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DEVELOPMENT OF A TECHNIQUE FOR DIGITAL COMPUTER CONTROL OF A SAFETY WARNING SYSTEM FOR URBAN FREEWAYS

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TRAFFIC MANAGEMENT AND CONTROL SYSTEMS

DEVELOPMENT OF
A TECHNIQUE FOR DIGITAL COMPUTER
CONTROL OF A SAFETY WARNING SYSTEM FOR
URBAN FREEWAYS

by

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ABSTRACT

A control technique for digital computer control of a safety
warning system for urban freeways was developed and evaluated. Traffic
energy was used as the control variable. Computer logic was developed
centered about critical energy as the control parameter. The ability
of the critical energy parameter to detect stoppage waves was studied
and evaluations were made of the performance, reliability, stability,
and sensitivity of the control logic. Based on the results of this
research, a revised control program was structured and later im-
plemented to automatically control three prototype safety warning
systems on the Gulf Freeway.

Key Words: Freeway control, traffic surveillance, safety, driver
           communications, traffic characteristics, shock waves.

DISCLAIMER

SUMMARY

This report is concerned with the development of a control technique for a safety warning system for urban freeways and the application of the technique to digital computer control of the system. The design concept of the safety warning system was presented in an earlier project report (1). The function of the safety warning system is to increase freeway efficiency by alerting motorists to stoppage waves on freeway sections having restricted sight distances (i.e., overpasses). It is anticipated that the improved efficiency will result in fewer accidents; reduced system travel time, driver anxiety, and driver discomfort; and improvement in the level of service.

Traffic energy was used as the control variable. The energy variable was computed based on one-minute speed and volume measurements updated every 30 seconds. Computer logic was developed centered about critical energy as the control parameter. The responsiveness of the critical energy parameter to stoppage waves using both a one-lane criterion and a two-lane criterion was studied. Evaluations were also made of the performance, reliability, stability, and sensitivity of the control logic.

Double loop detectors were installed in each lane of the inbound Gulf Freeway both upstream and downstream from three overpasses selected as the sites for the prototype safety warning signs. A data acquisition program was written to collect and store information received from these subsystem detectors.

When an incident was observed to occur on the inbound Gulf

Freeway that generated stoppage waves upstream, the program was loaded

into the computer. Simultaneously, video tape recordings, using two

recorders, were made of the traffic operations at the detector stations.

The two video recorders provided the opportunity to record simultan-

eously operations at both the upstream and downstream detector stations

for a particular subsystem. Thus, the generation of stoppage waves

through the subsystem could be evaluated. Relevant information con-

cerning time, location, freeway conditions, etc., were recorded on the

audio portion of the tape for reference. In this way, a permanent

visual, as well as quantitative record, was made of the traffic situation

for analysis.

The adequacy of the critical energy parameter to detect or predict

stoppage waves and the performance of the control logic in responding

to stoppage waves were evaluated by comparing the computer and video

data.

Based on the results of this research, the control technique was

revised and later implemented to control three prototype safety warning

subsystems on the Gulf Freeway.

The following specific findings may be drawn from the results of

this research:

1. The critical energy criterion established in this report

    provides a good indicator of stoppage waves on an urban

    freeway operating under levels of service B, C, or D.

The energy variable was calculated using one-minute
measurements of volume and average speed updated
every 30 seconds.

2. A one-lane control criterion in which any one of the
   three lanes provides the alert of a stoppage wave was
   shown to work satisfactorily in all of the cases studied.

3. The median and middle lanes provided the first alert
   concerning the presence of stoppage waves for the
   majority of the incidents studied.

4. An evaluation of the original control technique developed
   for real-time computer operation of the safety warning
   device revealed that the logic using a one-lane control
   criterion would respond satisfactorily to stoppage waves
   resulting from incidents that occur when the freeway is
   operating at levels of service B, C, or D. However, the
   analysis also revealed an unacceptable frequency of
   detector failures which would at times cause the safety
   warning device to respond late (Type I error) or would
   cause the device to activate erroneously (Type II error).

5. It was observed that in off-peak traffic periods
   (particularly during the summer months), the energy
   variable, based on a one-minute sample period,

intermittently fell below the critical energy value. According to the control logic, this drop in energy would cause the safety warning device to be activated erroneously (Type II error). The problem was noticed to occur particularly on the shoulder lane at the Griggs detector station.

6. Increasing the time base to five minutes did not reduce the frequency of Type II errors to an acceptable level.

7. An approach whereby a computer check is maintained on the speed and volume of the middle lane at the downstream detector station reduced the frequency of Type II errors to an acceptable level.

8. The original control technique occasionally subjected the system to some instability. It was observed that the variation of traffic characteristics at the downstream detector station after an incident occurred would occasionally cause the safety warning device to cycle on and off intermittently before the stoppage waves reached the upstream detectors. This problem could be eliminated if the system would remain on for a three-minute minimum after the initial activation.

9. An evaluation of the original control technique using

a two-lane criterion in which the system would not
respond unless stoppage waves were detected on two
lanes, revealed that it can generally respond to
stoppage waves in adequate time. However, it is less
responsive than the one-lane criterion. The logic
would have responded satisfactorily to 96 percent
of the cases studied. The results also revealed
that in almost 50 percent of the cases studied, the
amount of advance warning was less than that provided
with a one-lane criterion.

10. The combination of the median and middle lane de-
tectors gave the first indication of a stoppage wave
in the majority of the cases studied using a two-
lane control criterion.

Implementation

This report documents the development of control logic for digital computer control of a safety warning system for urban freeways. The control logic, shown in Figure S-1, has been implemented in Houston to automatically control three safety warning devices located at overpasses on the inbound Gulf Freeway. The three signs have been under automatic digital computer control since April 3, 1972, and the system has responded very satisfactorily to shock waves on the freeway. The developed logic could be applied to warning systems at other locations on the Gulf Freeway and on other urban freeways.

Although the control logic was developed to be responsive to shock waves, it is anticipated that an extension of the results reported herein will lead to the development of techniques for automatic detection of incidents on urban freeways.

Recommendations for Further Research

1. Research should be directed toward evaluating traffic parameters for the control of the safety warning device which require only one detector to measure. Such a parameter would reduce the detector requirements for the system.

2. The application of the safety warning device to tangent freeway sections should be evaluated.

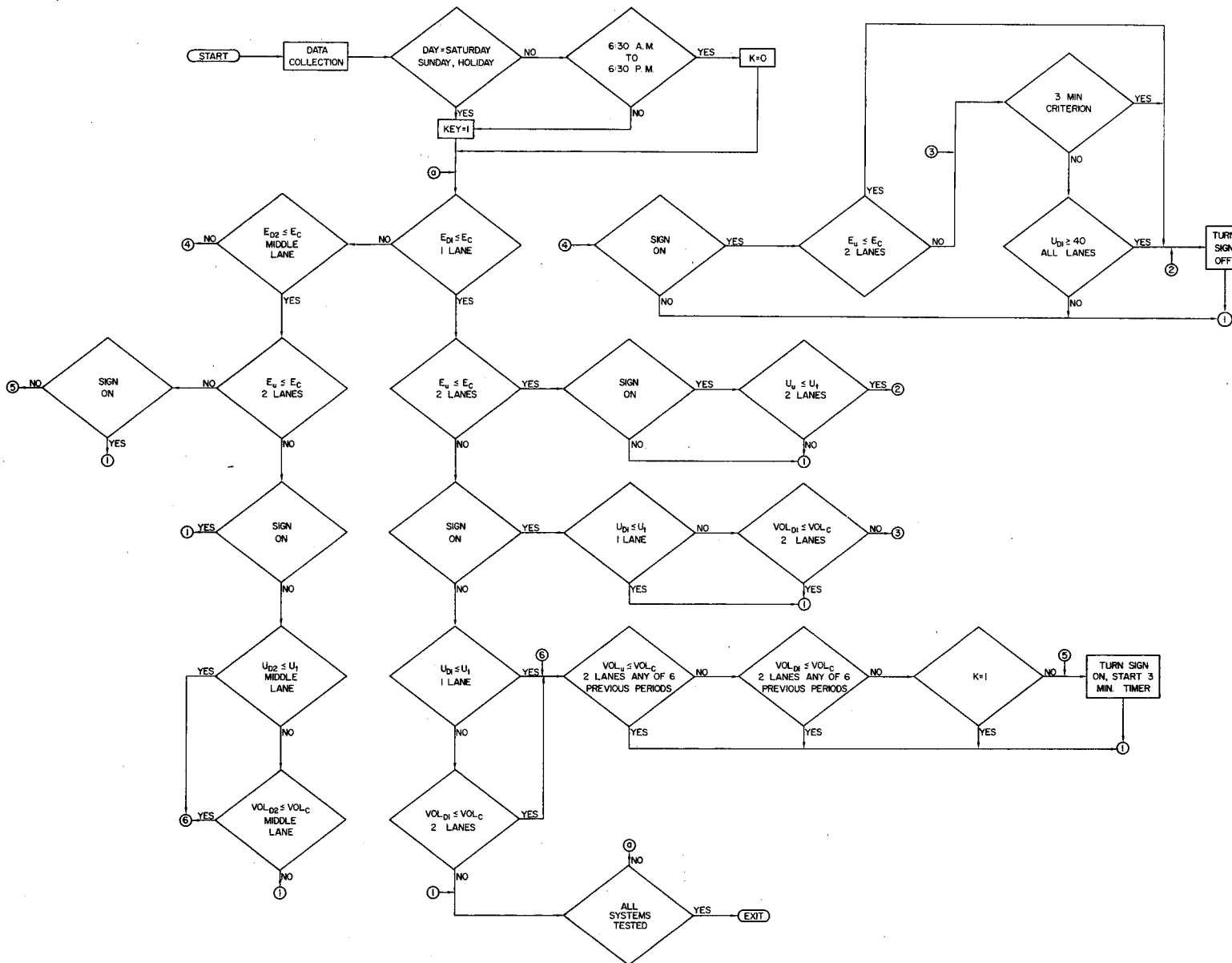3. Studies should be conducted to determine the reliability

FIGURE S-1-FLOW CHART OF CONTROL LOGIC FOR THE SAFETY
WARNING SYSTEM ON THE GULF FREEWAY

of detection systems for real-time freeway surveillance and control. The studies should result in specifications for detector arrangements for highly responsive systems such as the safety warning sign.

4. Ways must be sought to improve the reliability of detection equipment or to automatically locate defective detectors in real-time using computer programming methods so that incorrect control decisions for an urban freeway control and communications system can be eliminated.

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INTRODUCTION

An earlier project report (1), described the development of a warning system prototype designed to alert motorists of hazardous traffic conditions created by incidents on urban freeways. The system consists of a static sign with attached flashing beacons (Figure 1) located upstream of an overpass crest, and a flashing beacon mounted on the bridge rail on the top of the crest. Loop detectors, installed on each lane and located strategically on both sides of the overpass, transmit traffic information to the IBM 1800 digital computer located in the control center. The computer activates and deactivates the safety warning device according to preestablished criteria. Manual override features are also designed into the system. A schematic of the design concept is shown in Figure 2.

Objectives

This report is concerned with the development and evaluation of a computer control technique for the system. Specifically, the objectives of this research are to:

1. Develop a control technique for digital computer control of the prototype, and

2. Investigate the applicability of the control technique to operation of the prototype.

FIGURE I — WARNING SIGN WITH FLASHER

Safety Warning
Device

PROFILE OF FREEWAY

PLAN VIEW

Detectors

Safety Warning Device

Data from other
Fwy. Detectors

Compute Traffic
Parameters

Parameter
Critical

No

Sign
On

No

Yes

Yes

IBM 1800
Computer

Yes

Sign
On

No

Activate Sign

Deactivate Sign
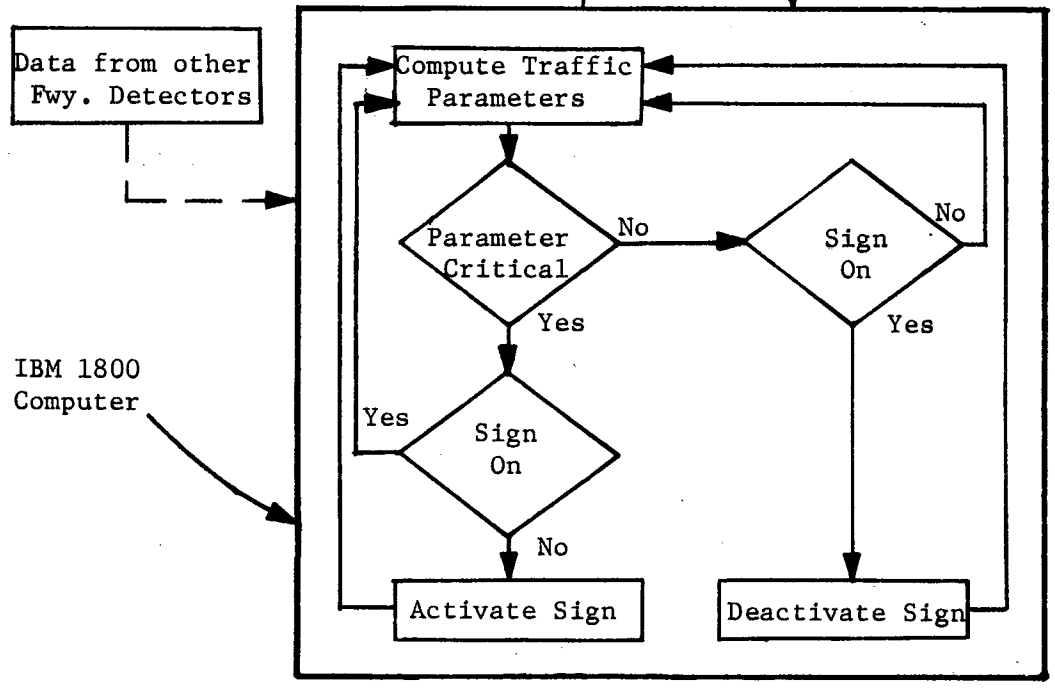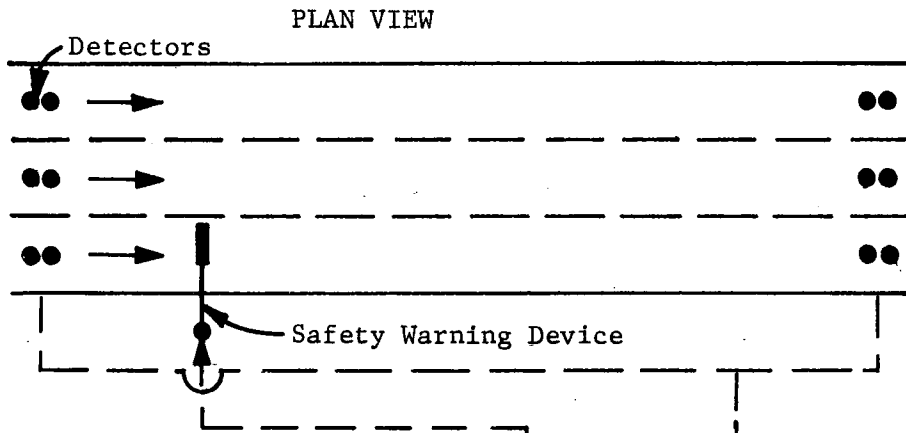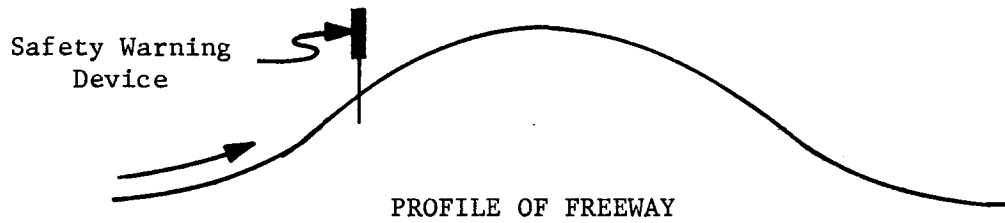
FIGURE 2 − DESIGN CONCEPT

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DEVELOPMENT OF CONTROL TECHNIQUE

Detection of Shock Waves

Several methods have been proposed to detect the movement of
shock waves as they progress upstream on a traffic lane. Barker (2)
suggested an approach whereby one of the parameters (speed, volume,
or density) would be measured at a selected station along a lane of
travel. Next, a measurement of the same parameter would be made at a
second station farther down the lane. The pattern measured at the
first station would then be projected by the travel time between
stations. It would then be compared with the pattern as it was being
measured at the second station. Any irregularity in the flow between
the two stations would be shown in the running difference of the two
patterns. This process would be repeated down the length of the road-
way with the parameter pattern being projected from one station to
the next for comparison.

Auer (3) further demonstrated the movement of discontinuities of
flow as they are delayed in time and space using a series of detectors
on a lane. Additional examples of this phenomenon have been shown
by others on the Holland Tunnel in New York (4) and on the Gulf Free-
way in Houston (5).

Weinberg, et al., (6) developed and evaluated mathematical logic
used to predict travel time in real-time on an urban freeway in the
event that a mishap caused a traffic flow breakdown. The approach
taken was to estimate travel time when a shock wave developed on the

freeway. Information was first acquired on the current behavior of traffic. From the current behavior and a knowledge of the shape of experimentally derived volume-density curves, envelopes of expected maximum performance (volume vs. density) were constructed periodically in real-time. If it was determined that a bottleneck existed, the volume being served at the bottleneck was compared to the volume upstream. In the event that a formation of a queue was indicated, the upstream volumes were integrated into a length of queue in which the vehicles were moving at the speed specified by the maximum density which yielded the bottleneck volume. Then the travel time was computed for the vehicles upstream.

Six approaches to the automatic detection and location of incidents during the peak period were explored by Courage (7) as part of NCHRP research conducted by the Texas Transportation Institute on the John C. Lodge Freeway in Detroit. These approaches were based on:

1. Vehicle storage

2. Kinetic energy

3. Energy differential (longitudinal)

4. Energy distribution (transverse)

5. Speed-density characteristics

6. Metering rates

The first five approaches involved measurement of one or more variables by the detection system. The measured values were compared to pre-established limits determined from observed frequency

distributions. When these limits were exceeded, an incident was considered to have occurred on the freeway. The sixth approach utilized certain aspects to determine when unusual conditions existed.

The vehicle storage approach involved the measurement of the traffic volume at upstream and downstream detectors. An indication of reduced capacity operation was said to exist when the output of a given subsystem was reduced while the input remained substantially unaltered, resulting in vehicular storage.

In the studies based on the kinetic energy approach, one-minute kinetic energy values were compared with preestablished limits, and a probable incident was proclaimed whenever the measurements exceeded the lower limits. A logical extension of the kinetic energy approach was obtained by comparing the energy values at upstream and downstream freeway stations. This approach was referred to as energy differential.

Another extension of the kinetic energy approach was developed by examining the distribution of individual lane energies across the roadway. It was reasoned that when the traffic stream is undisturbed by an obstruction, the energy is distributed reasonably over the available lanes. An extremely biased distribution could, therefore, be an indication of a capacity reduction. The variable was the "Ratio of Biased Energy."

The speed-density approach examines the operating point over the last sampling interval (one-minute) on the speed-density plane and compares the operation at adjacent upstream and downstream detectors,

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seeking an abnormal shift in this value. This approach assumes that a linear relationship exists between speed and density.

The metering rates approach was a by-product of the calculations which were necessary for the metering system. Since maximum and minimum limitations were placed on all control parameters calculated for the metering system, it was reasoned that an examination of these parameters might indicate the location of incidents.

