf Freeway. These points have been isolated for analysis purposes only in order to compare the 3 alternative systems under investigation. It should be recognized that a wide range of operation does occur for each of the control levels because of 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 shown in Figure 3. Assumed in the analysis are a 5 percent vestcharge rate and a 10-year amortization period for all the equipment. It is also assumed that the computer software package that is used to control the system would be available to the operating engineer. Any modification requirements of the software are considered to be performed by the personnel assigned to the system, and the costs for the modifications are included within the wages of these personnel. The measures of effectiveness shown in Figure 3 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 4 levels of control.

Figure 3 shows that the analog satellite system is the most cost effective compared with the other alternatives under investigation. This system can provide absolute levels of effectiveness at a cost lower than either the digital satellite or the the digital central



▲ CENTRAL DIGITAL
□ DIGITAL SATELLITE
○ ANALOG SATELLITE
① CONTROL LEVEL

✱ REPRESENTS COST-EFFECTIVENESS WITH NO MERGING CONTROL
△ ASSUMES A 10-YEAR AMORTIZATION PERIOD AND A VEST-CHARGE RATE OF 5 PERCENT

Figure 3. Cost-effectiveness results.

control systems. For example, based on 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 42,000 vehicle-hours per year is about $49,700 for the analog satellite system, $53,000 for the digital satellite system, and $61,000 for the digital central control system. The tendency of the analog satellite system to be more cost-effective than the other 2 alternatives is consistent for each measure of effectiveness and applies throughout the total range of each measure of effectiveness shown in Figure 3.

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 that lie below circled numbers represent the operating conditions of the freeway at control levels 1, 2, 3, and 4 respectively. Figure 3 shows 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 later in the paper.

From the standpoint of the multilevel approach to the design of a freeway merging control system, it is important to determine the justification for the increases in system sophistication; therefore, an analysis was performed to provide some insight into this type of decision. Only the analog satellite system was selected for this phase of the analysis because it was found 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 3 alternative systems, not all can be assigned dollar values. Currently, economic coefficients can be safely assigned only to travel time, accidents, and motor vehicle operating costs. The monetary benefits due to these 3 measures of effectiveness can be combined to compute a cost-benefit ratio. In addition to this ratio, the remaining nonmarket factors can be assessed among the various levels of control.

Research by McFarland et al. (8) has shown the "average" value of time per vehicle-hour on the Gulf Freeway to be $2.92. This value was applied to the data to obtain monetary values of travel time.

Because no information was readily available as to the cost of motor vehicle accidents occurring on and near the inbound Gulf Freeway, a value of $600 per accident was set 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 memorandum issued by the National Safety Council (9).

The results of the analysis for the analog satellite system are given in Table 4. The benefit-cost ratio is the economic assessment of the benefits accrued through savings in travel time, accidents, and motor vehicle operating costs for the particular level of control. In addition, 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

TABLE 4

COST-EFFECTIVENESS OF ANALOG SATELLITE SYSTEM

Level	Net Annual Benefits[a] ($)	Net Annual Costs ($)	Benefit-Cost Ratio	Annual Increase in Total Travel (million vehicle-miles)	Increase in Average Speed (mph)	Increase in Kinetic Energy (vehicle-miles/hour^2)	Reduction in Potential Ramp Conflicts (percent)	Reduction in Average Ramp Acceleration Noise (ft/sec^2)
1	178,000	49,700	3.6	1.4	8	215,000	32	1.9
2	243,000	52,200	4.6	1.7	12	355,000	53	2.5
3	315,000	60,200	5.2	1.9	17	405,000	53	2.9
4	326,000	62,000	5.3	1.7	23	545,000	53	2.9

[a]Based on savings in travel time, accidents, and motor vehicle operating costs only.

energy, reduction in average ramp acceleration noise, and reduction in potential ramp conflicts are presented.

The results show that implementation of control level 1 will be highly cost-effective. The benefit-cost ratio, based on savings in travel time, accident, and motor vehicle operating costs, is 3.6. In addition, the following level of service improvements can be expected during the morning peak hour: an 8-mph increase in average speed; an annual increase of 1.4 million vehicle-miles in total travel; an increase of 215,000 vehicle-miles/hr^2; a reduction of 32 percent in potential ramp conflicts; and a reduction of 1.9 ft/sec^2 in average ramp acceleration noise. Similar analyses of the higher levels of control indicate that these levels of control would also be cost-effective. The benefit-cost ratios for control levels 2, 3, and 4 were 4.6, 5.2, and 5.3 respectively. In addition, the results show that significant improvements in the level of service would be realized at these higher levels of control.

