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16. Abstract

An automatic incident detection model using the standard normal deviate (SND) of the control variable (energy or lane occupancy) was proposed, developed, and evaluated. Two strategies were tested using a 3- and 5-minute data base for each control variable. The first strategy (A) required one SND value to be critical; whereas the second strategy (B) required two successive SND values to be critical. Strategy B using lane occupancy with a 5-minute time base was found to produce the best results. It detected 92 percent of the 35 incidents studied during moderate and heavy flow (750-1800 vph per lane) with a computer response time of 1.1 minutes, and operated at a 1.3 percent false alarm rate during the peak period. There were no cases of false incident detections during the off-peak periods. The peak period false alarm rate can be reduced to 0.2 percent by utilizing a two-station control criterion in which an incident would not be flagged until two successive upstream stations register critical SND values. The study results showed that the SND model was as effective as the Composite model which was considered to be the best existing model. Since the SND model does not require separate distribution curves for various traffic conditions, it may be a more attractive model for an operational system.

Relationships were developed and presented that identify sensor spacing requirements for an incident detection system using a station model.

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AUTOMATIC DETECTION OF URBAN FREEWAY INCIDENTS

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and

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Research Report Number 165-12

Development of Urban Traffic Management
and Control Systems

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Sponsored by
The Texas Highway Department
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ABSTRACT

AN APPROACH FOR INCIDENT DETECTION
ON URBAN FREEWAYS

An automatic incident detection model using the standard normal deviate (SND) of the control variable (energy or lane occupancy) was proposed, developed, and evaluated. Two strategies were tested using a 3- and 5-minute data base for each control variable. The first strategy (A) required one SND value to be critical; whereas the second strategy (B) required two successive SND values to be critical. Strategy B using lane occupancy with a 5-minute time base was found to produce the best results. It detected 92 percent of the 35 incidents studied during moderate and heavy flow (750-1800 vph per lane) with a computer response time of 1.1 minutes, and operated at a 1.3 percent false alarm rate during the peak period. There were no cases of false incident detections during the off-peak periods. The peak period false alarm rate can be reduced to 0.2 percent by utilizing a two-station control criterion in which an incident would not be flagged until two successive upstream stations register critical SND values.

The study results showed that the SND model was as effective as the Composite model which was considered to be the best existing model. Since the SND model does not require separate distribution curves for various traffic conditions, it may be a more attractive model for an operational system.

Relationships were developed and presented that identify sensor spacing requirements for an incident detection system using a station model.

ACKNOWLEDGMENT

The authors wish to thank Messrs. J. Gibbs and J. Ibanez of the Texas Transportation Institute for their efforts in collecting the data for this study. Mr. J. Gibbs is also recognized for programming the data collection and analysis computer subroutines.

This report discusses one phase of a research project entitled "Development of Urban Traffic Management and Control Systems," conducted by the Texas Transportation Institute and the Texas Highway Department in cooperation with the Federal Highway Administration. The contents of this paper reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This paper does not constitute a standard, specification or regulation.

Key Words: Freeway control, traffic surveillance, disabled vehicle detection, traffic safety and operations.

SUMMARY

This report is concerned with the development, testing and evaluation of automatic incident detection algorithms for urban freeways. The emphasis is on detection of disabled vehicles that block one or more lanes of the freeway during medium and heavy traffic flow conditions.

A model using the standard normal deviate (SND) of a control variable was proposed, tested and evaluated. The SND is a standardized measure of the deviations from the mean in units of the standard deviation, and is expressed by the following relationship:

$$SND = \frac{x - \bar{x}}{s}$$

In application to incident detection, the above variables take on the following meaning:

x = value of control variable at time t

$\bar{x}$ = mean of control variable over previous n sampling periods

s = standard deviation of control variable over previous n sampling periods

The overall incident detection concept incorporates an incident detection algorithm with a stoppage wave detection algorithm previously developed for operation of the safety warning devices on the Gulf Freeway (<u>14</u>, <u>15</u>). When stoppage waves are detected by the later algorithm, each wave is analyzed to ascertain whether the wave(s) resulted from a disabled vehicle on the freeway.

Two strategies shown in Figure S-1 were evaluated. Strategy A required one SND value to be critical; strategy B required two successive SND values to be critical. Lane occupancy and energy were used as control variables with 3- and 5-minute data bases. The above resulted in a combination of 8 approaches.

The SND model was evaluated on the inbound section of the 6-lane Gulf Freeway in Houston. The study indicated that the 5-minute SND model using strategy B and lane occupancy as the control variable resulted in the best performance. This approach detected 92 percent of the 35 incidents studied during moderate and heavy flow (750-1800 vph per lane) with an average computer response time of 1.1 minutes, and a false alarm rate of 1.3 percent during the peak period. Of the three incidents missed, one incident blocked the freeway for only two minutes. The other two occurred when the operating speeds were 48 and 53 mph, respectively. These factors lessened the degree of queueing and thus could have effected the detection capabilities if the shock wave did not reach the sensor station. The peak period false alarm rate could be reduced to 0.2 percent by utilizing a two-station control criterion in which an incident would not be flagged until two successive upstream stations register critical SND values.

A theoretical analysis of freeway operations during incident conditions revealed that the following factors affect the performance of incident detection systems: 1) sensor spacing, 2) duration of incident, 3) operating conditions prior to the incidents, 4) capacity of the bottleneck caused by the incident, 5) normal capacity of the

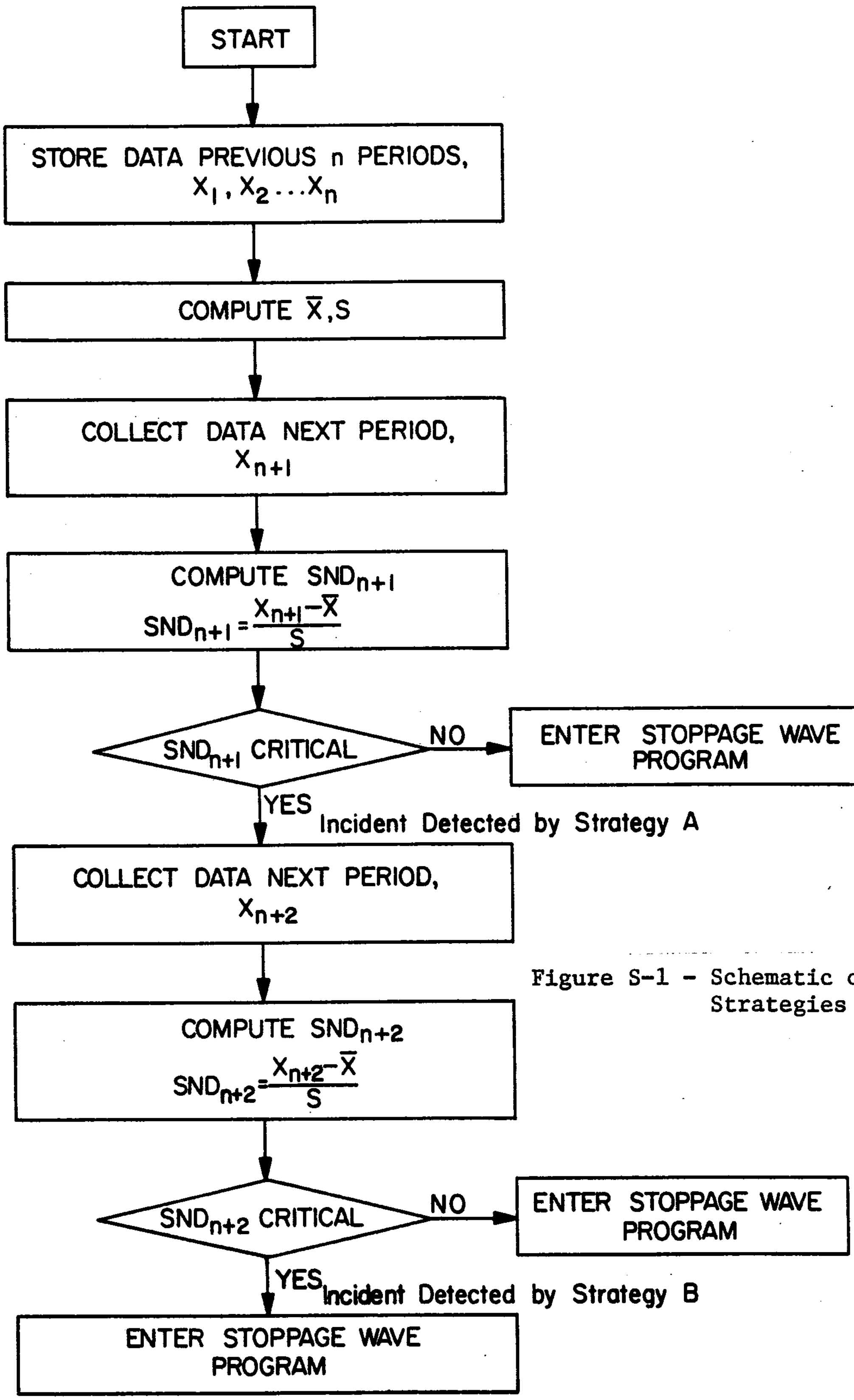


Figure S-1 - Schematic of Strategies A & B freeway, 6) computer response time of the algorithm, and 7) the required incident detection time.

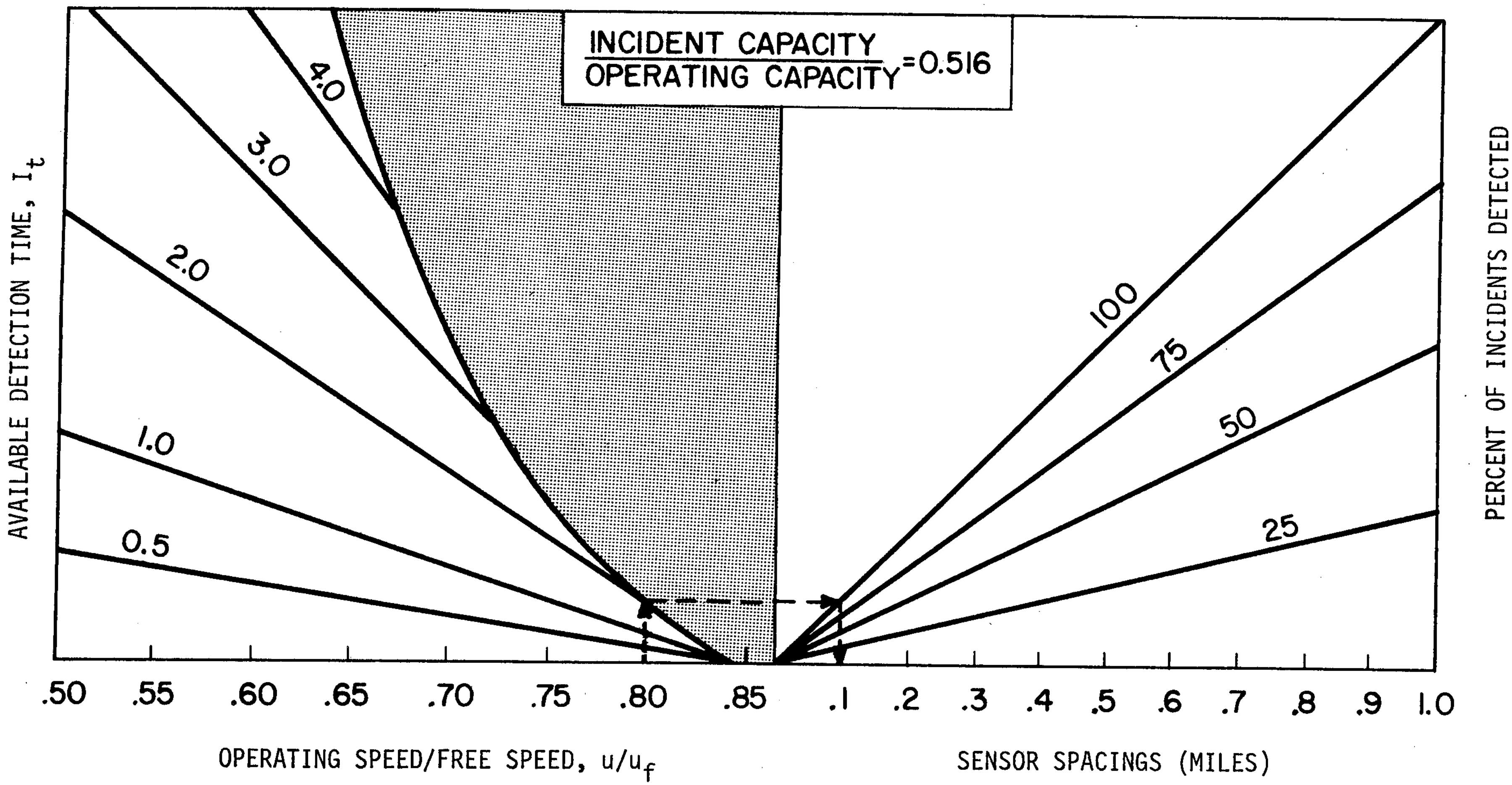
A comparison of the SND model with existing incident detection models indicated that the SND model performs as well as the best existing model. Since the SND model does not require separate distribution curves for various traffic conditions, it is a more attractive model for an operational system.

It is the belief of the authors that with proper sensor spacing, it is possible to approach 100 percent detection of incidents blocking a freeway lane for a duration equal to or greater than a preselected time during moderate and heavy flow. Trade-offs must be made concerning detection capabilities and cost associated with number of detectors and with computer and hardware requirements.

Implementation

An automatic incident detection algorithm has been developed that can be applied to other urban freeways.

Based on a theoretical analysis of freeway traffic characteristics during incident conditions, relationships were developed that relate sensor spacing requirements for an incident detection system spacifically for the Gulf Freeway. Figure S-2 applies to incidents that block a freeway lane for two minutes or more during moderate and heavy flow conditions. Similar graphs can be developed for other urban freeways once specific operating characteristics are analyzed. A hypothetical example is presented in the following paragraph that illustrates the use of Figure S-2.



I_t = [Required Detection Time (D_t)] - [Computer Algorithm Response Time (R_t)]

Figure S-2 - Sensor Spacings for an Incident Duration of Two Minutes or More

Example: The problem is to determine the maximum sensor spacing for an incident detection system on the Gulf Freeway. The system should be capable of detecting all incidents blocking a freeway lane for two or more minutes while the freeway is operating at speeds up to 48 mph ($u/u_f = 48/60 = 0.80$). The system should be capable of detecting all the incidents within 2 minutes after they occur. From Figure S-2, it is determined that the maximum sensor spacing to satisfy the above requirements is .10 miles. (This result is valid if the computer algorithm detects the incident as soon as the stoppage wave crosses the sensor station, $R_t = 0$).

Generalized computer programs, that provide a method for determining sensor spacing and a method for determining the percent of incidents that will be detected based on given sensor spacings, are listed in Appendix C of the report.

Recommendations for Further Research

1. Cost-effectiveness studies should be conducted to evaluate trade-offs between automatic incident detection capabilities and cost relative to sensors, computer capabilities, and associated hardware.
2. Research should be directed to develop systems for automatic incident detection during light flow conditions.

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I. INTRODUCTION

The Problem

The primary cause of traffic congestion on urban freeways is that the traffic demand exceeds the capacity of a section(s) of freeway to service it. The capacity of the critical section or "bottleneck" causing the congestion may be limited by the physical geometrics of the freeway section. This congestion often occurs daily, is generally recurrent and thus is quite predictable both in effect and duration. Freeway ramp control systems have proved their effectiveness in reducing recurring congestion thus improving the level of service afforded the freeway motorists. The success of freeway ramp control arises primarily from its capability to control entrance ramp traffic flow so that the total freeway traffic demand on a section of freeway will not exceed the normal geometric capacity of the freeway section.

The occurrence of an accident or other lane blockage incident on the freeway reduces the capacity of the section of freeway significantly below what is normally provided. Freeway incidents occur randomly, are unpredictable, and result in what is termed non-recurrent congestion. When a major incident occurs causing a significant bottleneck, the capabilities of present freeway ramp control systems are typically exceeded and freeway congestion and delay result even though unused capacity may exist on the frontage road or other parallel arterials within the freeway corridor. Information on the frequency of occurrence, the characteristics and effects of freeway incidents are documented in several reports (1 - 7).

Solution Approach

From a control system viewpoint, what is needed when an incident occurs on the freeway is to remove the vehicles as quickly as possible, to intercept freeway demand before it reaches the reduced capacity location caused by the incident, and to redirect the demand into areas of the freeway corridor where excess capacity exists. A freeway corridor is assumed to consist of the freeway, frontage roads, feeder streets to the freeway, and other arterials which may serve as alternative routes to the freeway. An urban freeway corridor is typically directionally oriented and usually lies between an outlying residential area of a city and the downtown section. From the viewpoint of a freeway corridor system, the freeway may contribute perhaps a third to a half of the available corridor capacity. Thus, it would be desirable if a system could be developed to prevent, or at least minimize, the amount of congestion and safety hazards experienced due to the occurrence of incidents on the freeway by rapid detection and removal of the incidents, and by better utilization of available capacity within the freeway corridor.

To obtain this desired redistribution in traffic demand, a corridor surveillance, information and control system will be required. The surveillance function is required to detect and evaluate the nature of incidents, and to determine the appropriate operational control strategy to follow. The real-time information system will provide information to motorists that will enable them to intelligently select and follow their best alternative course of action. The control function is desired to adjust the ramp control parameters for optimum redistribution of demand and to adjust the traffic controllers, located at the intersections along those alternate routes where increased usage is expected, to accommodate the short-term changes in traffic patterns and demands.

Automatic detection of incidents is a very important function of a corridor surveillance, information, and control system. Moskowitz (8) believes that the single most important problem in urban freeway traffic operations is the determination of methodology to detect stopped vehicles and the necessary steps to remove the stoppage. West (9) indicates that the nonrecurring freeway congestion due to incidents is responsible for as much motorist delay in the urban area as is the recurring congestion due to geometric bottlenecks.

Objective

This report is concerned with the development, testing and evaluation of automatic incident detection algorithms for urban freeways. The emphasis herein is directed toward incident detection during medium and heavy flow traffic conditions.

II. PREVIOUS WORK ON INCIDENT DETECTION MODELS

Six approaches to the automatic detection and location of incidents during the peak period were explored by Courage (10) as part of NCHRP Project 20-3 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, and 6) metering rates. (In the University of Michigan study, discussed later in this section, these models were referred to as 1) Subsystem Shock Wave Model, 2) Station Energy Model, 3) Subsystem Energy Model, 4) Station Discontinuity Model, and 5) Subsystem Discontinuity Model, respectively. No analysis was made by the University of Michigan using the metering rates approach.)

