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16. Abstract

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A STUDY OF DETECTOR RELIABILITY FOR A SAFETY WARNING SYSTEM ON THE GULF FREEWAY

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Research Report Number 165-7

Development of Urban Traffic Management
and Control Systems

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The Texas Highway Department
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Federal Highway Administration

Texas Transportation Institute
Texas A&M University
College Station, Texas

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ABSTRACT

An experimental warning system has been installed on the Gulf Freeway in Houston as a means of alerting drivers approaching crest type vertical curves of stoppages downstream of the crest. Successful automatic operation of the warning system is dependent upon the reliability of the system components. Earlier studies showed that the developed control logic is responsive to stoppage waves providing the hardware functions properly. The studies also indicated a relatively high frequency of detector failures. The frequency of detector failures prompted a study to evaluate the reliability of the warning system based on the detector failure and repair rates experienced on the Gulf Freeway surveillance and control system to ascertain whether detector redundancy or improved maintenance would be necessary. Classical models relating to reliability of maintained and non-maintained systems were employed.

Reliability functions for warning signs installed at isolated locations are also presented.

Key Words: Freeway control, traffic surveillance, driver communications, traffic detectors, reliability.

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SUMMARY

This report is concerned with an analysis of detector reliability associated with the safety warning system on the Gulf Freeway. Earlier reports indicated that the software is responsive to stoppage waves during moderate and heavy flow providing the detectors function properly. A one-lane control criterion resulted in 100 percent wave detection; whereas, 96 percent of the waves were detected using a two-lane control criterion.

Malfunctions and repairs of all the Gulf Freeway surveillance and control hardware including the 96 detector subsystem were recorded for a five-month period beginning in December, 1971. The data revealed that 54 failures occurred during the analysis period - 47 detector, 6 computer hardware, and 1 cable failures. Detectors 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. Relays accounted for 40.5 percent of the detector failures. Also, 40.5 percent of the detector failures resulted from the internal circuitry.

Using the above data and employing classical models for maintained and non-maintained systems, the availability of the detector subsystem associated with the three warning devices on the Gulf Freeway was analyzed to ascertain whether detector redundancy would be desirable for the operational system. The availability of the 30-detector subsystem was found to be 0.95 and 0.99 for the one- and two-lane criteria, respectively. These results assume that all other hardware is functioning.

Following the above analysis period, changes were made to the system as a requirement before the Texas Highway Department purchased the detection and ramp control system from the supplier. In addition, multiplexing equipment and detectors were added to the system for the increasing research

and operational program. A follow-up study was conducted during a five-month period beginning in March, 1974, to evaluate the effects of these changes with respect to the reliability of the detectors used for the warning system.

The results of the follow-up study revealed that changes in the system design have significantly reduced the detector failure rate. During the follow-up study 49 failures occurred - 20 detector, 21 multiplexer, 4 computer hardware, and 4 cable failures. A comparison of the initial and follow-up study data, revealed that the number of detector failures dropped from 47 to 20, a reduction of 57 percent. The most significant reduction was attributed to the relay problems that reduced from 19 to 3, an 84 percent reduction. Although detector failures were reduced, multiplexer failures accounted for a relatively high proportion of the system failures. Detectors failed at a rate of 1.47×10^{-4} failures per detector hour; detectors were repaired at a rate of 0.14 repairs per hour. The availability (reliability) of the 30-detector subsystem used with the warning system was found to be 0.96 and 0.99 for the one- and two-lane control criteria.

Analysis was also made of an isolated warning sign installation where full time maintenance personnel may not be available. The reliability of such a system assuming that the detector failure rate is the same as experienced on the Gulf Freeway during the follow-up study are shown in Figure S-1. One curve illustrates the reliability of a single warning sign installation using energy as a control criterion. This requires double loop detectors on all lanes both upstream and downstream of the curve crest--a total of 12 detectors. The second curve assumes that lane occupancy will be used as a control variable, thus requiring only 6 detectors.

