STUDY OF DETECTOR RELIABILITY FOR A MOTORIST INFORMATION SYSTEM ON THE GULF FREEWAY

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An experimental warning system has been installed on the Gulf Freeway in Houston as a means of alerting drivers approaching crest type of vertical curves to stoppages downstream of the crest. Successful automatic operation of the warning system depends on the reliability of system components. Earlier studies showed that developed control logic is responsive to stoppage waves, provided that the hardware functions properly. A one-lane control criterion resulted in 100 percent detection whereas 96 percent of the waves were detected using a two-lane control criterion. The studies also indicated a relatively high frequency of detector failures. The frequency of detector failures prompted a study to evaluate reliability of the warning system based on detector failure and repair rates experienced on the Gulf Freeway surveillance and control system and to ascertain whether detector redundancy or improved maintenance would be necessary. Malfunctions and repairs of all the Gulf Freeway surveillance and control hardware, including the 96-detector subsystem, were recorded for a 5-month period. The data revealed that the detectors on the Gulf Freeway failed at a rate of 3.78×10^{-4} failures per detector hour. Detectors were repaired at a rate of 0.23 repairs per hour. The reliability in terms of availability of the safety warning system was analyzed using these data and classical models for maintained systems. Availability of the system was 0.95 and 0.995 for the one- and two-lane criteria respectively. The results indicated that the current detector configuration and maintenance practices were adequate.

•RAMP CONTROL has resulted in significant improvements in peak-period freeway operation and reduction of accidents. Certain safety and operational problems continue to exist because of geometric features of the freeway and environmental phenomena that restrict driver sight distances. For example, the grade line and alignment of several freeways are such that sufficient sight distance is not always available for the motorist to confirm his expectations of traffic flow downstream. Problems arise because of unexpected traffic stoppages resulting from accidents and stalled vehicles or from stoppage waves generated during peak-period flow.

An experimental warning system has been installed on the inbound control section of the Gulf Freeway in Houston to reduce the effects of traffic incidents and congestion (1). The purpose of the system is to assist the freeway driver approaching crest type of vertical curves in formulating his expectations of the actual downstream traffic flow by alerting him to stoppage waves downstream of the crest.

Three overpasses were selected as the sites for pilot installations to study the effectiveness of the warning system, to develop automatic control algorithms, and to further evaluate the design concepts. The system currently consists of a static sign with

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attached flashing beacons (Fig. 1) located upstream of each overpass crest and a flashing beacon mounted on the bridge rail on the top of each crest (Fig. 2). The warning signs are controlled automatically by a digital computer. Double loop detectors are installed on each lane and located on both sides of the three overpasses (Fig. 3). Inasmuch as one detector station serves as the downstream station for one subsystem and as the upstream station for the next subsystem, only 30 detectors are included in the installation. The primary function of the detectors downstream of the overpass is to sense stoppage waves in order to activate the warning sign. The upstream detectors would indicate the time that the sign should be turned off.

PROBLEM STATEMENT

Successful automatic operation of the warning system depends on the reliability of the software and hardware components. Earlier studies (2, 3) showed that the developed control logic is responsive to all stoppage waves, providing that the detectors function properly. During the development of the computer control logic, a relatively high frequency of detector failures was noted. Because of the function of the system, it is important that it respond to all stoppage waves and maintain an extremely low level of false activations. Detector failures, of course, would have adverse consequences on the system. Because of the relatively high frequency of detector failures while the system was being developed, a study was conducted to evaluate the reliability of the warning system based on the detector failure and repair rates experienced and to ascertain whether detector redundancy or improved maintenance practices were necessary to increase the reliability of the warning system. The study also provided some insight about hardware failures and the suitability of maintenance activities for the entire surveillance and control system.

CONTROL PARAMETERS AND CRITERIA

Computer algorithms that have been successfully developed and implemented for the Gulf Freeway warning system use either traffic energy, speed, or occupancy as control variables (2, 3). Stoppage waves are predicted at the downstream detector station whenever the control variable reaches a predetermined critical value. Likewise, the stoppage waves are sensed as passing over the crest of the overpass when the variable at the upstream detector station reaches a critical value. Although the performance of each control variable is about the same on the average, traffic energy was selected for the system in Houston because of certain desirable features. The energy variable is more responsive to slow-moving trucks during the off-peak period and in many cases sounds an alarm when particular hardware problems arise.