The first five approaches involved measurement of one or more variables by the detection system. Measured values were compared to pre-established limits determined from observed frequency distributions. When these limits were exceeded, an incident was considered to have been detected on the freeway. The sixth approach utilized certain aspects of the computational logic of a dynamic ramp metering system 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 the given subsystem was reduced while the input remained substantially unaltered, resulting in vehicle storage.

In the studies based on the kinetic energy approach, one-minute kinetic energy values were compared with pre-established limits and a probable incident was proclaimed whenever the measurements exceeded the lower limits. The logical extension of the kinetic energy approach was obtained by comparing the energy values at upstream and downstream freeway stations. This latter 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 reasonable over the available lanes. An extremely biased distribution could, therefore, be an indication of the capacity reduction. The variable was termed 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 the adjacent upstream and downstream detectors, 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 of the control parameters calculated for the metering system, it was reasoned that an examination of these parameters might give some clue as to the location of the incidents.

Only limited studies were conducted to test the feasibility of the six incident detection approaches. It was concluded by Courage that all models demonstrated some ability to detect incidents and may, therefore, merit further consideration. They did exhibit a high false alarm rate and it was felt that considerable refinement would be required to produce an operational incident detection scheme.

California developed an incident detection model for use on the Los Angeles Freeway System (11). Whereas Courage's models were intended to detect the passage of the incident shock wave, the California Model was designed to detect the dynamic sequence of events that result in the deterioration of operations from those prevailing before the incident to the congested situation. The California Model consists of three sequential tests all based on occupancy changes at the upstream and downstream stations of a subsystem. An incident is signaled only when the threshold values for all three variables are exceeded, indicating that the sequence of events associated with a typical capacity-reducing incident has occurred. The model is applied to moving average data for the most recent two minutes and updated every 20 seconds. Like most of the models developed by Courage, the California Model also requires cumulative distribution curves to be drawn for each location.

Whitson (12) suggested a detection model using volume as the controlling parameter. The critical value was determined by using a running mean with a constant standard deviation. A running five-minute mean of the flow rate was plotted with corresponding upper and lower limits. The limits were two standard deviations away from the five-minute running mean. An incident was detected when the one-minute flow rate fell below the lower limit for 30 seconds. This model required a separate constant standard deviation to be computed for each sensor location.

The University of Michigan (U of M) recently completed a study on the John C. Lodge Freeway in which the California Occupancy Model and the first five models developed by Courage were analyzed (13). The U of M study also combined Courage's energy distribution model with the speed-density model into a Composite Model as a means of improving the reliability of detection technique. In addition, exponential smoothing of traffic stream variables was investigated as a possible technique for incident detection. However, due to the limited work with this latter technique, definite conclusions as to its applicability could not be reached. The effectiveness of the former seven models analyzed by U of M was determined based on a set of 50 incidents. The results of the analysis are summarized in Table 1 and Figure 1. A brief discussion of some of the relevant findings is presented in the following paragraphs.

The results of the U of M study indicated that the Station Discontinuity Model detected 90 percent of the incidents observed. The average time lag from the moment congestion was first detected until the model detected the incident was 2.07 minutes, which was below average for all the models (2.8 minutes). Also, the Station Discontinuity Model operated better than the others at longer subsystems. The disadvantages were its high standard deviation of detection time (4.05) and its lack of sensitivity in termination time. The termination time is defined as the moment that the freeway returns to "normal" conditions after an incident has occurred.

Use of the Subsystem Discontinuity Model resulted in a lower detection percentage (74 percent), and a lower standard deviation of detection time

Table 1

Review of Individual Detection Model Performance (13)

Model	Means of Detection	Type	Specific to Incidents	Incidents Detected (Percent)	False Alarm Rate (Percent)
Composite	Lane Blockage and/ or Flow Discontinuity	Subsystem	Yes	96	2
Station Discontinuity	Stopped Vehicles or No Traffic in Blocked Lanes	Station	Yes	90	1
Subsystem Discon-tinuity	Shift in Traffic Flow Characteristics Between Stations	Subsystem	No (Bottle-necks, also)	74	1
Subsystem Energy	Congestion Upstream, Reduced Flow Downstream	Subsystem	No (Bottle-necks, also)	58	1
Station Energy	Congestion Upstream of Incident	Station	No	56	1
California	Congestion Upstream, Reduced Flow Downstream	Subsystem	Yes	52	≃0.1
Subsystem Shock Wave	Upstream Congestion Shock Wave or Wave of Reduced Operations Downstream	Subsystem	No	32	1

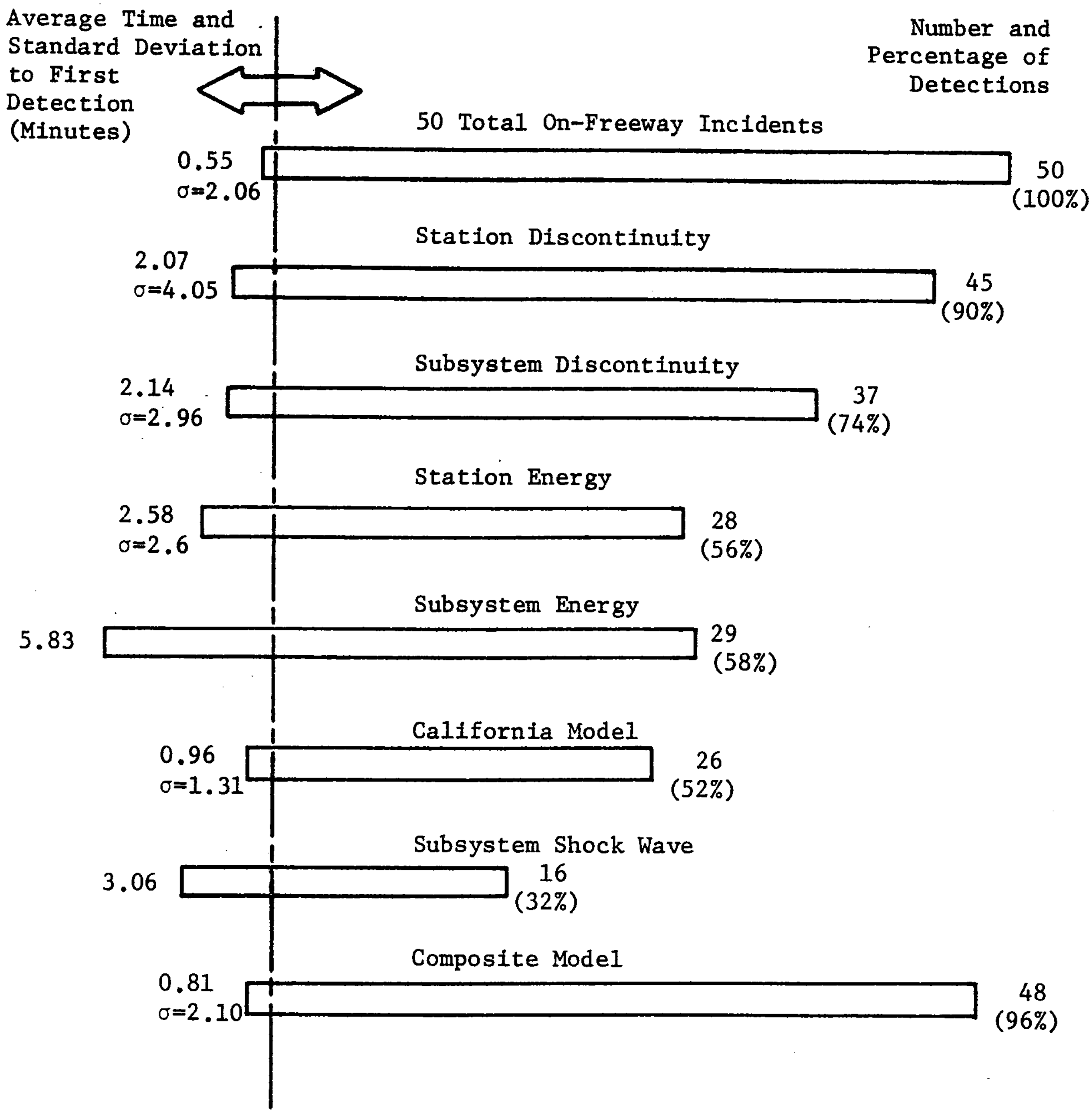


Figure 1 - Individual Model Incident Detection Performance (13)

(2.14). It performed better than other models studied in shorter subsystems. The model was less affected by incidents in the middle of the subsystem when the subsystem was relatively short. It was the best model in signifying the end of congestion (61 percent).

The Modified California Model exhibited the lowest detection time (0.96) and standard deviation (1.31), but had one of the lowest detection percentages. It was very sensitive to geometrics. A lane drop in one subsystem resulted in a high rate of false alarms and a lower detection percentage than in all the other subsystems. The model exhibited a false alarm rate of only 0.1 percent and was successful in detecting 80 percent of the incident terminations.

The U of M researchers observed that the two models developed by Courage which performed the best (Station Discontinuity and Subsystem Discontinuity) were also independent of each other. They therefore combined these two models into a Composite Model. The Composite Model detected 96 percent of all incidents studied and 75 percent of all terminations. The average time lag, the time elapsed from the moment the incident-caused shock wave crossed the detectors until the moment that the model detected the incident, was only 0.81 minute. This was an improvement from the 2.1 minute average time lag experienced with the two individual models. The 0.81 minute time lag represented a better performance than the Modified California Model and indicated that the great majority of detections take place within the first or second minute of the onset of congestion. The false alarm rate for the Composite Model was computed to be 2 percent. This model was considered to be the most effective of those studied.

The U of M researchers observed specific weaknesses in the models studied. Particularly, since the threshold values for Courage's models were set at a one percent level, the level of false alarms will also be one percent. The threshold levels could not be made more stringent without reducing model effectiveness. The researchers observed that in most cases the threshold values could be estimated as one standard deviation away from the mean value. They suggested that a more effective method for determining the threshold may be the use of real-time estimates of the standard deviation of the parameter values. Thus, the false alarm rate possibly could be reduced, and the thresholds would be responsive to such factors as time of day, day of week, and environmental conditions. This approach might also eliminate the need for separate frequency distribution curves for each freeway station and for different periods of the day or weather conditions.

In work related to incident detection, Dudek, et al. (14, 15, 16) developed control logic which automatically operates safety warning signs at three locations on the Gulf Freeway in Houston. The control logic is responsive to stoppage waves and activates the warning system when a stoppage wave is predicted or sensed downstream of one of the critical overpasses. The logic also turns the system off when the conditions on the freeway no longer warrant the alert provided by the warning system. Three control logics have been developed. Three control algorithms were developed with one of the following control variables: energy, speed, or lane occupancy. One program utilizes energy measurements. Each program has been successfully tested on an operating freeway. The logic utilizing the energy variable has been operating the safety warning system on the Gulf Freeway since April 3, 1972, and the system has responded very satisfactorily to the shock waves on the freeway. Of significance is the fact that, barring the occurrence of hardware failures, the warning system responds to 100 percent of the shock waves and is operating such that no false alarms are generated. These are two important criteria in the establishment of incident detection algorithms as well.

III. FACTORS AFFECTING INCIDENT DETECTION

This section discusses the influence of detector spacing and the level of freeway operation on automatic incident detection.

Incident Detection Time

Incident detection time can be defined as the elapsed time from the moment the incident occurs until it is detected. Considering an automatic incident detection system using a station model, the detection time consists of the following two components: 1) the shock wave travel time--the elapsed time between the occurrence of the incident and the time the shock wave crosses the upstream detector station, and 2) the computer algorithm response time--the time required for the computer algorithm to recognize an incident after the shock wave crosses the sensor station. The shock wave travel time is dependent on the level of freeway operation and the spacing between the incident and the upstream detector station. The computer algorithm response time is dependent on the strategy used to detect the incident.

Theoretical Analysis

Messer, et al. (17) have developed relationships that express the movement of shock waves as a function of speed when a freeway incident occurs and immediately following the removal of the incident. These relationships are presented in Figure 2.

The representation illustrates that when an incident occurs on a freeway, the first shock wave that generates upstream will travel at a speed W_{u1}. W_{d1} is the speed of the metered wave that travels

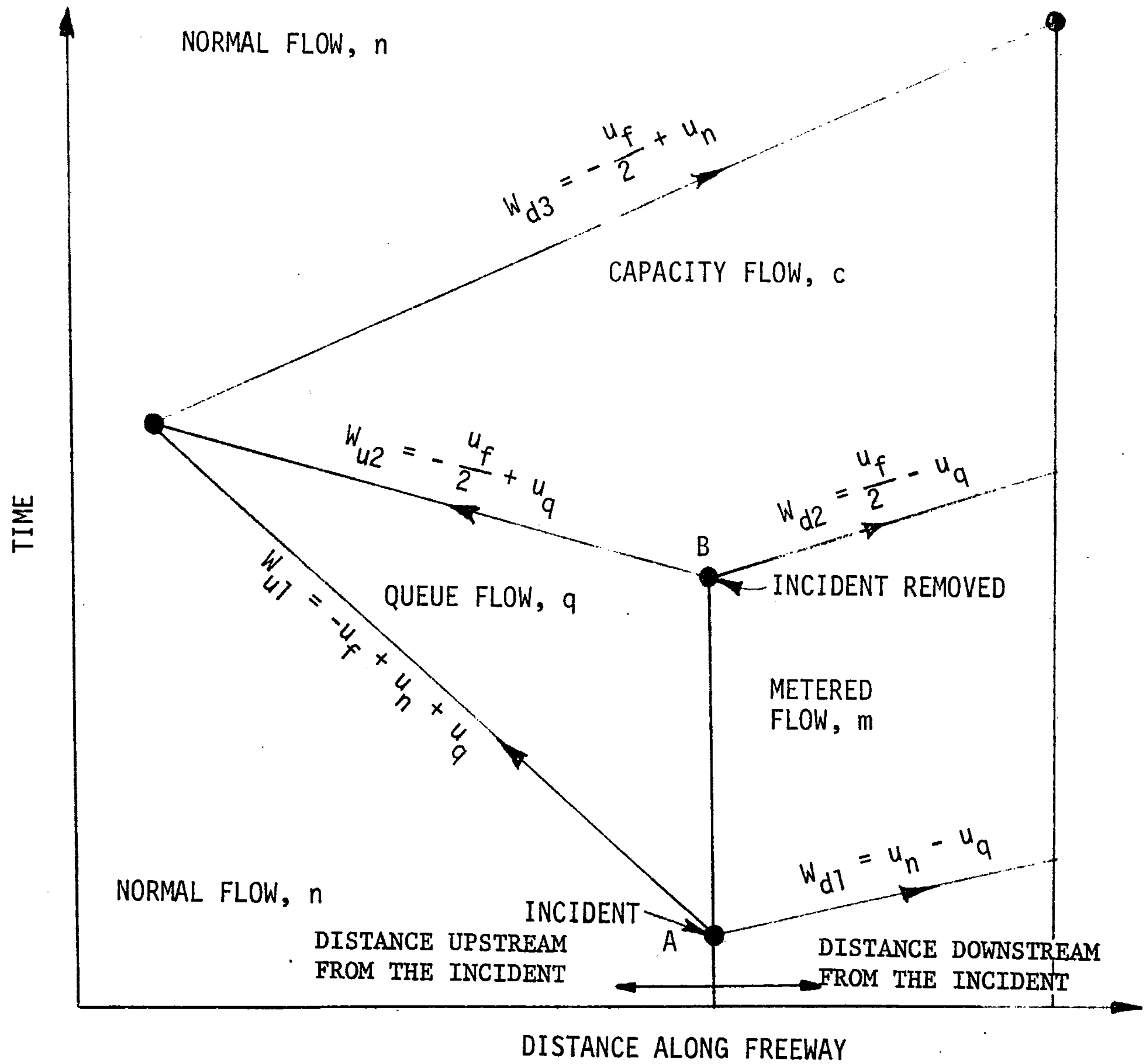


Figure 2 - Model of Freeway Traffic Conditions
Due to an Accident (17)

downstream. The shock wave and the metered wave are depicted as the boundary vectors emanating upstream and downstream from point A, which defines the beginning of the incident.

After a time T has elapsed, the incident is assumed to be completely removed from the freeway. When the incident is removed (point B), the capacity of the freeway is increased to normal, and the vehicles stored upstream of the incident site then begin to travel downstream. The flow of these vehicles out of the downstream end of the congested queue also begins to shorten or clear-up the queue upstream of the incident site. Associated with removal of the incident is the movement upstream of the capacity flow wave at a speed W_{u2}. Likewise, a wave that defines the boundary between the capacity flow and the metered regions moves downstream from the site of the incident (when it is removed) at a speed W_{d2}.

As indicated in Figure 2, one remaining wave occurs before the freeway traffic conditions return to normal. Sometime after the incident is removed, the capacity flow wave W_{u2} will catch the shock wave W_{u1} and the congested queue will have been dissipated. At this point, the final clearing wave forms and begins to move downstream at a speed W_{d3}. This wave defines the boundary between the high density capacity flow region and normal traffic flow. It is important to note that the location where W_{u1} and W_{u2} intersect, defines the maximum distance from the incident the sensors can be positioned in order to detect the shock wave for the given duration of incident. Thus, if the first sensor station were farther upstream, the incident would probably not be detected regardless of the efficiency of the computer algorithm

From the foregoing, it is clear that two important variables, as far as sensor spacing is concerned, are the speed of the shock wave moving upstream, W_{u1}, when an incident occurs, and the speed of the capacity flow wave, W_{u2}. The shock wave speed can be determined from the following relationship:

$$W_{u1} = - u_f + u_n + u_q \qquad (1)$$

where

u_f = mean free speed

u_n = normal speed prior to the incident

u_q = average speed within the congested queue

The capacity flow wave can be expressed as follows:

$$W_{u2} = - \frac{u_f}{2} + u_q \qquad (2)$$

Negative values in the expression for W_{u1} and W_{u2} indicate that the waves are moving upstream.