Figure S-1 can be useful in establishing a periodic detector preventive

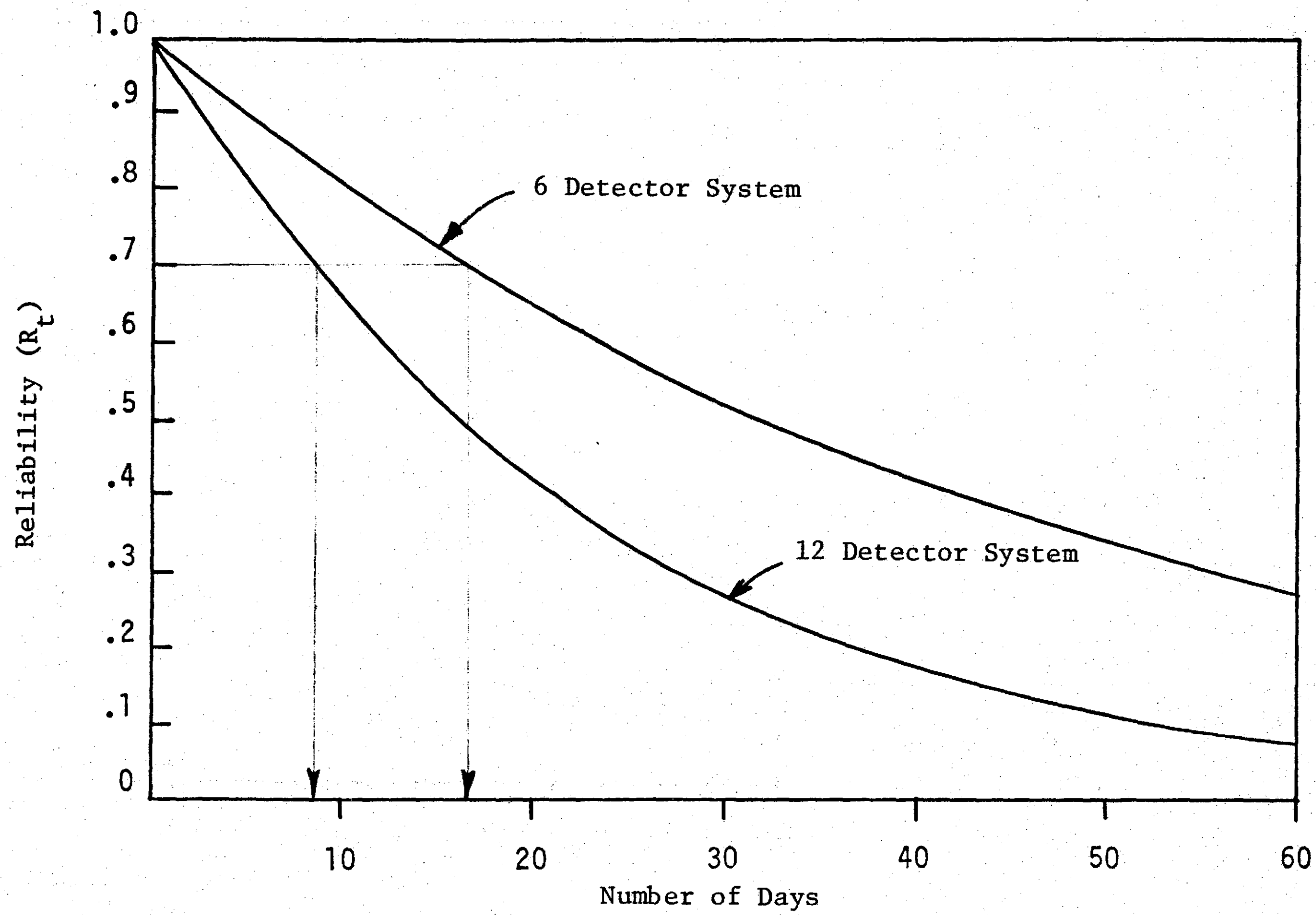

Figure S-1 - Reliability of Non-maintained System maintenance policy for the isolated warning system. For example, assuming that the operating agency decides that it is not willing to accept less than a 0.70 probability that the system has failed due to the detectors, then the detectors should be serviced every 9 days for the 12-detector system and every 17 days for the 6-detector system.

Implementation

The results of this research have assisted the project personnel in analyzing the detector and maintenance requirements for the safety warning system on the Gulf Freeway and are thus important for designing systems for implementation on other freeways. The results also focus attention on the types and frequency of hardware problems that were experienced on one operational surveillance and control system and should be helpful in deciding where improvements need to be made.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

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 due to unexpected traffic stoppages resulting from accidents, stalled vehicles, etc., 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 as an approach to reducing the effects of the above problem (1). The purpose of the system is to assist the freeway driver approaching crest type vertical curves in formulating his expectations of the actual downstream traffic flow by alerting him of 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 attached flashing beacons (Figure 1) located upstream of each overpass crest, and a flashing beacon mounted on the bridge rail on the top of each crest (Figure 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 as shown in Figure 3. Since one of the five detector stations serves as the downstream station for one subsystem and as the upstream station

