Real-Time Evaluation of Freeway Quality of Traffic Service

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The freeway control process follows reasonably well-known laws that can be stated mathematically. The process can vary due to changes in flow characteristics, input constituents, economic factors, or policy decisions; but generally the control action to be exercised can be determined from the mathematics of the problem. Consequently, a freeway control system can permit a control computer to make decisions to select and implement control alternatives. This paper deals with the techniques and methodology needed to effectively control a freeway system in real-time.

The extent to which an optimum control policy can be established is directly related to the extent to which the pertinent traffic and control system variables can be measured and interpreted. Toward this idea, the report develops input-output analysis techniques that can be applied to a control environment. Using this analysis, a method of traffic block detection and location is presented and a step-by-step control action is developed.

With the application of real-time control to the problems of freeway congestion, the true science of freeway operation has emerged. The appealing idea of reacting to the problem as it happens can now be realized.

•INTRODUCTION of the electronic computer a little more than a decade ago fundamentally changed techniques of data processing. Work previously undreamed of soon became possible. Today, a second revolution is in progress, and its effect will ultimately be more rewarding than the first. Systems described as on-line and real-time are now being planned and installed. In these, data may be entered directly into the computer system from the environment in which they work and information sent back. To be precise, real-time refers to the performance of a computation during the actual time that the related physical process transpires so that results of the computations can be useful in guiding the physical process. This report deals with the application of this concept to the operation of an urban freeway.

As of now, several freeway surveillance and control projects are in the operational stage. The Chicago Area Expressway Surveillance Project on the Eisenhower Expressway, the John C. Lodge Freeway in Detroit, and the Gulf Freeway in Houston are the most notable, with other projects started in Seattle, Dallas, and Los Angeles. These control projects have worked toward the objective of real-time control of a freeway system, and to some degree the concept has been applied and its benefits realized. However, a single unified approach to freeway control has not yet been developed and applied on a real-time basis. It was to satisfy the need of developing the system requirements to perform the task of freeway control and traffic evaluation on a real-time basis that the Texas Transportation Institute was awarded a research contract by the U. S. Bureau of Public Roads.

TOWARD A SOLUTION

To achieve on-line, real-time control, a freeway control system must satisfy certain functional requirements. These requirements include (a) the ability to detect or

Paper sponsored by Committee on Quality of Traffic Service.

sense the presence of vehicles at certain locations; (b) the ability to measure certain traffic and vehicle characteristics to the required accuracy; (c) the ability to predict ensuing conditions on a real-time basis; (d) the ability to determine a value for each control parameter; (e) the ability to determine and display, on a real-time basis, the state of the system and the ability to use this information as feedback to the control system; and (f) the ability to detect and react in real-time to transients in the traffic flow.

Several of these requirements invoke a data processing system in which at least one process is critically defined with regard to elapsed time (measured in fractions of a minute). When considering a freeway control system, the aggregate of the subprocesses must satisfy the critically defined deadline of releasing ramp vehicles for gaps—i.e., the critically timed process within the real-time system produces control outputs.

REAL-TIME SYSTEM FEATURES

To discuss a real-time evaluation scheme, several system components need to be defined (1). There are many more features than the ones to be considered here; however, only those applicable to a freeway control system are presented.

Input

Inputs from a freeway system arrive at the control computer at random intervals. These random inputs interrupt the computer and therefore must identify themselves. The number of input types affects the number and kind of formatting and editing programs, as well as computer storage allocations. An interrupt from a freeway lane detector requires servicing programs completely different from an interrupt indicating a green light confirmation from an on-ramp signal. Most inputs automatically deposit their data in temporary storage buffers to give the computer some leeway in servicing an interrupt. In the freeway control system described, the interrupts from the freeway and ramp detectors are handled in this manner to permit simultaneous detector interrupts to be serviced one at a time.

Software

Programs for real-time systems are constrained by the system deadlines. To keep the execution time short, some form of optimum programming is needed. Although useful for some processing routines, higher order languages, such as FORTRAN, are seldom acceptable for writing control programs because of compiler inefficiency. Real-time systems, therefore, incur the extra expense of machine-language coding for large portions of their programs. Also, time constraints result in program segmentation problems. When programs plus data requirements exceed main-storage capacity, the programs are broken up and stored in external storage units. This creates an access-time delay that must be added to the execution time of the program for estimating real-time throughput.

Reliability

Because of the urgency that justifies a real-time system in controlling a freeway, it seems evident that interruptions due to system failure cannot be tolerated. Thus, system specifications call for "fail-soft" operation (where some degradation of system performance is allowed, but total outages are not allowed). The goal of uninterrupted operation can be achieved by a simple, fixed-rate controller at the signal in the field. This would be a temporary control at a significantly degraded but safe level of performance.

REAL-TIME CONTROL SYSTEM

A real-time control system is one "which controls an environment by receiving data, processing them and returning the results sufficiently quickly to affect the functioning of the environment at that time" (2). The control system appears to the operator to be

an integrated complex of equipment that monitors the environment, evaluates the environmental parameters, predicts environmental changes, and then makes optimal decisions for controlling the environment so that its changes stay within desired limits. The environment in this case is the freeway, service roads, and cross-street intersections. Even though the actual control is exerted on the on-ramps, the entire system of influence is considered.