The actual conditions observed by Courage using the kinetic energy approach are shown in Figure 3. Comparable curves were observed for the other approaches as well. It was noted that false alarms, that is, an indication of an incident when none existed, accounted for a large share of the output, especially during short term incident indications. The number of occurrences of false alarms decreased with duration of incident, as would be expected. Reductions in false alarms ranging from 50 to 85 percent were observed by the end of the second minute. This suggests that incidents of longer duration may be amenable to detection by the six methods evaluated.

The results experienced by Courage indicate considerable error in detecting incidents of very short duration during the peak period. However, these errors were primarily in terms of false alarms; that is, they gave an indication of an incident when one had not occurred. Although these results were not totally successful for detecting incidents of short duration, they do suggest considerable promise for detecting discontinuities in the traffic stream which would be relevant

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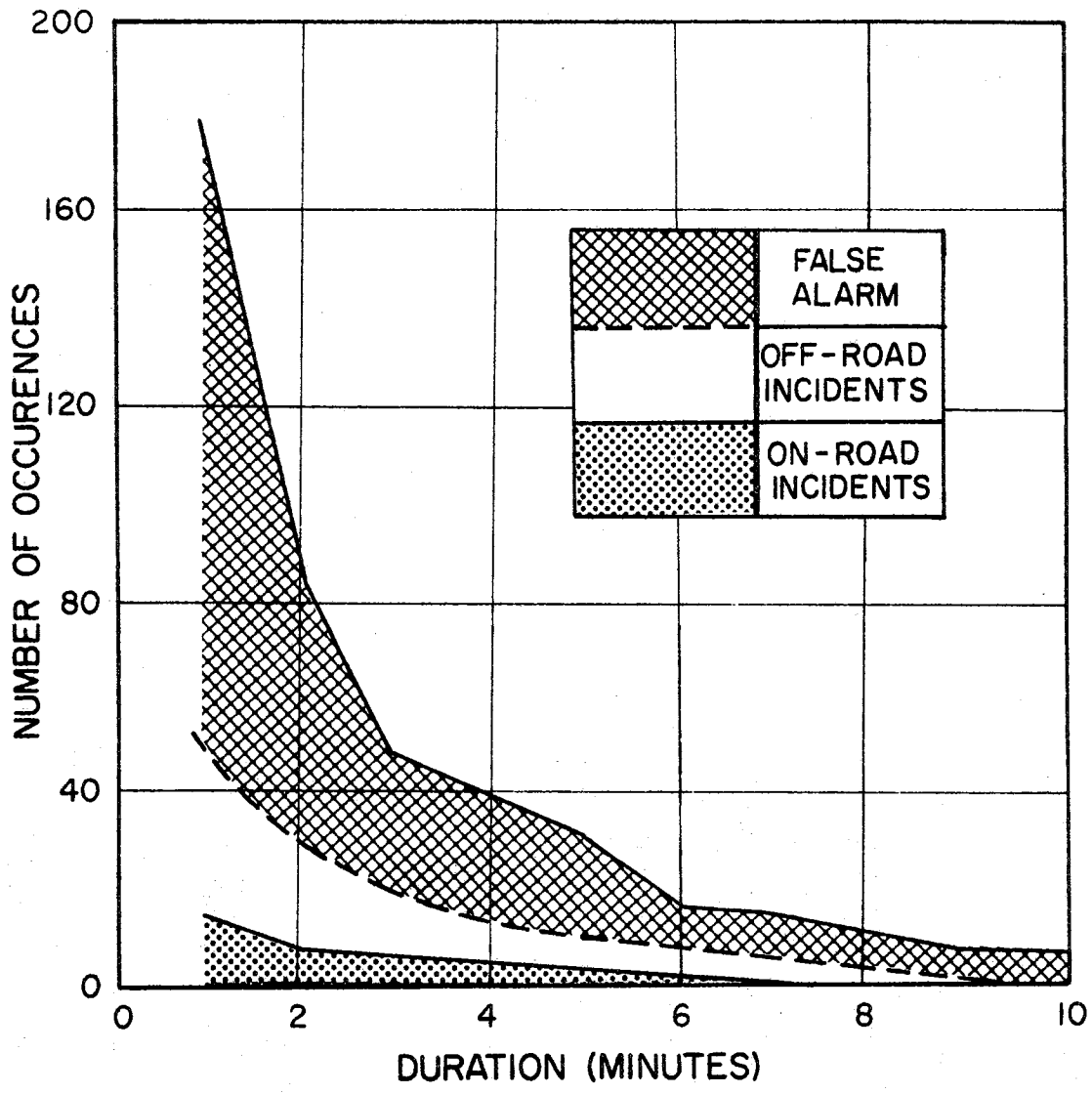
FIGURE 3 — OBSERVED CONDITIONS DURING PERIODS IN WHICH THE KINETIC ENERGY VALUES EXCEED THE THRESHOLD LIMITS (7)

for the objectives of the research reported herein. The large number of false alarms indicate that several discontinuities in the traffic stream were detected, but were considered by the models as incidents of short duration. This finding would seem to indicate that some of the models suggested by Courage might indeed be capable of providing the parameters necessary for the activation of the safety warning devices on the Gulf Freeway, at least during the peak period. Whether or not a specific incident such as an accident, stalled vehicle, etc., can be detected is not considered relevant to this work. What is important is the ability to measure and respond to the discontinuities in the traffic stream which are potentially dangerous conditions in the areas with restricted sight distances.

The Control Variable

The traffic variable selected for automatic control of the warning system is referred to as kinetic energy. The basic theory and the correspondence between momentum, kinetic energy, and acceleration noise have been well documented in the literature (8, 9, 10). In summary, the momentum of a traffic stream is described by

$$q = ku \qquad (1)$$

where   q = mean flow rate

   k = mean concentration

   u = mean speed

The kinetic energy, E_k, is given by

$$E_k = \alpha k u^2 \tag{2}$$

where α is a constant

Assuming a linear function between speed and density, the normalized relationships of Eqs. 1 and 2 can be written as a function of speed as follows:

$$q = k_j \left[u - \frac{u^2}{u_f} \right] \tag{3}$$

$$E_k = \alpha k_j u^2 - \alpha \frac{k_j}{u_f} u^3 \tag{4}$$

where k_j = jam concentration

u_f = free speed

The correspondence between momentum, kinetic energy, and acceleration noise is illustrated in Figure 4. Optimum service volume, based on maximizing kinetic energy and minimizing acceleration noise, corresponds to a level of flow which is less than capacity. Operating speed, on the other hand, is higher than the speed realized at capacity. Referring to the right side of Figure 4, it is seen that a small increase in demand above the volume at maximum energy (or critical level of service) tends to increase greatly the density of the traffic stream, accompanied inevitably by a sharp decrease in operating speed.
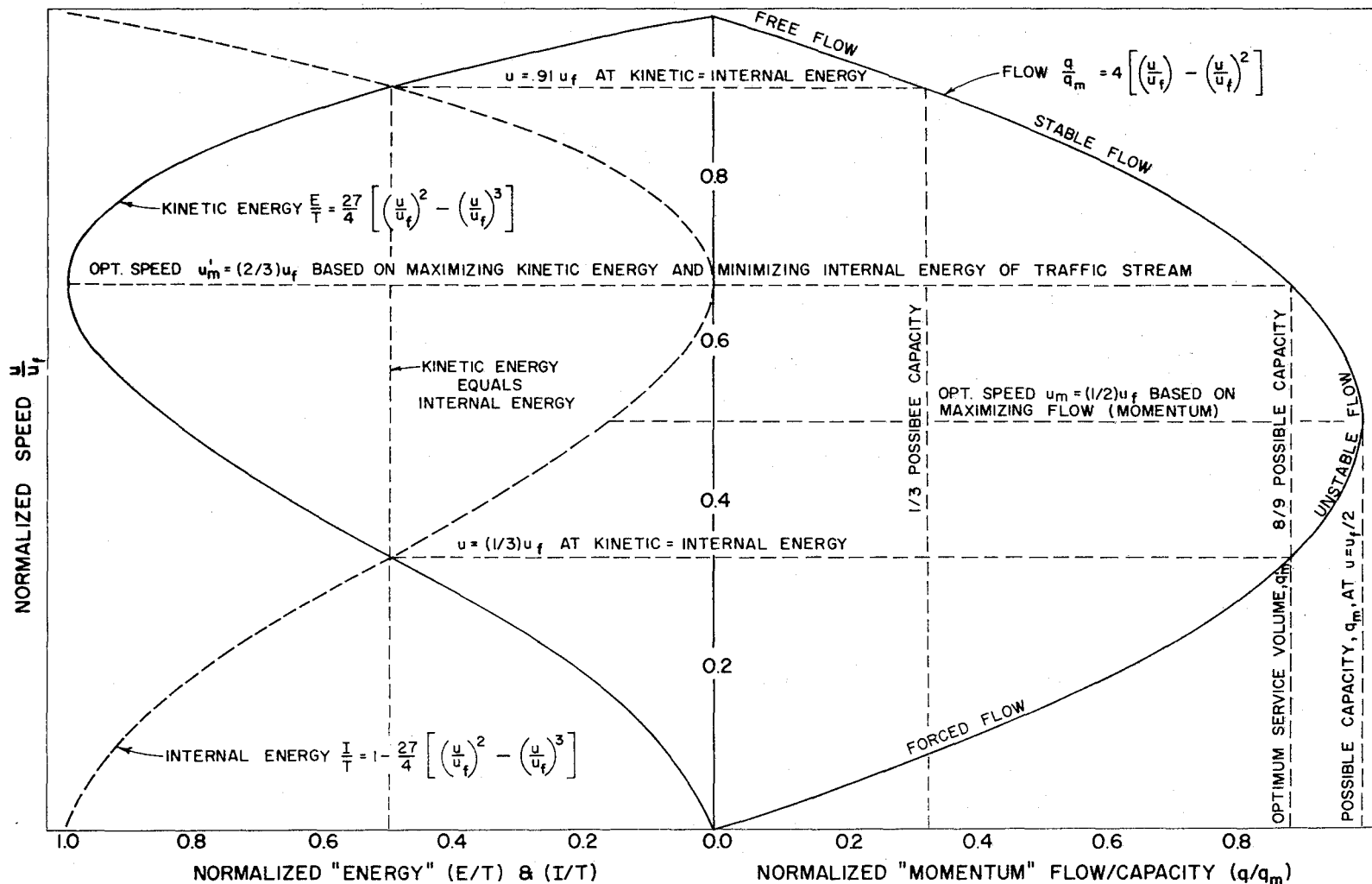
FIGURE 4 – QUANTITATIVE APPROACH TO LEVEL OF SERVICE USING THE "TOTAL ENERGY" – MOMENTUM ANALOGY (9)

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Analysis of the energy characteristic curve suggests that a deterioration in the level of service due to disturbances in the traffic stream would initially cause the kinetic energy to increase, if the initial operation was at level of service A, B, and C. This deterioration, in effect, would initially result in a higher level of kinetic energy near the disturbance in comparison to those at up-stream locations which have not yet been affected. The relative differences in kinetic energy between downstream and upstream sections of the freeway would, therefore, provide an indication of the degree of transition that the motorist would encounter. The expected degree of transition would provide a decision-making basis for activation of the safety warning device. Figure 5 illustrates the expected change in kinetic energy resulting from a disturbance in the traffic stream when operating characteristics are at levels of service A, B, or C.

If the freeway were operating at level of service D (Figure 5), disturbances caused by incidents at the downstream detectors would cause the kinetic energy to reduce rapidly at this location. The traffic upstream would not be affected until the shock wave generates back. Initially, then, the kinetic energy of the traffic stream would be considerably lower downstream relative to the upstream locations.

Hypothesis

An examination of the relationship between the energy and the

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NORMALIZED ENERGY (E/E$_f$) & (E$_i$/E$_f$) NORMALIZED MOMENTUM (q/q$_m$)
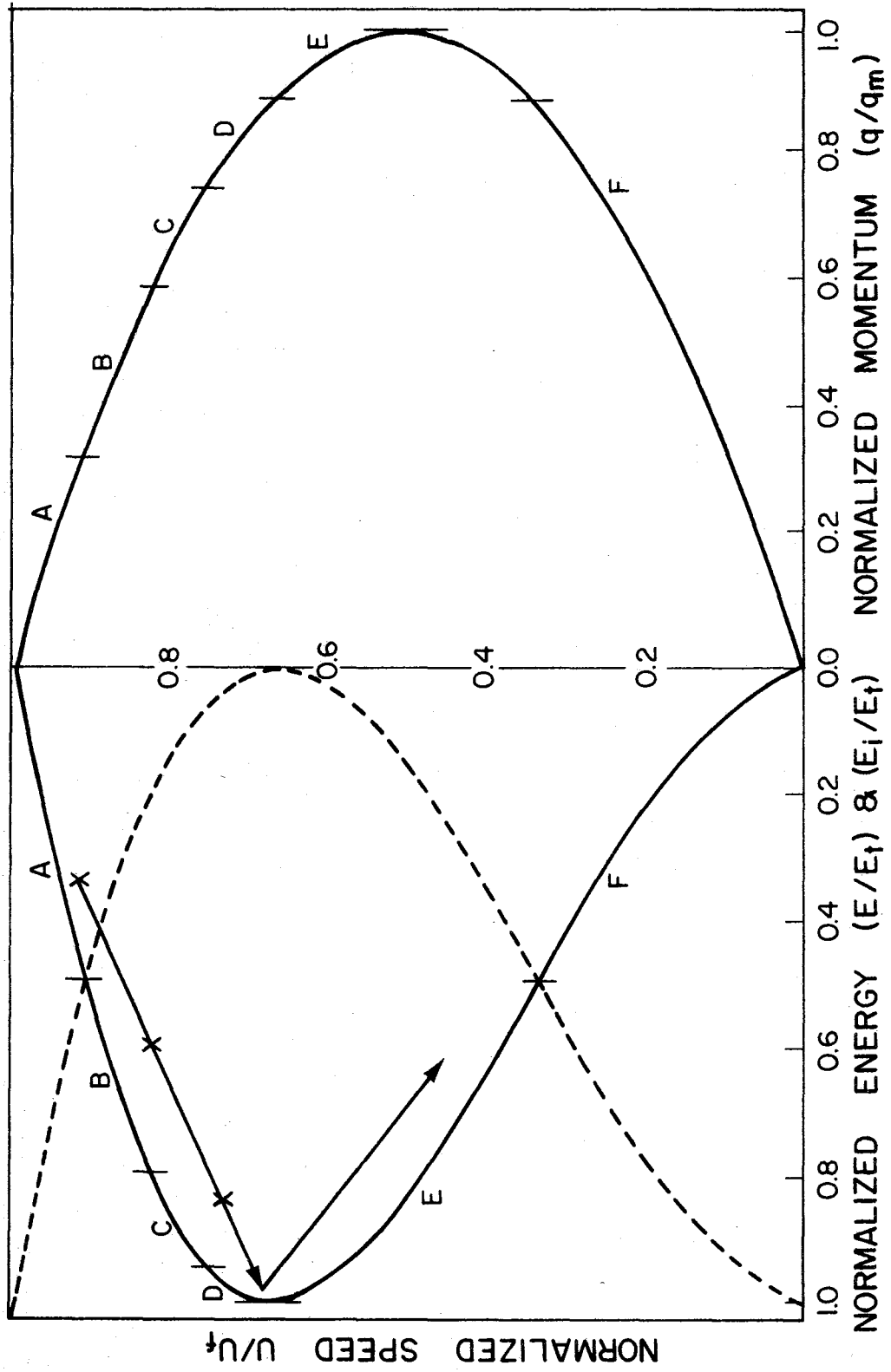
FIGURE 5 – EXPECTED CHANGE IN ENERGY–INITIAL
OPERATION AT LEVEL OF SERVICE A, B, C, OR D

NORMALIZED SPEED U/U$_f$

momentum curves shown in Figure 4 reveals that one of the intercepts

of energy and acceleration noise curves identifies forced flow (level

of service F) conditions on the freeway. Flows are below capacity,

and storage areas consisting of queues of vehicles form. This type

of operation is indicative of stop-and-go motion of the traffic

stream. The transition to the forced flow condition occurs rather

rapidly. Good operation is not achieved until the storage is dissipated.

The intercept of the energy and acceleration noise curves occurs when

the energy is one-half the maximum energy (E_m') of the stream. Based

on the theory and discussions previously presented, the hypothesis is

made that stoppage waves can be expected to exist on the freeway when

the energy drops below one-half the maximum energy. This energy level

can be referred to as the critical energy, E_c. Thus,

$$E_c = \frac{1}{2} E_m'$$ (5)

It is emphasized that the energy will also be less than one-half

maximum energy when the freeway is operating at level of service A.

On most urban freeways, level of service A would be experienced only

during the early morning periods, say between 1 a.m. and 5 a.m. The

transition from level of service B to A will probably be gradual. The

energy model assumes that the energy will drop below E_c due to the

queues of vehicles resulting from an incident.

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Operation of the Safety Warning Device

This section describes the automatic operation of the safety warning device. The control logic and assumptions underlying the logic are also presented.

The control logic developed as part of this work is concerned with traffic incidents and discontinuities of flow which occur while the freeway is operating at levels of service B, C, and D. Figure 5 illustrates that the traffic stream can be expected to operate at energy levels above E_c during these conditions and, therefore, represents a base operating level for the logic structure.

Assuming that the critical energy parameter, E_c, is capable of predicting or measuring the occurrence of a shock wave, the control logic must be capable of activating and deactivating the safety warning device automatically. The design of the prototype requires that detectors for each subsystem be placed both upstream and downstream from the crest of the vertical curve. Since traffic incidents are random events, there exists the possibility of an incident occurring in any one of three major areas relative to the detectors, namely:

1. Downstream of the subsystem (Case I)

2. Between the upstream and downstream detectors (Case II)

3. Upstream of the subsystem (Case III)

A comparison of the expected operating characteristics with respect to energy for the three cases is illustrated in Figure 6.