It has also been shown that the average speed within the congested queue, u_q, can be expressed as a function of the flow during incident conditions and the available capacity under normal conditions as follows:

$$u_q = \frac{u_f}{2} \left[1 - \sqrt{1 - \frac{q}{q_m}} \right] \qquad (3)$$

where

q = the flow under incident conditions

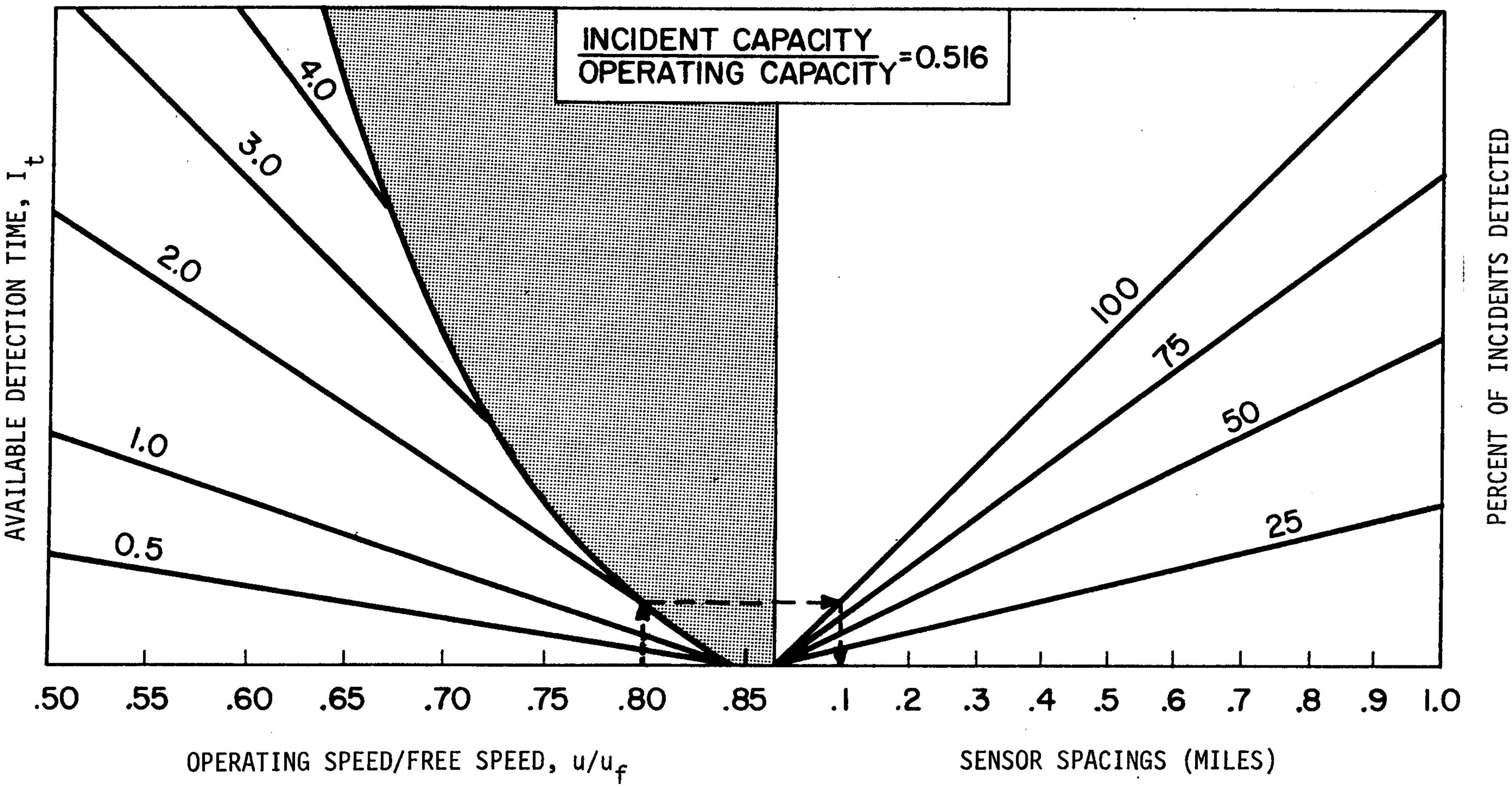
q_m = the available capacity under normal conditions

Sensor Spacing

As indicated in the previous section, the maximum sensor spacing required to detect the shock wave resulting from an incident is the intersect distance between the shock wave traveling upstream at a speed of W_{u1} and the capacity flow wave propagating upstream at a speed of W_{u2}. From Equations 1, 2, and 3, it is noted that the wave speeds W_{u1} and W_{u2} are functions of the flow during incident conditions, q, and the available capacity under normal condition, q_m. The intersection distance of the two waves is a function of the wave speeds and the incident duration. Thus, the lower the level of service prior to an incident, the farther upstream will the intersection of the two waves occur for a given duration of incident. Likewise, the longer the incident duration for a given set of operating conditions, the farther upstream will the intersection of the two waves occur. It is therefore necessary to select the minimum duration of incident and the level of freeway operations during which time the incident must be detected in order to determine sensor spacing requirements. For example, the operating agency may decide that all incidents of two minutes or more must be detected while the freeway is operating at speeds up to 50 mph.

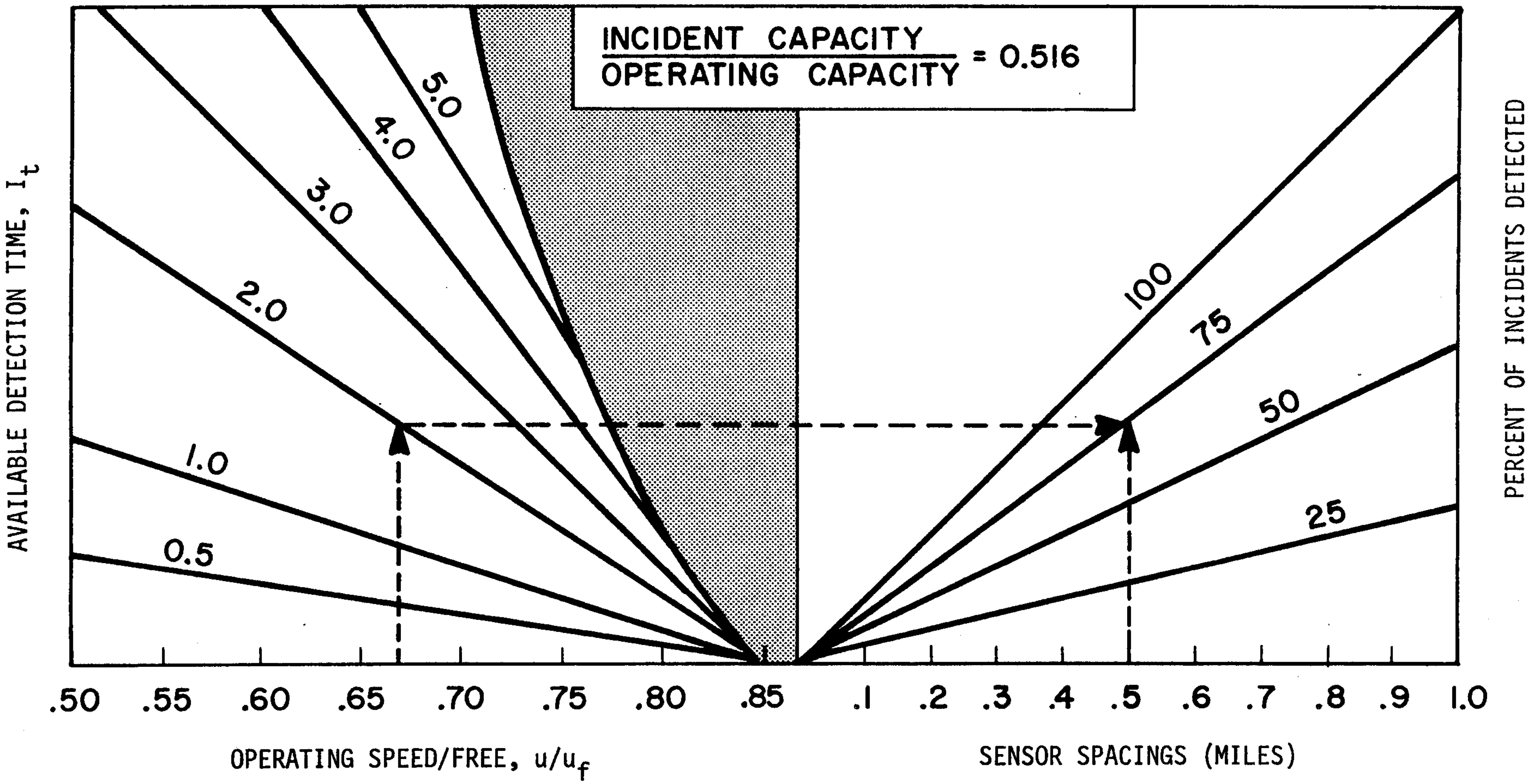
Another criterion that must be established to determine sensor spacing is the incident detection time. Since incident detection time is the sum of the shock wave travel time and the computer algorithm response time, these two factors will influence sensor spacing requirements. The shock wave travel time is affected by the freeway operational characteristics previously described. The computer algorithm response time is a function of the particular algorithm selected for incident detection. For a given duration of incident, freeway level of service, and incident detection time, the sensor spacing requirements will be influenced by the computer response time of the incident detection algorithm. Thus, if the algorithm provides a fast response time, the sensors can be positioned farther apart than for a sluggish algorithm.

Using Equations 1, 2, and 3, two graphs were developed that relate maximum sensor spacing to normal operating speed, incident detection time, and percentage of incidents that will be detected, based on characteristics observed on the Gulf Freeway in Houston. Figure 3 applies to incidents of two minutes or more; Figure 4 applies to incidents of four minutes or more. The available detection time (available shock wave travel time), I_t, is the difference between the required incident detection time, D_t, and the computer algorithm response time, R_t. The assumption inherent in the two figures is that incidents occur randomly and uniformly over the freeway section. These figures were developed using the following characteristics measured on the Gulf Freeway (1):



I_t = [Required Detection Time (D_t)] - [Computer Algorithm Response Time (R_t)]

Figure 3 - Sensor Spacings for an Incident
Duration of Two Minutes or More



I_t = [Required Detection Time (D_t)] - [Computer Algorithm Response Time (R_t)]

Figure 4 - Sensor Spacings for an Incident Duration of Four Minutes or More

u_f = 60 mph

q = 2880 vph (one lane blockage)

q_m = 5560 vph

$\frac{q}{q_m}$ = 0.516

Two hypothetical examples are presented in the following paragraphs that illustrate the use of Figures 3 and 4. Both examples assume that the computer algorithm can detect an incident as soon as the shock wave reaches the upstream sensors, that is, $R_t = 0$.

Example a - The problem is to determine the maximum sensor spacing for a freeway incident detection system. The system should be capable of detecting all incidents blocking a freeway lane for two or more minutes while the freeway is operating at speeds up to 48 mph ($u/u_f = 0.80$). The system should be capable of detecting the incidents within 2 minutes after they occur. From Figure 3 it is determined that the maximum sensor spacing to satisfy the above requirements is 0.1 miles. Note that if the sensors are spaced 0.4 miles apart, only 25 percent of the incidents would be detected within the two minute incident detection requirement.

Example b - The problem is to estimate the percentage of incidents that will be detected by an incident detection system having a given sensor spacing. The sensors are spaced 0.5 miles apart. The system should be capable of detecting incidents that block a freeway lane for four minutes or more while the freeway is operating at speeds up to 40 mph ($u/u_f = 0.67$). The system should be capable of detecting the incidents within 2 minutes after they occur. From Figure 4 it is observed that the system will detect approximately 70 percent of the incidents. Note that the sensor spacing to detect 100 percent of the incidents is approximately 0.37 miles.

The reader is reminded that the above results apply to only those freeways that have the same traffic operating conditions as the Gulf Freeway. When these conditions are different, separate curves as shown in Figures 3 and 4 would need to be developed using Equations 1, 2, and 3. Also, the reader is reminded that the discussion and development in this section of the paper applies to station incident detection models that utilize the upstream sensor station to analyze the discontinuity in flow.

Two computer programs with typical output for general application were developed and are presented in Appendix C. The first program computes the sensor spacing requirements to detect 100, 75, 50, and 25 percent of incidents of equal to or greater than a selected duration. The second program computes the percent of incidents, equal to or greater than a selected duration, that will be detected for given sensor spacings.

IV. INCIDENT DETECTION

General

The discussion presented in the preceding chapter suggests inherent weaknesses in the existing models. Most models require development of frequency distributions for the measured traffic control variable as the procedure for identifying threshold values for incident detection. For example, assume that kinetic energy threshold values will be used for incident detection. This requires the development of distribution curves showing the frequency of kinetic energy values during non-incident periods at each detector. The distribution curves represent the values of kinetic energy that would be expected to be measured on non-incident days. Threshold values of kinetic energy can then be selected that would typify incident conditions.

Figure 5 represents a cumulative frequency distribution for one-minute values of kinetic energy measured by Courage at one detector location during the peak period on the John C. Lodge Freeway in Detroit (10). Under congested freeway conditions, the one-minute energy values would be low. Likewise, the energy values would be low when incidents occur. The objective of selecting an incident detection threshold value from a distribution curve involves choosing some value that will maximize incident detection capabilities while minimizing false detections. If a kinetic energy threshold value is chosen at the 1 percentile, a 1 percent false alarm rate would then be expected. Selecting a lower threshold value would reduce the frequency of false alarms at the

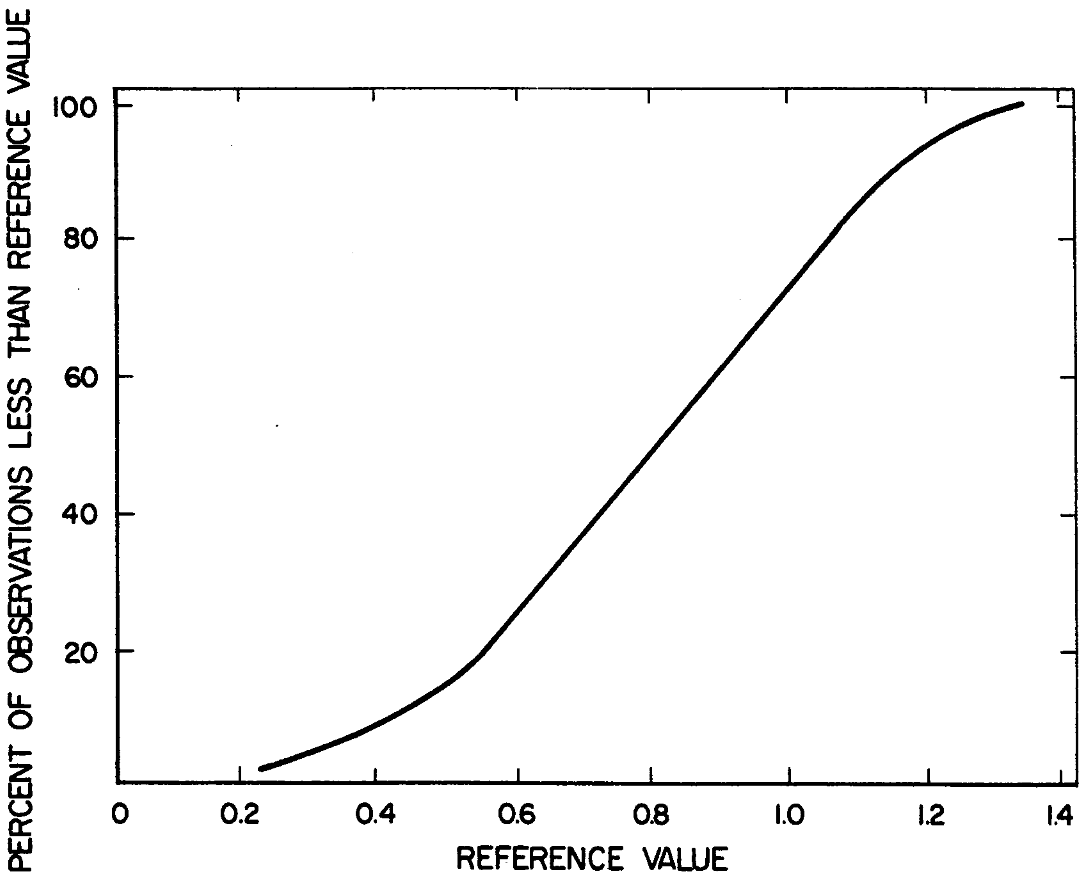


Figure 5 - Typical Cumulative Distributions for Kinetic Energy (10)

expense of reducing the number of incidents that will be detected. The threshold values cannot be made more stringent without reducing model effectiveness in terms of detecting incidents. Outwardly, a false alarm rate of one percent appears insignificant; however, it must be recognized that this rate will apply at each detector station. Thus, the total number of false alarms generated will be a multiple of the number of detector stations in the system.

Because of the hourly and daily variations in traffic flow and the effects attributed to pavement and environmental conditions, several frequency distributions would be required for each set of conditions at each freeway sensor station. It may be difficult to account for all variables involved.

Standard Normal Deviate Model

One approach to circumvent the above weaknesses is to consider the rate of change rather than a threshold value of the control variable. Experience has prompted the authors to hypothesis that a high rate of change in the control variable will be reflective of an incident situation as distinguished from a normal demand-capacity problem due to geometrics. The statistic proposed for the control function is the Standard Normal Deviate (SND) of the control variable. The concept is to evaluate the trends in the control variable (occupancy, energy, etc.) and to recognize when the variable changes rapidly in relationship to expected changes due to normal fluctuations in traffic flow.

The SND is a standardized measure of the deviation from the mean in units of the Standard Deviation and is expressed by the following relationship:

$$\mathrm{SND} = \frac{x - \bar{x}}{s} \qquad (1)$$

where

x = a given value from the data set

$\bar{x}$ = mean of data set

s = standard deviation of data set

Considering the application of SND to incident detection, the above variables take on the following meaning:

x = value of control variable at time t

$\bar{x}$ = mean of control variable over previous n sampling periods

s = standard deviation of control variable over n sampling periods

The value of SND will thus reflect the degree to which the control variable has changed during a given time interval (such as one minute) in relationship to the average trends measured during a preset number of previous intervals (such as three minutes). A large SND value would be reflective of a major change in operating conditions on the freeway.

The overall incident detection concept suggested in this research is to incorporate the incident detection algorithm with the stoppage wave detection algorithms previously developed for operation of the safety warning devices on the Gulf Freeway presented in earlier reports by Dudek, et al. (14, 15, 16). When stoppage waves are detected by the latter algorithm, each wave will be analyzed by the incident detection algorithm to ascertain whether the wave(s) resulted from a freeway incident (accident, stalled vehicle, etc., in contrast with geometric bottleneck). The model proposed is a station model that detects incidents that occur downstream of the sensor station. That is, the model reacts to discontinuities in flow propagating upstream of an incident.