Discussion of Results

Although the results shown in Figure 3 indicate that the analog satellite system is a better system than either the digital satellite or the digital central control system, 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 paper. Second, the magnitude of the system under control greatly affects the cost of the systems and will, therefore, alter the choice of systems. Figure 4 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 19-ramp facility is less than that of the other 2 systems at the third and fourth levels of con-

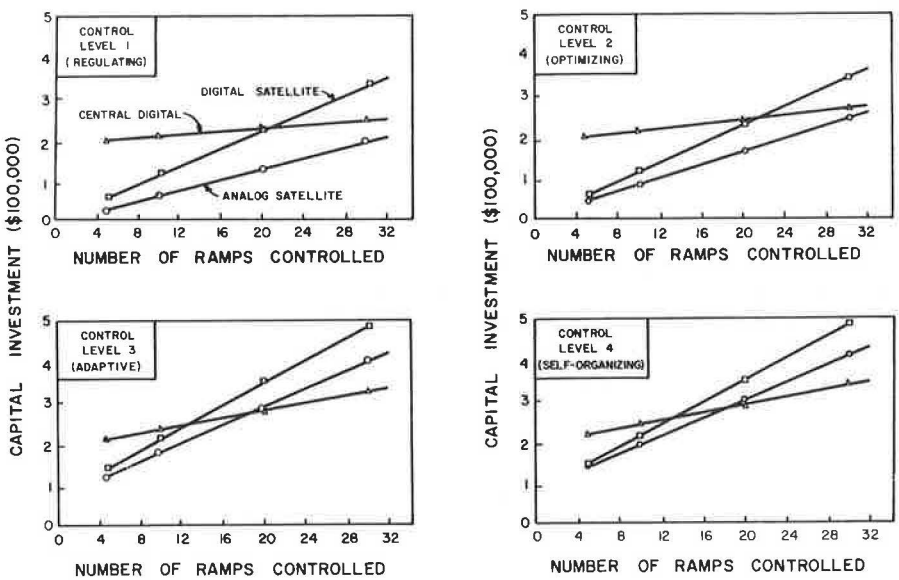


Figure 4. Comparison of capital investment and the number of ramps controlled on 10 miles of freeway in one direction.

trol. The preference of the central digital system for a large number of ramps should be apparent. Third, the benefits shown in Figure 3 represent the benefits accrued from only 1 hour of control per day and in only 1 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 and total travel time characteristic curve, shown in Figure 2, in relation to the implementation of a ramp control system consistent with the multilevel design concept. The reader should be aware that the characteristic curve represents the operating characteristics for the case study section of the Gulf Freeway. The improvements resulting from the implementation of the 4 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 so 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 system at control level 1.

The results of the study indicate that substantial improvements in freeway operation can be realized by implementation of a merging control system at the first level of control. This suggests that highway administrators should consider implementation of a system at this level of control as an immediate step toward improving freeway operations where known major problems exist. Consideration should also be given to immediate application where accident experience on entrance ramps is high. This level of control constitutes a very basic system that can be increased in sophistication at a later date if the need exists.

SUMMARY OF FINDINGS

This report has quantified the cost effectiveness of alternative freeway merging control systems consistent with a multilevel design approach. The following findings may be drawn from the evaluation presented in this paper:

1. The analog satellite system appears to be the preferred alternative for the 8-ramp system studies on the Gulf Freeway;
2. When a large number of ramps are controlled, the cost of implementing the digital central control system will eventually be less than that of either the analog satellite or the digital satellite systems, but the breaking point will vary, depending on the level of control selected;
3. Implementation of control level 1, which constitutes the control level with the lowest sophistication and the lowest cost, results in a substantial improvement in freeway operations, and in some cases implementation of a system at this level may be sufficient to alleviate freeway congestion in certain areas; and
4. The multilevel system design concept provides a rational basis for evaluating the cost-effectiveness of alternative freeway ramp control systems.

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DISCUSSION

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The authors of the paper are to be congratulated for their method and thoroughness of presentation after 3 years of study of the ramp control system on the Gulf Freeway. The use of the Gulf Freeway in Houston, Texas, was an excellent choice of location for this study due to its well-defined characteristics and its morning peak-hour intensity and directivity.

The authors have reviewed the objectives of freeway merging control to the extent that the case for this type of control may be proved and accepted by highway administrators. This method is a practical solution for reducing delays and accidents and for increasing the effectiveness of the highway system.

For the purpose of evaluating the study, the authors have assigned a multilevel approach consisting of 4 levels and are in the process of establishing the efficiency and cost effectiveness of each level. It is hoped that this study will be adequately financed to continue through levels 3 and 4 so that the actual figure of merit can be determined at all levels of control. The increase of the time duration encompassed by the study to extend beyond the morning peak hour of control would certainly be most beneficial to similar types of facilities.