Case I. - When an incident occurs downstream of the subsystem,
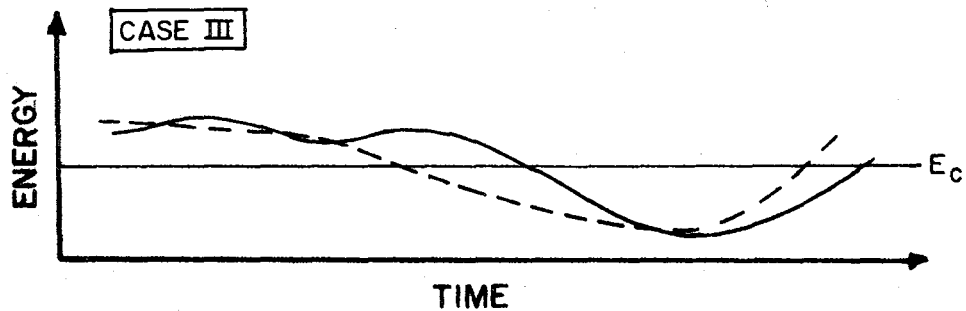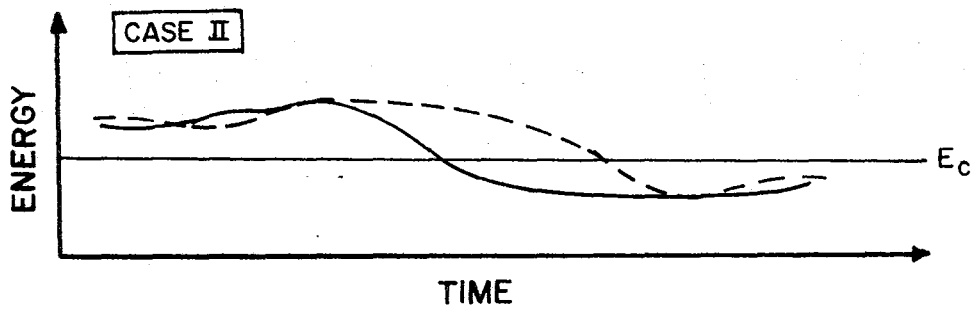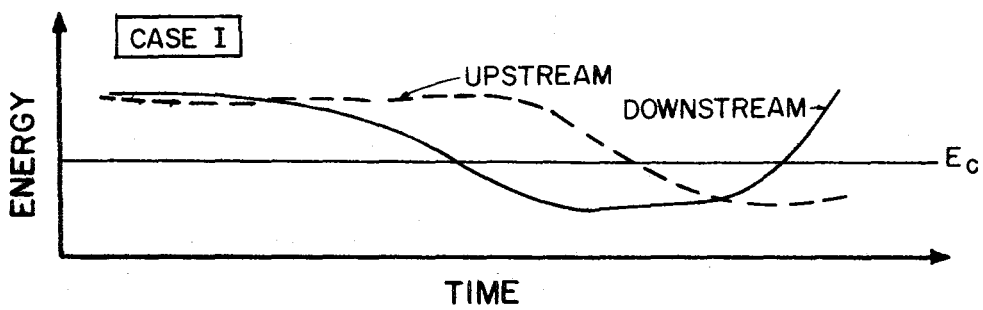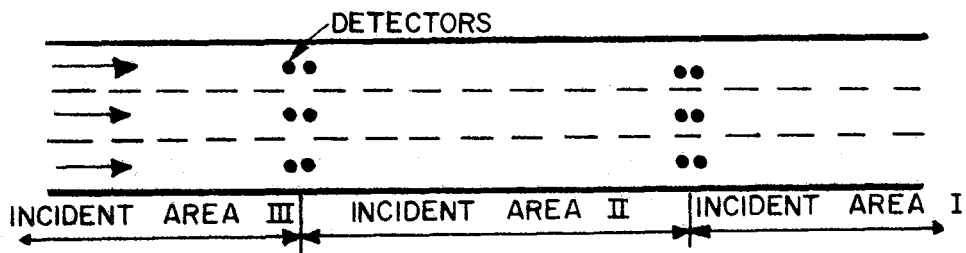
FIGURE 6 — EXPECTED ENERGY CHARACTER-
ISTICS FOR EACH INCIDENT
CASE

the downstream detectors would provide the alert that a major discontinuity of flow exists and a stoppage wave is being generated upstream. When the stoppage wave is detected, the safety warning device would be activated. When the stoppage wave has progressed over the upstream detectors, the device would be turned off.

The control sequence for the operation of the warning device is illustrated in Figure 7. Energy measurements are made on each lane at both the upstream and downstream detector locations. The logic assumes that current operating conditions are at level of service B, C, or D which, in effect, means that the energy values are above E_c. If the energy at both the downstream and upstream locations is above the critical levels, no action is taken. When an incident occurs, the stoppage wave will be detected by any one of the lane detectors at the downstream location when the energy level drops below E_c. The energy at the upstream detectors at this point in time will still be above E_c. When this condition exists, the safety warning device would be activated and would remain in this status until the relative energy levels change.

When the stoppage wave generates over the upstream station detectors, it is expected that the energy at this location will drop below the critical level. Once this occurs, the warning device can be turned off.

As the traffic operation improves downstream, the energy at the downstream detectors will again increase above the critical level

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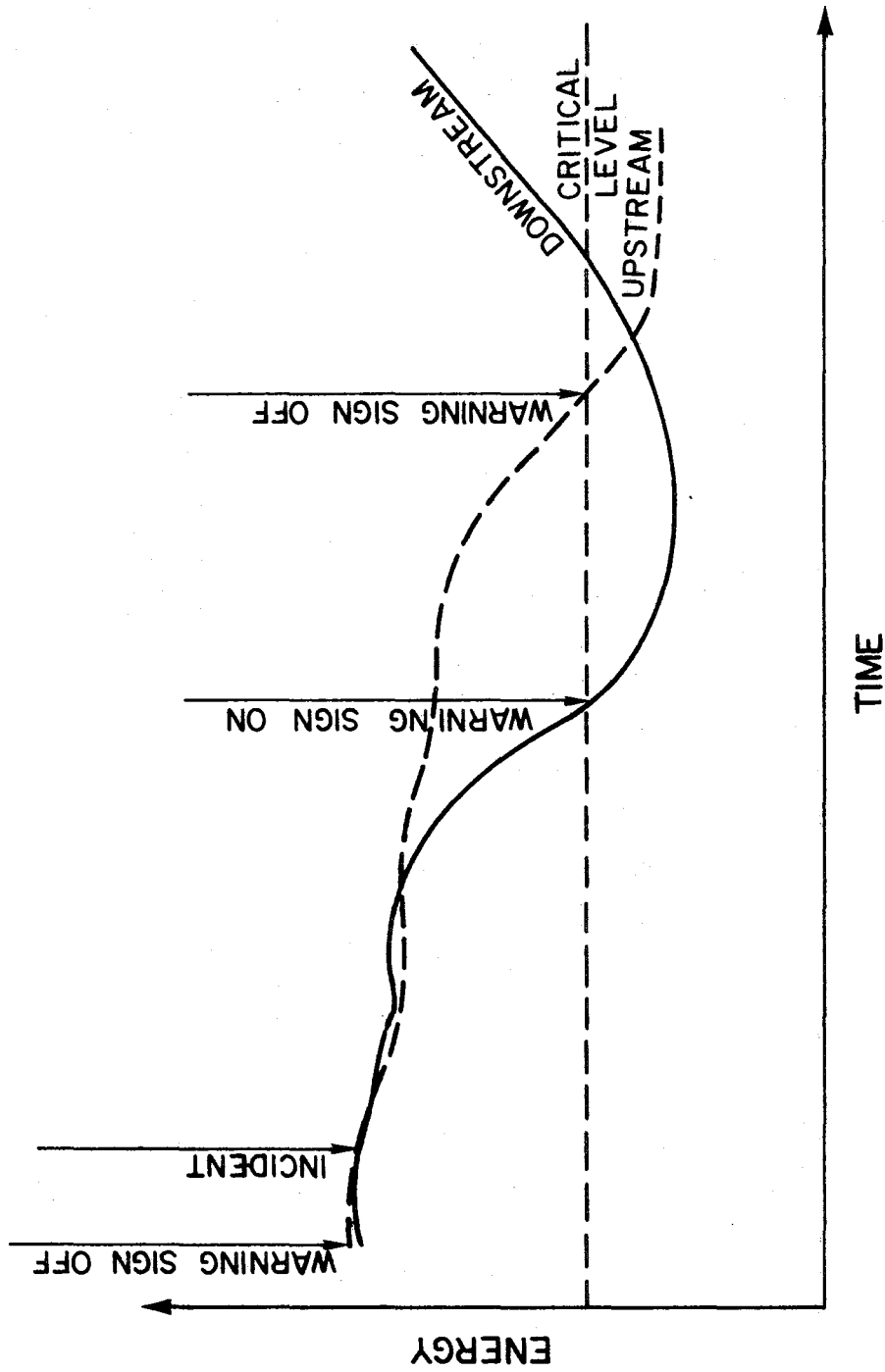
FIGURE 7 — EXAMPLE OF ENERGY CONTROL CRITERION FOR A SUBSYSTEM — CASE I

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while remaining below the critical level upstream. The warning device will remain in the off position.

Case II. - When an incident occurs between the detectors within a subsystem, the need to activate the warning device will depend upon the location of the incident relative to the crest of the curve. If an incident occurs downstream of the crest, the warning sign should be activated.

The control logic for this case differs from Case I. The key to the operation in Case I is the detection of a stoppage wave at the downstream detector stations. In Case II, it is obvious that the stoppage wave will originate between the detector stations, and the warning device must be activated prior to detecting a stoppage wave. For Case II then, it is the absence of normal traffic at the downstream detector stations that provides the flag.

The energies at both the upstream and downstream detectors are expected to be greater than E_c under normal operating conditions. When an incident occurs downstream of the crest, the momentary reduction of volumes at the downstream detector station will cause the energy to drop below E_c. However, in contrast to Case I, the speeds will be relatively high. This operation is equivalent to level of service A. Since the energy at the upstream station is expected to remain above E_c at this point in time, the warning device would be activated. When the stoppage wave progresses over the upstream detectors, the energy will drop below E_c, and the device will be turned

off. The control sequence is illustrated in Figure 8.

An incident occurring upstream of the curve crest will cause the upstream energy to drop below E_c as the stoppage wave passes over the detectors while the energy downstream will remain above E_c. The warning device would remain off under this condition. The energy downstream will eventually drop below E_c due to reduced volumes. The speeds, however, will remain relatively high. The warning device would continue in the null status.

Case III. - Unlike the two previous cases, the concern when an incident occurs upstream of the subsystem is to insure against false activations. Again, under normal conditions, the energies upstream and downstream are expected to be above E_c. When an incident occurs that restricts the flow of traffic into the subsystem, it is highly likely that the reduction in volume could cause the energy at the upstream detectors to shift below E_c. A short period later, both the upstream and downstream stations could conceivably be operating below E_c. These conditions, however, are comparable to level of service A. Consequently, the warning device should remain in the off position.

Seconds after the incident is cleared from the freeway, the increase in volumes will cause the energy at the upstream station to rise above E_c while the downstream station registers energy below E_c. Again, the warning device should remain in the null position. When the higher volumes reach the downstream station, the energy both
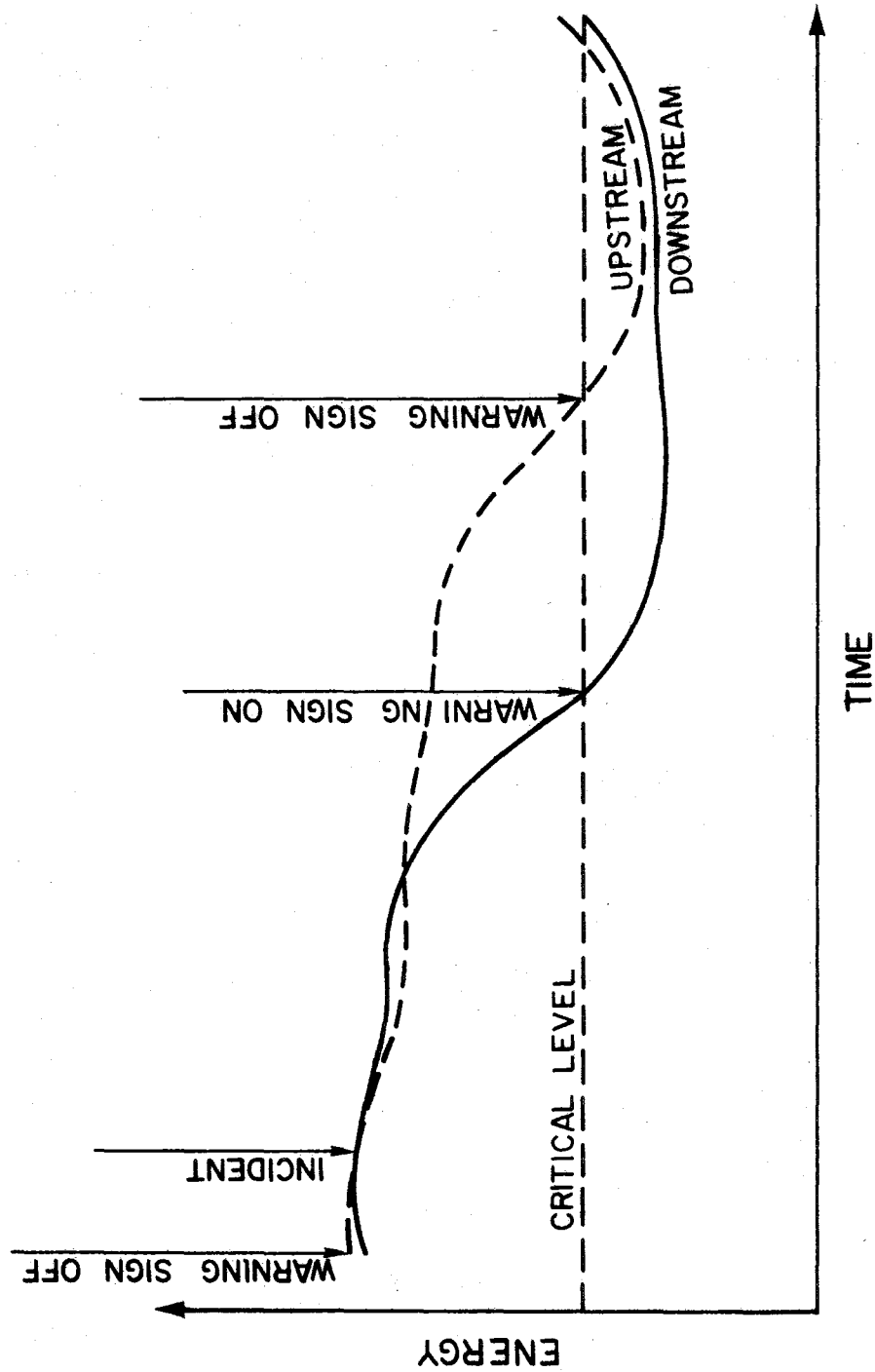
FIGURE 8 — EXAMPLE OF ENERGY CONTROL CRITERION
FOR A SUBSYSTEM — CASE II

upstream and downstream will be above E_c, placing the subsystem back
into a standby position.

Subsystem Operation. - To help facilitate the description of the
possible operating conditions and the required status of the warning
device, a decision listing is presented in Table 1. Inspection of the
table reveals that the decision logic for Cases I and II are identical.
In other words, the logic is the same regardless of whether an incident
occurs downstream of the subsystem or between the upstream and down-
stream detectors.

TABLE 1

DECISION TABLE FOR OPERATION OF WARNING DEVICE

Energy $\leq E_c$		Status of Warning Device		
Upstream	Downstream	Case I	Case II	Case III
No	No	Off	Off	Off
No	Yes	On	On	Off
Yes	Yes	Off	Off	Off
Yes	No	Off	Off	Off

The logic for Case III is essentially the same as Cases I and
II with one major exception. When the energy is above E_c upstream
and below E_c downstream, Case III requires that the sign be in the
null position. This is in contrast to Cases I and II in which a
stoppage is detected when the above conditions exist. Therefore,

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an additional check is necessary to insure that the warning device

is not turned on when an incident occurs upstream of the subsystem.

One approach would be to check the speed and energy at the upstream

location over n previous time periods. Had the upstream energy dur-

ing the previous n time periods been below E_c and the speed above

some critical speed, u_c, the warning device should remain off. A logic

flow chart was structured based on the requirements for the three

incident cases, and is presented in Figure 9.

Operational States of the System

An examination of the operation of the safety warning device

reveals that four operational states can exist. These states are

illustrated in the matrix presented in Table 2. The first and most

important state of the system exists when a stoppage wave is generated

on the freeway and the warning device responds to it. (The device is

activated.) The second state occurs when a stoppage wave is not

present and the warning sign accordingly is not activated.

The remaining two system states in effect constitute errors

of the system and will be referred to as Type I and Type II errors.

A Type I error occurs when a stoppage wave is generated on the free-

way but the system does not respond. From a safety and operational

standpoint this is the most critical error. A Type II error occurs

when a stoppage wave does not exist but the warning sign is activated.

This error can produce latent safety and operational problems. For

example, if the warning sign is falsely activated a sufficient number

START

DATA COLLECTION

$E_D \leq E_C$

SIGN ON — NO → EXIT

NO

YES

TURN OFF

EXIT

$E_u \leq E_c$ — YES → SIGN ON — NO → EXIT

YES → TURN OFF → EXIT

NO

SIGN ON — YES → KEEP ON → EXIT

NO

$E_u \leq E_c$
$U_u \geq U_c$
ANY PREVIOUS n PERIODS — NO → TURN ON → EXIT

YES

EXIT
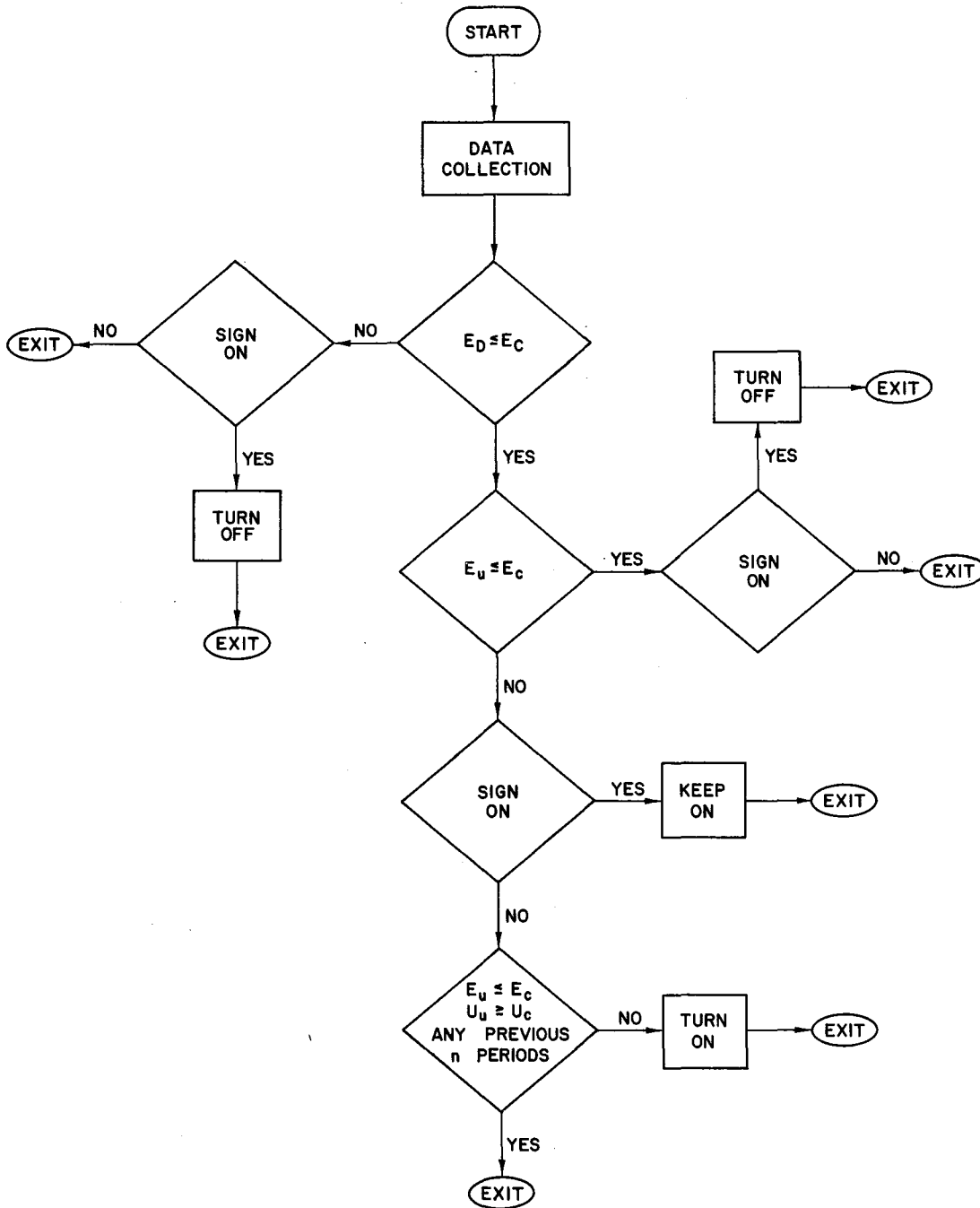
FIGURE 9 — INITIAL LOGIC FLOW CHART FOR CONTROL OF SAFETY WARNING DEVICE

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of time, there is a distinct possibility that the motorist would begin to ignore the sign at other times when the danger conditions exist.