Because the computer is simply one functional component of the system, control-system computers are usually specified to fit the initial system objectives exactly. This approach succeeds in freeway-control systems where the number of controlled on-ramps may expand and where the number of process control functions tends to remain constant.

The freeway control process follows reasonably well-known laws that can be stated mathematically. The process can vary due to changes in flow characteristics, input constituents, economic factors, or policy decisions; but generally the control action to be exercised can be determined from the mathematics of the problem. Consequently, a freeway control system can permit the control computer to make decisions to select and implement control alternatives. To do this and at the same time reduce the requirement for human operators in the system, the vehicle detectors and ramp control signals are automated and tied directly to the computer. Both the time constraints and the completeness of the freeway control algorithm relieve the control computer from storing a large data base needed to help make decisions. With the application of real-time control to the problems of freeway congestion, the true science of freeway operation has emerged. The requirements for the traditional extensive evaluation studies no longer exist. The appealing idea of reacting to the problem as it happens can now be realized.

ANALYSIS TECHNIQUES

Any analysis techniques used in a real-time environment must meet the following set of requirements:

1. They must be applicable to a fairly long section of freeway, perhaps several miles.
2. They must be capable of measuring the quality of traffic service in a system.
3. They must be adaptive to any freeway control site.
4. They must produce data suitable for feedback to the control models.

The prime example of an analysis technique that meets these requirements is the input-output analysis used by all three freeway surveillance and control projects. During the early Gulf Freeway studies, this technique was used in manual form by the Texas Transportation Institute (3). It is important that this analysis permit a close look at congestion formation and duration on any system of interest. To apply this scheme consider Figure 1, which shows a system in which the procedure may be used.

With the count stations as shown, the system would be the freeway within the count stations, or that area cordoned off by the count stations. Within this area, all of the following variables can be obtained for any time period:

1. Freeway input flow rate (V_i);
2. Freeway output flow rate (V_o);
3. Freeway flow rate by lanes;
4. Total and individual ramp input flow rate;

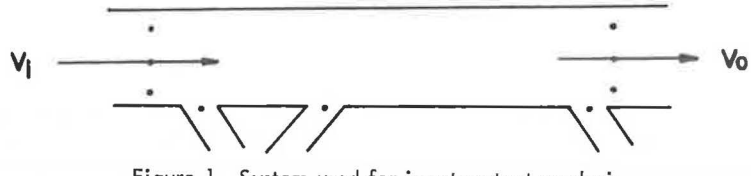

Figure 1. System used for input-output analysis.

5. Total and individual ramp output flow rate;
6. Total system travel time;
7. Total system travel;
8. Average speed in the system; and
9. Kinetic energy in the system (4).

QUALITY OF TRAFFIC SERVICE EVALUATION

With the use of a digital computer in the control of a freeway system, the traffic engineer can handle large volumes of data and operate in a real-time environment. Furthermore, in using a digital computer the operator has the flexibility to change the control philosophy, an asset he does not have when using a hard-wired or analog system.

The process control computer presently being used on the Gulf Freeway is an IBM 1800 Data Acquisition and Control System. The equipment available for input-output includes the following:

1443 Printer (150 lines per minute)
1442 Card Read-Punch (300 cards per minute)
2310 Disk Storage (storage device with both random and sequential access)
1627 Plotter
1816 Printer-Keyboard

Data Acquisition Software

To achieve and maintain responsive control of a process, it is necessary to continually sense the state of that process and to evaluate certain parameters and variables that describe the current operation of the process. This is the duty of the data acquisition program. As such, it is the subsystem of the control program or the feed-

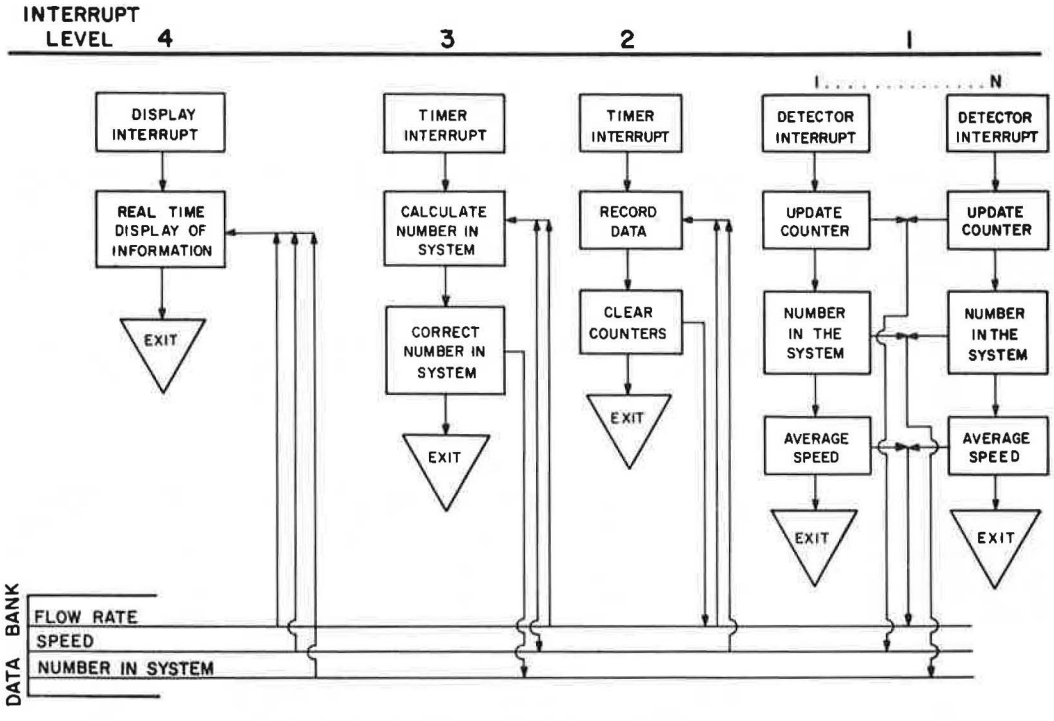

Figure 2. Logic diagram for data acquisition program.