Operational Approaches

Two operational approaches or strategies are identified and evaluated in this research. The first strategy only requires the present minute SND to be critical; the second strategy requires two successive SND values to be critical. These strategies are consistent with techniques developed in earlier research work on incident detection discussed in Section II of this report. Schematics of the two strategies, labeled A and B, are presented in Figure 6.

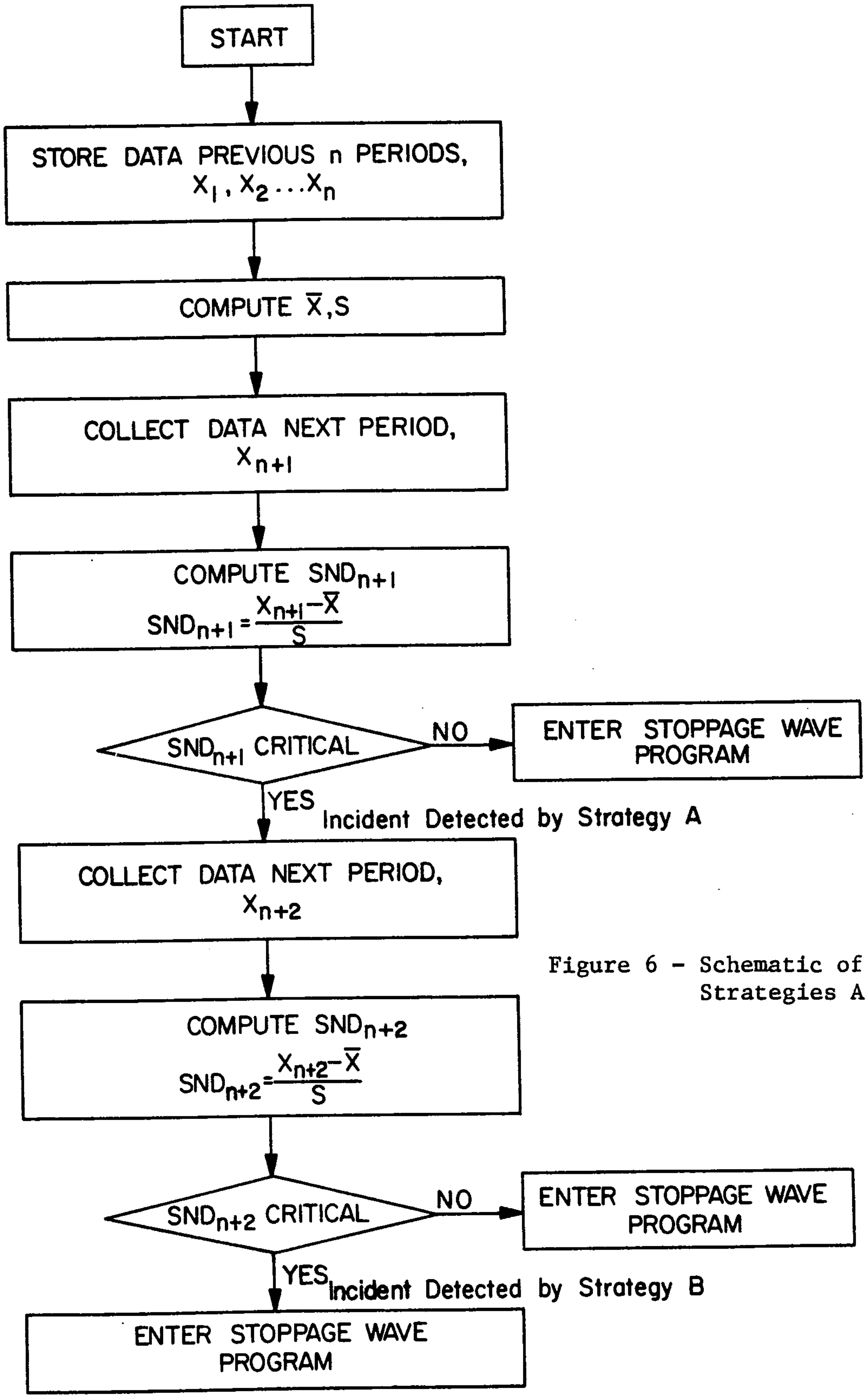


Figure 6 - Schematic of Strategies A & B

V. METHOD OF STUDY

Study Site

The SND incident detection model was tested and evaluated on the Gulf Freeway in Houston. The facility is a six-lane freeway with surveillance and control implemented in the inbound direction only. For the purposes of this study, five inbound freeway locations having double-loop sensors on each lane as illustrated in Figure 7 were used to evaluate the model.

Data Collection and Reduction

Lane occupancy and energy were evaluated as control variables. Energy was computed from volume and speed measurements. Computer programs were written to store data from the sensors at one-minute time intervals. Speed, volume, and occupancy measurements were made on each lane at all five sensor locations. Speed was computed based on the travel time of the vehicle between the lead and lag detectors.

The SND models were tested using two time bases, namely 3 and 5 minutes. The first method utilized data from the previous 3 minute sampling periods to compute the mean, $\bar{x}$, and standard deviation, s. The second method considered parameters from the previous 5 minutes. With the two strategies A and B, two variables of energy and occupancy, and two time bases, a total of 8 combinations were tested.

When an incident was observed to occur on the inbound Gulf Freeway, pertinent data concerning the characteristics of the incident were recorded in an incident log book that was kept at the surveillance center.

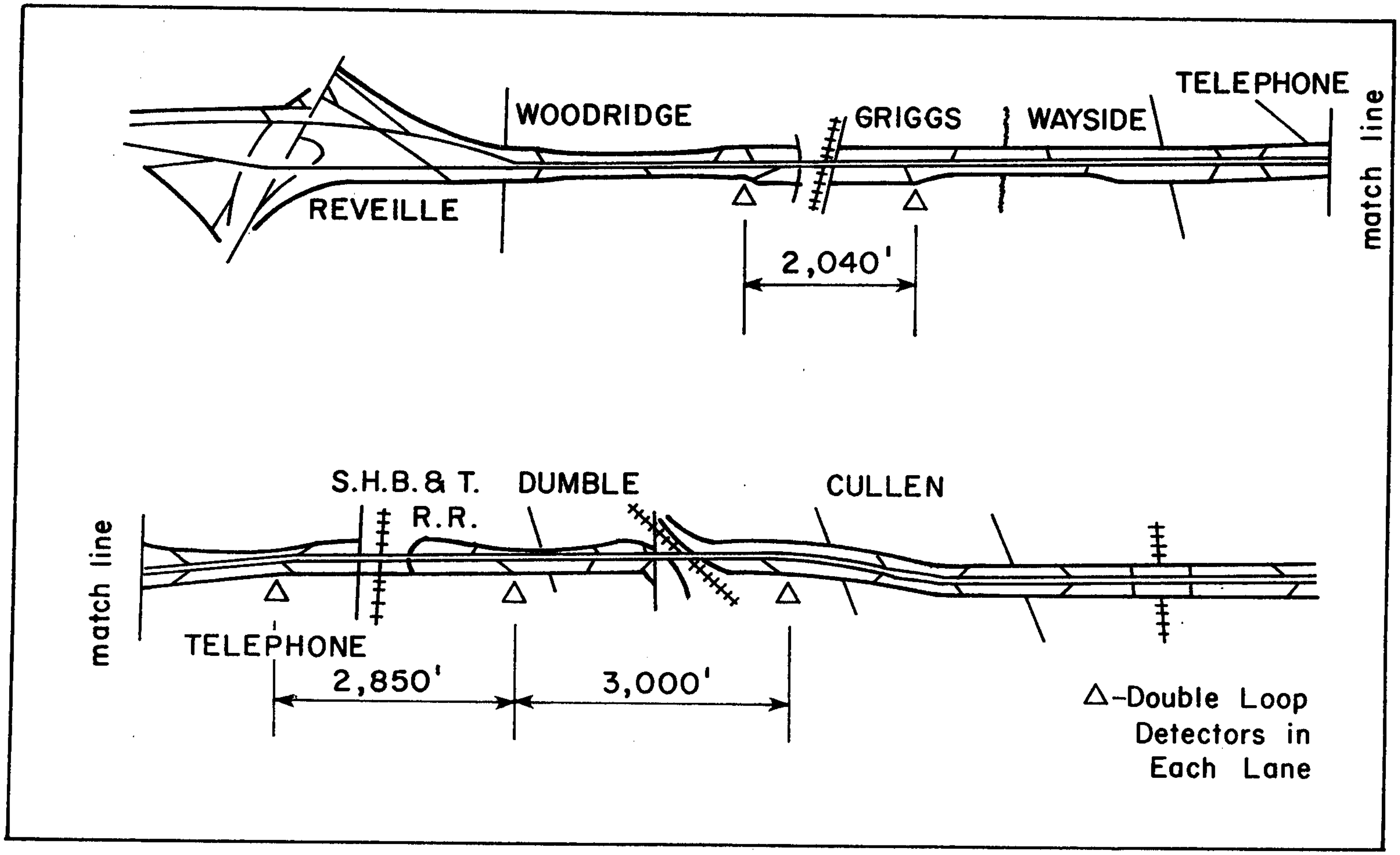


Figure 7 - Schematic - Gulf Freeway

In addition, the computer program was activated to collect data concerning the freeway characteristics. These data permitted an off-line analysis of the incident detection model.

Data were collected during 35 incidents that occurred on the inbound section of the Gulf Freeway. Three peak hour periods (7-8 a.m.) in which no incidents were observed were used for the investigation of false alarms caused by the incident detection model. The peak hours analyzed had many "slow-downs" and stoppage waves that provided a good test for the model.

The computer and incident log information were at times difficult to synchronize due to the fact that the exact moment the shock wave arrived at the detectors was difficult to determine from the data. Therefore, the exact time that the shock wave caused by the incident crossed the sensors could only be estimated. This was accomplished by using the shock wave detection program output of energy and occupancy that were used for the control of the safety warning system as described on pages 11 and 12 of this report (14, 15, 16). Since the shock wave program is predictive in nature, the estimate of the shock wave arrival time was probably earlier in most cases than the actual time.

VI. RESULTS OF SND MODEL ANALYSIS

Characteristics of Incidents Evaluated

A summary of the 35 incidents used in this study is presented in Table A-1 in the Appendix. Since the duration of an incident and the existing operating conditions on the freeway both influence the capabilities for incident detection, it was of particular interest to evaluate these characteristics of the 35 incidents. Cumulative distributions of the duration of incidents and the operating speed/free speed ratio are presented in Figures 8 and 9, respectively. The results show that 11 percent of the incidents blocked a freeway lane for a duration of 2 minutes or less. Approximately 90 percent of the incidents occurred when the freeway was operating at or below 50 mph (u/u_f = .83).

Effectiveness of SND Models on the Gulf Freeway

The effectiveness of the incident detection models can be evaluated in part by the percent of incidents detected and the frequency of false alarms. Cumulative plots of the percent of incidents detected and the percent of false alarms using strategy B with lane occupancy as the control variable with a five-minute time base is presented in Figure 10. Similar plots for the other strategies, variables, and time bases tested are presented in Figures B-1 through B-7 of the Appendix.

A study of the cumulative frequency plots indicated that there is probably an optimum SND value that can be used for each strategy. One would need to trade-off incident detection capabilities with false alarms. The authors decided that SND values producing results approaching 90 percent incident detection and 1 percent false alarms would be the critical

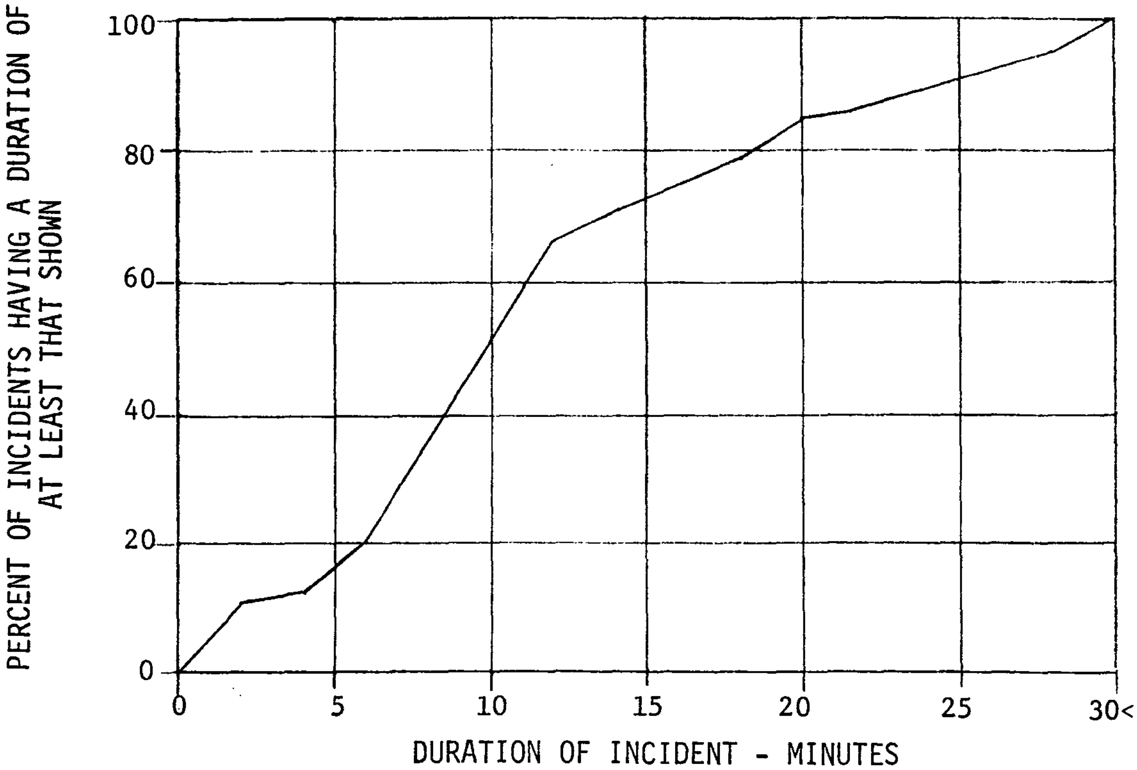


Figure 8 - Cumulative Distribution of the Duration of the Incidents Investigated

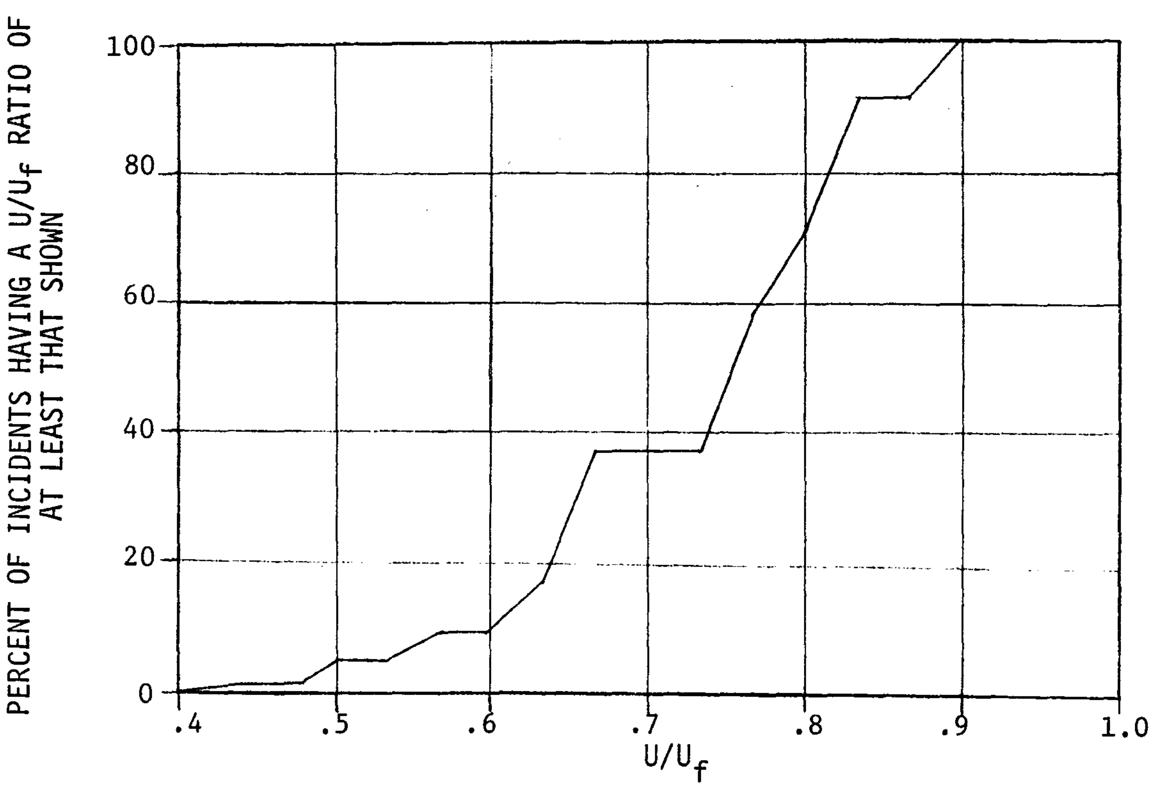


Figure 9 - Cumulative Distribution of the Ratio of u/u_f of the Incidents Investigated