Figure 1 - Warning Sign with Flashers

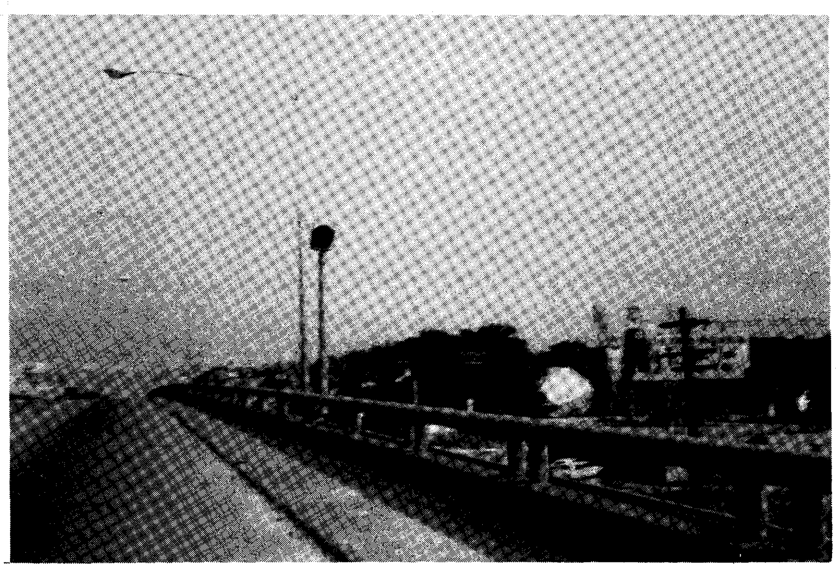

Figure 2 - Flasher Unit at Crest of Overpass

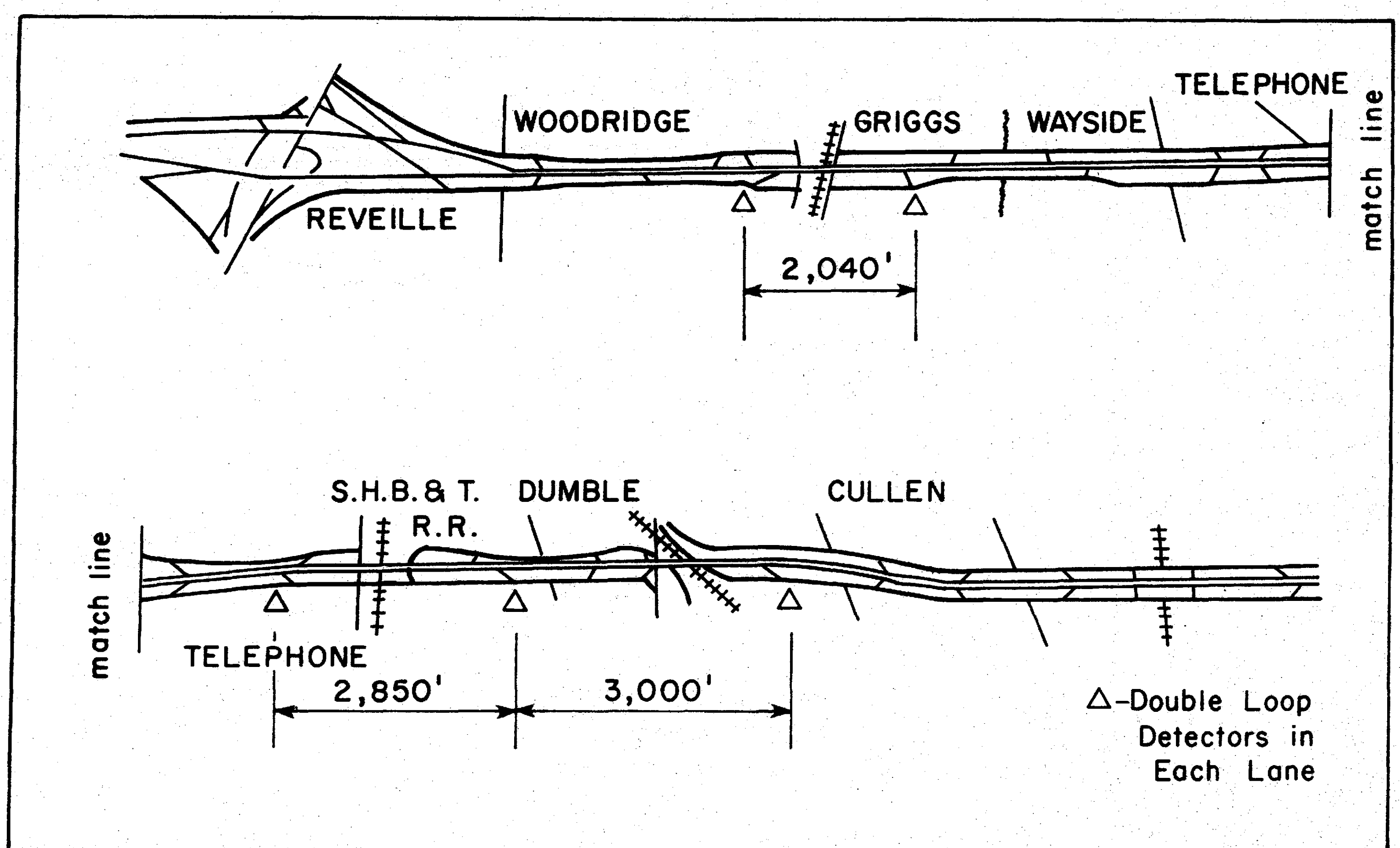

Figure 3 - Detector Locations for the Warning Subsystems

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 is dependent upon 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 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. Due to 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 on the Gulf Freeway to ascertain whether detector redundancy was necessary to increase the reliability of the warning system. The study also provided some insight regarding hardware failures and maintenance requirements.

Control Parameters and Criteria

The computer algorithms which have been successfully developed and implemented for the Gulf Freeway warning system utilize 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 to pass 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, 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 control approaches 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 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 criterion using energy as the control variable is shown in Figure 4.

Detection System

Figure 5 denotes the basic functional design of the detection system. With the exception of the cable, all components and equipment were leased from the supplier. The initial system was put into operation sometime in 1967. There were 26 main lane detectors and 37 entrance and exit ramp detectors. Each of the 63 detectors was implemented as depicted in Figure 5.