back required for the optimal control of any process. The data acquisition program also serves to evaluate and display the state of the operation for the benefit of the operating agency and can provide a permanent record of operation for use in comparing different control strategies and for use in the development of new ones. The data acquisition subsystem further serves to detect equipment failures and provide the operator with an analysis of what effect the failure will have on the operation of the process.

Since the program is based on the concept of process control, several operations proceed in parallel. Figure 2 is the logic diagram for the program, with the interrupt levels listed at the top of the figure. The interrupt levels assign a priority to each section of the program. Using level one as the highest priority, an interrupt from the field, indicating the presence of a vehicle, will never be missed or delayed. Levels two and three operate from timer interrupts with the interrupt frequency specified by the operator. The frequency of level two is the frequency at which the flow rate is recorded. Level three is provided to check and correct errors introduced by the detectors in the field. This particular algorithm, using speed-volume-density relationships, calculates the number in the system so that any error introduced by the detectors will not be cumulative. The display interrupt, level four, can be manually or automatically set. Therefore, any desired interrupt frequency can be specified. The data bank at the bottom of Figure 2 is common to all levels of the program.

As an example of the information available for each subsystem, Table 1 gives the output for a 2-hour evaluation (6:30 to 8:30 a.m.) of two adjacent subsystems.

At any instant, the two basic traffic variables of volume and density are available for any subsystem. Figure 3 illustrates this aspect of the data acquisition program. The subsystem presented in this figure is 1 mile long, making the number in the system correspond to the system's vehicular density. Although the minute volumes are erratic, the variation is only random and does not indicate a breakdown in flow.

The information available through the data acquisition programs can also be used to determine the speed-volume-density relationships for each subsystem. The derived relationships for the Griggs-Telephone subsystem are shown in Figure 4. An

TABLE 1

SYSTEM CHARACTERISTICS AND PROCESS FEEDBACK FROM THE DATA ACQUISITION PROGRAM

SUBSYSTEM 1
DATE 2/ 2/68

LOCATION	630-830 VOLUME	700-800 VOLUME	PEAK HOUR	PEAK HOUR VOLUME	PEAK HALF-HOUR	PEAK HALF-HOUR VOLUME
FREEWAY AT 225 (3)	6577	3349	637	3766	652	1992
35 OFF RAMP (1)	177	73	732	111	801	65
225 ON RAMP (1)	1566	657	606	888	625	527
35 ON RAMP (1)	1427	640	618	780	629	456
WOODRIDGE OFF RAMP (1)	255	129	732	181	732	95
FREEWAY AT WOODRIDGE (3)	9137	4615	637	5033	640	2606

TIME	TOTAL TRAVEL (VEH-MI)	TOTAL TRAVEL TIME (VEH-HOURS)	KINETIC ENERGY (VEH-MI**2/HOUR)	AVERAGE SPEED (MPH)
630-830	4027.9	183.2	88529.6	21.9
700-800	2023.4	120.9	33866.9	16.7

SUBSYSTEM 2
DATE 2/ 2/68

LOCATION	630-830 VOLUME	700-800 VOLUME	PEAK HOUR	PEAK HOUR VOLUME	PEAK HALF-HOUR	PEAK HALF-HOUR VOLUME
FREEWAY AT WOODRIDGE (3)	9137	4615	637	5033	640	2606
WOODRIDGE ON RAMP (1)	611	307	721	359	752	195
MOSSROSE OFF RAMP (1)	146	53	733	94	757	59
MOSSROSE ON RAMP (1)	437	315	653	331	721	181
FREEWAY AT GRIGGS (4)	10037	5246	644	5473	644	2758
WAYSIDE OFF RAMP (1)	1060	466	733	560	620	308
FREEWAY AT BAYOU (3)	8977	4780	644	5028	652	2538

TIME	TOTAL TRAVEL (VEH-MI)	TOTAL TRAVEL TIME (VEH-HOURS)	KINETIC ENERGY (VEH-MI**2/HOUR)	AVERAGE SPEED (MPH)
630-830	9594.8	295.1	311896.0	32.5
700-800	4889.4	169.4	141123.4	28.8