TABLE 2

STATE OF SYSTEM MATRIX

Safety Warning Device	Stoppage Wave	
	Exists	Does Not Exist
Response	+	**
No Response	*	+

*Type I Error
**Type II Error

It is apparent that the first two states of the system must be maximized while the Type I and Type II errors minimized. The control logic, therefore, must be sensitive enough to respond to a stoppage wave but most minimize the number of false alarms.

METHOD OF STUDY

Study Site - The Gulf Freeway

The Gulf Freeway in Houston, Texas, was selected as the study

site because of the available facilities and the ongoing research

study being conducted.

Double loop detectors were positioned on each lane of the inbound

freeway both upstream and downstream of three overpasses selected as

the sites for the prototype safety warning signs. Information from

these detectors is transmitted by direct cable to an IBM 1800 digital

computer located in the surveillance and control center. The informa-

tion is then processed to compute traffic variables that can be used

for control, stored on disk, printed, or punched on cards. The

location of the three subsystems and their associated detectors are

illustrated in Figures 10 and 11.

Data Collection

A data acquisition computer program was written to collect and

store information received from the subsystem detectors every 30

seconds. Speed and volume were measured on each lane at both the

upstream and downstream stations for the three subsystems. Speed was

computed based on the travel time of each vehicle between the lead

and lag detectors; volume was obtained from the lag detectors.

When an incident was observed to occur on the inbound Gulf Free-

way resulting in generation of stoppage waves upstream, the program

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FIGURE 10 — STUDY SITES

INBOUND LANES

MOSCROSE STATION

SUBSYSTEM 1
2040'

GRIGGS STATION

INBOUND LANES

LOMBARDY STATION

S. HB&T R.

SUBSYSTEM 2
2850'

DUMBLE STATION

MATCH LINE A

MATCH LINE A

INBOUND LANES

HB&T R.
N.

SUBSYSTEM 3
3000'

CULLEN STATION

NOT TO SCALE
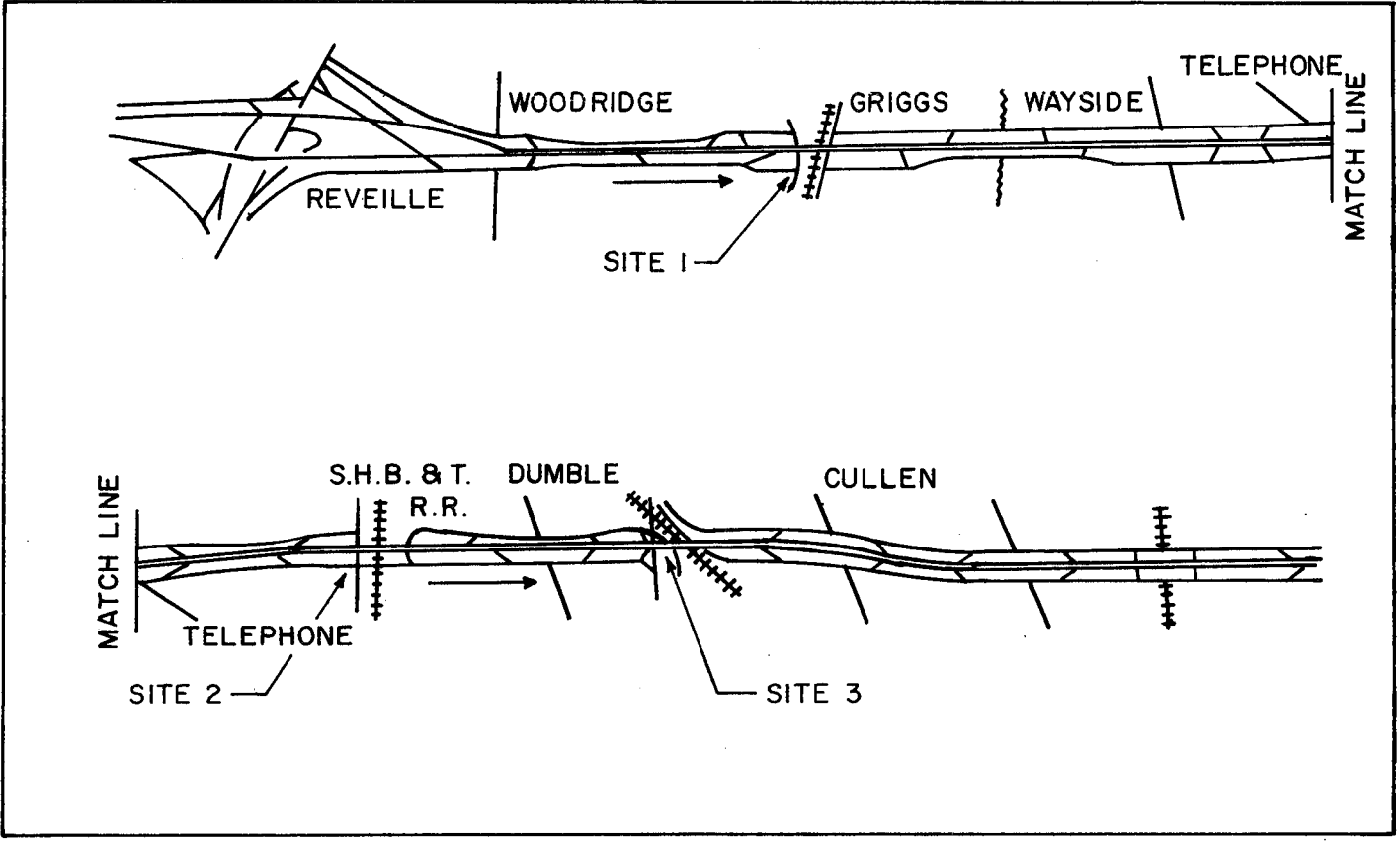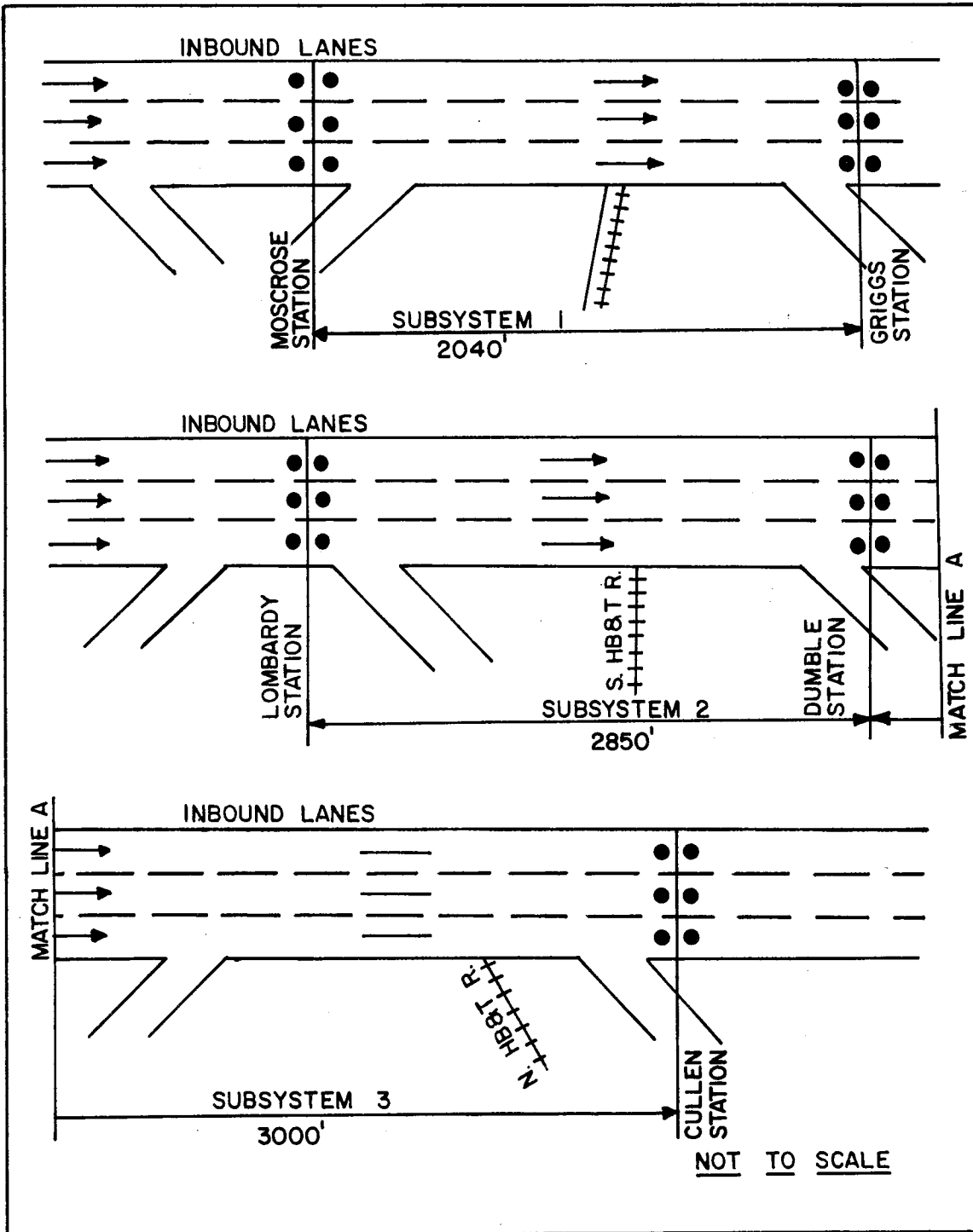
FIGURE II — DETECTOR LOCATIONS

was loaded into the computer. Simultaneously, video tape recordings, using two recorders, were made of the traffic operations at the detector stations. The two video recorders provided the opportunity to record simultaneously operations at both the upstream and downstream detector stations for a particular subsystem. Thus, the generation of stoppage waves through the subsystem could be evaluated. Relevant information concerning time, location, freeway conditions, etc., were recorded on the audio portion of the tape for reference. In this way a permanent visual as well as quantitative record was made of the traffic situation for analysis at a future date.

Both the data acquisition program and the video tape recorders were on a standby basis so that data could be collected when major breakdowns in traffic operation occurred. Because of the randomness of traffic incidents and the existing computer and personnel requirements for other functions associated with the normal operations of the control center and with the total research program, it was not practical to collect data continuously, or to collect data for each incident. Consequently, the sample of incident data used in this research had been collected over a period of several months.

Selection of Time Base

The discussions in the preceding section illustrate the need for a responsive system in which the control variable is not overly sensitive to slight changes in traffic which may result in false indications. One factor that will affect the variability of a traffic

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variable is the time base used for computations. An extremely short time base can introduce so much fluctuation making the variable unacceptable for control. A time base that is too long, on the other hand, tends to smooth the peaking characteristics of the variable and thus reduces its capability to be responsive.

Several time bases ranging from 10 seconds to 2 minutes were considered for the safety warning device control program. Based on a preliminary study of the sensitivity of several traffic variables using different time bases within the aforementioned range, and a knowledge of computation time bases used for freeway control in different parts of the country, it was assumed that a time base of one minute would produce the necessary results.

Selecting a one-minute computational base introduced the probability that the system at times might respond to a stoppage wave one minute after it passes the detector station. An analysis of the detector locations relative to the vertical curve crests at the three subsystems indicated that this response time would be too long. It would, therefore, be desirable to update the one-minute values at more frequent intervals. It did appear that a 30-second update would be sufficient. In other words, the traffic variables would be computed for one minute, but the values would be updated every 30 seconds by adding the most recent 30 seconds of data and dropping the oldest 30 seconds.

Data Reduction

The data stored in the computer was later processed to compute one-minute values of energy, speed, and volume at successive 30-second time intervals. These data were then processed on a printed format. The video tapes were also replayed and specific information regarding the generation of stoppage waves were observed and recorded on log sheets. The following information was identified on each lane at the five detector stations:

1. Time of transition from normal flow to slow flow down-stream of the detector location.

2. Time of transition from normal flow to slow flow at the detector location.

3. Time of stoppage wave downstream of the detector location.

4. Time that the stoppage wave reached the detector location.

Since the computer and video information were synchronized in time, the adequacy of the control logic to detect or predict stoppage waves could be readily evaluated by comparing the computer and video data. In addition, the ability of the control logic to respond to stoppage waves by actuating the safety warning device could be evaluated. Stability, sensitivity, and reliability analyses could also be made.

ANALYSIS OF DATA

Energy-Speed Relationships

In an earlier chapter, it was shown that the kinetic energy of
the traffic stream can be expressed as a function of speed according
to the following relationship:

$$E_k = b_1 u^2 - b_2 u^3 \tag{6}$$

where b_1 and b_2 are constants.

If the relationship of energy as a function of speed can be determined,
then the parameters of flow can be computed. The problem of fitting
a curve to a set of points objectively is one of estimating the
parameters of the curve. A widely accepted method of performing the
estimation of such parameters is known as the method of least squares.
In applying this procedure to energy-speed data, a function $E_k = f(u)$
would be sought which fits the data points such that the sum of the
squares of the deviations between the ordinates of the points and the
ordinates of the curve are minimized.

Regression analyses and tests of significance of the regressions
and the regression coefficients as discussed by Williams (11) were made
of the data collected on each lane at the five freeway detector sta-
tions. A standard regression computer program of the Data Processing
Center at Texas A&M University was used.

Critical Energy, E_c

Once the coefficients of Eq. 5 were determined for each lane at each station, the optimum speed, u_m', which yields maximum energy, E_m', was found by setting the first derivative to zero:

$$\frac{dE}{du} = 2b_1 u - 3b_2 u^2 = 0 \tag{7}$$

Maximum energy was then computed by substituting the values of u_m' into Eq. 5. Critical energy, E_c, was then calculated using the following relationship:

$$E_c = \frac{1}{2} E_m' \tag{8}$$

Detection of Stoppage Waves

It was hypothesized earlier that a stoppage wave can be detected when the energy at a detector location drops below the critical energy. Using the computed value of the critical energy as an indicator of a stoppage wave, a comparison was made between the actual observation of stoppage waves crossing each detector and the time when the critical energy parameter registered the occurrence of a wave.

System Performance

The traffic incidents were classified according to the location of occurrence relative to the subsystem detectors, that is, according to whether they occurred downstream of the subsystem, upstream of the

subsystem, or between the subsystem detectors. A further classification
was made according to the level of service existing on the freeway
prior to the occurrence of the incident. The level of service was
determined using speed and volume data recorded from the detectors
before the incident affected the traffic operation at the detector
locations. Capacity parameters were obtained from the regression
analyses discussed earlier. Once the incidents were classified, the
performance of the developed control logic was evaluated.

Type II Errors

In addition to the ability of the control logic to be responsive
to stoppage waves, it was also important to evaluate if the logic would
at any time result in false activations when a stoppage wave did not
exist (Type II error). To supplement the data collected during in-
cidents, several hours of additional data were collected during both
the peak and off-peak periods when incidents did not exist.

System Stability

The stability of the safety warning device operation was also
tested. It is desirable that once the safety warning device is acti-
vated, it remain in this status until the stoppage waves cross the
upstream detectors. The operation of the system was, therefore, tested
to determine if the energy variable based on a one-minute data base
would cause intermittent on-off cycling.

Energy-Speed Relationships

The results of the least squares regressions of kinetic energy as a function of speed consistent with the basic relationship

$$E_k = b_1 u^2 - b_2 u^3$$

are presented in Table 3.

Tests of significance were performed on the regression coefficients using the Student's t test. The results of these tests were in all cases significant at the .01 level. The R^2 values for each regression were all above .92 indicating good correlation between kinetic energy and speed according to the above relationship. The results indicate that each regression equation represents a good fit to the data.

Figure 12 is presented to illustrate the relationship between kinetic energy and speed resulting from the regression analyses. The relevant parameters are identified.