Two approaches to control have been previously tested. In one approach, referred to as the one-lane criterion, a warning device is activated whenever any one of the three lanes indicates the presence of a stoppage wave. The second approach was developed in an attempt to compensate for the detector failures experienced at the time of system development. This approach is referred to as a two-lane control criterion, and it relies on information from a second lane to verify conditions on the first. In other words, the warning device is not activated until detectors on two lanes sense the presence of stoppage waves. Tests have shown that the one-lane criterion logic was responsive to all stoppage waves studied in relation to the existing detector locations and was subject to the proper functioning of the detectors. The two-lane control logic was responsive to 96 percent of the cases studied. The relative responsiveness of the system for each of the criteria using energy as the control variable is shown in Figure 4.

METHOD OF STUDY

Malfunctions and repairs of all the Gulf Freeway control and communications hardware subsystems, including the 96-detector subsystem, were documented for a 5-month period. The data were collected to establish the relative degree of subsystem failures and specifically to determine the failure rates and repair rates for the detector subsystem. Classical models relating to reliability of maintained systems were employed to ascertain the reliability of the detector subsystem to establish whether detector redundancy or changes in maintenance practices would be required if the automatic warning system were to operate with a high degree of confidence.

HARDWARE SUBSYSTEMS

Table 1 gives the outages experienced on the Gulf Freeway during the 5-month analysis period (December 1971 through April 1972) for the primary subsystems that are related to the operation of the safety warning system. The data do not include the outages experienced with the closed-circuit television subsystem or with the ramp control signals.

The results reveal that 47 detector failures were experienced during the analysis period. In addition, 19 outages relating to the computer hardware, 1 cable outage, and 3 wiring outages were experienced. These data include both failures and outages due to maintenance, installation of additional equipment or control subsystems, and the like. Removing the latter from the totals, in addition to failures of those components of the computer peripheral equipment that would not have a bearing on the operation of the warning system, gives the total number of subsystem failures (Table 1).

Eleven percent of the subsystem failures related to the computer hardware. Generally, these failures were attributed to electrical power failures. In addition, one incident of a cable problem occurred when the main cable was accidentally cut by a construction crew. In general, this type of problem is rare and in the long run would constitute an insignificant percentage of subsystem failures.

The data also reveal that detector failures represented 87 percent of the problems experienced with the hardware that would be associated with a real-time freeway warning system. These data, from the individual detector failures of 96 detectors within the Gulf Freeway system, illustrate the relative frequency of failures that have been experienced in an operational control system.

When the computer fails, the entire system is inoperative. When a detector fails, a portion of the control and communication system becomes inoperative. A computer failure is easily recognized, but detector failures are more difficult to detect during control operations, and thus the control strategies can easily become ineffective.

Table 2 gives the types of detector problems experienced on the Gulf Freeway during the 5-month analysis period. Relay burns and internal circuitry problems accounted for 81 percent of the 47 failures (40.5 percent relay contact burns, 40.5 percent circuitry failures). There was only one case of failure of the loop itself. In addition, 17 percent of the failures were attributed to other problems such as blown fuses and defective wiring from the freeway lanes to the control box.

The relatively high frequency of detector failures, particularly the relay contact burns, was due in part to the equipment configuration on the Gulf Freeway. During the development of the safety warning system, the surveillance subsystem was operating between 48 and 72 volts DC, whereas the relay contacts were rated for 24-volt DC operation. The increased voltage was necessary because of the extensive length of the communications cable and associated interconnections. The communications subsystem was modified after this study was conducted.

ANALYSIS OF DETECTOR SUBSYSTEM RELIABILITY EFFECTIVENESS

There is a similarity between reliability problems of maintained systems and problems of queuing theory. For example, in the general queuing problem, one is concerned with serving arrivals with the objective of minimizing the length of the waiting line. The analogy here is that the repairman is the server of equipment failures, and the objective is to minimize system downtime.

A full description of the reliability of a given system that can be maintained requires specification of the equipment failure process, the system configuration, the repair process, and the state in which the system is to be defined as failed. If the times between individual equipment failures follow the negative exponential distribution and the times-to-repair are also exponentially distributed, then a Markovian representation can be used.

Figure 1. Warning sign with flashers.

Figure 2. Flasher unit at crest of overpass.

Figure 3. Locations of detectors for warning signs.