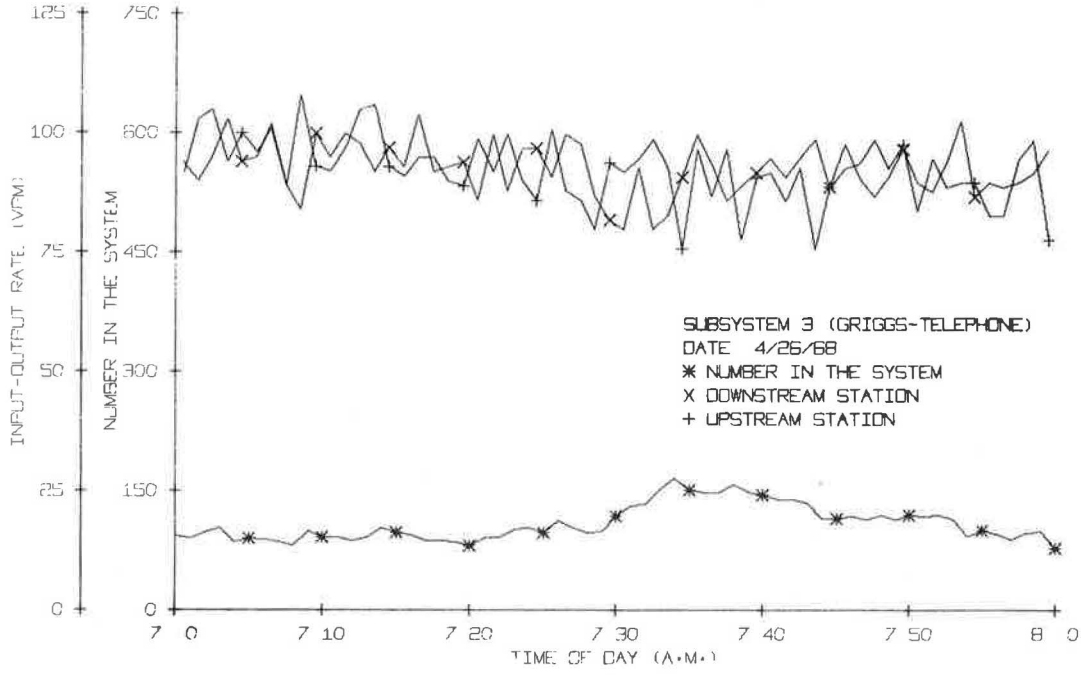

Figure 3. Real-time information provided by the data acquisition program.

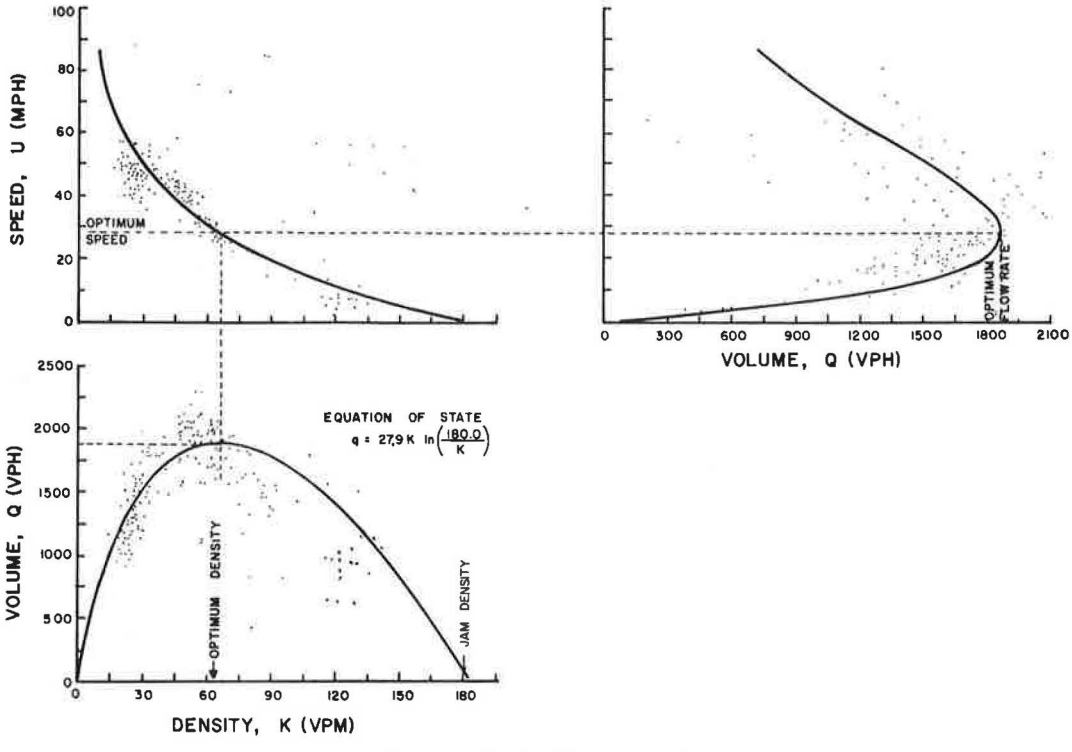

Figure 4. Volume-density-speed curves for Gulf Freeway inbound morning peak operation.

exponential model was used with the following equation:

$$q = ku_m \ln \frac{k_j}{k}$$

The parameters k_j and u_m were found through the use of a polynomial regression technique. The results of the regression were

jam density, k_j = 180.0 vehicles per mile
optimum speed, u_m = 27.9 miles per hour

and, from the curves in Figure 4, the following additional parameters can be found:

optimum concentration, k_m = 66.5 vehicles per mile
optimum volume, q_m = 1875 vehicles per hour

MULTILEVEL APPROACH TO SYNERGISTIC FREEWAY CONTROL

Drew et al (5) introduced a multilevel approach to the design of a freeway control system. They state, "The central idea behind this design is to share the effort of solution among two or more levels, each of which communicates both with the level directly above and that directly below."