Critical Energy, E_c

The maximum energy, E_m, critical energy, E_c, and critical speed, U_c, were calculated for each detector station using the equations resulting from the regression analyses and are listed in Table 4. The results revealed that the critical energy ranged between the values of 24,000 and 39,850 veh-miles/hour^2. The maximum energies on the

TABLE 3

REGRESSION RESULTS

MODEL: $E_k = b_1 u^2 - b_2 u^3$

Location	Lane[*]	b_1	t	Sign.	b_2	t	Sign.	R^2
Mossrose	3	0.1337	28.78	**	0.00228	21.17	**	0.9745
	2	0.1160	29.95	**	0.00184	20.97	**	0.9766
	1	0.0948	27.72	**	0.00149	20.30	**	0.9691
Griggs	3	0.1286	22.47	**	0.00203	16.26	**	0.9694
	2	0.1227	16.88	**	0.00195	11.98	**	0.9731
	1	0.1096	16.36	**	0.00199	12.75	**	0.9432
Lombardy	3	0.1304	19.45	**	0.00203	13.61	**	0.9712
	2	0.1181	15.43	**	0.00175	10.31	**	0.9709
	1	0.1086	19.98	**	0.00159	14.05	**	0.9690
Dumble	3	0.1332	14.19	**	0.00212	10.10	**	0.9619
	2	0.1265	17.19	**	0.00202	12.49	**	0.9699
	1	0.0752	7.91	**	0.00114	5.41	**	0.9211
Cullen	3	0.1336	18.77	**	0.00219	13.84	**	0.9568
	2	0.1099	14.21	**	0.00164	9.65	**	0.9591
	1	0.0898	14.92	**	0.00141	10.56	**	0.9418

[*]
3 = Median
2 = Middle
1 = Shoulder

Hypothesis H: $\beta_1 = 0$
           A: $\beta_1 \neq 0$
Test Statistic: $t = (b_1 - \beta)/S_{b_1}$

Reject H if: $t \geq t_{(1-\alpha/2)(n-2)}$

$t \leq -t_{(1-\alpha/2)(n-2)}$

** :Reject H at .01 level. Coefficient is significant.

MAX. ENERGY

$E = 0.1286 U^2 - 0.00208 U^3$

CRITICAL ENERGY

KINETIC ENERGY (1000 VEH-MI/HR^2)

SPEED (MPH)
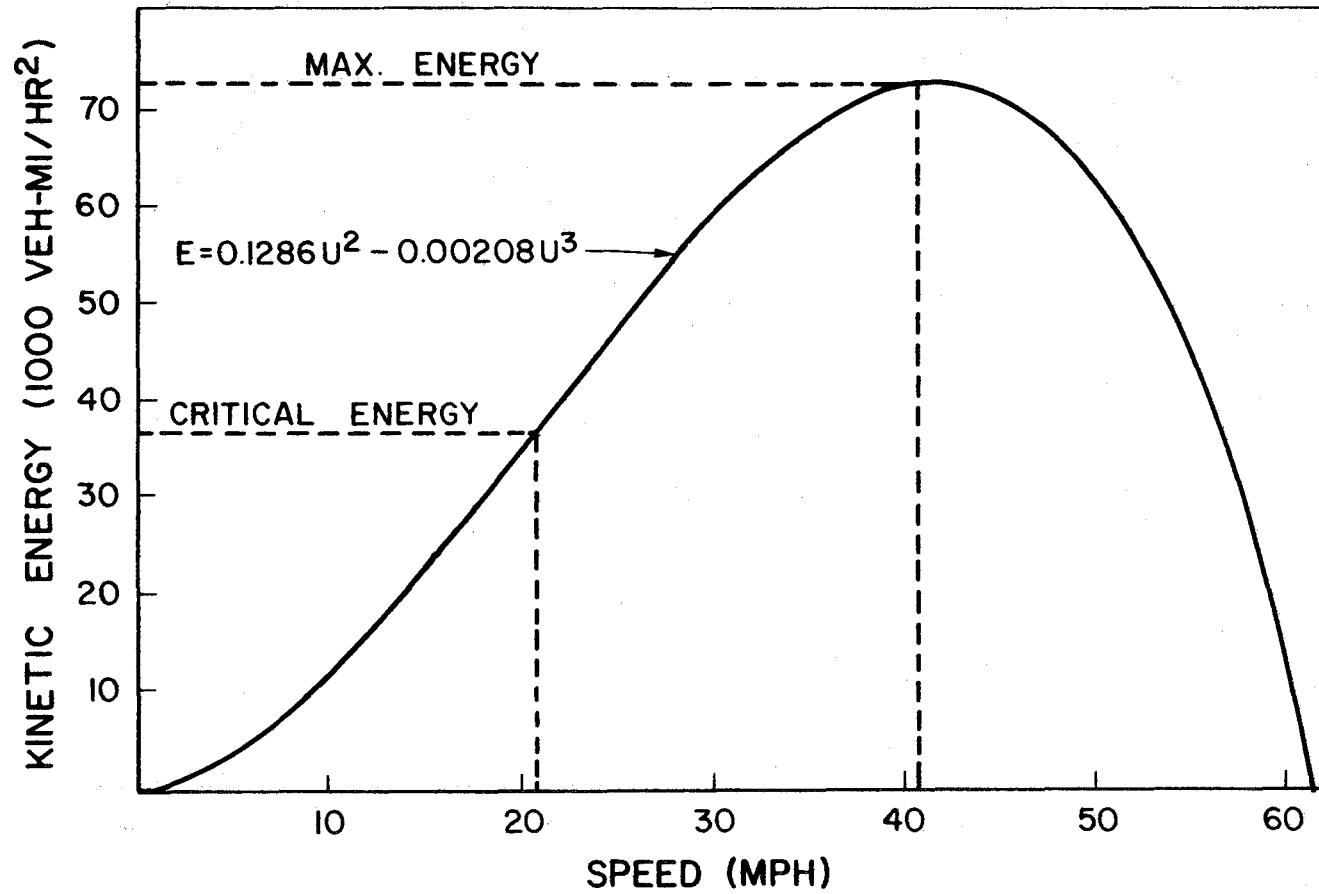
FIGURE 12 — SPEED VS. ENERGY RELATIONSHIP —
GRIGGS INSIDE LANE

TABLE 4

TRAFFIC PARAMETERS

Location	Lane[*]	Maximum Energy,E_m (1,000Veh-Mi/Hr^2)	Critical Energy,E_c (1,000Veh-Mi/Hr^2)	Critical Speed,u_c (Mi/Hr)
Mossrose	3	67.6	33.80	19.5
	2	68.3	34.15	21.0
	1	56.9	28.45	20.9
Griggs	3	72.7	36.35	20.5
	2	72.0	36.00	21.2
	1	49.2	24.60	19.5
Lombardy	3	79.7	39.85	21.3
	2	79.5	39.75	22.4
	1	75.0	37.50	22.6
Dumble	3	77.9	38.95	21.4
	2	73.0	36.50	21.2
	1	48.0	24.00	22.2
Cullen	3	73.7	36.85	20.1
	2	73.1	36.55	23.0
	1	53.7	26.85	20.8

*
  3 = Median
  2 = Middle
  1 = Shoulder

median and middle lanes at the individual detector stations, generally, were found to be essentially the same. However, in all cases except for the Lombardy station, the critical energy on the shoulder lane was found to be considerably lower than the other lanes. This difference is important but is not too surprising. Under high volume conditions, motorists tend to use the median and middle lanes on a three-lane section of freeway (12) to avoid the friction created by the ramp traffic and the influence of a high percentage of truck traffic (13). Consequently, the median and middle lanes will carry a higher percentage of the traffic in comparison to the shoulder lane. The Highway Capacity Manual (14), for example, indicates that when the freeway is operating at or near capacity, the median and middle lanes will each carry approximately 37 percent of the traffic whereas the shoulder lane will handle only 26 percent. Furthermore, studies on the Gulf Freeway reported by Drew (13) revealed that the utilization of the shoulder lane at selected study sites was generally much lower than either the median or middle lanes.

The effect of the detector location relative to a high volume off-ramp was evidenced by the range of the maximum energy between the shoulder lane and the other two lanes. The greatest difference occurred at the Griggs, Dumble, and Cullen stations. In each case, the detectors are positioned immediately downstream from high volume off-ramps. In contrast, the detectors at the Lombardy station are located just upstream from an off-ramp; the detectors at Mossrose are positioned

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upstream from an on-ramp.

Detection of Stoppage Waves

Using the critical energy, E_c, as an indicator of a stoppage wave, a comparison was made between the actual observation of stoppage waves crossing each detector and the time that the critical energy parameter registered the presence of a wave. The observations were made during various conditions when the freeway was operating at levels of service B, C, and D prior to the occurrence of a stoppage wave.

The results of the analysis are tabulated in Table A-1 of the Appendix and are presented as a performance curve in Figure 13. The values presented in the figure and table represent the difference in seconds between the time when the energy on the lane dropped below E_c and the actual observed time of the stoppage wave moving over the detector. A positive value indicates that the energy dropped below E_c prior to the actual movement of the wave over the detectors. A negative value represents a late response by the parameter.

The results indicate that critical energy is a good parameter for the identification of a stoppage wave under levels of service B, C, and D. Generally, the parameter was able to predict the presence of a downstream stoppage wave.

The critical energy parameter detected the presence of a stoppage wave either at the time the wave was moving over the detector or several seconds before the wave reached the detector stations in 131 of the 142 cases. A total of 141 observations fell within the expected limits of the logic. Since the one-minute energy values were updated every

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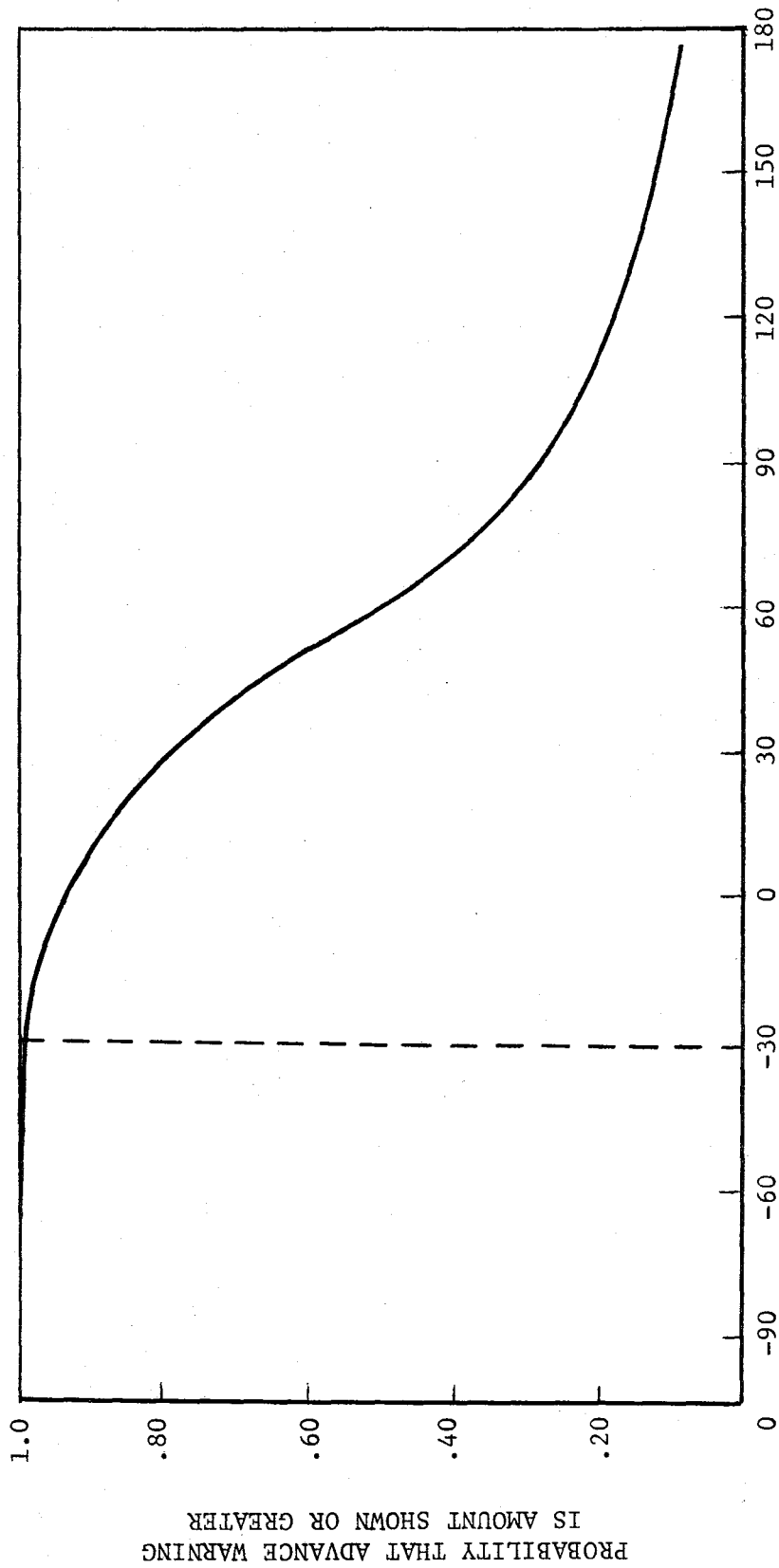
FIGURE 13 — PERFORMANCE CURVE — INDIVIDUAL LANES

ADVANCE WARNING IN SECONDS

PROBABILITY THAT ADVANCE WARNING
IS AMOUNT SHOWN OR GREATER

30 seconds, it was expected that a stoppage wave in some cases could conceivably pass over the detectors 30 seconds before the computed energy fell below E_c. Therefore, late responses as high as 30 seconds (-30) would be expected. The results in Table A-1 show that the parameter was late in responding in eight cases. However, seven of these were within the 30-second boundary. In only one case did the parameter respond late by more than 30 seconds (Type I error). The reason for the lack of agreement for the one case could not be ascertained from the data and can only be conjectured at this time. However, the critical energy parameter has shown to possess a predictive characteristic for stoppage waves.

When it was apparent that the critical energy parameter produced the desired results, the next step was to evaluate the response of a set of detectors at a particular station. Experience has shown that although there is a degree of sympathy of speed between lanes regardless of volume (12), it appears that stoppage waves do not move in unison on each lane of a freeway (15). Generally, there are differences in the time that the waves on the individual lanes will reach a certain point on a freeway. An analysis of the relative movement of waves between lanes on the Gulf Freeway was made and is presented later. Since detectors for the safety warning device would be placed on each lane, any one of the lanes might serve as the control lane. That is, the system would be activated when a stoppage wave is sensed on any one of the lanes. An analysis was, therefore, made to test the

responsiveness of the three-lane detector station to the occurrence

of a stoppage wave. The results of the analysis are summarized in

Figure 14 and in Table A-2 of the Appendix.

The advance warning of a stoppage wave shown in the figure rep-

resents the difference between the time that the energy dropped

below E_c on any one of the lanes and the time that the first stoppage

wave was observed to cross one of the detectors. Again, positive

values represent advance warning; negative values represent late

responses. The control lanes represent the lanes which initially in-

dicated the presence of a wave.

The results clearly show that with a three-lane detection station,

adequate advance warning of stoppage waves is achieved within the

limitations of the measurement technique. This is accomplished by

allowing any one of the three lanes to give the warning. In only one

case did the wave pass over the detectors before the energy fell below

E_c on any one of the lanes. However, the difference was only 17 seconds

which is well within the limit because of the 30-second update of the

data base.

A review of the control lanes listed in Table A-2 reveals an in-

teresting finding. For the incidents studied, the stoppage waves were

first detected on the median and middle lanes the majority of the

cases. An explanation of this result can be surmised. Because of the

traffic leaving the shoulder lane via the off-ramps, the stoppage wave

at times is interrupted and, therefore, will take longer to travel
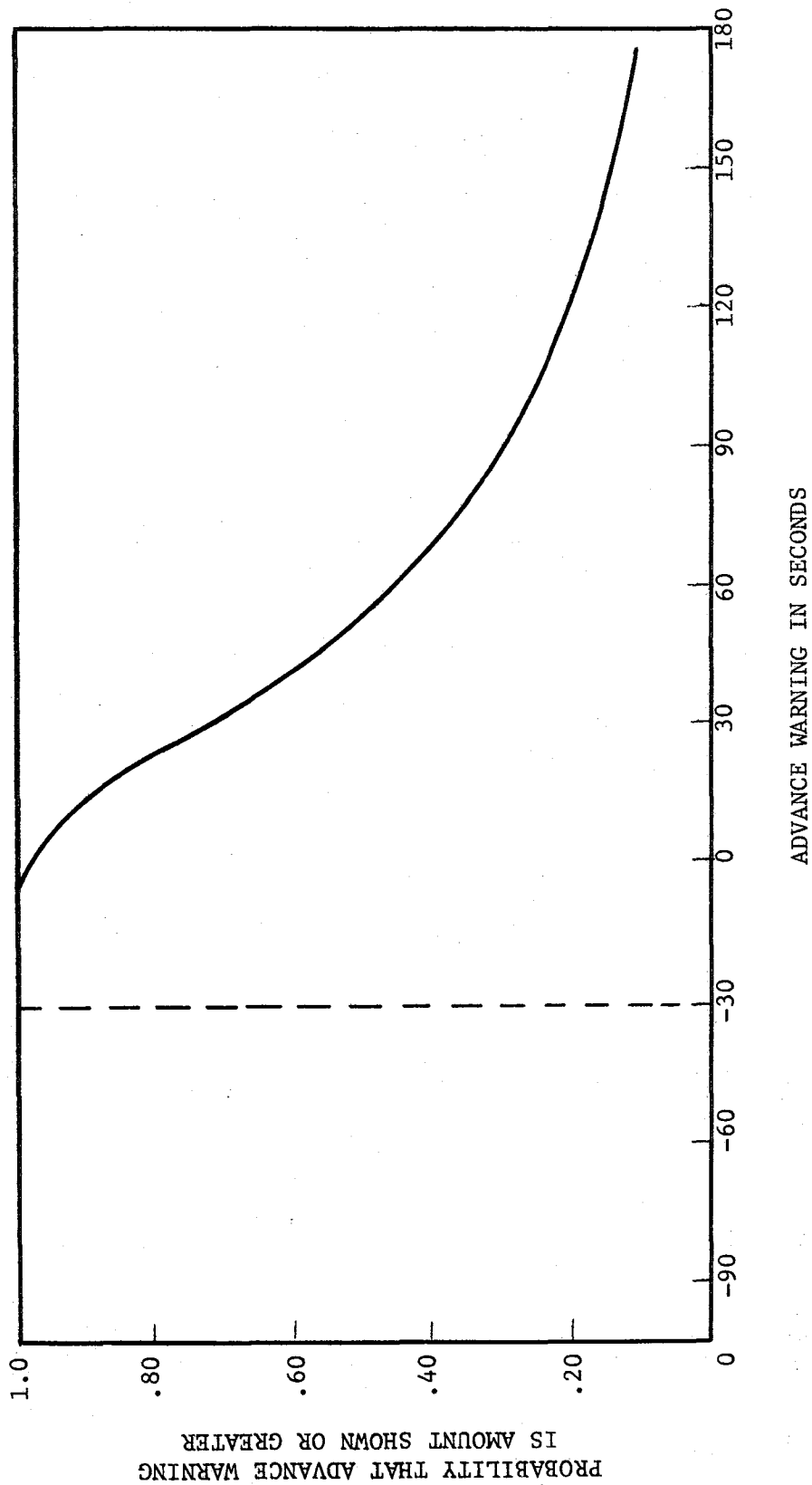
FIGURE 14 — PERFORMANCE CURVE — ONE-LANE CRITERION

ADVANCE WARNING IN SECONDS

PROBABILITY THAT ADVANCE WARNING IS AMOUNT SHOWN OR GREATER

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upstream. Earlier research on the Gulf Freeway by Drew (13) indicated that there does not seem to be any transverse pattern of failure prompted by the spread of congestion from one lane to another. He suggested that drivers seem to compensate for turbulence in the shoulder lane.

The high frequency of stoppage wave detection on the median and middle lanes does not automatically negate the need for detection on the shoulder lane. The probability exists that an incident will occur on the shoulder lane immediately downstream from a detector station. In many cases, the other lane detectors may not sense the condition until after the stoppage wave on the shoulder lane progresses upstream over the crest.

System Performance and Reliability

This section is concerned with the evaluation of the control logic performance. The logic operates under the premise that detectors are mounted on each lane both upstream and downstream from the vertical curve. The safety warning device would be activated when any one of the lane detectors indicates the presence of a stoppage wave based on the energy value downstream from the crest. The system would be deactivated when the wave or waves pass over the upstream detectors. A more detailed discussion of the system operation is presented in reference 1.

The results of the performance evaluation are presented in Tables 5, 6, and 7. The results show that the control scheme did perform

TABLE 5

EVALUATION OF CONTROL LOGIC FOR ACTIVATION OF SAFETY WARNING
DEVICE – INCIDENTS OCCURRING DOWNSTREAM OF SUBSYSTEM

Incident Number	Level of Service Before Incident	Subsystem*	Control Lanes	Control Logic Satisfactory	Remarks
1	B	1	3	Yes	
2	B	1	3,2	Yes	
3	B	1	3,2	Yes	
4	B	1	2	Yes	
5	B	2	--	No	Defective Detector
6	B	2	3	Yes	
7	B	2	3,2	Yes	
8	B	2	2,1	Yes	
9	B	2	3,2	Yes	
10	B	3	3,2	Yes	
11	B	3	3	Yes	
12	C	1	--	No	Defective Detector
13	C	1	3,2	Yes	
14	C	1	3,2	Yes	
15	C	2	3	Yes	
16	C	3	3,2	Yes	
17	C	3	3,2	Yes	
18	C	3	3,2	Yes	
19	D	1	--	No	Defective Detector
20	D	1	--	No	Defective Detector
21	D	1	1	Yes	
22	D	2	2	Yes	
23	D	2	3	Yes	
24	D	3	3,2	Yes	

*Subsystem:

   1 - Mossrose-Griggs
   2 - Lombardy-Dumble
   3 - Dumble-Cullen

TABLE 6

EVALUATION OF CONTROL LOGIC FOR ACTIVATION OF SAFETY
WARNING DEVICE - INCIDENTS OCCURRING BETWEEN DETECTORS

Incident Number	Level of Service Before Incident	Subsystem	Control Lanes	Control Logic Satisfactory	Remarks
1	B	3	3	Yes	
2	C	3	3,2	Yes	
3	C	3	3,2	Yes	
4	D	3	3,2	Yes	

TABLE 7

EVALUATION OF CONTROL LOGIC FOR ACTIVATION OF SAFETY
WARNING DEVICE - INCIDENTS OCCURRING UPSTREAM OF SUBSYSTEM

Incident Number	Level of Service Before Incident	Subsystem	Control Lanes	Control Logic Satisfactory	Remarks
1	C	2	N/A	Yes	
2	C	3	N/A	No	Defective Detector
3	C	3	N/A	Yes	
4	C	3	N/A	Yes	
5	D	2	N/A	Yes	
6	D	3	N/A	Yes	

satisfactorily for the incidents studied except in certain cases when one or more of the detectors at a particular subsystem was defective, that is, a detector was either not functioning or was defective to the point of producing erroneous information. Detector problems associated with an operational system will be discussed in subsequent sections.