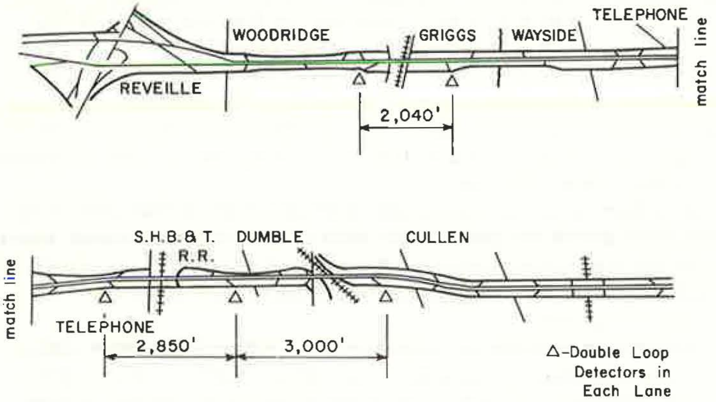

Table 1. Subsystem outages and failures.

	Outages		Failures	
Type	Number	Percent	Number	Percent
Detector	47	67	47	87
Computer hardware	19	27	6	11
Wiring (office)	3	4	0	0
Cable	1	2	1	2
Total	70	100	54	100

Table 2. Detector failures.

Type	Failures	Percentage of Failures
Relay contact burn	19	40.5
Internal circuitry	19	40.5
Other	8	17.0
Loop	1	2.0
Total	47	100.0

Figure 4. Stoppage wave detection performance curves using energy as control variable (2).

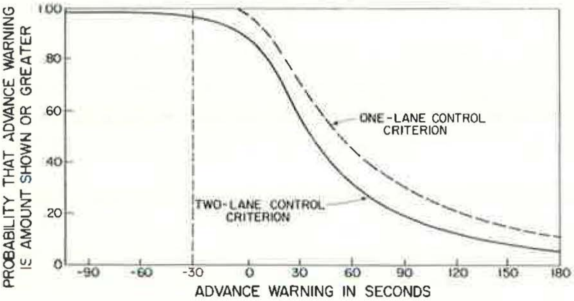

Table 3. Detector failures by month.

Month	Failures	Total Time of Failures (hours)
December	6	32.00
January	19	99.17
February	10	20.16
March	8	37.67
April	4	16.50
Total	47	205.50

Note:

Failure rate,

$$\lambda = \frac{47 \text{ failures}}{96 \text{ detectors} \times 108 \text{ days} \times 12 \text{ hours/day}}$$

$$= 3.78 \times 10^{-4} \text{ failures/detector-hour,}$$

Repair rate,

$$\mu = \frac{47 \text{ repairs}}{205.5 \text{ hours}} = 0.23 \text{ repairs/hour.}$$

Measure of System Reliability Effectiveness

Several measures of system reliability effectiveness are available for consideration (4). The selection of an appropriate measure of effectiveness is determined primarily by the mission of the system. Availability is one measure of system reliability effectiveness that is applicable to maintained systems. It is defined as the proportion of time that the system will spend in acceptable states. Because of the particular mission of the safety warning system, it was of particular concern to establish the system's availability. Consequently, detector availability was selected as the measure of system reliability effectiveness.

Assumptions

The control and communication system on the Gulf Freeway is operated each weekday from 6 a.m. to 6 p.m. Consequently, any malfunction that developed after 6 p.m. was noted the following morning. In addition, all repairs were made during the 12-hour operational period. For the purposes of this study, the assumption was made that one repairman would be used to service the 96-detector subsystem. Inasmuch as the 30 detectors used for the warning system are more critical than the remaining detectors because of the function they serve, these 30 detectors would receive priority by the repairman on a first-come-first-served basis.

Because the detectors fail randomly, the detector failures can be assumed to be Poisson distributed; thus the time between failures will be negatively exponentially distributed. Likewise, the times-to-repair were assumed to follow a negative exponential distribution. A chi-square goodness of fit test was applied to the repair data, and the results indicated that the data did not quite fit a negative exponential distribution. However, the fit was relatively close, and it was felt that the small sample size may have influenced the fit. To make the analysis tractable, the negative exponential distribution was assumed.