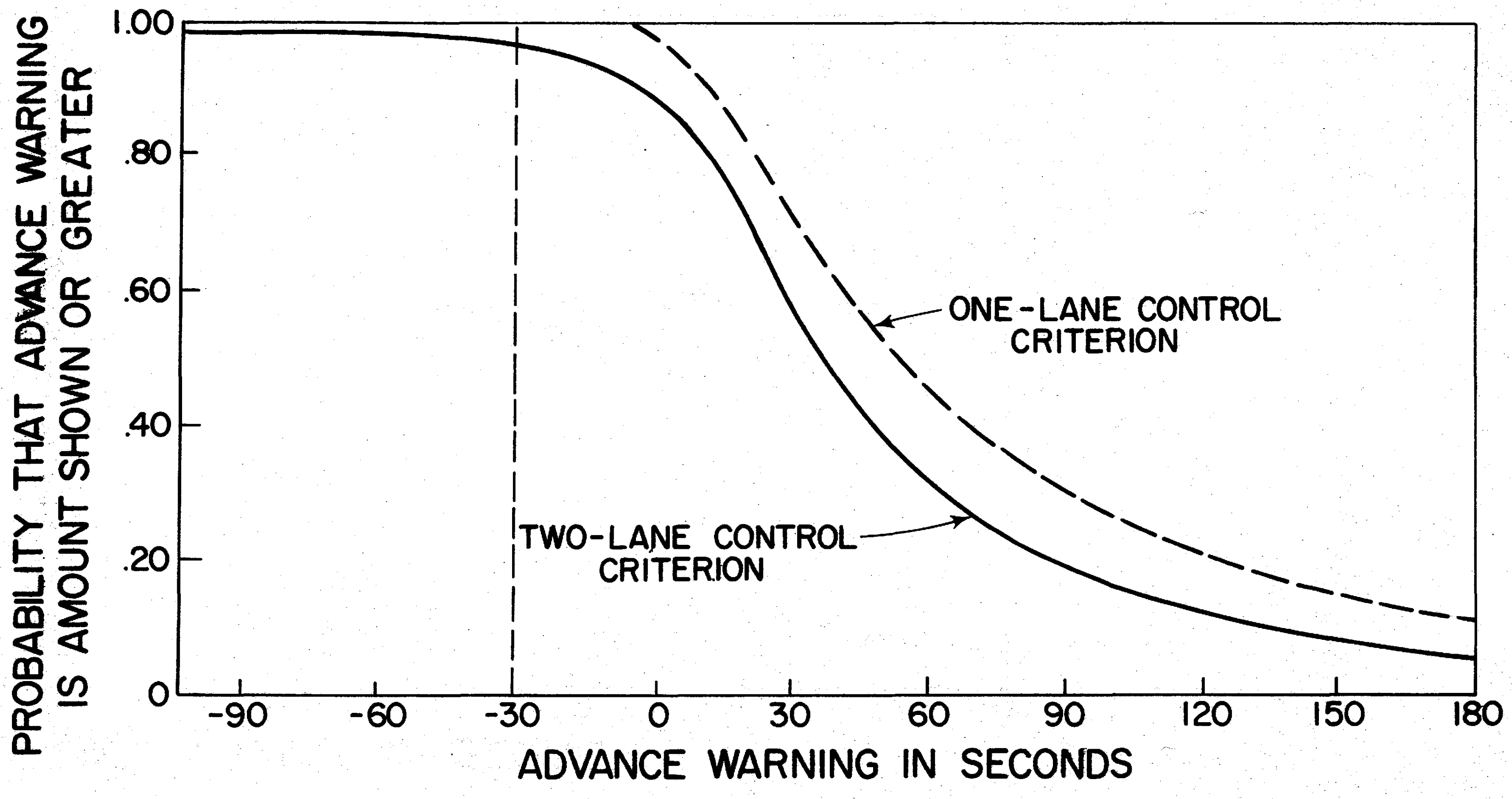

Figure 4 - Performance Curves - One-Lane vs. Two-Lane Control Criterion

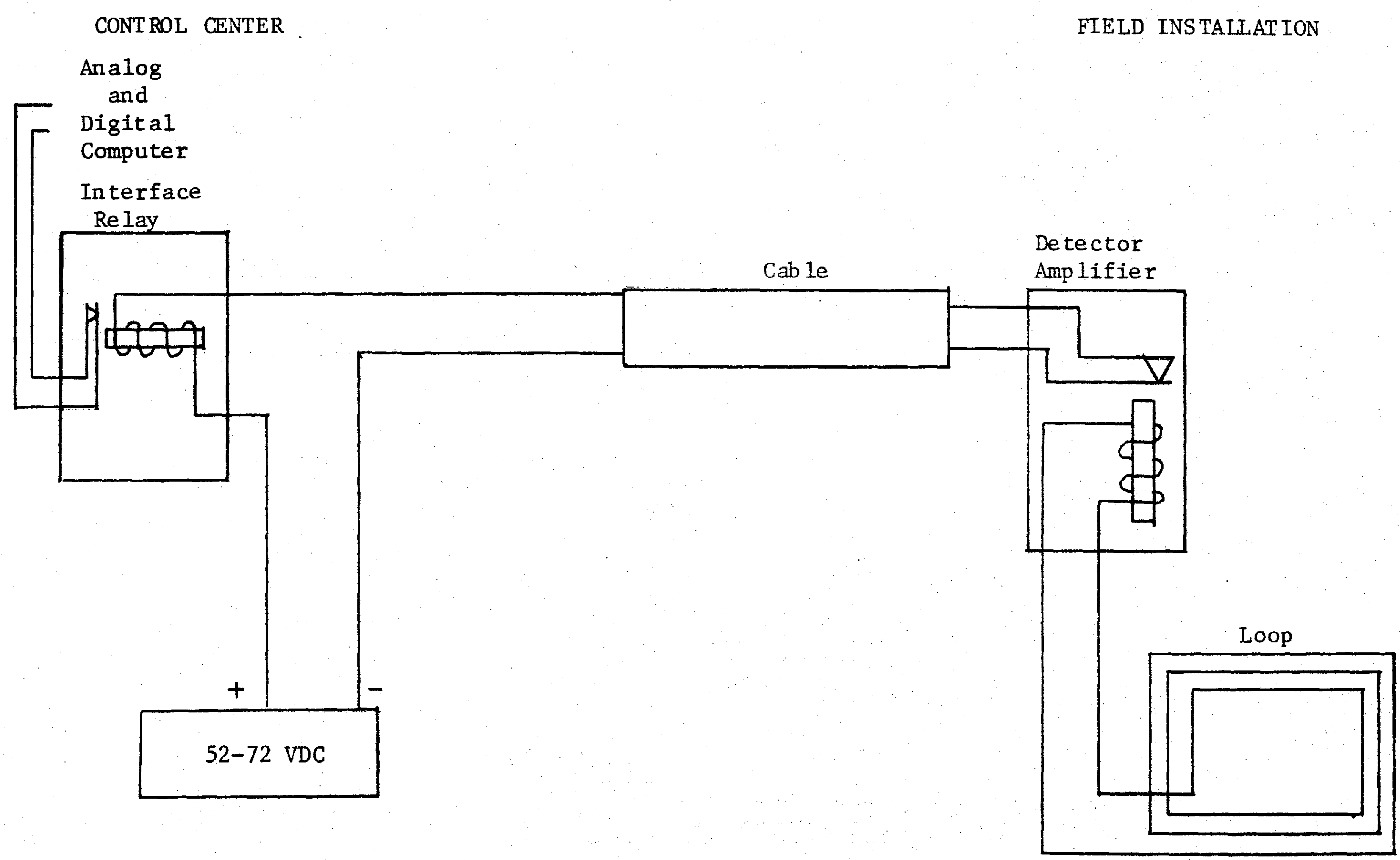

Figure 5 - Basic Detection System Design

The relay in the Control Center is an interface between the field voltages and the voltages used in the computer and control system. The control system (ramp control operations) was designed to operate on 24 volts DC. The detection system was designed by the supplier to operate between 52 volts DC and 72 volts DC. The increased research program on the Gulf Freeway in later years required additional detectors. Thirty-three new detectors were installed in 1969, raising the total to 96 detectors.

METHOD OF STUDY

Malfunctions and repairs of all the Gulf Freeway control and communications hardware subsystems including the 96 detector subsystem were maintained for a five-month period beginning in December, 1971. 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 and non-maintained systems were employed to ascertain the reliability of the detector subsystem to establish whether detector redundancy would be required in order to operate the automatic warning system with a high degree of confidence.

Following the above analysis period, changes were made to the system as a requirement before the Texas Highway Department purchased the detection and control system from the supplier. The specifics of these changes are discussed later on page 21. In addition, multiplexing equipment and detectors were added to the system for the increasing research and operational system. A follow-up study was conducted during a five-month period beginning in March, 1974, to evaluate the effects of these changes with respect to the reliability of the detectors used for the warning system.

HARDWARE SUBSYSTEMS - INITIAL EVALUATION

Table 1 summarizes the failures experienced on the Gulf Freeway during the initial five-month analysis period for the primary subsystems that are related to the operation of the safety warning system. The data do not include the failures experienced with the closed circuit television subsystem or with the ramp control signals.

The results reveal that there were 47 detector, 6 computer hardware, and 1 cable failures during the initial analysis period. Generally, the computer hardware 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 the 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. 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 illustrates the types of detector problems experienced on the Gulf Freeway during the five-month analysis period. Relay burns and internal circuitry problems accounted for 81 percent of the 47 failures (40.5 percent relay 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, defective wiring from the freeway lanes to the control box, etc.