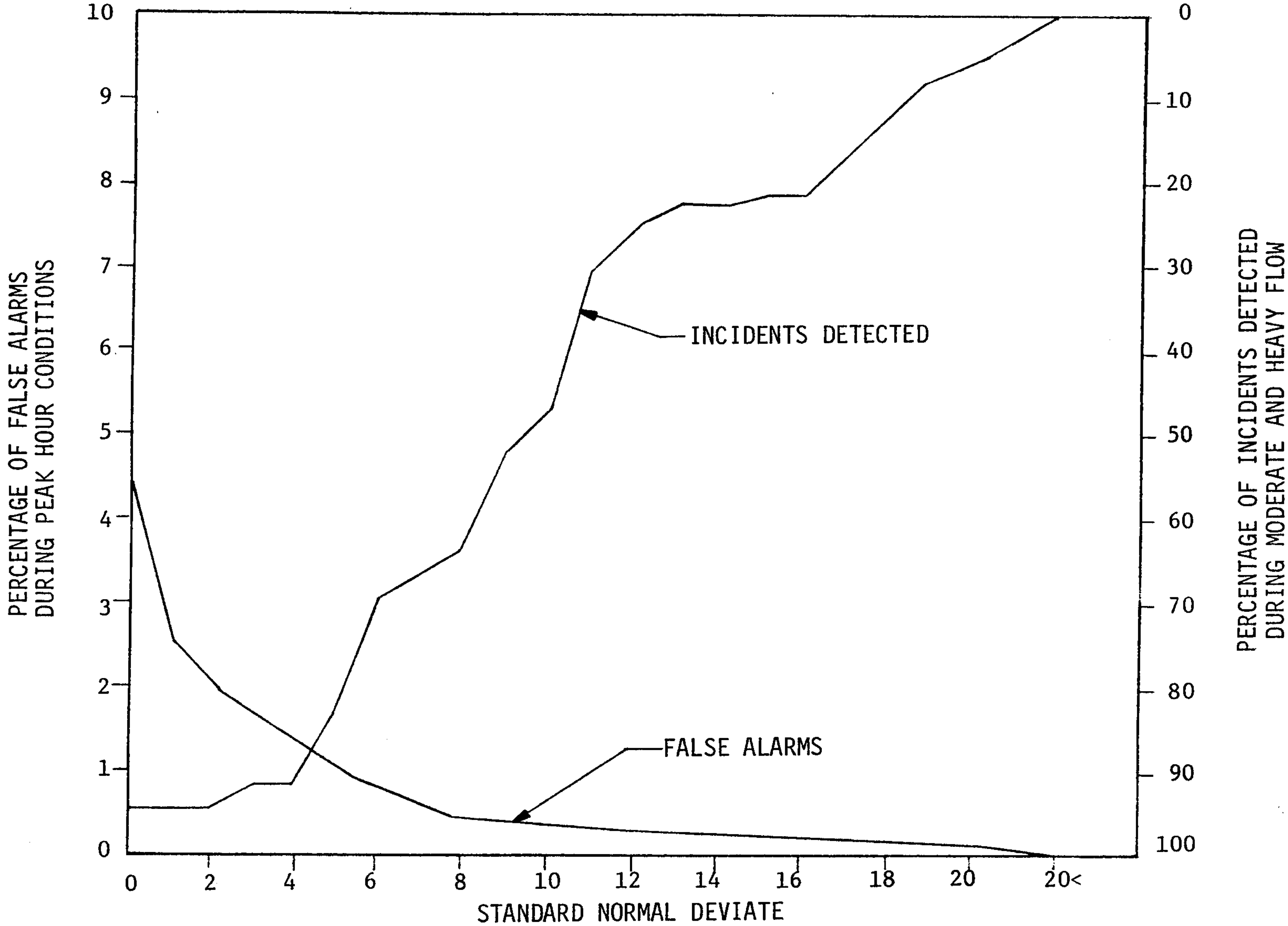


Figure 10 - Performance Curves - Lane Occupancy, Approach B, 5-Minute Time Base

SND values. Based on this selection, the performance of the strategies was evaluated and is summarized in Table 2.

Using strategy A that required only one SND value to be critical, the occupancy and energy variables both detected 86 percent of the incidents studied. The performance of the occupancy variable was considered somewhat better, however, because of the lower frequency of false alarms. Changing the time base seemed to have little effect on the performance of the variables.

Strategy B that required two successive SND values to be critical resulted in a higher percentage of incidents detected using occupancy, and a lower percentage using energy in comparison to strategy A. Both variables resulted in a lower frequency of false alarms. Changing the time base did not affect the performance of the energy variable. However, a larger time base using the occupancy variable resulted in a higher percentage of incidents detected.

A review of Table 2 shows that strategy B, using a 5-minute time base with lane occupancy as the control variable, resulted in the best performance. This approach detected 92 percent of the 35 incidents with an average computer response time of 1.1 minutes. The false alarm level during the peak period was 1.3 percent.

Two-Lane Criterion

According to television observations, a high percentage of the false alarms during the peak period using one-lane criterion were due to vehicles momentarily stopping on the freeway. These stoppages usually occurred in one lane and were influenced by trucks on steep grades and

Table 2

Effectiveness of the Detection Strategies

Strategies	Variable	Time Base (Minutes)	Critical SND Values	Average Computer Response Time (Minutes)	Standard Deviation Computer Response Time	Incidents Detected[1] (Percent)	False Alarms[2] (Percent)
A	Occupancy	5	6	0.5	1.1	86	1.7
	Occupancy	3	6	0.7	1.9	86	2.0
	Energy	5	-4	0.8	2.6	86	2.4
	Energy	3	-3	0.3	0.7	86	2.5
B	Occupancy	5	4	1.1	0.6	92	1.3
	Occupancy	3	4	1.1	1.5	89	1.4
	Energy	5	-3	1.1	0.5	83	1.4
	Energy	3	-3	1.1	0.5	83	1.4

[1]During moderate and heavy flow conditions (750-1800 vph per lane)

[2]During peak periods

vehicles forcing their way into the traffic stream from unmetered ramps. A two-lane detection criterion was therefore considered as an approach to reduce the percent of false alarms. The two-lane criterion would require that two of the three lanes simultaneously register the presence of an incident. The approach selected utilized strategy B with a 5-minute time base and occupancy as the control variable. The results are shown in Figure 11.

The results indicate that the two-lane criterion would not be an improvement because the benefit of fewer false alarms was more than negated by the smaller number of incidents detected. The two-lane criterion resulted in a reduction in the percentage of false alarms from 1.3 percent for the one-lane criterion to 1.0 percent for the two-lane criterion. The percentage of incidents detected for the occupancy control variable was reduced from 92 percent to 45 percent.

Two-Station Criterion

A two-station criterion was another approach evaluated to reduce the frequency of false alarms during the peak period. This approach flags the incident when the SND is critical at one sensor station and confirms the incident if the SND becomes critical at the next upstream station a short time period later. The time lag associated with detection at the next upstream station will be related to the anticipated speed of the shock wave.

An analysis of data collected during three peak periods of non-incident conditions revealed that this approach would reduce the frequency

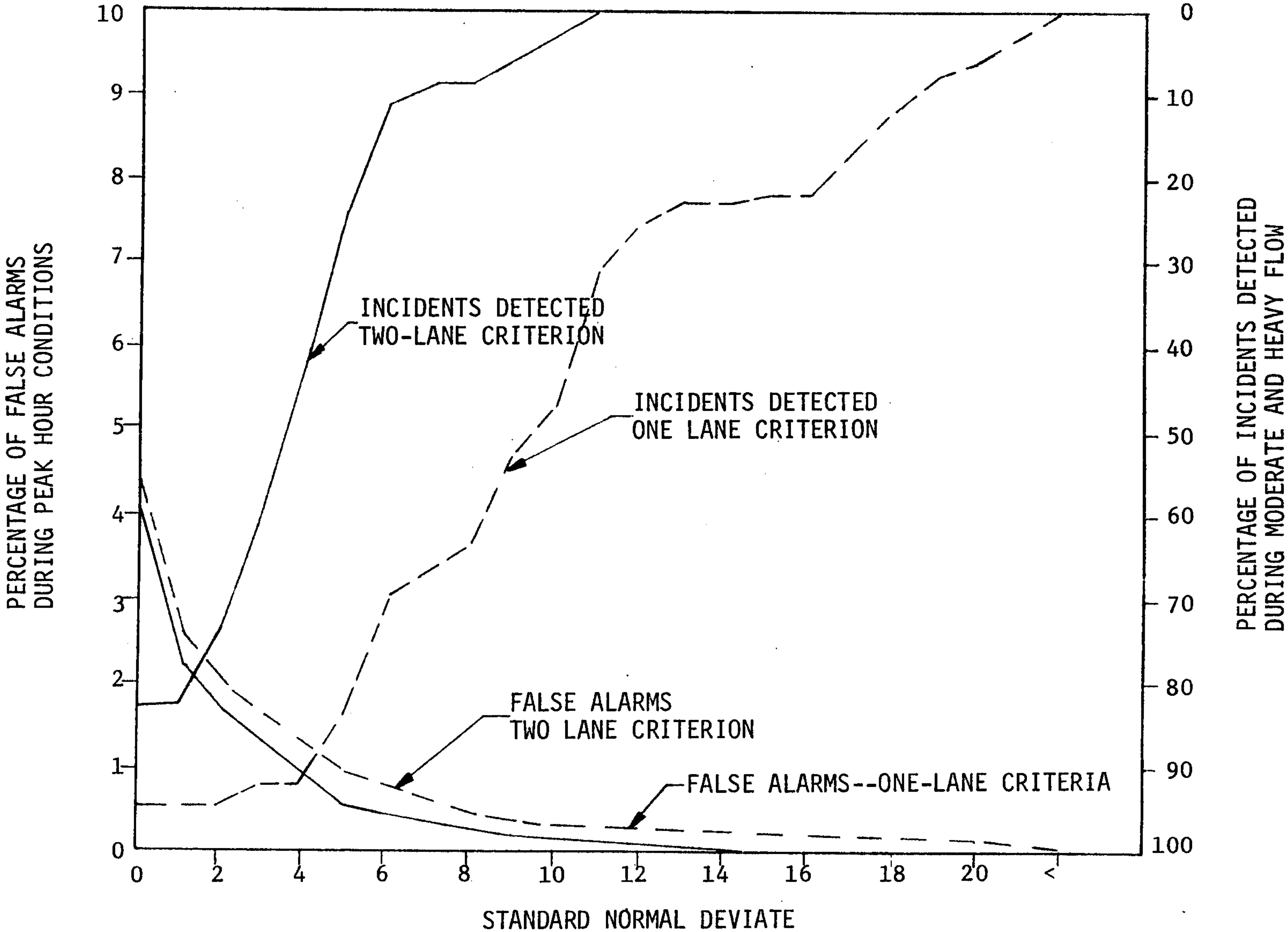


Figure 11 - Performance Curves - One-Lane vs. Two-Lane Criterion
Lane Occupancy, Strategy B, 5-Minute Time Base

of false alarms from 1.3 percent to 0.2 percent per sensor station. The reduction in false alarms is accompanied by an increase in incident detection time for a given sensor spacing because of the added delay associated with the movement of the shock wave to the second sensor station.

The added delay, may not be all that critical to effect proper response in the form of control or dispatching assistance. Shock waves travel very fast during the peak periods because of the approaching demand. On the Gulf Freeway, as an example, shock waves could conceivably travel upstream more than 1,000 feet in one minute when a lane is blocked during the peak period. In addition, the incident detection and control algorithms would need to provide assurance that an incident is of significant proportion before traffic is diverted or assistance vehicles are dispatched. Since false alarms are generated only during the peak periods, a single-station approach could be used for incident detection during the off peak.

Comparison of the SND Model to Other Detection Models

It was of interest to compare the SND model to the existing incident detection models to evaluate their relative performances. It is not appropriate to use the results reported in the literature directly because the conditions are different than those on the Gulf Freeway. In particular, the sensor spacings and the relative location of the incidents to the sensors do not compare with the Gulf Freeway data. The conditions must be the same to permit a fair comparison. Unfortunately, during the early stages of the research reported herein, sufficient data were not collected for the other models. As of this writing, data for only 26 incidents were available for proper comparison. Therefore, the results shown in this section should be considered as provisional and not necessarily conclusive.

So that a good comparison could be realized, distribution curves, similar to those discussed by Courage and Levin (10) and Cook and Cleveland (13) were developed at each sensor at the five sensor stations on the Gulf Freeway for the most effective models reported in the literature. These distribution curves permitted the authors to select critical values that would result in approximately the same percentage of false alarms for each model. The percent of incidents detected were then determined using these critical values.

A comparison of the SND model to the existing incident detection models is presented in Table 3. The results indicate that the SND model is as effective as the Composite model. The SND and Composite models detected 26 and 25 incidents while operating at a 1 percent level of false alarms during the peak period. The Station Discontinuity and Subsystem Discontinuity models detected 22 and 23 incidents while operating at a 1 percent level of false alarms during the peak period. Since the SND model does not require separate distribution curves for various traffic conditions, it appears that it may be a more attractive model for an operational system.

Table 3

Comparison of Incident Detection Models

Model	Control Variable	False Alarms Per Station (Percent)	False Alarms Per Subsystem (Percent)	Number of Incidents Detected*
Station Discontinuity	Energy	1	--	22
Subsystem Discontinuity	Energy	--	1	23
Composite	Energy	0.5	0.5	25
SND, Strategy B, 5-Minute Time Base	Occupancy	1	--	26

*Based on 26 observed incidents

Summary and Discussion of Results

The results indicated that the 5-minute occupancy SND model using strategy B (two successive SND values must be critical) produced the best results of the strategies and variables tested. The model detected 92 percent of the 35 incidents that occurred during moderate and heavy flow, and operated with 1.3 percent false alarms during the peak period on the Gulf Freeway system. Although the control parameter could be changed to detect a higher percentage of incidents on the existing system, the desire for this capability would be at the expense of a higher frequency of false alarms. The peak period false alarm rate can be reduced to 0.2 percent by utilizing a two-station control criterion.

The failure by the model to detect all the incidents could conceivably be caused from one or a combination of the following: 1) failure in the model logic, 2) very short duration of an incident, 3) sensor spacing and 4) a high operating speed prior to an incident. The SND model is dependent on the passage of a shock wave over a set of sensors. If the "shock wave" passes over the sensors, its effect must be noticeable. As discussed in earlier sections of this paper, the duration of the incident, the sensor spacing, and the normal operating speed of the freeway prior to the occurrence of the incident effect the passage of the shock wave over the sensors.

An analysis of the data (Table A-2) revealed that, of the three incidents missed by the 5-minute occupancy SND model, one incident blocked the freeway for only two minutes. The relative location of the incident to the upstream detectors could have been a factor in the lack of detection. The other two incidents that were missed occurred when the operating speeds were 48 and 53 mph, respectively. The relative degree of queueing was lessened which may have contributed to the model's failure. It is questionable, therefore, whether the model itself was to blame.

It is important to re-emphasize that the efficiency of the strategies using the SND model evaluated in this paper apply to the Gulf Freeway with the given sensor spacings shown in Figure 5. It is the opinion of the authors that the 5-minute occupancy model is capable of detecting close to 100 percent of the incidents of say 2-minute duration or more during moderate and heavy flow if the sensor spacing was adequate.

The authors wish to re-emphasize that the inability of the SND and other incident detection models to detect all the incidents is not necessarily a reflection of the individual model inadequacies. The duration of an incident, the sensor spacing, and the relative location of the incident to the sensors, and the operating conditions immediately prior to the occurrence of the incident are all important factors that affect the capabilities of any incident detection model. Therefore, the results of incident detection model capabilities reported in the literature must be placed in proper perspective.

It is the belief of the authors that with proper sensor spacing, it is possible to approach 100 percent detection of incidents blocking a freeway lane for a duration equal to or greater than a preselected time during moderate or heavy flow.

VII. FINDINGS

General

This report was concerned with the development of an automatic incident detection model for freeway incidents that occur during moderate and heavy flow. A Standard Normal Deviate (SND) model was proposed as a method for eliminating some of the weaknesses of existing incident detection models. Two strategies were tested and evaluated using a 3-minute and a 5-minute time base with both energy and lane occupancy as control variables. The performance of the SND model was also compared with the existing incident detection models. An approach to determine sensor spacing requirements for an incident detection system was developed for systems using a station model. The significant findings of the research reported herein are listed in the following section.

Findings

1. A theoretical analysis of shock waves resulting from incidents revealed that sensor spacing requirements for an incident detection system are related to the following factors: 1) duration of incident, 2) operating characteristics of the freeway prior to the incident, 3) normal capacity of the freeway, 4) capacity of the bottleneck section caused by the incident, 5) the computer response time of the detection algorithm--the difference in time between the arrival of the shock wave at the upstream sensor station and the recognition of the incident by the computer algorithm, and 6) the required incident detection time.

2. Of the six combinations of strategy, time base, and control

variable tested, the 5-minute lane occupancy SND model using strategy B produced the best results based on the 35 incidents evaluated. Strategy B required two successive SND values to be critical before an incident was signaled by the computer algorithm. This model detected 92 percent of the incidents studied during moderate and heavy flow (750-1800 vph per lane), operated at a false alarm level of 1.3 percent during the peak period, and had a computer response time of 1.0 minute.

3. The incident detection capabilities of the SND model in item 2 above were limited by several external factors, and the fact that 100 percent of the incidents studied were not detected is not attributed to weaknesses in the model. The following factors limited the detection capabilities of the models studied: 1) short duration of incident, 2) high operating speed, thus low density, prior to the incident, and 3) large spacings between detectors on the Gulf Freeway. It is the observation of the authors that 100 percent detection capabilities during moderate and heavy flow conditions can be approached with adequate sensor spacing.

4. One problem associated with automatic incident detection during moderate and heavy flow conditions appear to be related to the high rate of false alarms generated during the peak periods of flow. The 1.3 percent false alarms for the model in item 2 applies to each sensor station. The number of false alarms are thus related to the number of sensor stations in the incident detection system.

5. A two-lane detection criterion that required two lanes to be critical, was incorporated in the SND logic as an approach to reduce

the number of false alarms. The results revealed that the percent false alarms were reduced only slightly at the expense of the decrease in the percent of incidents detected.

6. Application of a two-station control criterion that required two sensor stations upstream of the incident to register critical SND values, reduced the peak period false alarm rate from 1.3 to 0.2 percent.

7. A comparison of the SND model with existing incident detection models based on a limited sample size (26 incidents) revealed that the 5-minute SND model using strategy B and lane occupancy as the control variable performs as well as the Composite model which was considered to be the best of existing models. From an operational standpoint, the SND model may be more practical.

VIII. REFERENCES

1. Messer, C. J., Dudek, C. L., and Loutzenheiser, R. C., "A Systems Analysis for a Real-Time Freeway Traffic Information System for the Inbound Gulf Freeway," Texas Transportation Institute, Research Report 139-5, April 1971.

2. Goolsby, M. E., "Influence of Incidents on Freeway Quality of Service," Highway Research Record No. 349, 1971.

3. Goolsby, M. E., and McCasland, W. R., "Evaluation of an Emergency Call Box System," Texas Transportation Institute, Research Report 132-1F, December 1969.

4. DeRose, F., Jr., "An Analysis of Random Freeway Traffic Accidents and Vehicle Disabilities," Highway Research Record No. 59, 1964.