A review of Table 5 reveals that the control scheme responded satisfactorily to incidents downstream of the subsystems when the freeway was operating at levels of service B, C, and D prior to the occurrence of the incidents. In 20 of the 24 incidents studied, the simulated operation of the safety warning device indicated acceptable operation. The four cases in which the logic was proven to be unacceptable were attributed to defective detectors. False information received from detectors would have resulted in improper activation or deactivation of the safety warning device. The results, however, indicate the suitability of the critical energy criterion and the control logic to respond to incidents downstream from the subsystem barring the existence of a defective detector.

It is interesting to note again the distribution of stoppage wave warnings given by the individual lane detectors. The median and middle lanes provided the first clue about the presence of a stoppage wave in 19 of 20 incidents.

Although a small sample was available, the data presented in Tables 6 and 7 suggest that the control logic would also be sufficiently responsive to incidents occurring between the detectors within a

subsystem and to incidents that occur upstream from the subsystem.
The logic was shown to be responsive in all cases studied except when
a defective detector influenced the data measurements.

Type II Errors

The preceding section has shown that, for the incidents studied,
the control logic using a one-lane criterion was acceptable except
when a detector failed. The results revealed that there were no Type
I errors, other than those associated with detector problems. This
section discusses the results of an analysis for Type II errors-
false activations when a stoppage wave does not exist.

The control logic assumes that the freeway will be operating at
levels of service below A during the normal periods of control
(6 a.m. - 6 p.m.) owing to the demands normally experienced on the
freeway at these times. If for some reason short-period demands
become light at the downstream detector station, the energy values
could conceivably drop below E_c resulting in a false activation of
the safety warning device. Several hours of data, collected during
off-peak and peak periods when no incidents occurred within the
study section, were evaluated for the possibility of Type II errors.

The results revealed that, generally, the operation of the device
was correct. However, it was observed that in some instances during
the off-peak periods, particularly during the summer months, a re-
duction in freeway demand would have caused false activations. Al-
though the false activations would not occur frequently, the data

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indicated that the Type II error was a severe problem particularly during the summer and, therefore, would require attention. This was particularly true at Subsystem 1 (Mossrose-Griggs).

The detector station at Griggs is located about 4000 feet downstream from a major interchange and immediately downstream from an off-ramp. It appeared that the influence of the off-ramp coupled with the motorists' desires to assume a comfortable headway after merging at the major interchange resulted in intermittent low-volume, high-speed measurement periods, particularly on the shoulder lane. The conditions were sufficiently severe to cause the energy to fall below E_c. This would give the indication of a stoppage wave based on the control logic and would cause the warning device to turn on falsely. Examples of false activations due to low volumes are illustrated in Table 8.

There are at least two approaches that can be taken to circumvent this problem. One approach is to maintain a check of the speed and volume of the downstream detectors. Since the middle lane will carry a higher volume than the other two lanes during the off-peak periods (14), this lane can be used in the decision process. If the speeds remain above a threshold value, say 30 mph, while the volume on the middle lane stays above a critical volume, say 8 vehicles per minute, this is an indication of random light flow on the affected lane. The safety warning device would not be activated.

A second approach is to maintain the same control logic but

TABLE 8

EXAMPLE OF FALSE ACTIVATION
BECAUSE OF LIGHT VOLUMES ON SHOULDER LANE AT GRIGGS
(DATE: 7-30-71)

Time	Volume (Veh/Min)			Average Speed (Mi/Hr)			Energy (1000 Veh-Mi/Hr^2)		
	Lane			Lane			Lane		
	3	2	1	3	2	1	3	2	1
15:28:00	29	22	12	39	40	44	68.9	54.1	31.9
15:28:30	30	24	9	43	43	43	77.6	62.6	23.6*
15:29:00	24	24	13	45	46	42	66.2	67.1	33.4
15:29:30	22	18	12	45	44	45	60.3	47.8	32.4
15:30:00	21	19	7	43	42	46	54.6	48.1	19.5*
15:30:30	21	22	7	44	43	45	56.5	58.0	19.1*
15:31:00	25	21	9	46	45	46	70.4	57.3	25.1*
15:31:30	20	18	9	44	47	46	53.8	51.2	24.9*
15:32:00	17	19	12	44	45	45	45.8	51.7	32.6
15:32:30	22	21	14	43	44	43	57.2	56.5	36.4
15:33:00	25	20	9	45	46	44	68.8	56.3	24.0*
15:33:30	22	23	9	43	45	47	57.9	62.6	25.4*
15:34:00	23	28	15	41	41	42	56.8	69.2	38.5
15:34:30	30	30	15	43	40	40	79.9	72.9	36.1
15:35:00	27	27	10	44	44	42	70.3	71.4	25.5*
Critical Energy, E_c							36.5	36.0	28.0

*False indication of a stoppage wave

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increase the sampling time base. This would in effect smooth the energy function and reduce the severe peaking characteristic of the variable.

Each of the above approaches was analyzed to determine its merits. Off-peak data which indicated the highest frequency of Type II errors were used as the basis for the analysis. Thus, the approaches were evaluated under the worst noticeable conditions with respect to the Type II error. Data from 414 sampling periods (30-second periods) collected at the Griggs detector station on July 28 and 30 and on August 3 and 4, 1971, were used as the base. The results of the analysis are shown in Figure 15.

The results indicate that using the basic control logic with an increased time base of up to five minutes reduces the frequency of the false activations, but the reduction is not sufficient to be acceptable. Data were not available to determine the effects of an increased time base on the Type I error. It would appear with all other things being equal that the Type I error would increase with an increased time base.

The results also show that the approach, whereby the middle lane at the downstream station is given a volume and speed check to determine the need to activate the safety warning device, appears to be an acceptable solution. Using a one-minute sampling period, a false activation would have occurred less than two-tenths of one percent (virtually zero) of the time under the worst possible conditions.
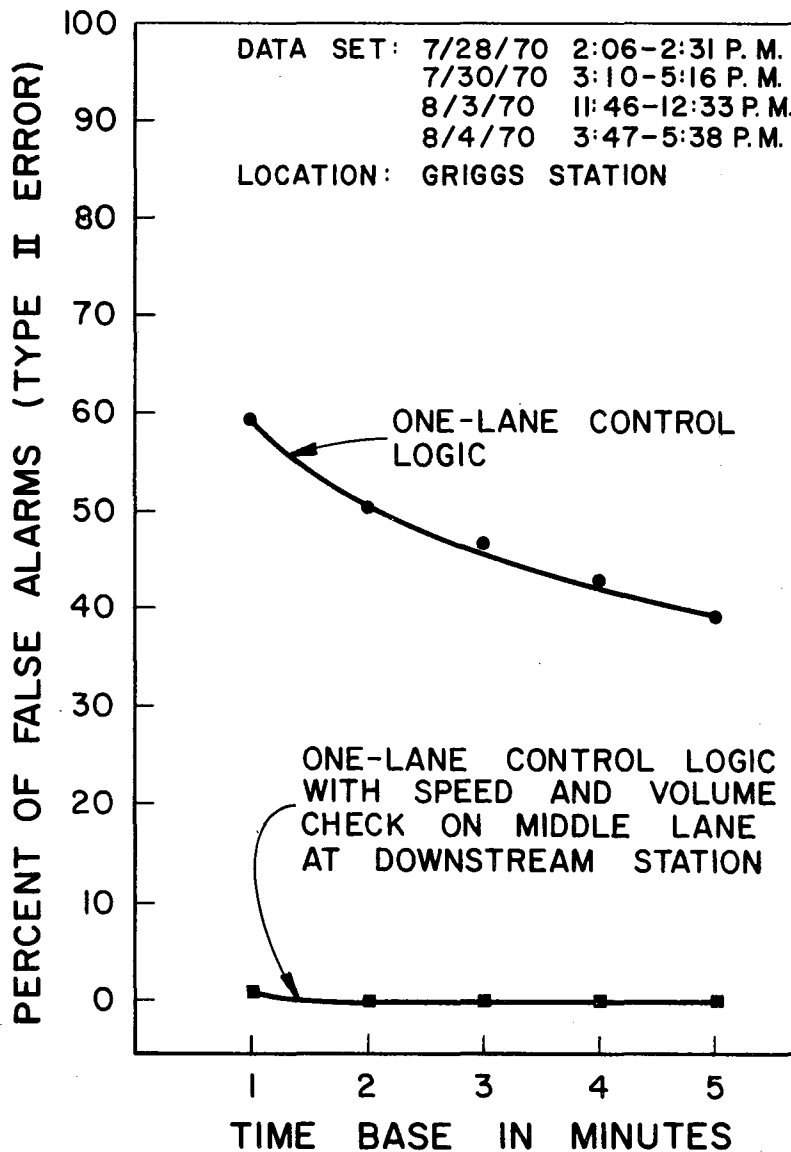
FIGURE 15 —EFFECT OF TIME BASE ON TYPE Ⅱ ERROR

*Note: The data used represent time periods during which the highest frequency of Type II errors occurred. On an annual basis, the frequency would be much lower than that illustrated in the graph. However, the data serves to illustrate the effect of the time base for the two methods of interest.

System Stability

It is imperative that the sign continue to operate from the time a stoppage wave is sensed until the wave or waves pass over the upstream detector station. Intermittent on-off operation is not desirable for apparent reasons.

The results of a system stability analysis revealed that owing to the fluctuations of traffic flow, there is some system instability when a one-minute data base is used to compute energy. It was observed that the variation of traffic characteristics at the downstream detector stations would occasionally cause the safety device to turn off and on intermittently before the stoppage wave reached the upstream detector stations. An example of the variation of energy at a downstream detector station after a stoppage wave is detected is illustrated in Figure 16.

One solution to the problem is to require that the unit continue to operate for a fixed time following the initial period that resulted in energy values which called for system activation. For example, if the warning device had been initially activated at time t_o and any one subsequent 30-second period of t_o+1, t_o+2, $\cdots$, t_o+n resulted in energy values which indicated that the system be off, then the system would remain activated for N periods following t_o+n. An analysis of the data indicates that a hold time, N, of six sampling periods (three minutes) would be adequate to compensate for the possible instability of on-off cycling. This minimum time period can be reduced if the stoppage waves
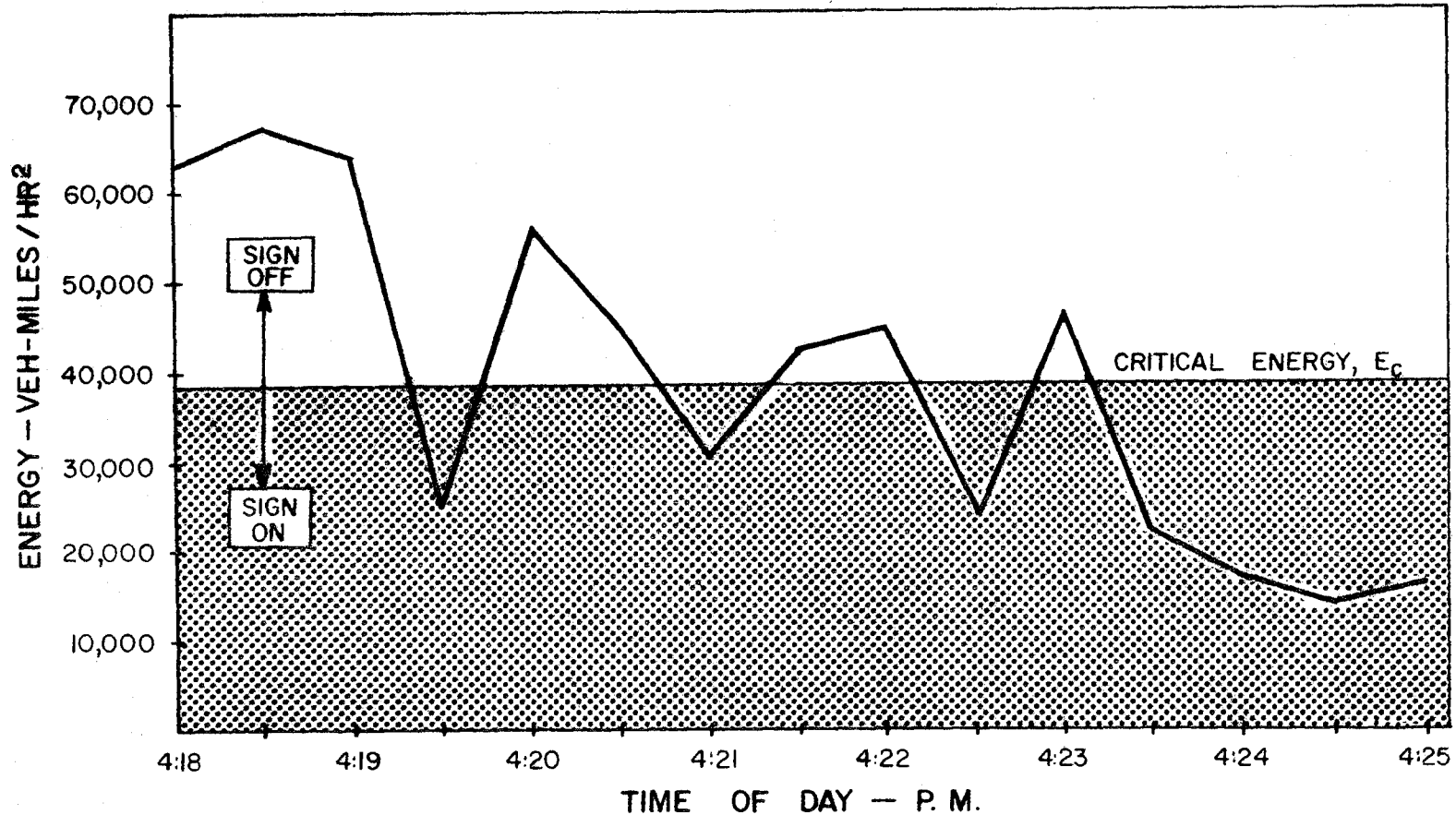
FIGURE 16 — EXAMPLE OF INSTABILITY OF SIGN OPERATION FOLLOWING AN INCIDENT — DUMBLE MEDIAN LANE

propagate over the upstream detectors sooner than three minutes. The minimum time can also be reduced when the sign is activated due to slow vehicles (i.e., trucks, funeral processions, etc.)

Redundancy

The results presented in Tables 5, 6, and 7 concerning the evaluation of the control logic revealed a problem common to operational freeway control systems—defective detectors. Because of the nature of the electronics associated with automatic traffic detection equipment, a possibility exists that a particular detector may become defective and thus transmit erroneous data to the computer, or perhaps transmit no data at all. The detector problem is perplexing because a detector may become defective at any instant in time. Therefore, even though the detection equipment is thoroughly checked prior to control, there is no assurance that every detector will perform satisfactorily throughout the day.

The frequency of detector failure in an operational traffic control system is not yet completely known. A check of 60 detectors made on the Gulf Freeway in June and July of 1970 indicated an average of two detector failures per operating day. However, modifications to the detector electronics have been made since that time. Data are currently being collected to evaluate current detector failure rates. Preliminary data indicate a lower frequency of detector malfunctions.

The consequential effects of a defective detector associated with an automatic warning system for motorists become apparent. However,

there are safeguard features that can be designed into the system to minimize their effects. One approach is to employ redundancy techniques.

The concept of redundancy was established long ago and has found wide applications in electronic systems (16, 17). Redundancy techniques utilize two parallel elements to reduce the probability of failure. For example, if the probability of failure of one element over a given period of time is 0.001, then the probability of failure of two redundant elements is $(0.001)^2$, or 0.000001. Therefore, by using twice as many elements, the probability of failure has been reduced 1,000 times. The same analysis can be employed when redundant detectors are used in a freeway control system.

Timely response to a stoppage wave is of the upmost importance for the safety warning device system. On the other hand, failure to turn the system off on time is not overly critical. Redundancy of only the downstream detectors would appear to be sufficient to alleviate the problem attributed to defective detectors.

Redundant detectors can be positioned in two arrangements. One method is to install a complete set of double-loop detectors on each lane. A second method would be to add only one additional detector on each lane adjacent to the initial double loops. The latter arrangement would produce a system consisting of three loops in succession on each lane. The additional detector can be used for volume measurements, and can be grouped with one of the other detectors to provide a redundancy in speed measurements.

Another approach to the detector failure problem is to rely on detectors on two lanes to give the alert of a major discontinuity in flow. That is, the safety warning device would not be activated unless the energy on two lanes dropped below E_c. This approach, in effect, uses information from a detector on a second lane to verify the reliability of the data from the first. To test the feasibility of a two-lane control criterion, an analysis was made of the relative movements of stoppage waves between lanes and the performance of the logic. These are discussed in the following sections.

Relative Movement of Stoppage Waves Between Lanes

The cumulative frequency of the time difference between the arrival of the first and second stoppage wave at the detector stations is shown in Figure 17. The plot reveals that in approximately 23 percent of the cases studied, the second wave reached the detector station more than 30 seconds after the first wave. Ten percent of the cases resulted in a time difference of 97 seconds or more.