The cost-effectiveness for alternate control systems has been presented in a very straightforward manner in its control applications for this highway. These data will prove extremely valuable to the highway administrator in assisting in the determination and implementation of the control level and degree of sophistication that his budget may afford. One of the most important variables that must be considered during the

planning stage of a new system is an exact definition of roadway geometrics, selected control strategy, and long-range planning for the additional installation of equipment. This additional equipment may include the digital central control system as defined by the authors. This more complex system, while more costly in the special highway study, will lend itself more readily to software modification and changes in control strategy as additional ramps are brought under control. This more sophisticated approach will also permit more economical control of a larger number of ramps, operation of diversion signing, and control of frontage road traffic signal systems, in conjunction with the freeway control if required.

The authors stated "that technological advances will drastically reduce the cost of digital equipment in the near future." The IBM System 7, announced in October 1970, and similar types of process flow control systems already announced or being tested may cause the authors' speculation of drastic cost reduction to be realized sooner than possibly expected.

In my opinion this paper should create interest and enthusiasm by highway administrators in investigating the implementation of a system that will improve an existing freeway. These improvements may consist of increasing the maximum throughput and reducing total travel time. The authors note that "although total travel time is reduced, the restriction is at the expense of a more restricted ramp control policy." This action creates the desirability of further study of the increase of diversion signs and control of traffic on the frontage roads to compensate for the ramp control restrictions. Again this warrants further funding and investigation to determine the cost effectiveness not only of the highway section but of the complete corridor.

The recurring theme of the paper is to evaluate the cost effectiveness of the candidate systems on the Gulf Freeway at the first 2 levels and, from the knowledge and experience gained through these studies, to project benefits through the next 2 levels of the hierarchy and attempt to apply these results to other proposed highway systems. This is an extremely difficult and empirical method of projection because in no way can it be conceived as the straight-line evaluation and cost assignment.

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For those considering freeway control, this paper offers information on the costs of 3 systems for performing gap-acceptance control at 8 ramps on Houston's Gulf Freeway. In addition, the costs and effects of 4 levels of gap-acceptance control refinement are estimated. The authors have defined the subject scope, pointed out most limitations, and indicated the speculative nature of some estimates. I wish to discuss items needing clarification and comment on general freeway control implementation considerations.

In regard to the costs presented in the paper, more information would have been desirable to better define the hardware details. It is not clear what kinds of detectors are specified or whether the controllers use front-to-front time headways or gaps between vehicles as implied by data shown in Figure 1. In any event, costs are relative, and local labor and market conditions can change component or total system costs drastically. For example, costs for the same basic ramp control installation with loop detectors and buried interconnect in the Chicago area would run 2 to 3 times the costs in Houston. Similarly, maintenance and operating costs will reflect local labor conditions.

In regard to the effectiveness of various control levels (Fig. 2), the basic operating characteristics curve seems quite speculative. In my opinion, Figure 2 shows a very weak base for a cost-effectiveness analysis because theoretical material can be easily misunderstood to be empirical.

Figure 3, the cost-effective results, shows that the effectiveness is the same at each control level regardless of the system. Therefore, the choice of system—analog satellite, digital satellite, or central digital—can be made on cost alone for particular control requirements. Because the effectiveness of levels 3 and 4 are speculative estimates, only the comparison of levels 1 and 2 and no control appear to be directly useful for implementation elsewhere.

Further analysis of the cost-effectiveness results shows that, when compared to control level 1, control level 2 reduced ramp delay but increased average freeway speed. This finding is most significant and deserves elaboration, particularly because the effectiveness data at these levels are based on documentation of actual field experience.

As far as the implementation of results is concerned, freeway merging control is only one technique for improving rush-period traffic operations. The analysis did not consider ramp control in either the ramp metering or ramp closure form. Ramp closure, pretimed metering, and traffic-responsive metering can be impelemented locally at costs less than those of the regulatory gap-acceptance level. Although gap-acceptance control is intuitively attractive, especially with poor merge area geometrics, the less costly forms of control can perform the regulatory function and are probably more cost effective. As the report indicated, the major benefits result from having some form of ramp control in lieu of no control. As refinements are added to the basic regulatory function, costs increase and the additional effectiveness becomes more difficult to measure and justify.

The next level of control performs the local optimizing function, which precludes use of the non-traffic-responsive techniques of ramp closure and pretimed metering. The choice for local control is then ramp metering or gap-acceptance merge control. If the merge geometrics and traffic patterns produce operational problems resulting from the conflict between ramp vehicles and freeway merging lane traffic, then gap-acceptance merge control should be considered. In the Chicago area, where there are good merge geometrics and trucks are restricted to the 2 right lanes, overloading congestion usually becomes introduced on the freeway in the left lanes downstream of the merge area, primarily because ramp vehicles change lanes after merging. The availability of acceptable gaps in the merge area may have little or no relation to critical conditions in the whole freeway traffic stream. In other words, optimization of each merge area does not necessarily optimize local freeway and ramp operations. Also, it may be undesirable to fill all available acceptable gaps at an upstream merge area if there are several entrance ramps downstream feeding a system bottleneck, especially if intermediate exit traffic is low.