5. Kuprijanow, A., Rosenzweig, S., and Warskow, M. A., "Motorists' Needs and Services on Interstate Highways," NCHRP Report 64, 1969.

6. Shufflebarger, C. L., and Bergsman, S. E., "Shoulder Usage on an Urban Freeway," John C. Lodge Freeway Traffic Surveillance and Control Research Report, Study 417, January 1962.

7. Lynch, F. L., and Keese, C. J., "Restoring Freeway Operation After Traffic Accidents," Texas Transportation Institute, Bulletin No. 28, Undated.

8. Moskowitz, K., "Analysis and Projection of Research on Traffic Surveillance, Communication, and Control," NCHRP Report No. 84, 1970.

9. West, J., "Proposed Real-Time Surveillance and Control System for Los Angeles," Paper presented to the Freeway Operations Committee, Highway Research Board, Los Angeles, California, August 1969.

10. Courage, K. G., and Levin, M., "A Freeway Corridor Surveillance Information and Control System," Texas Transportation Institute, Research Report 488-8, December 1968.

11. Schaefer, W. E., "California Freeway Surveillance System," California Division of Highways, Department of Public Works, November 1969.

12. Whitson, R. H., Buhr, J. H., Drew, D. R., and McCasland, W. R., "Real-Time Evaluation of Freeway Quality of Traffic Service," Highway Research Record No. 289, 1969.

13. Cook, A. R., and Cleveland, D. E., "The Detection of Freeway Capacity Reducing Incidents by Traffic Stream Measurements," NCHRP Contract 20-3A, HSRI Preliminary Report No. TrS-1, 1970.

14. Dudek, C. L., "Development of a Technique for Digital Computer Control of a Safety Warning System for Urban Freeways," Texas Transportation Institute, Research Report 165-5, May 1972.

15. Dudek, C. L., Messer, C. J., and Friebele, J. D., "Investigation of Lane Occupancy as a Control Variable for a Safety Warning System for Urban Freeways," Texas Transportation Institute, Preliminary Research Report 165-6, March 1973.

16. Dudek, C. L., and Messer, C. J., "Detecting Stoppage Waves for Freeway Control," Highway Research Record No. 469, 1973.

17. Messer, C. J. and Dudek, C. L., "Development of a Model for Predicting Travel Time on an Urban Freeway," Texas Transportation Institute Research Report 165-8, January 1974.

APPENDIX A

Table A-1

SUMMARY OF INCIDENTS EVALUATED

Incident Number	Location Detected	Date	Time	Incident Duration Minutes	Normal Operating Speed
1	Cullen	3-31-72	9:42	2	50
2	Cullen	5-10-72	8:08	27	38
3	Cullen	5-26-72	9:09	14	53
4	Griggs	6-2-72	6:44	2	38
5	Dumble	6-13-72	7:19	25	40
6	Griggs	6-13-72	7:31	2	39
7	Dumble	6-13-72	16:17	13	50
8	Cullen	8-4-72	16:19	20	50
9	Griggs	8-17-72	7:51	9	30
10	Mossrose	8-18-72	16:50	14	45
11	Griggs	8-22-72	6:54	8	45
12	Cullen	8-22-72	16:42	60	48
13	Cullen	8-23-72	10:40	9	48
14	Griggs	8-23-72	11:16	10	45
15	Dumble	8-24-72	14:26	5	50
16	Lombardy	8-24-72	15:03	7	50
17	Dumble	8-28-72	7:35	2	40
18	Griggs	8-29-72	15:53	11	45
19	Lombardy	9-14-72	9:30	6	50
20	Dumble	9-14-72	11:10	12	49
21	Lombardy	9-22-72	11:33	9	53
22	Griggs	10-6-72	16:08	24	40
23	Dumble	10-13-72	12:12	9	53
24	Dumble	10-16-72	9:36	15	48
25	Lombardy	10-19-72	7:30	17	40
26	Cullen	10-27-72	8:02	20	40
27	Lombardy	10-31-72	8:46	8	39

Table A-1 (Cont.)

SUMMARY OF INCIDENTS EVALUATED

Incident Number	Location Detected	Date	Time	Incident Duration Minutes	Normal Operating Speed
28	Dumble	10-31-72	15:39	6	45
29	Griggs	11-1-72	6:58	4	40
30	Cullen	11-3-72	7:49	8	25
31	Lombardy	11-6-72	9:04	20	33
32	Griggs	11-14-72	6:41	8	45
33	Lombardy	11-14-72	16:40	12	48
34	Griggs	12-1-72	16:01	12	48
35	Cullen	12-8-72	15:46	9	45

Table A-2

SUMMARY OF THE SND MODEL'S EFFECTIVENESS IN DETECTING INCIDENTS

Location Detected	Incident Number	Incident Duration (Minutes)	Normal Operating Speed (mph)	Strategy A Occupancy 5	Strategy A Occupancy 3	Strategy A Energy 5	Strategy A Energy 3	Strategy B Occupancy 5	Strategy B Occupancy 3	Strategy B Energy 5	Strategy B Energy 3
Mossrose	10	14	45	*	*			*	*		
Griggs	4	2	38	*	*	*	*	*	*	*	*
"	6	2	39			*	*				
"	9	9	30	*	*	*	*	*	*	*	*
"	11	8	45	*	*	*	*	*	*	*	*
"	14	10	45	*	*	*	*	*	*	*	*
"	18	11	45	*	*	*	*	*	*	*	*
"	22	24	40	*	*	*	*	*	*	*	*
"	29	4	40	*	*	*	*	*	*	*	*
"	32	8	45	*	*	*	*	*	*	*	*
"	34	12	48	*	*	*	*	*	*	*	*
Lombardy	16	7	50	*	*	*	*	*	*	*	*
"	19	6	50	*	*	*	*	*	*	*	*
"	21	9	53	*	*	*	*	*	*	*	*
"	25	17	40	*	*	*	*	*	*	*	*
"	27	8	39	*	*	*	*	*	*	*	*
"	31	20	33	*	*	*	*	*	*	*	*
"	33	12	48	*	*	*	*	*	*	*	*

Table A-2 (Continued)

SUMMARY OF THE SND MODEL'S EFFECTIVENESS IN DETECTING INCIDENTS

Location Detected	Incident Number	Incident Duration (Minutes)	Normal Operating Speed (mph)	Strategy A Occupancy 5	Strategy A Occupancy 3	Strategy A Energy 5	Strategy A Energy 3	Strategy B Occupancy 5	Strategy B Occupancy 3	Strategy B Energy 5	Strategy B Energy 3
Dumble	5	25	40	*	*	*	*	*	*	*	*
"	7	13	50	*	*	*	*	*	*	*	*
"	15	5	50	*	*	*	*	*	*	*	*
"	17	2	40	*	*			*	*	*	*
"	20	12	49	*	*			*	*		
"	23	9	53			*	*				
"	24	15	48			*	*				
"	28	6	45	*	*	*	*	*	*	*	*
Cullen	1	2	50	*	*	*	*	*	*	*	*
"	2	27	38	*	*	*	*	*	*	*	*
"	3	14	53	*	*	*	*	*	*	*	*
"	8	20	50	*	*			*	*		
"	12	60	48	*	*	*	*	*	*	*	*
"	13	9	48					*			
"	26	20	40	*	*	*	*	*	*	*	*
"	30	8	25			*	*	*	*	*	*
"	35	9	45	*	*	*	*	*	*	*	*