The following implications relate to the assumptions that the individual detectors fail in accordance with the negative exponential distribution and that the times-to-repair are also exponentially distributed:

1. The conditional probabilities of failure and of repairing a detector are constant.
2. The probability of a single detector failure in the time interval t to t+dt, given that it was working at time t, is λdt where λ is the failure rate.
3. The probability of repairing a detector in the time interval dt, given that it was not working at time t, is μdt where μ is the repair rate.
4. The major portion of failures can be repaired in a short time, and those that take a long time to repair occur infrequently.
5. Only one detector will fail during time interval dt; similarly, only one detector can be repaired at a time.

Failure and Repair Rates

The frequency of detector failures during the 5-month analysis period is shown in Table 3. Also presented is the total time of failure, which in effect constituted the repair time for the detectors. From these data, a failure rate λ of 3.78×10^{-4} failures per detector-hour and a repair rate μ equal to 0.23 repairs per hour are computed.

One-Lane Criterion

For the purposes of this analysis, the three warning devices are considered as one complete system. All the detectors must function to have an operating system. As mentioned earlier, 30 basic detectors are used to operate the three warning devices on the Gulf Freeway. Thus, the system is considered to be in a failed state when any one detector is defective. The reliability analyzed in the following paragraphs refers to the availability of all three warning devices operating simultaneously.

It has been shown that the following steady-state probabilities apply for the general case of n detectors and r repairmen (4):

$$P_k = \frac{n!}{(n-k)\,!\,k!}\,\rho^k P_o \qquad \text{for } k < r \tag{1}$$

$$P_k = \frac{n!}{(n-k)\,!\,r!}\,\rho^r\left(\frac{\rho}{r}\right)^{k-r} P_o \qquad \text{for } k \geq r \tag{2}$$

where

P_k = probability of being in state P_k,
k = number of detectors down,
n = number of detectors in the system, and
$\rho = \frac{\lambda}{\mu}$

Availability is the measure of system reliability effectiveness selected for the analysis of the safety warning system. Availability is the proportion of time that the system will spend in acceptable states. The steady-state availability A of a system can be computed from the following relationship (4).

$$A = P_o = \left[\sum_{l=0}^{r-1} \frac{n!}{(n-k)\,!\,k!}\,\rho^k + \sum_{k=r}^{n} \frac{n!}{(n-k)\,!\,r!}\,\rho^r\left(\frac{\rho}{r}\right)^{k-1}\right]^{-1} \tag{3}$$

For the case of one repairman, Eq. 3 reduces to the following:

$$A = P_o = \left[\sum_{k=0}^{n} \frac{n!}{(n-k)\,!}\,\rho^k\right]^{-1} \tag{4}$$

For the special case of a 30-detector system, Eq. 4 can be written as follows:

$$A = P_o = \left[\sum_{k=0}^{30} \frac{30!}{(30-k)!}\,\rho^k\right]^{-1} \tag{5}$$

Substituting the computed values for the failure rate $\lambda = 3.78 \times 10^{-4}$ and the repair rate $\mu = 0.23$, the steady-state availability of the warning system becomes

$$A = P_o = 0.95 \tag{6}$$

Under steady-state conditions, there is a 95 percent chance that all 30 detectors will be functioning. Thus, there is a 95 percent chance that all three safety warning subsystems would be available, assuming that all other hardware components are functioning.

The probability that one, two, or three detectors will be out of operation can likewise be computed:

$$P_1 = 30\rho\ P_o = 0.045 \tag{7}$$

$$P_2 = \frac{(30)(29)}{2!}\,\rho^2\ P_o = 0.001 \tag{8}$$

$$P_3 = \frac{(30)(29)(28)}{3!}\,\rho^3\ P_o = 0.00002 \tag{9}$$

Two-Lane Criterion

For a two-lane criterion, the availability function is slightly more complex. This criterion requires that the energy variable can be measured in at least two lanes. Because the system consists of 3 warning devices having a total of 30 detectors and is in a failure state when any one of the devices is inoperative, then, at most, two detectors in the same lane can fail at each detector station without the system reaching a failure state. Thus, if a total of 10 detectors failed in one lane, the system would still be operational. However, if detectors fail in two lanes at a particular station, the system is considered unavailable.