Table 1

SUBSYSTEM FAILURES
(December 1971 through April 1972)

Type	Number of Failures	Percent of Failures
Detector	47	87
Computer Hardware	6	11
Cable	1	2
Wiring (Office)	0	0
	54	100

Table 2

DETECTOR FAILURES
(December 1971 through April 1972)

Type	Number of Failures	Percent of Failures
Relay	19	40.5
Internal Circuitry	19	40.5
Other	8	17.0
Loop	1	2.0
	47	100.0

It should be noted that 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 52 and 72 volts DC, whereas the relay contacts were rated for 28 volt DC operation. The increased voltage was necessary due to the extensive length of the communications cable and associated interconnections.

ANALYSIS OF DETECTOR SUBSYSTEM RELIABILITY EFFECTIVENESS - INITIAL EVALUATION

General

There is a similarity between reliability problems of maintained systems to problems of queueing theory. For example, in the general queueing problem one is concerned with the serving of 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 which can be maintained requires a specification of: 1) the equipment failure process, 2) the system configuration, 3) the repair process, and 4) 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 classical models of maintained systems can be used in analyzing system reliability.

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 applicable to maintained systems. It is defined as the proportion of time the system will spend in acceptable states. Because of the particular mission of the safety warning system, detector availability was selected as the measure of system reliability effectiveness.

Assumptions

The control and communication system on the Gulf Freeway is operated each week day 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. Since 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-serve basis.

If traffic arrives randomly on a highway, the arrivals will follow a Poisson distribution. The headways or times between arrivals will follow a negative exponential distribution. Similarly, since the detectors fail randomly, the detector failures can be assumed to be Poisson distributed; thus the time between failures will follow a negative exponential distribution. 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. It was felt that the small sample size may have influenced the fit. To make the analysis tractable, the negative exponential distribution was assumed).

Failure and Repair Rates

The frequency of detector failures during the intitial five-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

Table 3

DETECTOR FAILURES BY MONTH
(December 1971 through April 1972)

Month	Number of 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
TOTALS	47	205.50

$$\text{Failure Rate, } \lambda = \frac{47 \text{ failures}}{96 \text{ det.} \times 108 \text{ days} \times 12 \text{ hrs/day}} = 3.78 \times 10^{-4} \text{ failures/detector-hr.}$$

$$\text{Repair Rate, } \mu = \frac{47 \text{ Repairs}}{205.5 \text{ hrs.}} = 0.23 \text{ repairs/hr.}$$

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 as being in a failed state when any one detector is defective. The reliability analyzed refers to the availability of all three warning devices operating simultaneously. The mathematical models and reliability computations are presented in the Appendix.

From page 35 in the Appendix, it is shown that for the one-lane control criterion, 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.

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. The reader is reminded that the system consists of 3 warning devices having a total of 30 detectors. The system is in a failure state when any one of the devices is inoperative. Thus, 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.

From page 36 of the Appendix it is shown that there is a 99 percent chance that the system would be available using a two-lane control criterion. 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 four 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 an earlier warning of stoppage waves.

SYSTEM MODIFICATIONS

In 1972, the Texas Highway Department, as a requirement before purchasing the detection and control system, requested that the supplier find and implement a workable, permanent solution to the relay contact burn problem. The problem that developed was the contacts in the detector relay were being burned off because of high DC voltage and current. The burn problem caused high resistance whenever the relay was activated by a vehicle passing over the loop. As the buildup between the contacts grew, the accuracy of the detector was affected until it no longer gave any vehicle indications. The only solution that could be found (at that point in time) was to replace the relay in the detector whenever it gave grossly incorrect data. The supplier furnished relays and worked on a fix to this problem for several years. Several "fixes" were tried but had no real effect on the total burn problem.

The supplier designed and implemented a solid-state electronic detection interface that replaced each relay coil in the Control Center for a total of 160 solid-state relays. Figure 6 denotes the basic arrangement of the detection system. Each solid-state circuit was placed between the old mechanical interface relay and the assigned detector lines in the cable. The voltage placed on the detector relay contacts is 15 volts DC.
Figure 7 illustrates the basic arrangement of those detectors interconnected with the multiplexing equipment that was added to the system in 1972.

In addition to the above changes, more detectors were added to the system raising the total number of detectors to 105.