* Incident was detected

APPENDIX B

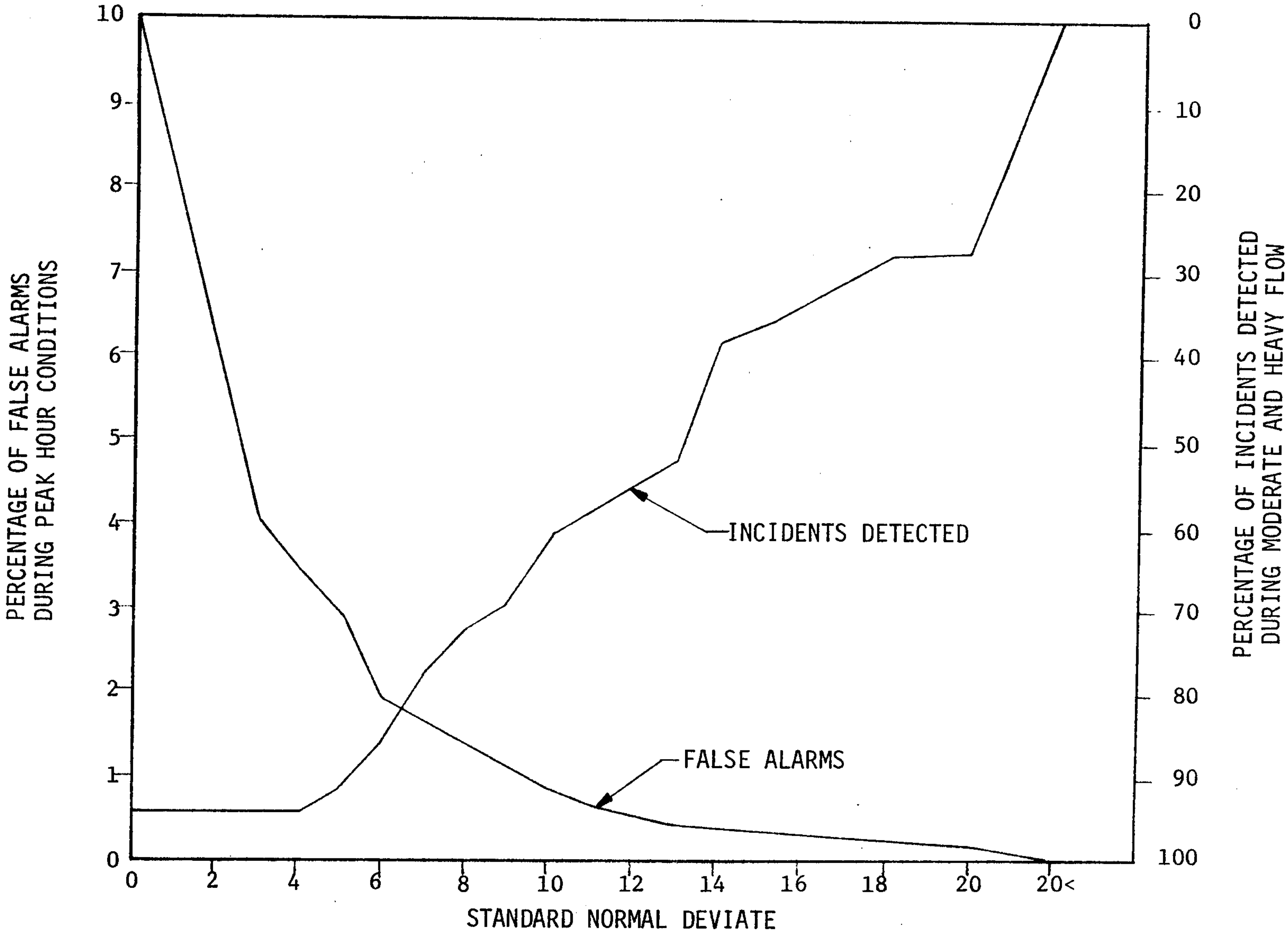


Figure B-1 - Performance Curves - Lane Occupancy, Strategy A, 3-Minute Time Base

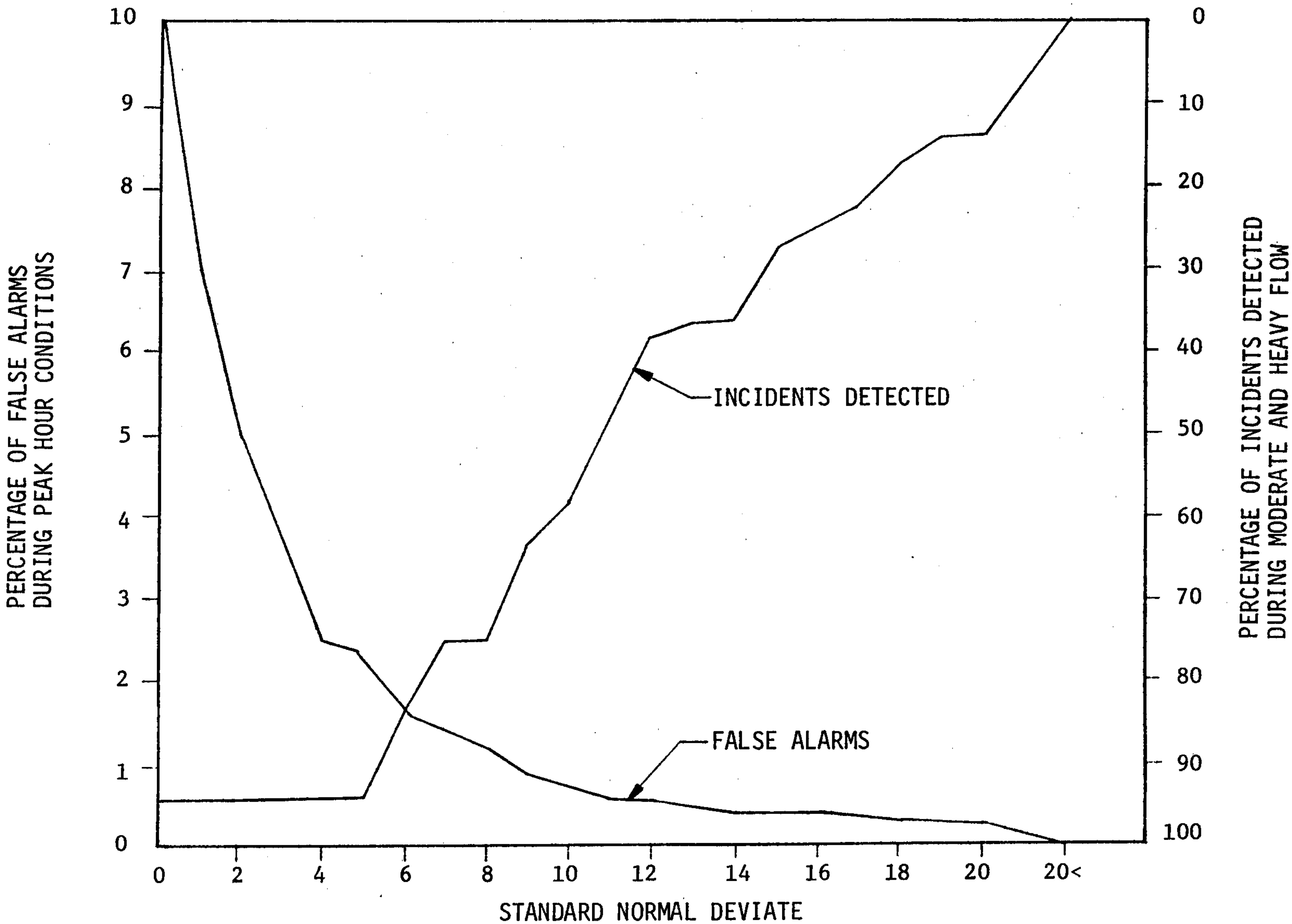


Figure B-2 - Performance Curves - Lane Occupancy, Strategy A, 5-Minute Time Base

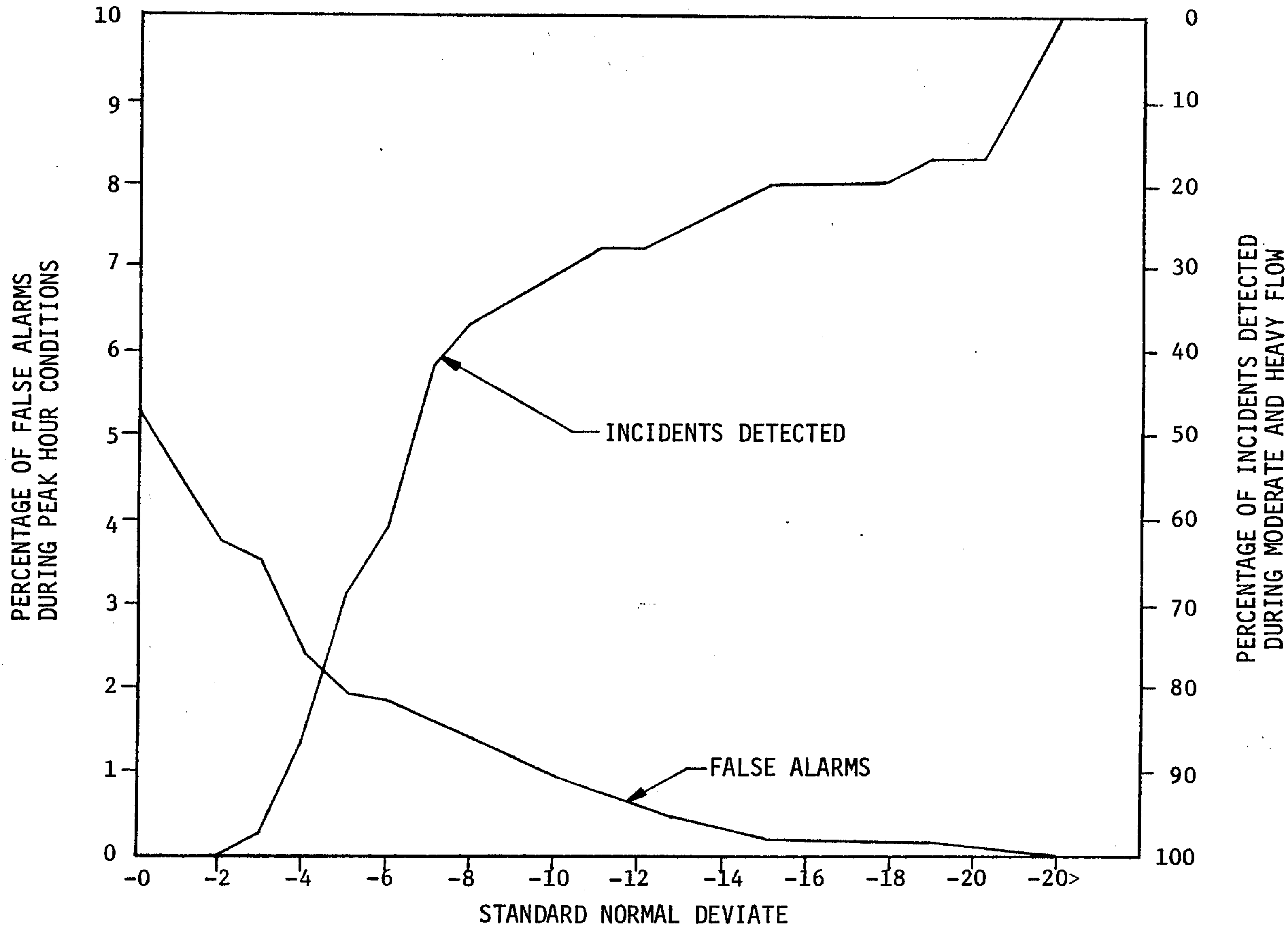


Figure B-3 - Performance Curves - Energy,
Strategy A, 3-Minute Time Base

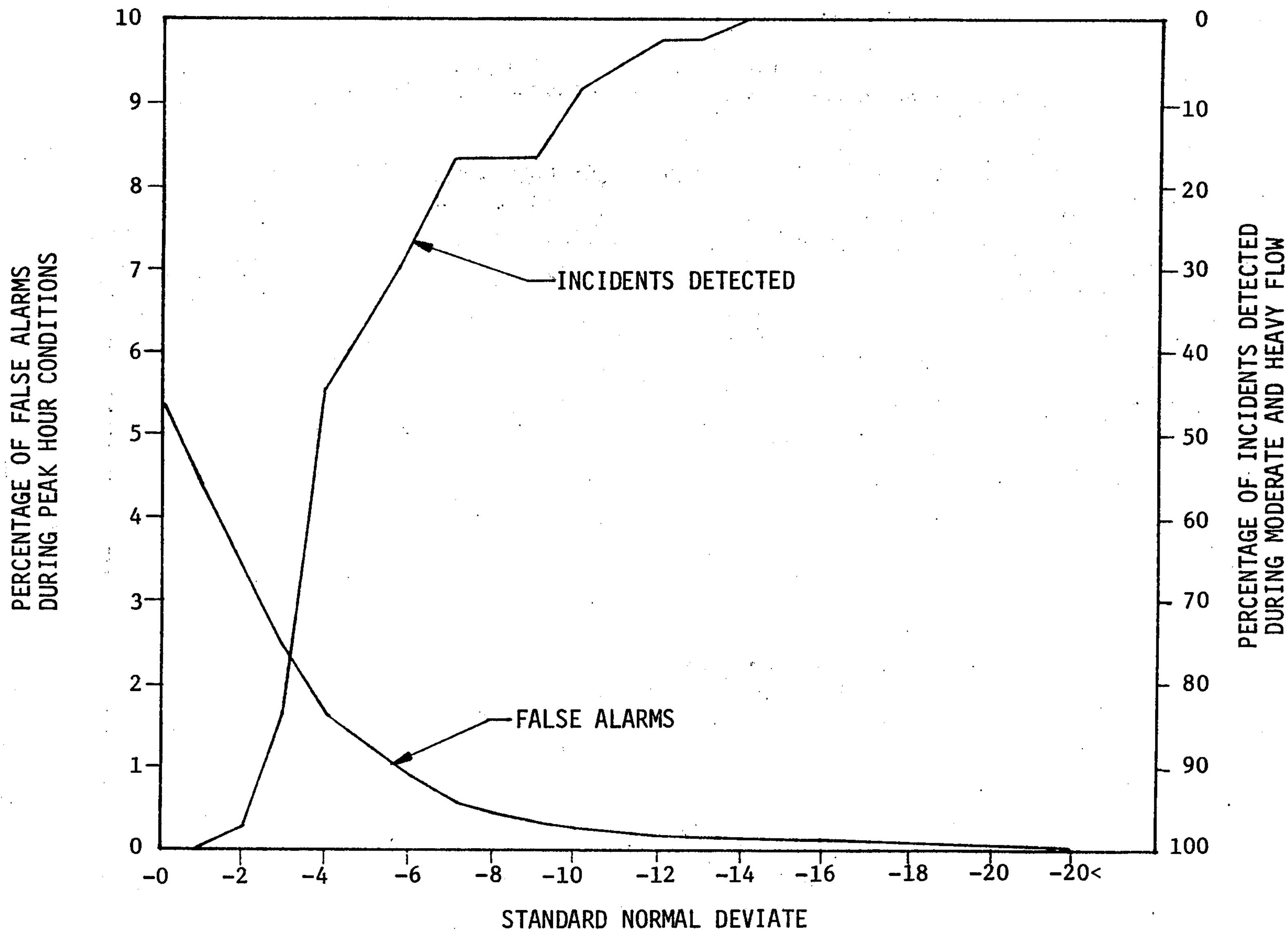


Figure B-4 - Performance Curves - Energy, Strategy A, 5-Minute Time Base

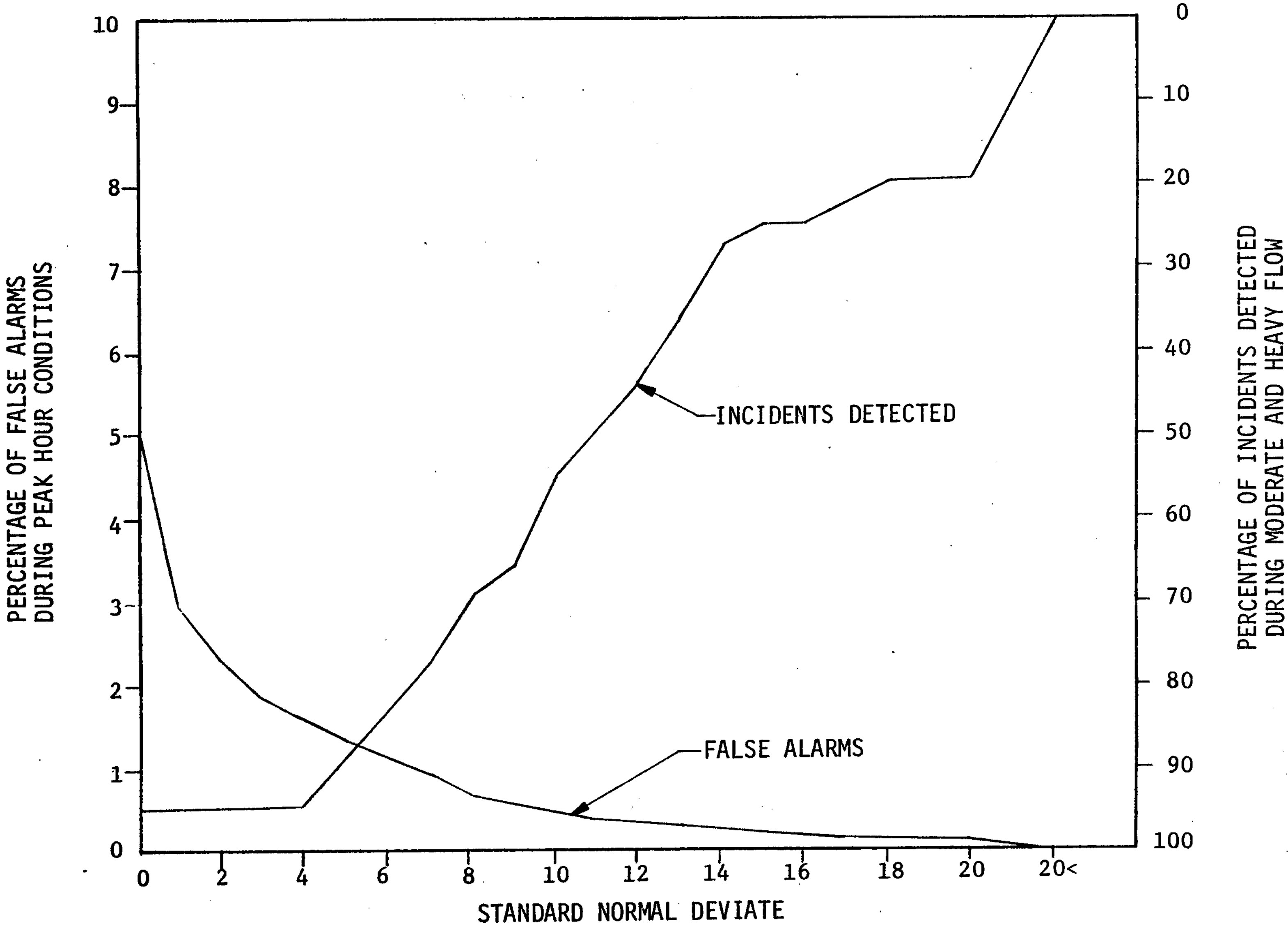


Figure B-5 - Performance Curves - Lane Occupancy, Strategy B, 3-Minute Time Base

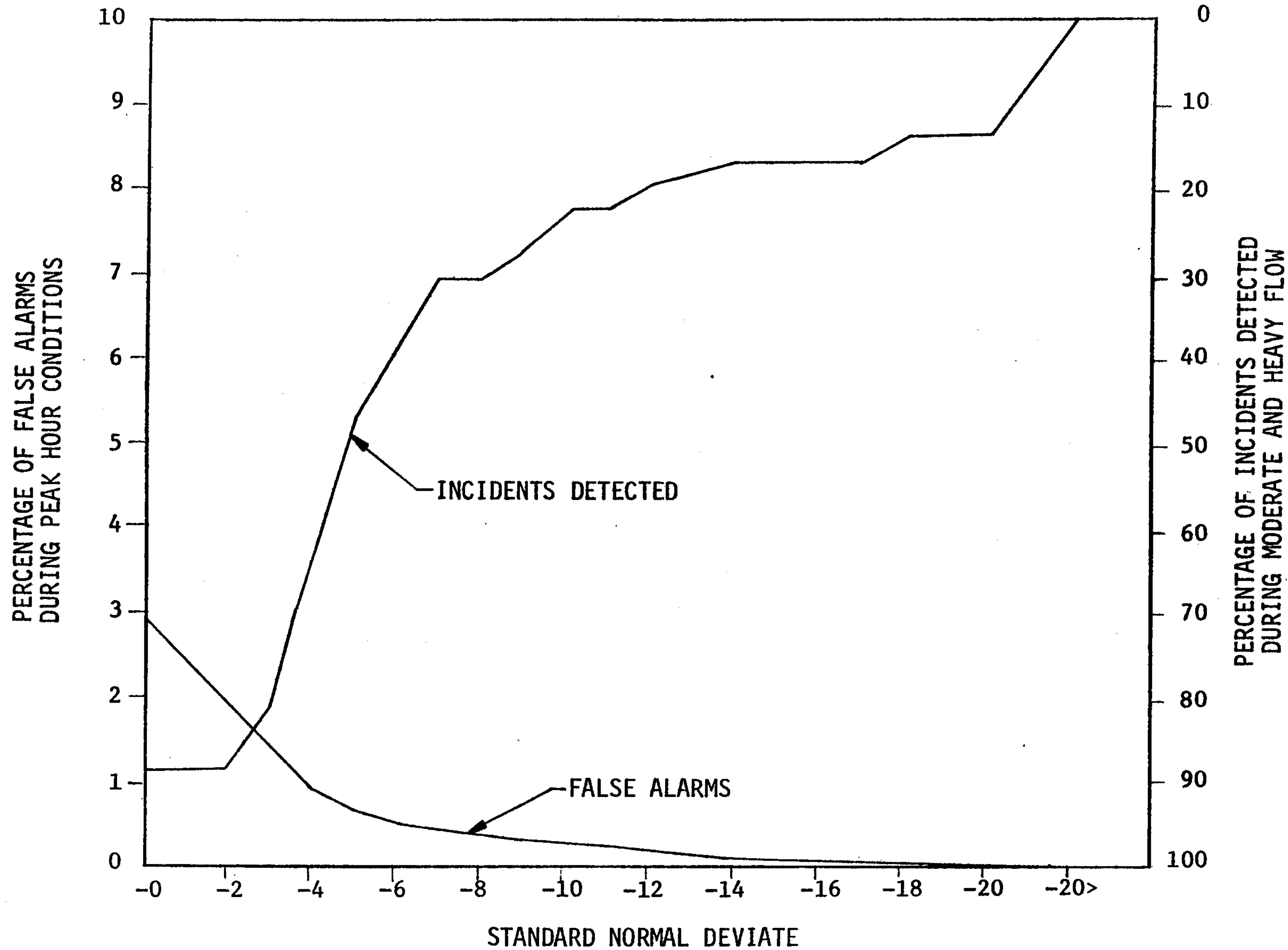


Figure B-6 - Performance Curves - Energy,
Strategy B, 3-Minute Time Base

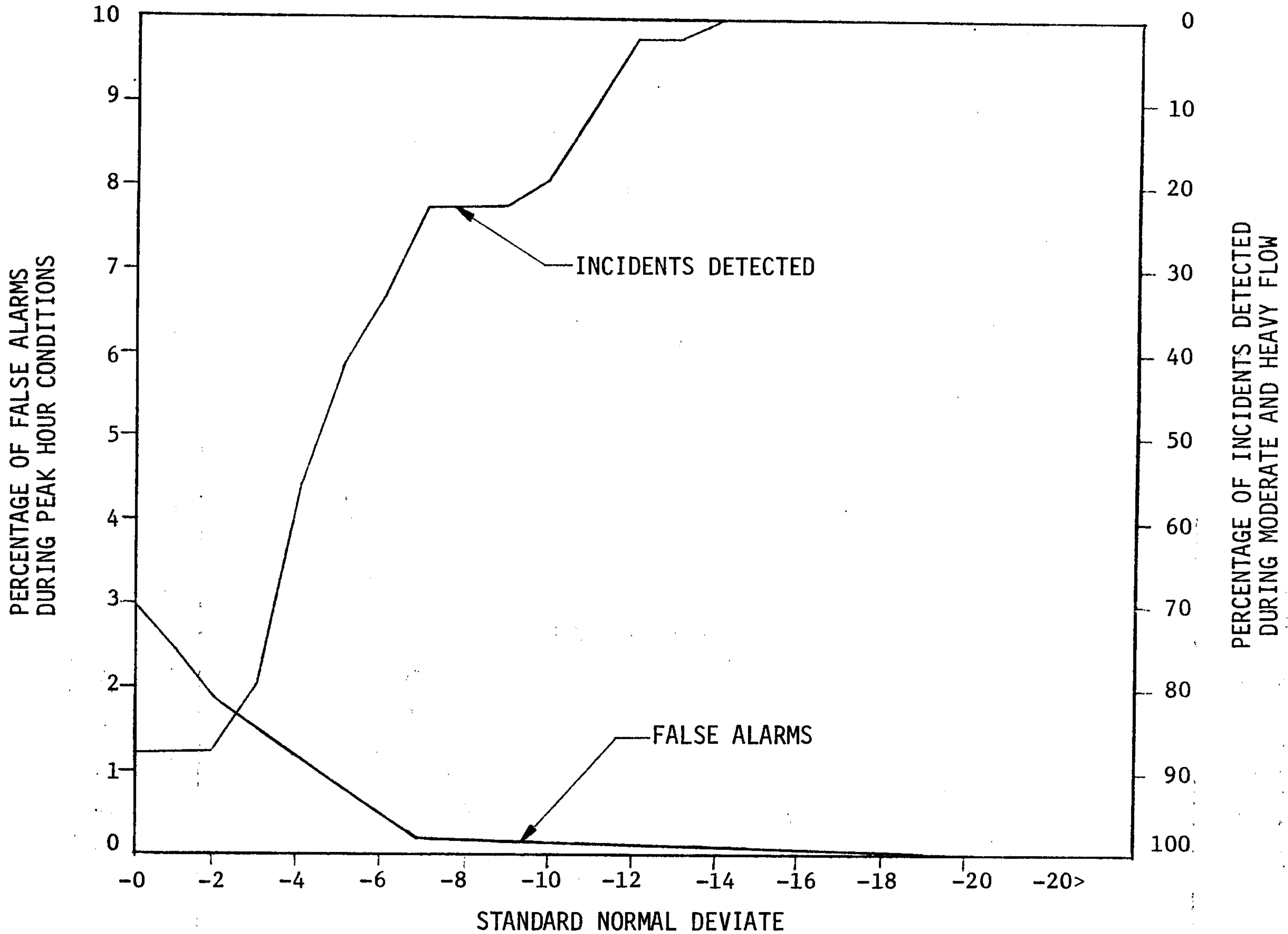


Figure B-7 - Performance Curves - Energy,
Strategy B, 5-Minute Time Base

APPENDIX C

```
C TTI PROGRAM TO DETERMINE MAXIMUM SENSOR SPACINGS FOR AUTOMATIC FREEWAY
C     INCIDENT DETECTION DURING MEDIUM AND HEAVY FLOW
C
C AN INCIDENT IS DEFINED AS ANY FREEWAY OBSTACLE THAT BLOCKS ONE OR MORE
C     LANES
C
C THIS PROGRAM ASSUMES THAT LANE BLOCKING INCIDENTS OCCUR RANDOMLY AND
C     UNIFORMLY ON THE FREEWAY SECTION
C
C THIS PROGRAM ASSUMES THAT THE INCIDENT DETECTION ALGORITHM DEVELOPED BY
C     TTI WILL BE USED. (COMPUTER RESPONSE TIME = 1.1 MINUTES)
C
C PROGRAM  COMPUTES MAX SENSOR SPACINGS FOR 100, 75, 50, 25 PCT INCIDENT DETECT.
C
C FRESPD = FREE SPEED (MPH)
C ANCAP  = NORMAL CAPACITY (VPH)
C AICAP  = INCIDENT CAPACITY (VPH)
C DURINC = MINIMUM DURATION OF INCIDENTS THAT MUST BE DETECTED (MINUTES)
C WAVEU1 = SPEED OF SHOCK WAVE MOVING UPSTREAM WHEN INCIDENT OCCURS (MPH)
C WAVEUZ = SPEED OF CLEARING WAVE MOVING UPSTREAM WHEN INCIDENT IS REMOVED (MPH)
C OPSPD  = OPERATING SPEED PRIOR TO INCIDENT (MPH)
C QSPD   = SPEED IN QUEUE (MPH)
C COMPRT = COMPUTER RESPONSE TIME (MINUTES)
C DETTM = MAXIMUM REQUIRED INCIDENT DETECTION TIME (MINUTES)
C SWTM   = SHOCK WAVE TRAVEL TIME AFTER INCIDENT (MINUTES)
C
      DIMENSION OPSPD(8)
      DIMENSION DETTM(5)
      DIMENSION DURINC(2)
C READ DATA : MAX. OPERATING SPEED AT WHICH INCIDENTS SHOULD BE DETECTED
C             REQD. INCIDENT DETECTION TIME
C             MINIMUM DURATION OF INCIDENTS THAT MUST BE DETECTED
      READ(5,80) OPSPD
      READ(5,81) DETTM
      READ(5,82) DURINC
C READ SPECIFIC FREEWAY CHARACTERISTICS
      READ(5,83) FRESPD, AICAP, ANCAP
C NEXT CARD IDENTIFIES THE COMPUTER ALGORITHM RESPONSE TIME (TIME DIFFERENCE
C     BETWEEN WHEN THE ALGORITHM DETECTS THE INCIDENT AND WHEN THE SHOCK WAVE
C     PASSES OVER THE SENSOR)
      COMPRT = 1.1
C INITIALIZE AND COMPUTE CONSTANTS
      Z = 0.0
      QSPD = (FRESPD/2) * (1-SQRT(1-(AICAP/ANCAP)))
      WAVEUZ = -(FRESPD/2) + QSPD
C DO LOOP TO CONSIDER UP TO TWO VALUES FOR MIN. DURATION OF INCIDENT
      DO 100 K=1,2
      IF(DURINC(K) .EQ. Z) GO TO 30
C WRITE HEADINGS
      WRITE(6,50) DURINC(K)
      WRITE(6,51)
C DO LOOP TO CONSIDER UP TO FIVE VALUES FOR INCIDENT DETECTION TIME
      DO 101 J=1,5
      IF(DETTM(J) .EQ. Z) GO TO 100
C COMPUTE VALUE OF MAX. SHOCK WAVE TIME ALLOWED
      SWTM = DETTM(J) - COMPRT
C DO LOOP TO CONSIDER UP TO EIGHT VALUES FOR OPERATING SPEED
      DO 102 L=1,8
```

```
      IF(OPSPD(L) .EQ. Z) GO TO 101
      WAVEU1 = -FRESPD + OPSPD(L) + QSPD
      SRATIO = OPSPD(L)/FRESPD
C COMPUTE TIME THAT IT TAKES INCIDENT AND CLEARING WAVES TO MEET
      X = WAVEUZ - WAVEU1
      IF(X .GE.Z) X=-.00000001
      WTIME = WAVEUZ * DURINC(K)/X
C COMPUTE MILES INCIDENT WAVE TRAVELS DURING MAX. ALLOWABLE SHOCK WAVE TIME
      WAVE = WAVEU1/60.
      WDIST = WAVE * SWTM * (-1.)
C CHECK TO SEE IF SOLUTION IS FEASIBLE
      IF(WTIME.GE.DETTM(J)) GO TO 60
      GO TO 99
C COMPUTE MAX. SENSOR SPACING FOR 100, 75, 50, AND 25 PERCENT DETECTION
   60 SS100 = WDIST
      SS75 = SS100/.75
      SS50 = SS100/.50
      SS25 = SS100/.25
      GO TO 98
   99 XDIST = (WTIME - COMPRT) * WAVE * (-1.)
      SS100 = XDIST
      SS75 = SS100/.75
      SS50 = SS100/.50
      SS25 = SS100/.25
   98 WRITE(6,202) FRESPD, ANCAP, AICAP, OPSPD(L), DETTM(J), SS100, SS75
     4, SS50, SS25
  102 CONTINUE
  101 CONTINUE
  100 CONTINUE
   50 FORMAT(1H1,5X,42HMAX. SENSOR SPACING TO DETECT INCIDENTS OF,F5.1,2
     4X,24HMINUTES OR MORE DURATION//)
   51 FORMAT(1H ,77X,8HINCIDENT,26X,4HMAX./6X,10HFREE SPEED,6X,11HNORMAL
     4 CAP.,6X,13HINCIDENT CAP.,6X,11HOPER. SPEED,6X,14HDETECTION TIME,
     47X,7HPERCENT,8X,6HSENSOR/9X,5H(MPH),11X,5H(VPH),11X,5H(VPH),15X,
     45H(MPH),13X,6H(MIN.),10X,8HDETECTED,5X,13HSPACING (MI.)/)
  202 FORMAT(1H ,6X,F5.0,11X,F5.0,12X,F5.0,13X,F5.0,15X,F5.1,14X,3H100,1
     40X,F5.2/98X,2H75,10X,F5.2/98X,2H50,10X,F5.2/98X,2H25,10X,F5.2/)
   80 FORMAT(8F10.0)
   81 FORMAT(5F10.0)
   82 FORMAT(2F10.0)
   83 FORMAT(3F10.0)
   30 STOP
      END
```

MAX. SENSOR SPACING TO DETECT INCIDENTS OF 2.0 MINUTES OR MORE DURATION

FREE SPEED (MPH)	NORMAL CAP. (VPH)	INCIDENT CAP. (VPH)	OPER. SPEED (MPH)	INCIDENT DETECTION TIME (MIN.)	PERCENT DETECTED	MAX. SENSOR SPACING (MI.)
60.	5560.	2880.	30.	1.6	100	0.17
					75	0.23
					50	0.35
					25	0.69
60.	5560.	2880.	33.	1.6	100	0.15
					75	0.20
					50	0.30
					25	0.59
60.	5560.	2880.	36.	1.6	100	0.12
					75	0.16
					50	0.25
					25	0.49
60.	5560.	2880.	39.	1.6	100	0.10
					75	0.13
					50	0.20
					25	0.39
60.	5560.	2880.	42.	1.6	100	0.07
					75	0.10
					50	0.15
					25	0.29
60.	5560.	2880.	45.	1.6	100	0.05
					75	0.06
					50	0.10
					25	0.19
60.	5560.	2880.	48.	1.6	100	0.02
					75	0.03
					50	0.05
					25	0.09
60.	5560.	2880.	50.	1.6	100	0.01
					75	0.01
					50	0.01
					25	0.03
60.	5560.	2880.	30.	2.1	100	0.35
					75	0.46
					50	0.69
					25	1.39
60.	5560.	2880.	33.	2.1	100	0.30
					75	0.40
					50	0.59
					25	1.19
60.	5560.	2880.	36.	2.1	100	0.25
					75	0.33
					50	0.49
					25	0.99
60.	5560.	2880.	39.	2.1	100	0.20
					75	0.26
					50	0.39
					25	0.79
60.	5560.	2880.	42.	2.1	100	0.15
					75	0.20
					50	0.29
					25	0.59
60.	5560.	2880.	45.	2.1	100	0.10
					75	0.13
					50	0.19
					25	0.39
60.	5560.	2880.	48.	2.1	100	0.05
					75	0.06
					50	0.09
					25	0.19
60.	5560.	2880.	50.	2.1	100	0.01
					75	0.02
					50	0.03
					25	0.05
60.	5560.	2880.	30.	3.1	100	0.69
					75	0.93
					50	1.39
					25	2.78
60.	5560.	2880.	33.	3.1	100	0.59
					75	0.79
					50	1.19
					25	2.38
60.	5560.	2880.	36.	3.1	100	0.49
					75	0.66
					50	0.99
					25	1.98
60.	5560.	2880.	39.	3.1	100	0.39
					75	0.53
					50	0.79
					25	1.58
60.	5560.	2880.	42.	3.1	100	0.29
					75	0.39
					50	0.59
					25	1.18
60.	5560.	2880.	45.	3.1	100	0.16
					75	0.22
					50	0.33
					25	0.65
60.	5560.	2880.	48.	3.1	100	0.06
					75	0.08
					50	0.11

					25	0.23
60.	5560.	2880.	50.	3.1	100	0.01
					75	0.02
					50	0.03
					25	0.05
60.	5560.	2880.	30.	4.1	100	1.04
					75	1.39
					50	2.08
					25	4.17
60.	5560.	2880.	33.	4.1	100	0.89
					75	1.19
					50	1.78
					25	3.57