The availability function under steady-state conditions for this case is given by the following relationship:

$$A = P_o + \sum_{k=1}^{10} C_k P_k \tag{10}$$

where C_k is a coefficient that is equal to the ratio of the number of ways in which k detectors can fail and yet the system be operable to the total number of ways in which k detectors can fail. Thus, the availability of the 30-detector system is

$$A = 0.95 + C_1(0.045) + C_2(0.001) + C_3(0.00002) + \ldots \tag{11}$$

The coefficient C_1 is computed as follows:

$$C_1 = \frac{\text{Number of ways in which one detector can fail and yet the system be available}}{\text{Number of ways in which one detector can fail}} \tag{12}$$

If one detector fails, the system would still be available; therefore

$$C_1 \frac{\binom{30}{1}}{\binom{30}{1}} = 1 \tag{13}$$

Likewise for C_2 and C_3,

$$C_2 = \frac{\binom{30}{2} - 5\left[\binom{6}{2} - 3\right]}{\binom{30}{2}} = 0.862 \tag{14}$$

$$C_3 = \frac{\binom{30}{3} - 5\left[\binom{6}{3}\right] - 120\binom{6}{2} - 3}{\binom{30}{3}} = 0.621 \tag{15}$$

The availability of the 30-detector system using a two-lane control criterion, therefore, is

$$\begin{aligned} A &= 0.95 + 1(0.045) + 0.862(0.001) + 0.621(0.00002) \\ A &= 0.995 \end{aligned} \tag{16}$$

The results indicate that the system availability using a two-lane control criterion is quite acceptable. However, it must be emphasized that, based on the results of previous studies (2), it would be expected that the warning system would be late in responding to 4 percent of the stoppage waves. Although the availability for the one-lane criterion is lower (i.e., 0.95), it is expected that this control approach would be responsive to all stoppage waves. Based on these results, it does not seem imperative to add redundant detectors to the system. This does not rule out the desirability of adding an additional detector station farther downstream to provide earlier warnings of stoppage waves.

Analysis of a Single Warning Device

The foregoing analysis is specific to the 3 warning devices on the Gulf Freeway having a total of 30 detectors. It was of interest to determine the reliability of a single warning device that may operate in isolation. The single warning device would require 12 detectors if the energy control variable is used. If one assumes that the same failure and repair rates apply as experienced on the Gulf Freeway and uses the same repair policy with a single repairman, then from Eq. 4 the system availability using a one-lane control criterion becomes

$$A = P_o = \left[\sum_{k=0}^{12} \frac{12!}{(12-k)!} \rho^k \right]^{-1} \tag{17}$$

$$A = P_o = 0.98 \tag{18}$$

Under steady-state conditions, there is a 98 percent chance that all 12 detectors will be functioning, assuming that all other hardware components are operative.

The probability that one, two, or three detectors will be out of operation can likewise be computed:

$$P_1 = 12\rho\ P_o = 0.019 \tag{19}$$

$$P_2 = \frac{(12)(11)}{2!} \rho^2\ P_o = 0.0002 \tag{20}$$

$$P_3 = \frac{(12)(11)(10)}{3!} \rho^3\ P_o = 0.0000 \tag{21}$$

For a two-lane criterion, the coefficients C_1, C_2, and C_3 are computed as follows:

$$C_1 = \frac{\binom{12}{1}}{\binom{12}{1}} = 1 \tag{22}$$

$$C_2 = \frac{\binom{12}{2} - 2\left[\binom{6}{2} - 3\right]}{\binom{12}{2}} = 0.636 \tag{23}$$

$$C_3 = \frac{\binom{12}{3} - 2\left[\binom{6}{3}\right] - 12\left[\binom{6}{2}\right] - 3}{\binom{12}{3}} = 0.164 \tag{24}$$

The availability of the 12-detector warning system using a two-lane control criterion is

$$\begin{aligned} A &= 0.98 + 1(0.019) + 0.636(0.0002) + 0.164(0.0000) \\ A &= 0.999 \end{aligned} \tag{25}$$

The results indicate that the one-lane criterion and the two-lane criterion are both acceptable based on the maintenance practices on the Gulf Freeway.

DISCUSSION OF FINDINGS

The analyses presented in this paper relate to the detector failures and maintenance practices experienced on the Gulf Freeway surveillance and control system. The results may not be directly translatable to other systems because the hardware failures and maintenance practices may differ. We believe that comparable data from other systems will help shed some light on hardware problems so that greater effort can be made to solve common problems.

It is our hope that the results have focused attention on the degree of maintenance necessary for reliable systems, especially with respect to detectors, and the types of hardware problems that have been experienced on one operational system.

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