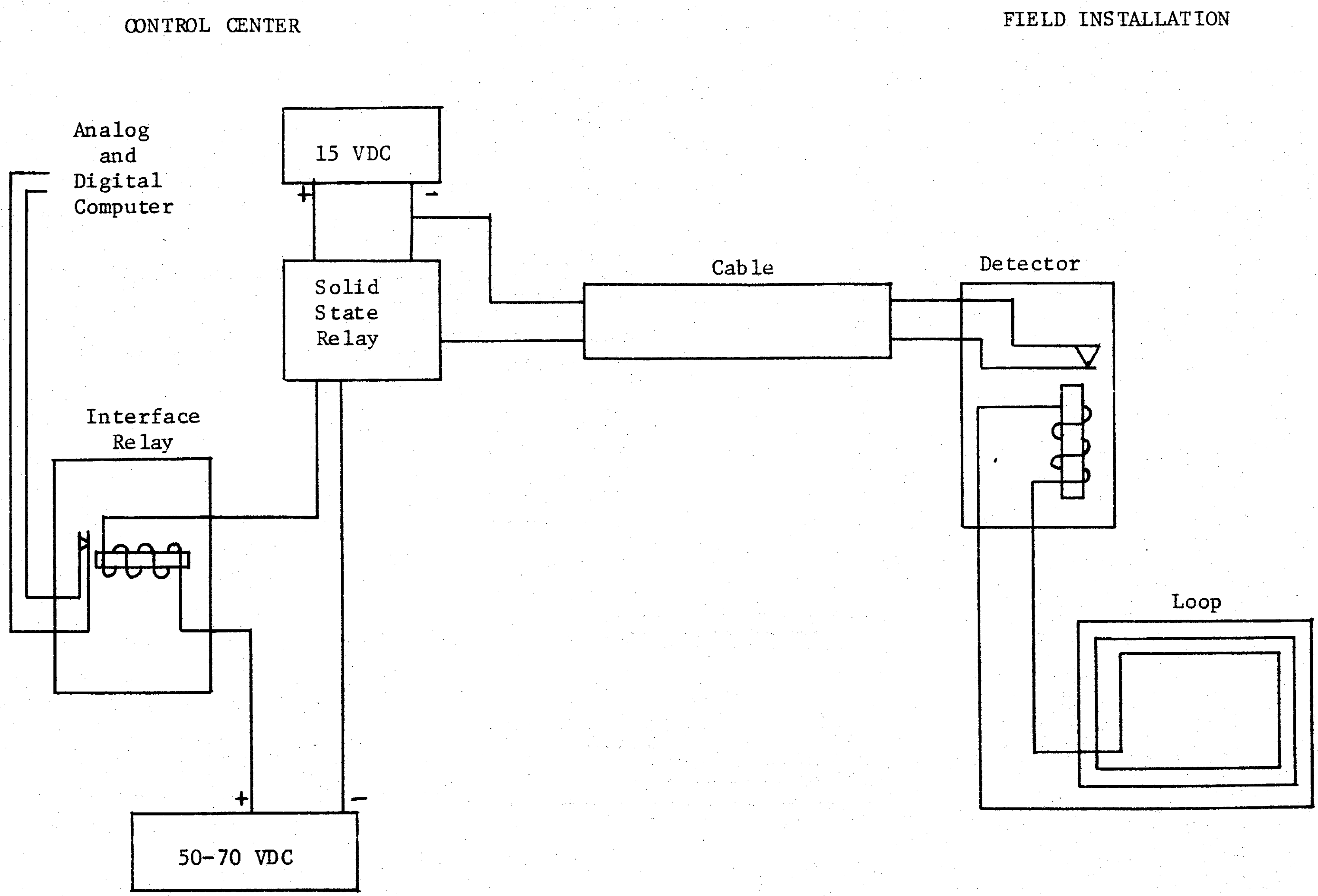

FIGURE 6 - Detector System Modification

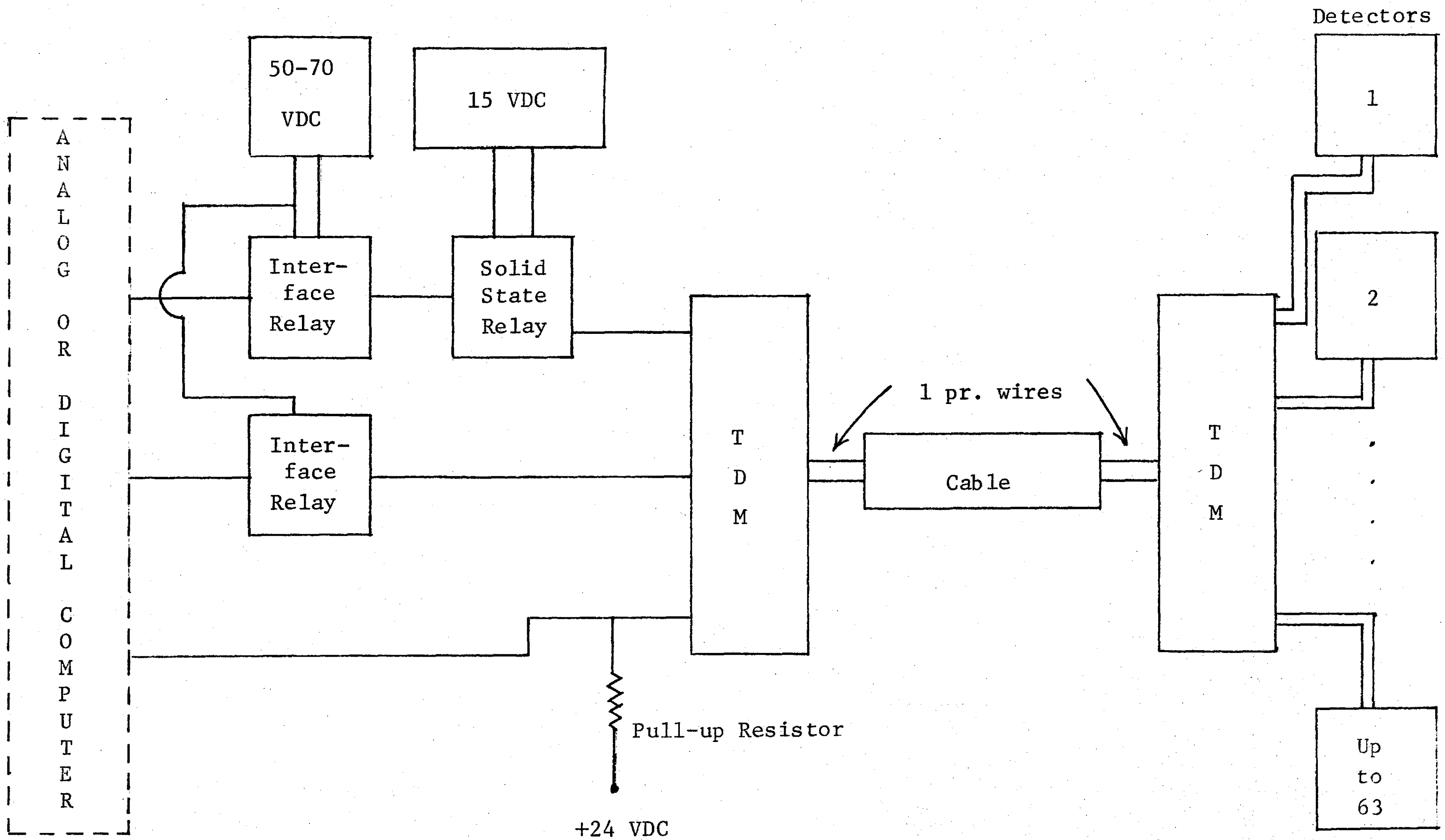

Figure 7 - Multiplexor Communications Systems

HARDWARE SUBSYSTEMS - FOLLOW-UP STUDY

Table 4 summarizes the hardware failures during the five-month follow-up study in 1974. A total of 49 failures occured during this period. Detectors and multiplexers accounted for 41 and 43 percent of the failures, respectively. The remaining failures were equally distributed between computer hardware and the cable.