The four levels of control, with the interaction between each level, are illustrated in Figure 5. Levels one and zero are controlled by the regulating function. This controller accomplishes what might be called the basic subgoal of the control system, which is optimal use of available gaps on the freeway and which is fulfilled by the timely release of ramp vehiches by the ramp signal.

The optimizing function adjusts the gap setting on the first level, regulating the controller in response to the outside-lane freeway operation (volume and speed) so as to maximize the ramp service volume. For example, if the setting on the regulating controller is too high, many gaps are left unfilled; if the setting is too low, many metered

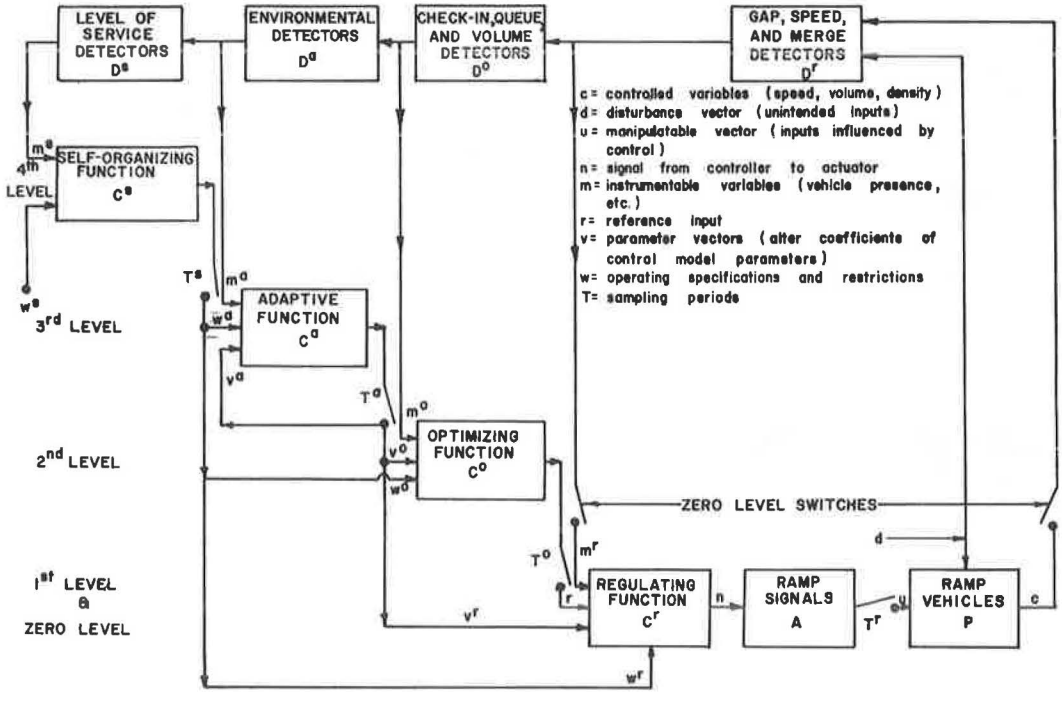

Figure 5. Decomposition of freeway control function.