The third and fourth levels of control serve to interconnect the local controllers for the purpose of overriding local conditions based on various system considerations. Once again, depending on the geometrics and traffic pattern involved, the freeway problems may be local in nature, such as at each merge area, or system in nature, where several ramps contribute to overloading one or more critical downstream bottlenecks. If a particular problem is local, then system considerations should override local control when required. If the problem is system-wide, however, then local conditions should override basic system considerations. There may not appear to be much difference between the 2 approaches, but for a less than complete initial installation it is important to provide the basic components initially and to expand later by adding the override elements.

Either way, any override usually imposes more restrictive control at critical ramps and less restrictive control at noncritical ramps. The major payoff with ramp control generally occurs with postponement or elimination of the onset of freeway congestion. As noncongested freeway conditions reach critical levels at particular bottleneck locations, it is often most beneficial to exert the maximum entrance ramp restrictions to keep the freeway from breaking down. Once turbulence enters the system and persists for several minutes, congestion develops that may lodge in a sustained manner at the nearest upstream geometric bottleneck, an upgrade, for example. Once congestion has become established, there may not be enough upstream ramp control available to effect a bottleneck demand drop, and the congestion may be irreversible until the overall demand decreases on the freeway at the end of the rush period. Thus, once the freeway breaks down, it may be more beneficial overall to be less restrictive with ramp controls that cause queues to interfere with surface street traffic flows.

The thrust of these comments is to point out that urban engineers and administrators considering some form of ramp control to relieve existing and potential freeway operational problems should also consider the flexibility needed for ramp control strategy changes, expansion, and integration into a larger system of various electronic traffic aids. Attacking the total freeway congestion problem on a broad scale may dictate a central digital system and a backbone surveillance network. Requirements for such future systems should influence the design of ramp controls implemented as the initial freeway improvement stage.

The philosophy of ramp control implementation in the Chicago area reflects experience with metering 39 ramps within a 75-mile freeway surveillance network. The backbone surveillance system features loop presence detection, leased phone line interconnect with a central process control digital computer, and tone telemetry signal communications. The surveillance system provides real-time incident detection that is serviced by emergency patrol trucks operated also by the Illinois Division of Highways. The data collection and evaluation capabilities of the surveillance system help define overloading conditions warranting ramp control or geometric improvements. Ramp control is added to the backbone surveillance system by installing 2 ramp signals, 2 ramp detectors, buried interconnect, cabinet, and tone equipment at each ramp. Additional freeway and ramp detection can be provided if research demonstrates increased sophistication is worth the cost. The backbone surveillance system is used to evaluate the operational effect of ramp control implementation and also other electronic traffic aids installed on an experimental or operational basis. Examples of other electronic components are changeable message signing, automatic reversible roadway control, and motorist aid systems.

All in all, the authors are to be complimented for documenting cost-effectiveness data for one aspect of freeway control. The paper is certainly a good starting point for more empirical data for more sophisticated control levels, for other forms of ramp control, and for other cost and effectiveness factors, such as equipment reliability and multipurpose applications.

AUTHORS' CLOSURE

The authors would like to express their appreciation to Hochstein and McDermott for their fine and stimulating discussions. Both have expressed the importance of analyzing the total system and of considering the flexibility needed for ramp control strategies and future expansion in the number of ramps controlled, surveillance and control of

adjacent arterials, and addition of real-time driver information hardware. Ramp controls implemented as the initial freeway improvement stage will be influenced by the total system requirements.

The cost-effectiveness analysis presented in this paper was performed for a freeway merging control system. Other forms of ramp control, such as ramp metering, had not been considered in the analysis. McDermott has presented an excellent summary regarding the application of the multilevel design concept to ramp-metering systems.

We agree that the choice of ramp control mode will be based on the geometrics and traffic patterns that produce operational problems between ramp vehicles and the freeway traffic. Depending on the nature of the operational problems, it may be desirable in some cases to intermix the modes of control within a system such as having some ramps closed, operating others under ramp metering, and operating others under ramp-merging control. It may even be desirable to interchange the modes of control at a particular ramp.

The characteristic curve (Fig. 2) was developed by measuring travel time and total travel through the study section during several hours over a wide operating range. Only operating conditions in which no adverse weather or major incidents affected the flow of traffic on the freeway are represented. The characteristic curve represents the best fit functions established by regression analysis. The ranges of operating conditions through control level 2 were then identified by observing several days of operation under these levels.