A comparison of the data during the initial studies and the follow-up studies, shown in Table 5, reveals a 9 percent reduction in failures. Although detector problems dropped 57 percent from 47 to 20 failures, multiplexer failures accounted for a relatively high proportion of the system failures.

The types of detector failures during the follow-up study are presented in Table 6. Table 7 is a comparison of detector failure types during the initial and follow-up studies. The results show an 84 percent reduction in relay burn problems, 42 percent reduction in internal circuitry failures, and an 87 percent drop in other types of problems. These reductions were accompanied with a 400 percent rise (1 to 5) in loop failures.

The results of the analysis reveal that the changes in the system design have significantly reduced the detector failure rate.

Table 4

SUBSYSTEM FAILURES
(March 1974 through July 1974)

Type	Number of Failures	Percent of Failures
Detector	20	41
Multiplexer	21	43
Computer Hardware	4	8
Cable	4	8
Wiring (Office)	0	0
	49	100

Table 5

COMPARISON OF SUBSYSTEM FAILURES -
INITIAL STUDY VS. FOLLOW-UP STUDIES

Type	Number of Failures Dec. 71 - Apr. 72	Number of Failures Mar. 74 - July 74	Percent Change
Detector	47	20	-57
Multiplexer	-	21	-
Computer Hardware	6	4	-33
Cable	1	4	+300
Wiring (Office)	0	0	0
	54	49	-9

Table 6

DETECTOR FAILURES
(March 1974 through July 1974)

Type	Number of Failures	Percent of Failures
Relay	3	15
Internal Circuitry	11	55
Other	1	5
Loop	5	25
	20	100

Table 7

COMPARISON OF DETECTOR FAILURES -

INITIAL STUDY VS FOLLOW-UP STUDY

Type	Number of Failures Dec. 71 - Apr. 72	Mar. 74 - July 74	Percent Change
Relay	19	3	-84
Internal Circuitry	19	11	-42
Other	8	1	-87
Loop	1	5	+400
	47	20	-57

ANALYSIS OF DETECTOR SUBSYSTEM RELIABILITY EFFECTIVENESS-FOLLOW-UP STUDY

Failure and Repair Rates

The total time and the frequency of detector failures during the five-month follow-up study are shown in Table 8. The failure rate, λ, was computed to be 1.47×10^{-4} failures per detector hour with a repair rate of 0.14 repairs per hour.

One-Lane Criterion

As discussed earlier, the three warning devices are considered as one complete system. All the detectors must function to have an operating system. Equation 5 in the Appendix can thus be used to analyze the availability of the warning system for the special case of a 30-detector system. Substituting the computed values for the failure rate ($\lambda = 1.47 \times 10^{-4}$) and repair rate ($\mu = 0.14$), the steady-state availability of the 30-detector warning system is computed to be:

$$A = P_o = 0.96$$

For the revised system, under steady-state conditions there is a 96 percent chance that all 30 detectors will be functioning. Thus, there is a 96 percent chance that all three safety warning subsystems would be available assuming that all other hardware components are functioning.

The probability of having 1 or 2 detectors out of operation can likewise be computed.

$$P_1 = 30\rho \, P_o = 0.030$$

$$P_2 = \frac{(30)\,(29)}{2!} \rho^2 \, P_o = 0.0005$$

Table 8

DETECTOR FAILURES BY MONTH
(March 1974 through July 1974)

Month	Number of Failures	Total Time of Failures (Hours)
March	3	22.5
April	5	64.75
May	3	31.5
June	4	16.5
July	5	11.0
	20	146.25

$$\text{Failure Rate, } \lambda_d = \frac{20 \text{ failures}}{105 \text{ det. x } 108 \text{ days x } 12 \text{ hrs/day}} = 1.47 \times 10^{-4} \text{ failures/detector-hr.}$$

$$\text{Repair Rate, } \mu_d = \frac{20 \text{ repairs}}{146.25 \text{ hrs.}} = 0.14 \text{ repairs/hr.}$$

Two-Lane Criterion

The availability function under steady state conditions for the two-lane criterion is given by Equation 10 in the Appendix. Substituting the appropriate values results in

$$A = P_o = 0.96 + 1(0.030) + 0.862(0.0005)$$

$$A = 0.99$$

The results indicate that based on the current detector failure rate and repair rate, the 30-detector warning system would be operational 99 percent of the time assuming that all other hardware components were functioning properly.

RELIABILITY ASSUMING NO MAINTENANCE

The preceding analysis is based on the failure and repair rates experienced on the Gulf Freeway system. Since the warning system on the freeway is part of a large control and communications system, full-time maintenance personnel are available. It is anticipated that operating agencies will implement similar types of warning systems at isolated freeway locations where stoppage problems exist. In these cases, full-time maintenance personnel may not be available to service the system. Therefore, it was of interest to determine the effects on the system if no maintenance were performed on the detectors.

If the detectors were not maintained, then the reliability, R, is a function of time and can be written as follows:

$$R(t) = e^{-n\lambda t}$$

where

t = Time

λ = Failure rate per detector

n = Number of detectors

If a single warning sign was installed at an isolated location on a freeway with three lanes in each direction, the control logic using energy as a control variable require 12 detectors, two on each lane both upstream and downstream of the crest. If a one-lane control criterion is employed, the system would fail whenever one detector fails. Assuming that the failure rate is the same as that currently experienced on the Gulf Freeway (Table 8), the reliability for a non-maintained system, then, is computed as follows:

$$R(t) = e^{-(12)(1.47 \times 10^{-4})t} = e^{-0.0018t} \quad (21)$$

The reliability function for the single warning system requiring 12 detectors and requiring 24 hours a day operation is shown in Figure 8. The plot illustrates the rapid change in reliability in a matter of days.

Now if lane occupancy is used as the control variable, then only six detectors would be required. The reliability would be computed as follows:

$$R(t) = e^{-(6)(1.47 \times 10^{-4})t} = e^{-0.0009t}$$

The reliability function for this system is presented in Figure 8.

The curves presented in Figure 8 would be of some value in determining the frequency of maintenance that would be required to assure a selected level of acceptability. For example, if the agency was willing to operate a 12-detector system with at least a 50 percent probability that the system is functioning (again assuming all other hardware is operational) then from Figure 8, the detectors should be serviced at 17-day intervals.