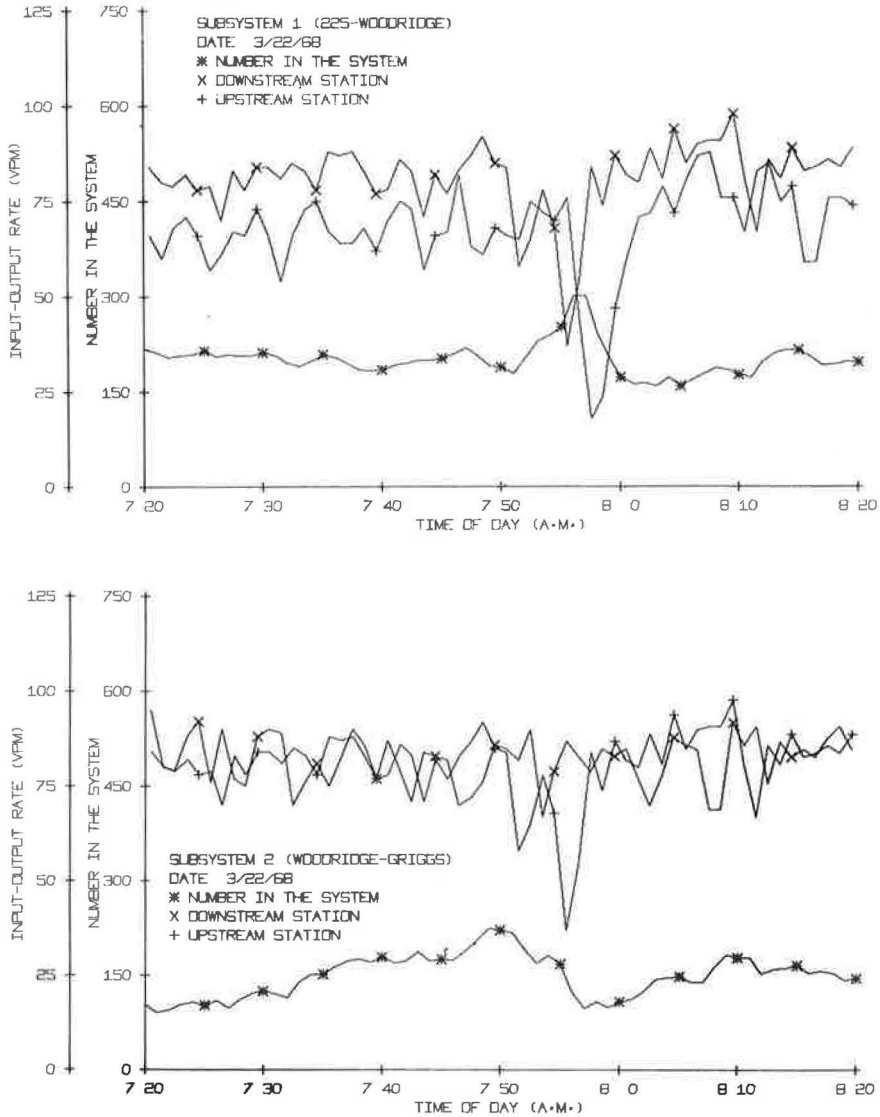

Figure 6. Progression of a shock wave and its effect on freeway volume and number in the system.

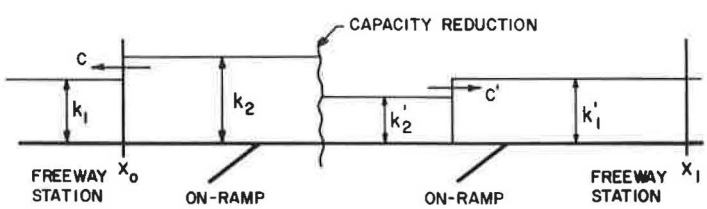

Figure 7. Stopping wave response to a reduction in capacity: k_2 density behind wave of stopping, k_1 and k_1' = density before block occurred, k_2' = density behind wave of clearing, c = velocity of stopping wave, and c' = velocity of clearing wave.

vehicles will reject the gaps and be forced to stop in the merging area where their presence will preempt metering. Both the regulating and optimizing functions are discussed by Brewer et al (6). The adaptive function and the self-organizing function deal with the freeway system and with the interaction between on-ramps.

The Adaptive Function

The function of the adaptive controller is to handle the unexpected system inputs, such as environmental factors and temporary capacity reductions. This third-level controller changes these transients in the traffic stream to inputs for the second- and first-level controllers.

Because of the devastating effects that a reduction in capacity has on freeway operation, a high priority must be given to detecting and locating this reduction when considering the system control of a freeway. This reduction could result from either an incident blocking one or more lanes or a bottleneck caused by a deficiency in design or a stalled vehicle on the shoulder. With the detection system in operation on the Gulf Freeway, capacity reductions and the resulting effects, such as shock waves, can be readily sensed.

Figure 6 shows the effect of a capacity reduction. Subsystem 2 clearly shows a shock wave moving through the subsystem. The shock wave reached the downstream freeway station at 7:57 a.m., with the block occurring about 1.5 miles downstream at 7:50 a.m. In Subsystem 2, it is of interest to note that, at the time when the wave crossed the upstream count station, its velocity was about 20 mph. The capacity reduction was caused by a stalled vehicle that momentarily blocked one lane of the freeway. Because there was such a high number of vehicles in the system before the stall, the downstream count station in Subsystem 3 did not show a reduction in flow rate.

Traffic Block Detection and Location

To reduce the effect of a capacity reduction on the operation of the freeway, it is important to devise a means of early detection. Some type of response to a reduction in capacity, such as regulating the upstream entrance ramp flow rates, must be made. Figure 7 is a graphic illustration of a stopping wave at freeway station X_0. At the

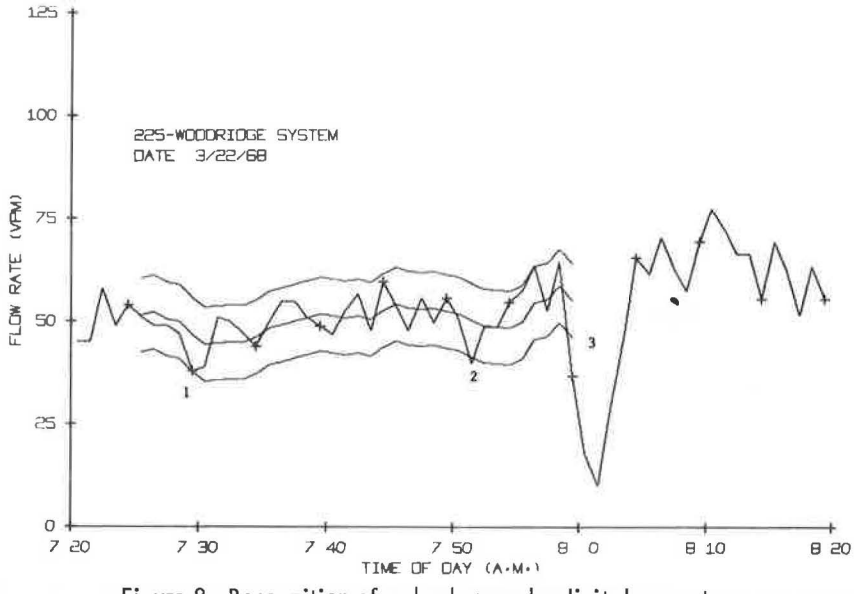

Figure 8. Recognition of a shock wave by digital computer.