It would appear at the outset that a great degree of efficiency might be lost using a two-lane control criterion. However, since the critical energy parameter did exhibit predictive qualities, the effect of the parameter might compensate for some of the large time differences between stoppage waves. The extent of the change in performance relative to the one-lane criterion was evaluated and is discussed in the following section.
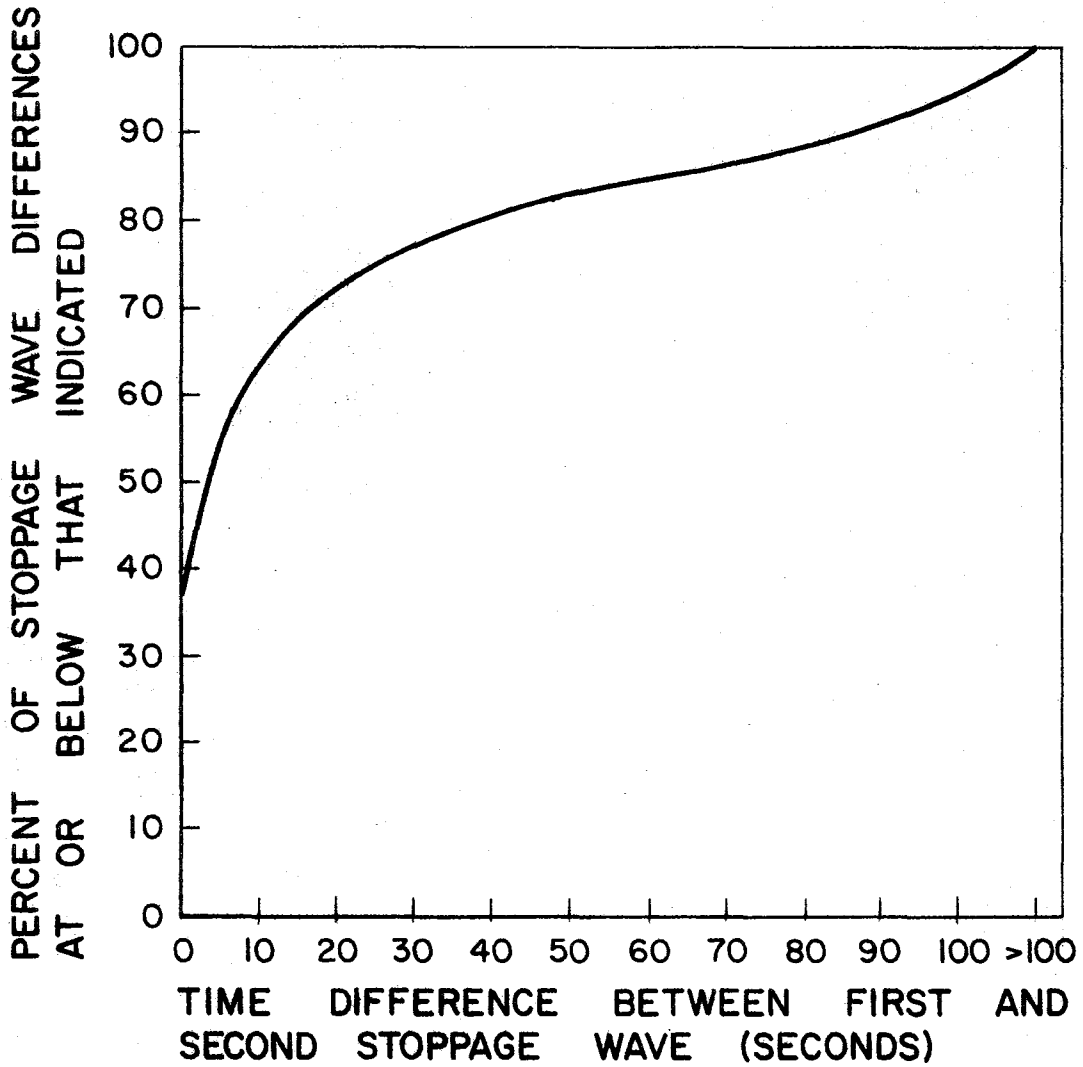
FIGURE 17 — RELATIONSHIP OF STOPPAGE WAVE DIFFERENCES BETWEEN FIRST AND SECOND WAVE

Two-Lane Control Criterion

The response times using a two-lane control criterion are pre-
sented in Table A-3 of the Appendix. These data indicate that, generally,
the system using a two-lane control criterion would respond later than
30 seconds after the initial stoppage wave crossed the downstream
detector station. However, in one extreme case, the system would not
have sensed the presence of a major discontinuity in flow until 180
seconds after the initial stoppage wave reached the detector station.
A study of the video tapes revealed that this would have been too late
to warn the motorists approaching the grade.

The results also revealed that the combination of the median and
middle lanes gave the first indication of a stoppage wave in the
majority of the cases studied. This meant that the stoppage waves
generally appear to move slower on the shoulder lane.

A comparison of response times between the one-lane and two-lane
criteria is presented in Table A-4 of the Appendix. The difference
listed in the table represents the amount of advance warning lost by
utilizing a two-lane criterion for control. The time lost ranged from
0 to 360 seconds. The results revealed that in almost 50 percent of
the cases studied, the amount of advance warning was reduced using the
two-lane criterion in comparison to the one-lane criterion.

To obtain a better understanding of the warning times attributed
to the one-lane and two-lane control criteria, performance curves for

the two approaches were developed and are presented in Figure 18.
The curves represent the probability of receiving a certain amount of
advance warning of stoppage waves for the two criteria based on the
cases studied. The results show that using a one-lane control criterion,
about 98 percent of the waves were sensed before or at the time that
the waves reached the downstream detectors. All waves were sensed by
the logic within the 30-second limit attributed to the sampling period.

Using a two-lane control criterion, it is seen that 90 percent of
the stoppage waves were sensed before or at the time they reached the
downstream detector station. In addition, 96 percent of the waves were
detected within the 30-second limit. The response of the system was
late in 4 percent of the cases.

Summary of Results

The preceding discussion was concerned with an evaluation of con-
trol logic for a freeway safety warning system. The system consists
of a warning sign, located upstream of an overpass crest, which would
be activated when traffic conditions warrant. Loop detectors located
strategically on both sides of the overpass will transmit traffic in-
formation to an IBM 1800 digital computer located in the control center.
The computer will activate the warning device when traffic conditions
warrant.

The proposed control logic utilized a critical kinetic energy
parameter which was defined as one-half maximum energy on the lane.
Specifically, the results in the preceding sections were concerned with
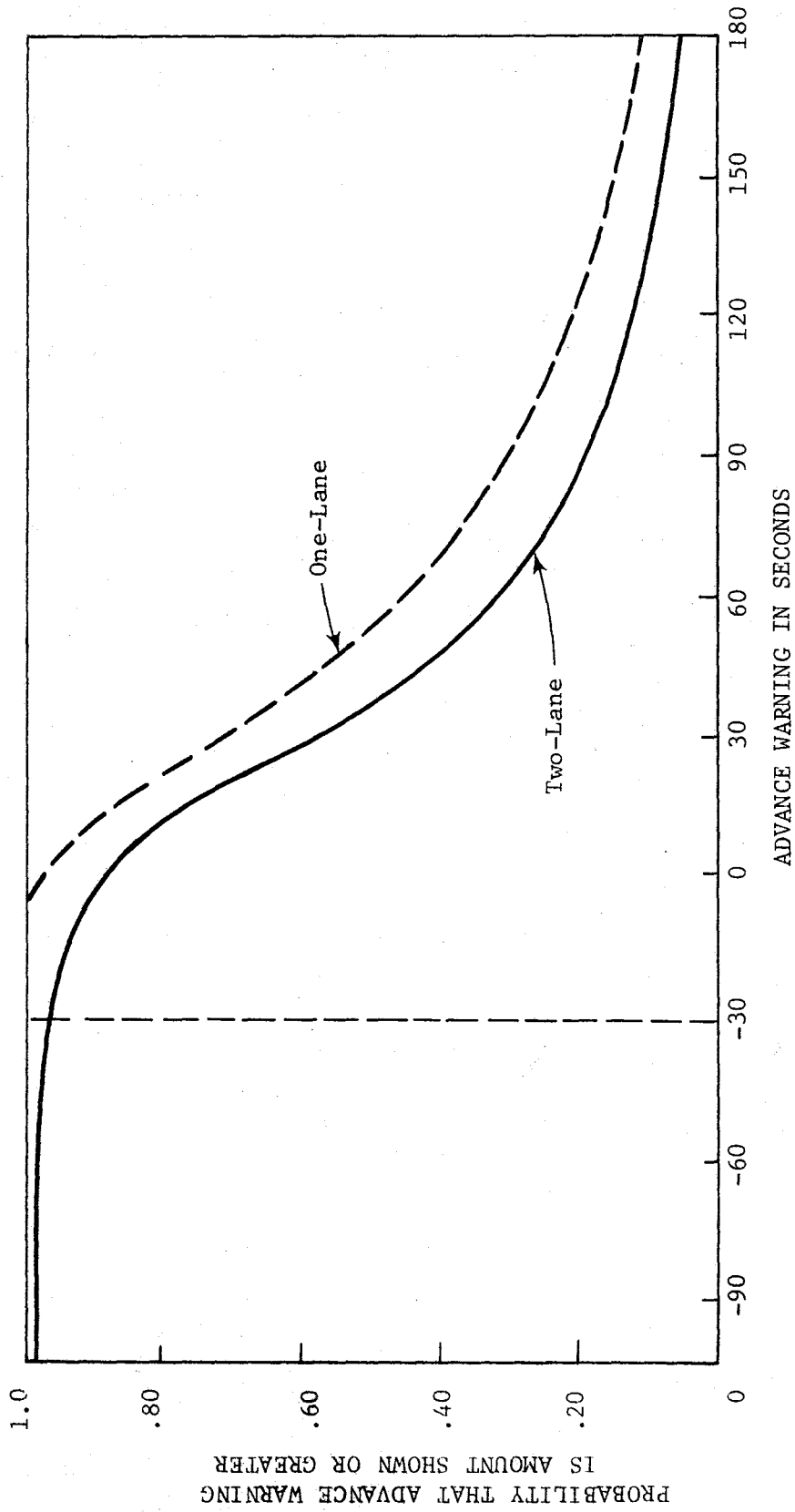
FIGURE 18 — PERFORMANCE CURVES — ONE-LANE VS. TWO-LANE CRITERION

evaluations of the following:

1. Relationships between kinetic energy and speed at each lane detector to arrive at the critical energy parameters.

2. Ability of the critical energy parameter to detect stoppage waves on each lane.

3. Ability of the critical energy parameter to detect stoppage waves using a one-lane control criterion.

4. The system performance and reliability of a one-lane control criterion logic.

5. False activations (Type II errors) using a one-lane control criterion.

6. System stability (on-off cycling of the warning sign).

7. The performance of a two-lane control criterion.

The results of the study indicated that the critical energy criterion, based on one-minute values of energy updated every 30 seconds, offers a good approach to measure the presence of stoppage waves on urban freeways when the level of service prior to an incident is B, C, or D. The logic developed for the automatic control of a safety warning device using a one-lane control criterion was shown to be satisfactory for the incidents studied. The logic activates the safety warning device when any one of the lane detectors on the three lanes senses the presence of a stoppage wave. It was found that for the majority of incidents studied, the detectors on the median and middle

lanes gave the first alert of a stoppage wave resulting from an incident.

The control logic was developed under the assumption that the operations on the freeway during normal surveillance and control periods (6 a.m. - 6 p.m.) would remain below level of service A. It was found, however, that during the off-peak periods, especially during the summer months, intermittent light volumes on the freeway, particularly on the shoulder lane at the Griggs detector station, resulted in erroneous stoppage wave indications (Type II errors). The control logic developed and evaluated herein would need to be modified to circumvent this problem.

Two approaches were evaluated to reduce the Type II errors. The results indicated that an approach whereby a computer check of the speed and volume of the downstream detectors is maintained would all but eliminate Type II errors. If the speed remains above a threshold level, say 30 mph, and the volume stays above say 8 vehicles per minute, then the safety warning device would not be activated.

The study also indicated that there is some instability in the operation of the safety warning device after the system is initially activated when a one-minute data base is used to compute energy. It was observed that the variation of traffic characteristics following the initial detection of a stoppage wave would cause the safety warning device to turn on and off intermittently before the wave reached the upstream detectors. The results suggested that the system can be made

stable by holding the device on for three minutes after the initial activation.

The study also indicated that the frequency of defective detectors constitutes a problem in a real-time freeway control system. One defective detector within a subsystem can cause the safety warning device not to be activated when it is needed (Type I error), or can cause false activations (Type II error). Suggested approaches to the solution of the problem were either to install a redundant set of detectors at the downstream detector station, or to use a two-lane control criterion. In the latter approach, two lanes rather than one lane would be used to confirm the presence of a stoppage wave.

The two-lane control criterion was evaluated and found to be less responsive to stoppage waves than the one-lane criterion. In four percent (2 of 47) of the cases studied, the two-lane criterion was late in responding by more than 30 seconds.

Tradeoffs must be made in deciding the alternative course of action for an operational system. The one-lane criterion was shown to be acceptable. However, this type of operation is subject to no response or erroneous activations due to detector failures. The two-lane control criterion appears to produce satisfactory results 96 percent of the time.

Another approach would be to install a redundant set of detectors at the downstream location. Redundant systems have been found extremely useful and receive wide application in real-time control systems, and would appear workable for the safety warning system. This, of course,

would slightly increase the cost of the total system since three additional detectors would be required for each unit.

It should be mentioned that the numerical results presented are a function of the specific freeway characteristics and the equipment used for measurement. The relationships on other freeways could conceivably differ. Different detectors or detector configurations may indeed affect the numerical values. No attempt was made in this report to evaluate the effects of weather. Traffic characteristics on a particular facility would be expected to change during adverse weather conditions or when the pavement is wet or icy.

APPLICATIONS

General

The safety warning device discussed in this report can be applied
to an urban freeway section which experiences accidents, or are deemed
to be accident potential locations, due to restricted sight distances.
An example of such a location would be a freeway overpass. This report
was concerned with the development of a control technique for digital
computer control of the safety warning device and an investigation of
the application of the logic to operational control of the device. The
following discussion is concerned with the applications of the results
reported herein.

Detector Location

The results of the study indicated that the critical energy param-
eter, E_c, was responsive to stoppage waves when the energy variable was
computed from one-minute volume and speed data updated every 30 seconds.
Since the data were updated every 30 seconds, the response to a stoppage
wave in some instances would be expected to be late by as much as 30
seconds. The downstream detectors must, therefore, be located a suf-
ficient distance downstream from the critical freeway section to cope
with this possibility.

Studies ([15]) have shown that the speed of stoppage waves will
reach as high as 26 ft/sec. Thus, it is possible that a wave could
travel about 800 feet before the logic responds to it. It is, therefore,

suggested that the downstream detectors be positioned at the following minimum distance from the crest.

$$D_d = \frac{L}{2} + 800$$

where D_d = Minimum distance in feet of detector location downstream from the vertical curve crest.

L = Length of vertical curve in feet.

The relationship between vertical curve length and location for the detectors downstream of the crest is presented in Figure 19.

Some practical considerations will affect the final positioning of the downstream detectors. One consideration is the relative location of an off-ramp. The results of this study suggest that if an off-ramp is in the near vicinity, it is preferable to place the detectors downstream from the ramp. Locating the detectors upstream will cause the shoulder lane detectors to be less responsive to stoppage waves because of vehicles leaving the freeway. However, if the exit maneuver is a problem in itself such that traffic backs into the freeway, an additional set of detectors may be required on the shoulder lane upstream from the ramp.

One major function of the upstream detectors is to signify when the conditions upstream of the overpass are such that a stoppage wave would result in hazardous conditions for the approaching motorists. Therefore, it is necessary that the upstream detectors be located such that local geometric deficiencies do not affect the measured traffic
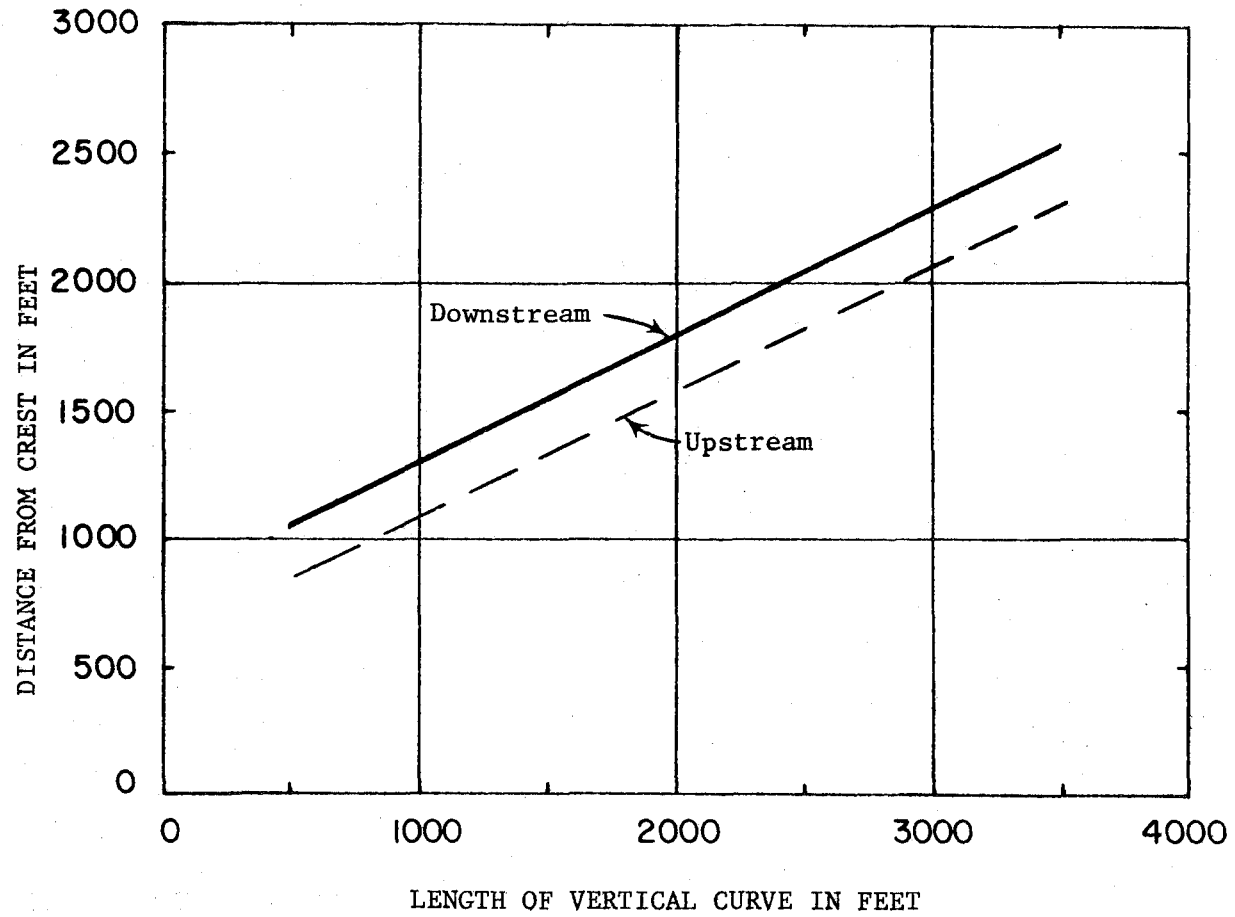
FIGURE 19 — SUGGESTED LOCATIONS OF BASIC DETECTORS

characteristics. The detectors should be located downstream from any bottlenecks existing in the immediate area. In some cases, a high-volume ramp may cause some congestion on the shoulder lane. To reduce the probability of not being responsive to a stoppage wave in the shoulder lane, it is desirable to position the detectors downstream from the ramp.

The results of the analysis on the Gulf Freeway indicated that detectors placed according to the following formula appear to work satisfactorily barring the influence of a ramp:

$$D_u = \frac{L}{2} + 600$$

where D_u = Distance in feet of detector location upstream from the vertical curve crest.

L = Length of vertical curve in feet.

Location of upstream detectors for selected vertical curve length is shown in Figure 19.

Number of Detectors

The use of energy as a control variable requires double-loop detectors on each lane both upstream and downstream of the crest. The use of redundant detectors at the downstream station has been suggested to circumvent the frequency of detector failure. However, additional studies should be conducted to determine the frequency of detector failure and its effect on the operation of the warning system. Future

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project studies on detector operation will result in a more complete description of detector requirements.

The desirability of a parameter using a single detector for measurement becomes apparent when one examines the detector requirements even without redundancy. For example, assuming that redundancy is not required, the number of detectors can be reduced by 50 percent when a control parameter can be measured from single-loop detectors.