Discussion

The analysis presented in this paper relates to the detector failures and maintenance practices as experienced on the Gulf Freeway Surveillance and Control system and should be regarded as such. The results may not be directly translatable to other systems because the hardware failures and maintenance practices may differ. The authors believe that comparable data from other systems will help shed some light on hardware problems so that a 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

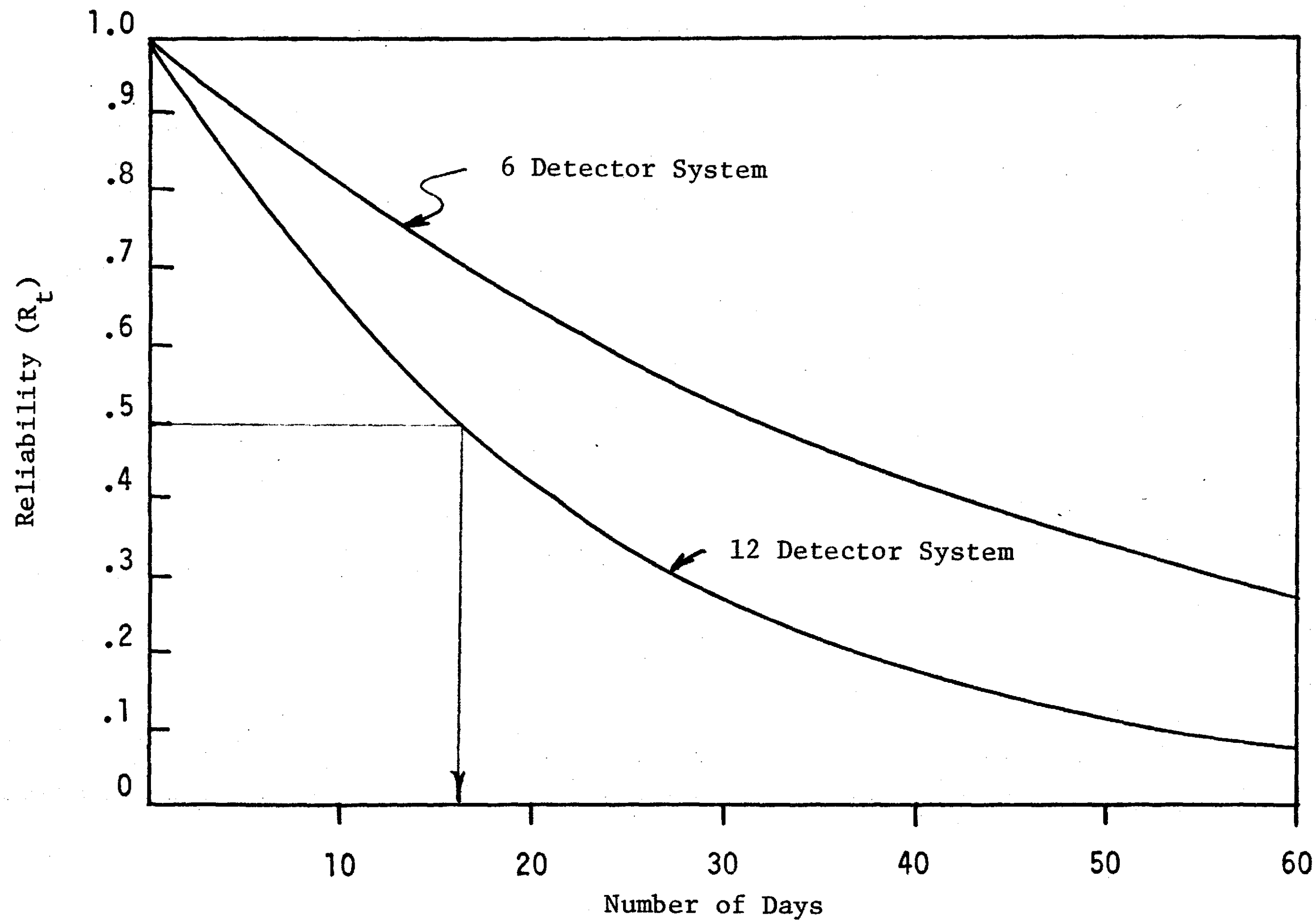

Figure 8 - Reliability of Non-maintained System

detectors and types of hardware problems that have been experienced on one operational system.

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APPENDIX

MODELS AND COMPUTATIONS

MODELS AND COMPUTATIONS

Assumptions

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.

One Lane Criterion

With the assumptions previously discussed, it has been shown that the following steady state probabilities apply for the general case of n detectors and r repairmen (4):

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

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

where

P_k = Probability of being in state P_k

k = Number of detectors down

n = Number of detectors in the system

$\rho = \frac{\lambda}{\mu}$

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):

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

For the case of one repairman, Equation (3) reduces to the following:

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

For the special case of a 30-detector system, Equation (4) can be written as follows:

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

Substituting the computed values for the failure rate (λ=3.78 x 10^{-4}) and the repair rate (μ = 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 of having 1, 2, or 3 detectors out of operation can likewise be computed.

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

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

$$P_3 = \frac{(30)\ (29)\ (28)}{2!}\ \rho^3\ P_o = 0.00002 \tag{9}$$

Two-Lane Criterion

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 which 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 given by:

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

The coefficient, C_1 is computed as follows:

$$C_1 = \frac{\text{Number of ways in which 1 detector can fail and yet the system be available}}{\text{Number of ways in which 1 detector can fail}} \qquad (12)$$

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

$$C_1 = \frac{\binom{30}{1}}{\binom{30}{1}} = 1 \qquad (13)$$

Likewise for C_2 and C_3,

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

$$C_3 = \frac{\binom{30}{3} - 5\left[\binom{6}{3} + 24\left[\binom{6}{2} - 3\right]\right]}{\binom{30}{3}} = 0.621 \qquad (15)$$

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

$$A = 0.95 + 1(0.045) + 0.862\ (0.001) + 0.621\ (0.00002) \qquad (16)$$

$$A = 0.99 \qquad (17)$$

Thus, there is a 99 percent chance that the system would be available using a two-lane control criterion.