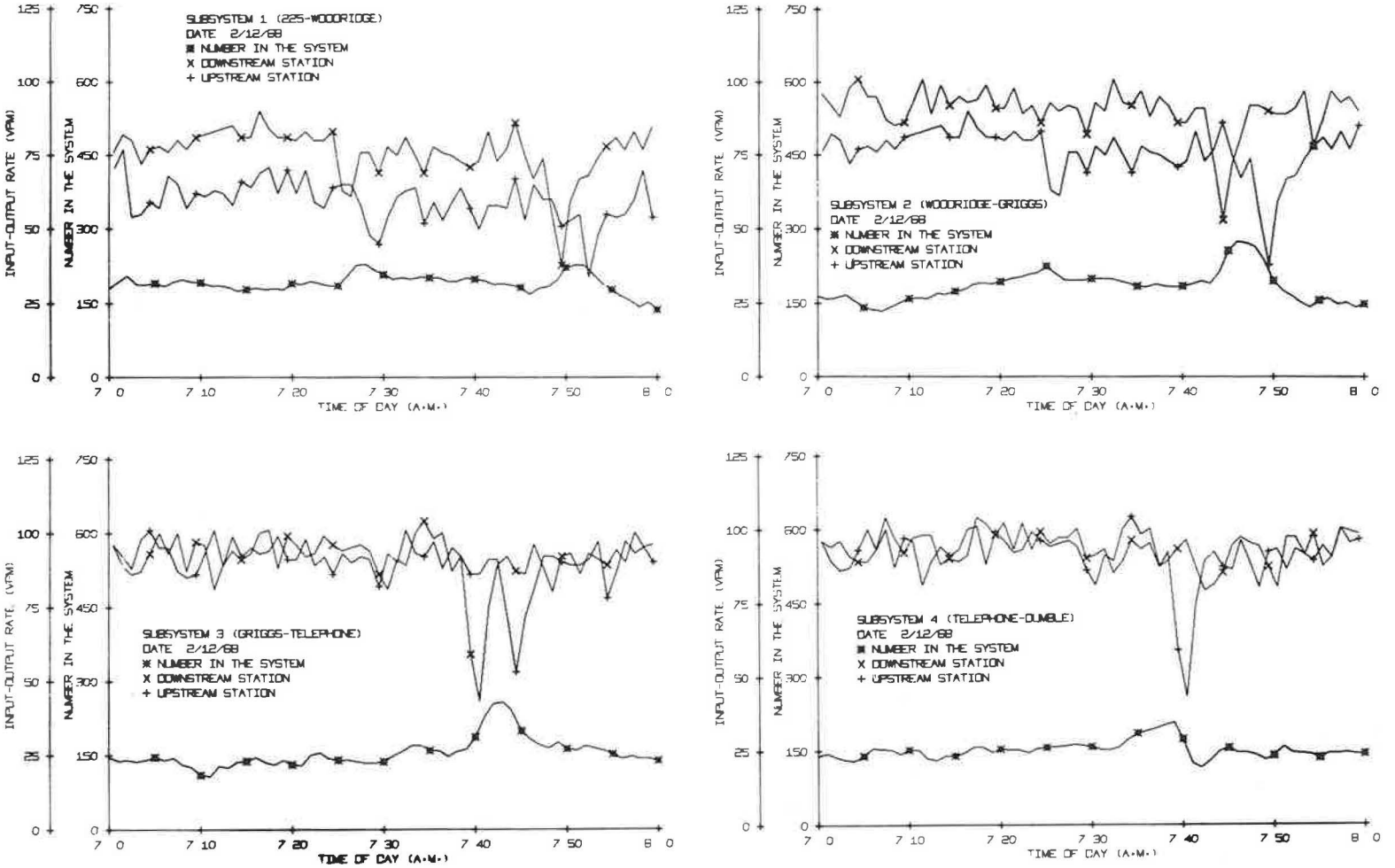

Figure 9. Effects of a capacity reduction on the operation of the Gulf Freeway control system.

position of the capacity reduction, the traffic on the freeway slowed down, and the stream immediately assumed a nearly saturated concentration of K_3. To the right of the capacity reduction, the density is reduced from K_1 (before the block occurred) to K_2', which in turn will reflect a higher mean traffic velocity. This differential in speed will be detected by the data acquisition program, locating the point of reduced capacity to within a few hundred feet.

Another method of shock wave recognition is illustrated in Figure 8. As mentioned before, some random variation of the flow rates over a count station is to be expected. To take this random variation into account, a running 5-minute average of the flow rate and corresponding upper and lower limits are plotted along with the 1-minute flow rates. The limits are two standard deviations away from the 5-minute average. As Figure 8 indicates, points 1 and 2 fell on or below the lower limit, but they remained there for less than 30 seconds. Point 3, however, fell well below the low limit for two consecutive 15-second periods. A decrease in the flow rate of this magnitude would indicate a capacity reduction of significant size. A comparison of the speed at this particular freeway station to the volume-density-speed curves would indicate either a stopping or clearing wave.

The block shown in Figure 7 could be caused by two different situations. The most common and frequent stoppage is a stalled vehicle or accident, either of which could affect the freeway a few seconds or several minutes. Shock waves can also be caused when the demand exceeds the capacity of a section. Figure 9 shows just such a situation. In Subsystem 4, the Telephone-Dumble section, there is a critical area in the vicinity of the Telephone on-ramp. The merging capacity in this area is about 500 vehicles per 5 minutes. The 5-minute flow rate just upstream of the merge area before the breakdown shown in Subsystem 4 was 515 vehicles. This is brought out only to show that, with some knowledge of the capacity of a freeway section under control, many breakdowns can be avoided. However, the process evaluation discussed in this paper is generalized to the point that the bottlenecks in the system do not have to be defined before control is started.