Revised Control Logic

The results of the study illustrated the deficiencies of the control logic. Particularly, there was some instability relative to on-off cycling of the system due to variation in traffic characteristics within a one-minute sampling period. In addition, extremely low volumes during off-peak periods occasionally caused the system to activate erroneously.

The control logic was, therefore, revised to eliminate these problems. The revised logic assumes that a one-lane criterion is used at the downstream station and a two-lane criterion at the upstream location. Additional changes were made to permit 24 hours a day operation for seven days each week. It should be understood, however, that the program is not overly sensitive to incidents occurring during periods of extremely light flow as would be experienced during the early morning hours. This is due to the limitations of detector placements in addition to the fact that the logic responds to the effects of incidents. As long as stoppage waves are present, the program will

be responsive. However, the program is not capable of responding to incidents occurring between the upstream and downstream detector stations during these early morning hours. A flow chart for the revised control logic is presented in Figure 20. The following list refers to the notation used in the figure and represent variables computed on a per lane basis:

E_c = Critical Energy

E_u = Energy Upstream

E_{D1} = Energy Downstream

Vol_c = Critical Volume (8 vpm)

Vol_u = Volume Upstream

Vol_{D1} = Volume Downstream

U_t = Threshold Speed (30 mph)

U_u = Average Speed Upstream

U_{D1} = Average Speed Downstream

System Considerations

It might be desirable in some cases to add additional detectors downstream from the original subsystem detector set. These additional detectors would provide the capability of earlier warnings of stoppage waves. The earlier alert can serve to increase the motorists confidence in the system. For example, if the basic downstream detectors are positioned 1500 feet from the curve crest, and a stoppage caused from off-peak incident propagated 2000 feet downstream from the crest, the congestion is clearly visible to the motorists as they drive over the

73
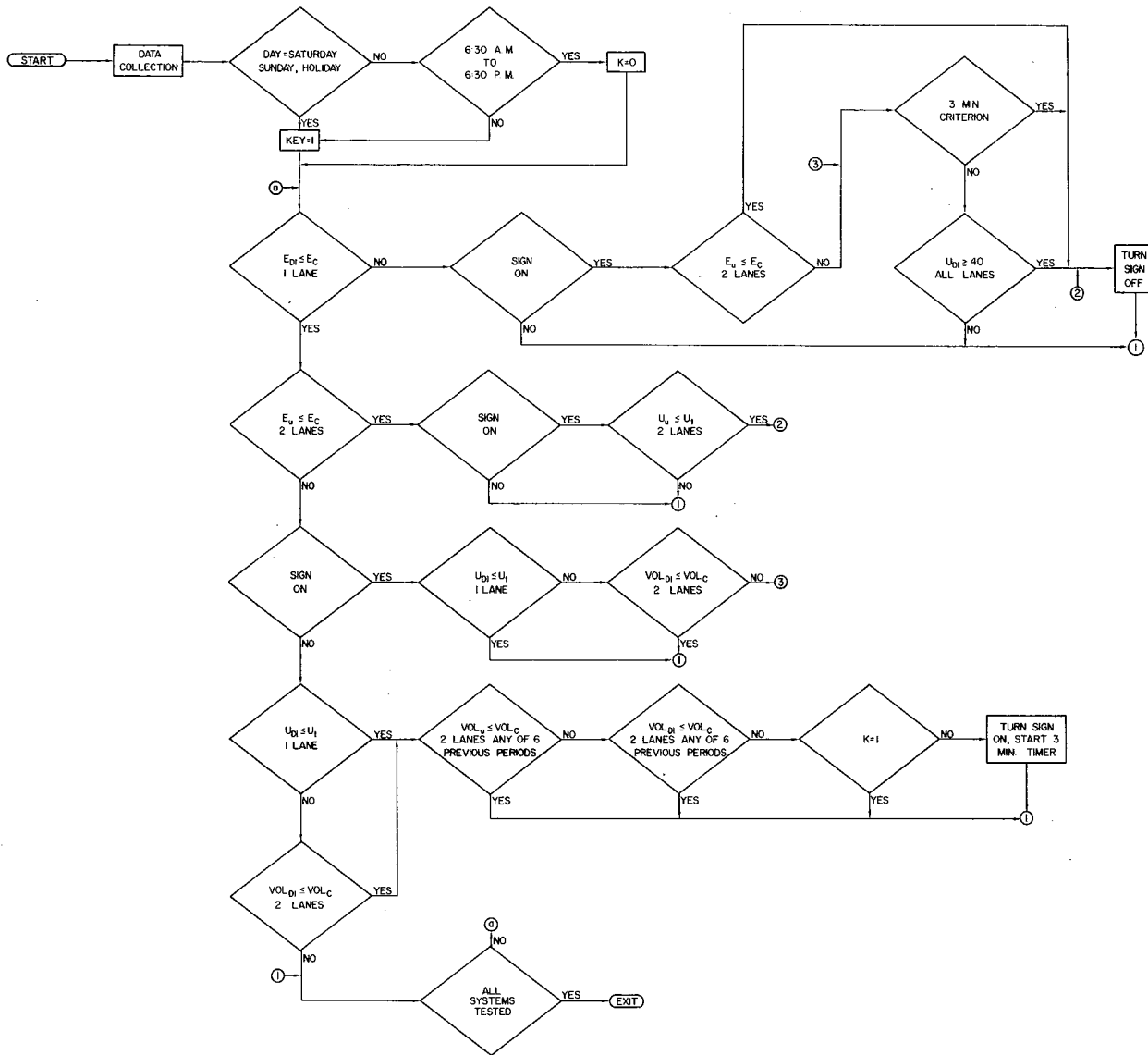
FIGURE 20 — FLOW CHART OF REVISED
CONTROL LOGIC

crest. The motorists might lose confidence in the system if the sign was not activated.

The positioning of the additional downstream detectors would depend on the specific requirements at the location. On the Gulf Freeway, double-loop detectors used for the ramp control logic are positioned on the center lane downstream from two of the study sites (Mossrose-Griggs and Lombardy-Dumble). These detectors were, therefore, integrated with the safety warning system to achieve earlier warnings of stoppage waves. The control logic presented in Figure 20 was further revised to incorporate the concept discussed above. The resultant control logic is presented in Figure 21. The notation is identical to that in Figure 20 with the following additions:

$$E_{D2} = \text{Energy at additional downstream location}$$

$$Vol_{D2} = \text{Volume at additional downstream location}$$

$$U_{D2} = \text{Average speed at additional downstream location}$$

Implementation

The logic illustrated in Figure 21 was adopted as the initial control package for the safety warning system on the Gulf Freeway. Operation of the three safety warning signs was initiated on March 13, 1972. Although the warning signs were initially operated manually, the operators relied on the information presented to them by the computer which illuminated status lights mounted on a console located in the control room. After a three-week period, the system was then placed on automatic control. Automatic computer operation of the system, using

75
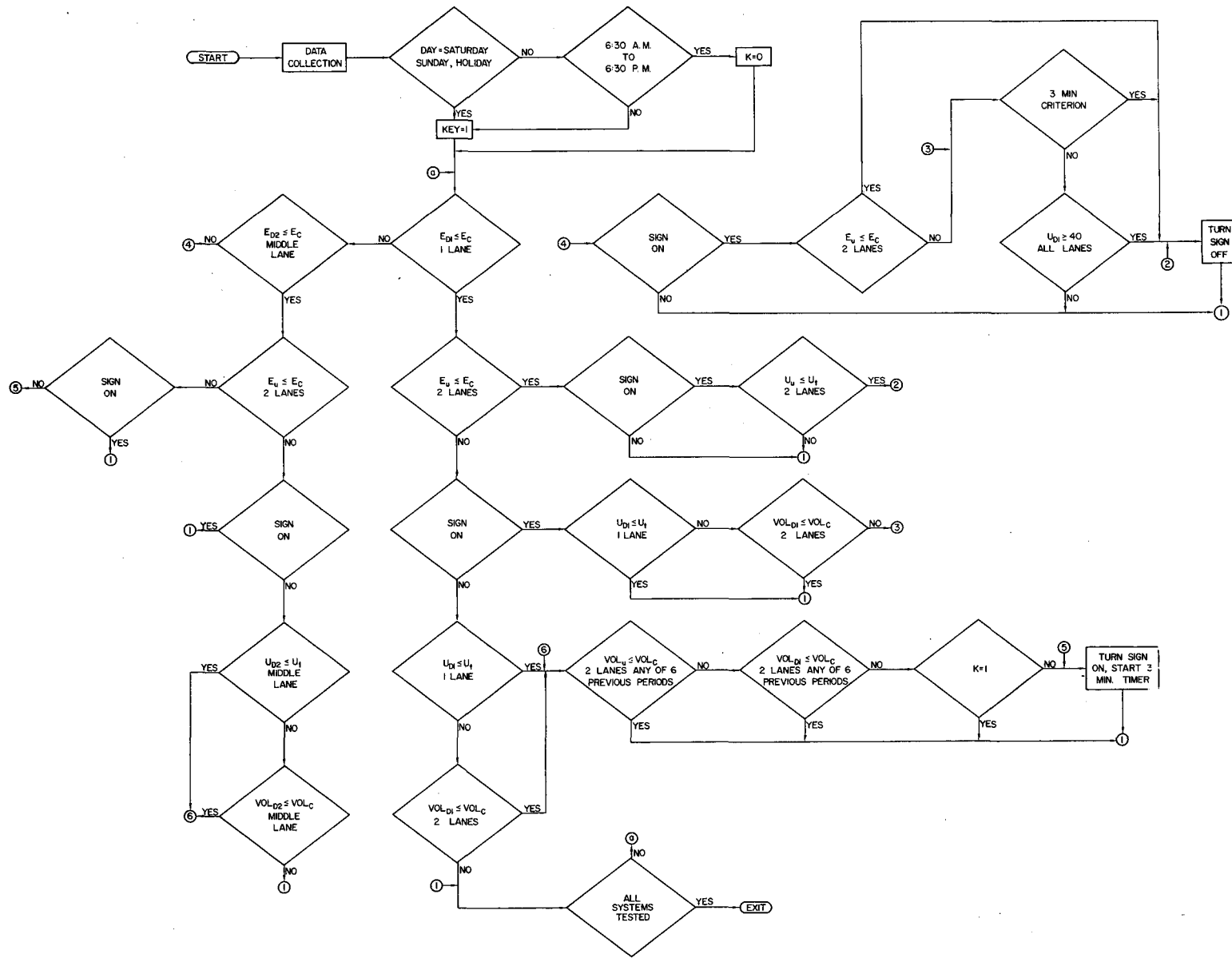
FIGURE 21 — FLOW CHART WITH ADDITIONAL DOWNSTREAM
MIDDLE LANE DETECTORS

the logic in Figure 21, has been very satisfactory to the extent that no additional changes were made in the logic.

FINDINGS AND RECOMMENDATIONS

General

This report was concerned with the development of a control technique for a prototype safety warning system for urban freeways and the application of the logic to digital computer control of the prototype. The design concept of the prototype was presented in an earlier project report (1). The function of the safety warning system is to increase freeway efficiency by alerting motorists to stoppage waves on freeway sections, such as overpasses, having restricted sight distances. It is anticipated that the improved efficiency will result in fewer accidents, reduced system travel time, driver anxiety, and driver discomfort, and improvement in the level of service.

Findings

The findings of the research reported herein are as follows:

1. The critical energy criterion established in this
   report provides a good indicator for the presence of
   stoppage waves on an urban freeway operating at
   levels of service B, C, or D. The energy variable
   was calculated using one-minute measurements of
   volume and average speed updated every 30 seconds.
   Using this computation base, the critical energy
   parameter resulted in advance warnings of stoppage
   waves ranging from 0 to 280 seconds in 134 of the 142

cases studied. An additional 7 waves were recognized by the energy parameter between 5 and 30 seconds after the wave passed the detector. However, this was within the expected capabilities of the logic because of a 30-second update of traffic data. Only one wave was recognized later than 30 seconds after the wave crossed the detector.

2. A one-lane control criterion in which any one of the three lanes provides the alert of a stoppage wave was shown to work satisfactorily. In only one of 42 cases was the stoppage wave detected after it had passed over the detector station. In this case, however, the logic was late by only 17 seconds which is within the expected time of detection based on the 30-second update of the measured data.

3. The median and middle lanes provided the first alert concerning the presence of stoppage waves for the majority of the incidents studied.

4. An evaluation of the original control technique for real-time computer operation of the safety warning device revealed that the logic using a one-lane control criterion would respond satisfactorily to stoppage waves resulting from incidents that occur while the freeway

is operating at levels of service B, C, or D. However, the analysis also revealed an unacceptable frequency of detector failures which would at times cause the safety warning device to respond late (Type I error) or would cause the device to activate erroneously (Type II error).

5. It was observed that in off-peak traffic periods (particularly during the summer months), the energy variable, based on a one-minute sample period, intermittently fell below the critical energy value. According to the control logic, this drop in energy would cause the safety warning device to be activated erroneously (Type II error). The problem was noticed to occur particularly on the shoulder lane at the Griggs detector station.

6. Increasing the time base to five minutes did not reduce the frequency of Type II errors to an acceptable level.

7. An approach whereby a computer check is maintained on the speed and volume of the middle lane at the downstream detector station reduced the frequency of Type II errors to an acceptable level.

8. The control technique occasionally subjected the system to some instability. It was observed that the variation of traffic characteristics at the downstream detector station after an incident occurred would occasionally cause the safety warning device to cycle on and off intermittently before the stoppage waves reached the upstream detectors. This problem could be eliminated if the system would remain on for a three minute minimum after initial activation.

9. An evaluation of a control technique, using a two-lane criterion in which the system would not respond unless stoppage waves were detected on two lanes, revealed that it can generally respond to stoppage waves in adequate time. However, it is less responsive than the one-lane criterion. The logic would have responded satisfactorily to 96 percent of the cases studied. However, in 4 percent of the cases, the response time would have been greater than 30 seconds after the wave crossed the detectors. The results also revealed that in almost 50 percent of the cases studied, the amount of advance warning was less than that provided with a one-lane criterion.

10. The combination of the median and middle lane detectors gave the first indication of a stoppage wave in the majority of the cases studied using a two-lane control criterion.

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APPENDIX

TABLE A-1

DIFFERENCE BETWEEN MODEL DETERMINATION AND ACTUAL
OBSERVATION OF STOPPAGE WAVE ON EACH LANE (SECONDS)

Mossrose			Griggs			Lombardy			Dumble			Cullen		
3	2	1	3	2	1	3	2	1	3	2	1	3	2	1
54	150	280	20	35	30	30	45	45	30	-30	-30	230	195	150
10	15	10	30	0	0	0	0	0	130	210	45	26	30	0
0	30	30	90	36	15	7	30	0	170	170	30	0	90	-30
20	0	0	15	15	30	*	195	0	60	90	90	270	180	180
*	50	47	42	48	30	-28	-17	-51	76	120	60	255	30	-30
90	90	90	0	0	20	240	150	30	101	81	51	180	240	180
50	0	105	20	25	10	72	76	115	45	45	33	40	40	65
3	37	172	40	60	120	32	36	65	66	63	45	60	62	108
7	45	-5	0	5	-20				42	48	*			
40	54	63	0	5	-20									
			60	60	*									
			126	126	*									
			97	93	*									
			45	50	70									
			30	30	46									

*Defective detector

| 7 | 45 | -5 | - Stoppage wave was sensed on lane 3 by the critical energy parameter 7 seconds before it passed over the detector. Likewise, the wave on lane 2 was sensed 45 seconds prior to it passing over the detector. The wave on lane 1 was sensed 5 seconds after it passed over the detector.

TABLE A-2

ADVANCE WARNING OF STOPPAGE WAVE - ONE-LANE CRITERION

Mossrose		Griggs		Lombardy		Dumble		Cullen	
Time (Sec.)	Control Lanes*	Time (Sec.)	Control Lanes*	Time (Sec.)	Control Lanes*	Time (Sec.)	Control Lanes*	Time (Sec.)	Control Lanes*
54	3,2	20	3	30	3	30	3	170	3,2
10	3	330	3	0	3,2,1	210	2	26	3
0	3	36	3,2	7	3,2	180	3,2	0	3,2
20	3	15	3,2	-17	2	90	2,3	180	3,2
90	3,2,1	42	3	240	3	106	2	30	3,2
50	3,1	0	3,2	72	3,2,1	101	3	180	3
93	1	20	3	32	3,2	45	3,2	40	3,2
[7	3]	60	2			63	3,2	60	3,2
40	3,2,1	0	3,2						
		60	3,2						
		270	1						

*Lanes which first registered the presence of a stoppage wave

[7   3] - The first stoppage wave was sensed by the critical energy parameter 7 seconds before it passed over the detector. The stoppage wave was first detected on lane 3.

ADVANCE WARNING OF STOPPAGE WAVE - TWO-LANE CRITERION

Mossrose		Griggs		Lombardy		Dumble		Cullen	
Time (Sec.)	Control Lanes	Time (Sec.)	Control Lanes	Time (Sec.)	Control Lanes	Time (Sec.)	Control Lanes	Time (Sec.)	Control Lanes
54	3,2	5	3,2	15	3,2	-30	3,2,1	170	3,2
5	3,2	0	3,2,1	0	3,2,1	205	3,2	20	3,2
-10	3,2	36	3,2	7	3,2	180	3,2	0	3,2
0	3,2	15	3,2	195	③,2	90	2,1	180	3,2
50	3,2	36	3,2	-47	3,2	76	3,2	-180	3,2
90	3,2,1	0	3,2	150	3,2	81	3,2	40	3,2
50	③,1	5	3,2	72	3,2,1	45	3,2	60	3,2
3	3,1	0	3,2	32	3,2	63	3,2		
-23	3,2	0	3,2			42	3,①		
40	3,2,1	60	3,2						
		126	3,2,①						
		93	3,2,①						
		30	3,2,1						

③ - Defective detector - lane 3

| 5 | 3,2 | - The stoppage was sensed by two of the three lanes 5 seconds before the first stoppage wave passed over the detector. The stoppage waves were first sensed on lanes 3 and 2.

TABLE A-4

COMPARISON OF ONE-LANE VERSUS TWO-LANE CRITERION

ADVANCE WARNING OF STOPPAGE WAVE (SECONDS)

Mossrose			Griggs			Lombardy			Dumble			Cullen		
One-Lane	Two-Lane	Diff.	One-Lane	Two-Lane	Diff.	One-Lane	Two-Lane	Diff.	One-Lane	Two-Lane	Diff.	One-Lane	Two-Lane	Diff.
54	54	0	20	5	15	30	15	15	30	-30	60	170	170	0
10	5	5	0	0	30	0	0	0	210	205	5	26	20	6
0	-10	10	36	36	0	7	7	7	180	180	0	0	0	0
20	0	20	15	15	0	-17	-47	30	90	90	0	180	180	0
90	90	0	42	36	6	240	150	90	106	76	30	30	30	0
50	50	0	0	0	0	72	72	0	101	81	20	180	-180	360
93	3	90	20	5	15	32	32	0	45	45	0	40	40	0
7	-23	30	60	0	60				63	63	0	60	60	0
40	40	0	0	0	0									
			60	60	60									
			270	30	240									

10	5	5

- The one-lane control criterion sensed the presence of a stoppage wave on one of the lanes 10 seconds before a wave reached the detector station. The two-lane criterion provided an advance warning of 5 seconds. Thus, the response using a one-lane criterion was 5 seconds earlier than the two-lane criterion.