Control Action

With a capacity reduction detected and located, action should be taken to reduce the effect of the shock wave on the operation of the freeway and perhaps to dissipate the shock wave altogether. Brewer et al (6) presented a model that describes the service flow rate of a controlled entrance ramp in terms of the freeway flow rate and the service gap setting on the controller. The family of curves generated by the model is shown in Figure 10. This ramp-service flow rate model gives the ramp flow rates

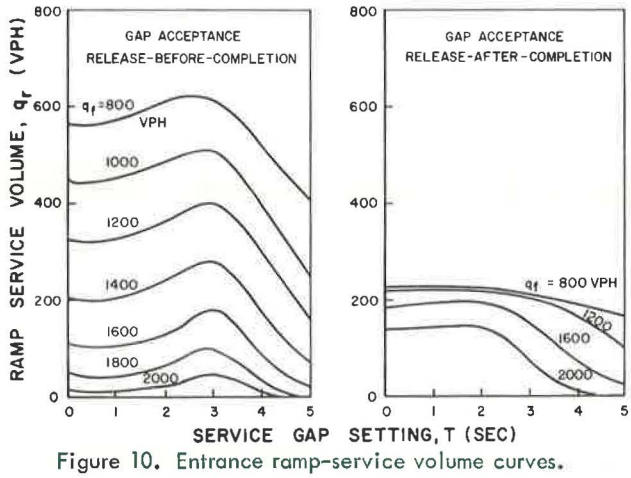

Figure 10. Entrance ramp-service volume curves.

that can be expected when a particular service gap is set on the controller. Therefore, the effect of a capacity reduction on freeway operation can be compensated for by increasing the service gap, thus decreasing the flow rates at the upstream ramps by the amount of the capacity reduction. A typical control example, using Figure 8 as the state of the system, might proceed as follows:

Step	Time	Description
1	7:59:45	The flow rate is below the lower limit, indicating a possible capacity reduction.
2	8:00:00	The flow rate has been below the limit for two consecutive 15-second periods, showing a significant capacity reduction.
3		At this point calculate the drop in flow rate over the last 1-minute period. For this example the flow rate for three lanes has been reduced by 30 vehicles per minute. The measured freeway flow rate, g_f, is 1,100 vph in the outside lane, and the current service gap, T_s, setting on the upstream ramps is 2.8 seconds.
4		Using Figure 10 and an intermediate type operation, the service gap setting on 8 of the upstream on-ramps is increased to 4.8 seconds to compensate for the first minute of the capacity reduction.
5		The outside-lane speed profile is now checked to locate the origin of the capacity reduction.
6	8:00:15	The freeway flow rate is again checked for the progress of the shock wave, and the control action is returned to step 3.

As the shock wave proceeds upstream and crosses each set of freeway detectors, the same procedure is repeated until the shock wave is dissipated or leaves the control section. When this happens, the control procedure would automatically return to the original service gap setting.

Self-Organizing Function

The fundamental property of a self-organizing, or learning, control system is its ability to perform better as time progresses. The fourth-level function can be programmed to automatically update the parameters used in the lower three levels of control. Capacity reductions offer an example of its application to third-level control. The capacities of a geometric bottleneck, an icy pavement, a wet pavement, etc., can

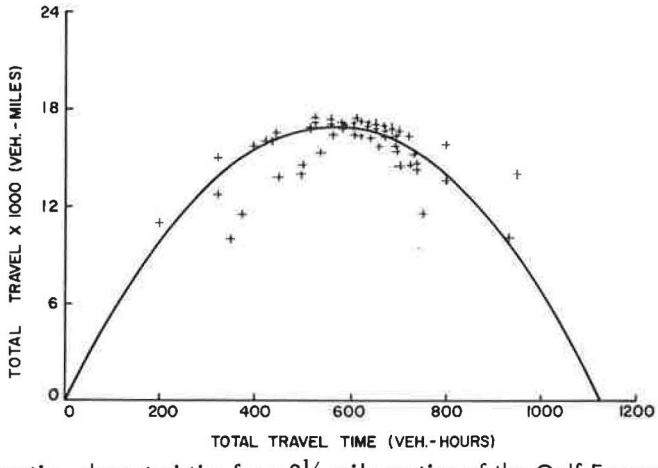

Figure 11. Operating characteristics for a 2½-mile section of the Gulf Freeway control system.

be "learned". Once the fourth-level computer has learned the capacity profile of the freeway, it will no longer allow the second level to exceed this capacity.

To judge whether 1 day's operation is better or worse than the previous average operation, a curve such as Figure 11 is also programmed into the self-organizing function. Using data collected from the control section, the self-organizing function could actually develop this curve, as was done for the Gulf Freeway inbound operation (7).

The self-organizing function determines what the decision vectors should be on the basis of measurable freeway characteristics and the intervention of the operation in the system. These decisions are based on the accumulated experience and understanding of the process being controlled, i.e., the freeway system. Furthermore, while they alter the control laws in the lower levels, these decisions are subject to the specifications, goals, and constraints embodied in the worth vector.

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