60.	5560.	2880.	36.	4.1	100	0.74
					75	0.99
					50	1.48
					25	2.97
60.	5560.	2880.	39.	4.1	100	0.59
					75	0.79
					50	1.18
					25	2.37
60.	5560.	2880.	42.	4.1	100	0.35
					75	0.47
					50	0.70
					25	1.40
60.	5560.	2880.	45.	4.1	100	0.16
					75	0.22
					50	0.33
					25	0.65
60.	5560.	2880.	48.	4.1	100	0.06
					75	0.08
					50	0.11
					25	0.23
60.	5560.	2880.	50.	4.1	100	0.01
					75	0.02
					50	0.03
					25	0.05
60.	5560.	2880.	30.	5.1	100	1.39
					75	1.85
					50	2.78
					25	5.55
60.	5560.	2880.	33.	5.1	100	1.19
					75	1.58
					50	2.38
					25	4.75
60.	5560.	2880.	36.	5.1	100	0.99
					75	1.32
					50	1.98
					25	3.95
60.	5560.	2880.	39.	5.1	100	0.70
					75	0.93
					50	1.39
					25	2.78
60.	5560.	2880.	42.	5.1	100	0.35
					75	0.47
					50	0.70
					25	1.40
60.	5560.	2880.	45.	5.1	100	0.16
					75	0.22
					50	0.33
					25	0.65
60.	5560.	2880.	48.	5.1	100	0.06
					75	0.08
					50	0.11
					25	0.23
60.	5560.	2880.	50.	5.1	100	0.01
					75	0.02
					50	0.03
					25	0.05

MAX. SENSOR SPACING TO DETECT INCIDENTS OF 4.0 MINUTES OR MORE DURATION

FREE SPEED (MPH)	NORMAL CAP. (VPH)	INCIDENT CAP. (VPH)	OPER. SPEED (MPH)	INCIDENT DETECTION TIME (MIN.)	PERCENT DETECTED	MAX. SENSOR SPACING (MI.)
60.	5560.	2880.	30.	1.6	100	0.17
					75	0.23
					50	0.35
					25	0.69
60.	5560.	2880.	33.	1.6	100	0.15
					75	0.20
					50	0.30
					25	0.59
60.	5560.	2880.	36.	1.6	100	0.12
					75	0.16
					50	0.25
					25	0.49
60.	5560.	2880.	39.	1.6	100	0.10
					75	0.13
					50	0.20
					25	0.39
60.	5560.	2880.	42.	1.6	100	0.07
					75	0.10
					50	0.15
					25	0.29
60.	5560.	2880.	45.	1.6	100	0.05
					75	0.06
					50	0.10
					25	0.19
60.	5560.	2880.	48.	1.6	100	0.02
					75	0.03
					50	0.05
					25	0.09
60.	5560.	2880.	50.	1.6	100	0.01
					75	0.01
					50	0.01
					25	0.03
60.	5560.	2880.	30.	2.1	100	0.35
					75	0.46
					50	0.69
					25	1.39
60.	5560.	2880.	33.	2.1	100	0.30
					75	0.40
					50	0.59
					25	1.19
60.	5560.	2880.	36.	2.1	100	0.25
					75	0.33
					50	0.49
					25	0.99
60.	5560.	2880.	39.	2.1	100	0.20
					75	0.26
					50	0.39
					25	0.79
60.	5560.	2880.	42.	2.1	100	0.15
					75	0.20
					50	0.29
					25	0.59
60.	5560.	2880.	45.	2.1	100	0.10
					75	0.13
					50	0.19
					25	0.39
60.	5560.	2880.	48.	2.1	100	0.05
					75	0.06
					50	0.09
					25	0.19
60.	5560.	2880.	50.	2.1	100	0.01
					75	0.02
					50	0.03
					25	0.06
60.	5560.	2880.	30.	3.1	100	0.69
					75	0.93
					50	1.39
					25	2.78
60.	5560.	2880.	33.	3.1	100	0.59
					75	0.79
					50	1.19
					25	2.38
60.	5560.	2880.	36.	3.1	100	0.49
					75	0.66
					50	0.99
					25	1.98
60.	5560.	2880.	39.	3.1	100	0.39
					75	0.53
					50	0.79
					25	1.58
60.	5560.	2880.	42.	3.1	100	0.29
					75	0.39
					50	0.59
					25	1.18
60.	5560.	2880.	45.	3.1	100	0.19
					75	0.26
					50	0.39
					25	0.78
60.	5560.	2880.	48.	3.1	100	0.09
					75	0.13
					50	0.19

					25	0.38
60.	5560.	2880.	50.	3.1	100	0.03
					75	0.04
					50	0.06
					25	0.11
60.	5560.	2880.	30.	4.1	100	1.04
					75	1.39
					50	2.08
					25	4.17
60.	5560.	2880.	33.	4.1	100	0.89
					75	1.19
					50	1.78
					25	3.57
60.	5560.	2880.	36.	4.1	100	0.74
					75	0.99
					50	1.48
					25	2.97
60.	5560.	2880.	39.	4.1	100	0.59
					75	0.79
					50	1.18
					25	2.37
60.	5560.	2880.	42.	4.1	100	0.44
					75	0.59
					50	0.88
					25	1.77
60.	5560.	2880.	45.	4.1	100	0.29
					75	0.39
					50	0.58
					25	1.17
60.	5560.	2880.	48.	4.1	100	0.14
					75	0.19
					50	0.28
					25	0.57
60.	5560.	2880.	50.	4.1	100	0.04
					75	0.06
					50	0.08
					25	0.17
60.	5560.	2880.	30.	5.1	100	1.39
					75	1.85
					50	2.78
					25	5.55
60.	5560.	2880.	33.	5.1	100	1.19
					75	1.58
					50	2.38
					25	4.75
60.	5560.	2880.	36.	5.1	100	0.99
					75	1.32
					50	1.98
					25	3.95
60.	5560.	2880.	39.	5.1	100	0.79
					75	1.05
					50	1.58
					25	3.15
60.	5560.	2880.	42.	5.1	100	0.59
					75	0.78
					50	1.18
					25	2.35
60.	5560.	2880.	45.	5.1	100	0.39
					75	0.52
					50	0.78
					25	1.55
60.	5560.	2880.	48.	5.1	100	0.17
					75	0.22
					50	0.33
					25	0.67
60.	5560.	2880.	50.	5.1	100	0.04
					75	0.06
					50	0.08
					25	0.17

```
C TTI PROGRAM TO DETERMINE THE PERCENT OF INCIDENTS OF GIVEN DURATION OR GREATER
C     DETECTED FOR GIVEN SENSOR SPACINGS DURING MEDIUM AND HEAVY FLOW
C
C AN INCIDENT IS DEFINED AS ANY FREEWAY OBSTACLE THAT BLOCKS ONE OR MORE
C     LANES
C
C THIS PROGRAM ASSUMES THAT LANE BLOCKING INCIDENTS OCCUR RANDOMLY AND
C     UNIFORMLY ON THE FREEWAY SECTION
C
C THIS PROGRAM ASSUMES THAT THE INCIDENT DETECTION ALGORITHM DEVELOPED BY
C     TTI WILL BE USED. (COMPUTER RESPONSE TIME = 1.1 MINUTES)
C
C FRESPD = FREE SPEED (MPH)
C ANCAP  = NORMAL CAPACITY (VPH)
C AICAP  = INCIDENT CAPACITY (VPH)
C DURINC = MINIMUM DURATION OF INCIDENTS THAT MUST BE DETECTED (MINUTES)
C WAVEU1 = SPEED OF SHOCK WAVE MOVING UPSTREAM WHEN INCIDENT OCCURS (MPH)
C WAVEUZ = SPEED OF CLEARING WAVE MOVING UPSTREAM WHEN INCIDENT IS REMOVED (MPH)
C OPSPD  = OPERATING SPEED PRIOR TO INCIDENT (MPH)
C QSPD   = SPEED IN QUEUE (MPH)
C COMPRT = COMPUTER RESPONSE TIME (MINUTES)
C DETTM = MAXIMUM REQUIRED INCIDENT DETECTION TIME (MINUTES)
C SWTM   = SHOCK WAVE TRAVEL TIME AFTER INCIDENT (MINUTES)
C
      DIMENSION OPSPD(8)
      DIMENSION DETTM(5)
      DIMENSION DURINC(2)
      DIMENSION SPACE(5)
      DIMENSION PCT(5)
C READ DATA : MAX. OPERATING SPEED AT WHICH INCIDENTS SHOULD BE DETECTED
C             REQD. INCIDENT DETECTION TIME
C             MINIMUM DURATION OF INCIDENTS THAT MUST BE DETECTED
      READ(5,80) OPSPD
      READ(5,81) DETTM
      READ(5,82) DURINC
C READ SPECIFIC FREEWAY CHARACTERISTICS
      READ(5,83) FRESPD, AICAP, ANCAP
C READ AVAILABLE SENSOR SPACINGS (UP TO 5 VALUES)
      READ (5,84) SPACE
C NEXT CARD IDENTIFIES THE COMPUTER ALGORITHM RESPONSE TIME (TIME DIFFERENCE
C     BETWEEN WHEN THE ALGORITHM DETECTS THE INCIDENT AND WHEN THE SHOCK WAVE
C     PASSES OVER THE SENSOR)
      COMPRT = 1.1
C INITIALIZE AND COMPUTE CONSTANTS
      DO 10 I=1,5
      PCT(I) = 0.0
   10 CONTINUE
      Z = 0.0
      QSPD = (FRESPD/2) * (1-SQRT(1-(AICAP/ANCAP)))
      WAVEUZ = -(FRESPD/2) + QSPD
C DO LOOP TO CONSIDER UP TO TWO VALUES FOR MIN. DURATION OF INCIDENT
      DO 100 K=1,2
      IF(DURINC(K) .EQ. Z) GO TO 30
C WRITE HEADINGS
      WRITE(6,50) DURINC(K)
      WRITE(6,51)
C DO LOOP TO CONSIDER UP TO FIVE VALUES FOR INCIDENT DETECTION TIME
      DO 101 J=1,5
```

```
      IF(DETTM(J) .EQ. Z) GO TO 100
C COMPUTE VALUE OF MAX. SHOCK WAVE TIME ALLOWED
      SWTM = DETTM(J) - COMPRT
C DO LOOP TO CONSIDER UP TO EIGHT VALUES FOR OPERATING SPEED
      DO 102 L=1,8
      IF(OPSPD(L) .EQ. Z) GO TO 101
      WAVEU1 = -FRESPD + OPSPD(L) + OSPD
C COMPUTE TIME THAT IT TAKES INCIDENT AND CLEARING WAVES TO MEET
      X = WAVEUZ - WAVEU1
      IF(X .GE.Z) X=-.00000001
      WTIME = WAVEUZ * DURINC(K)/X
C COMPUTE MILES INCIDENT WAVE TRAVELS DURING MAX. ALLOWABLE SHOCK WAVE TIME
      WAVE = WAVEU1/60.
      WDIST = WAVE * SWTM * (-1.)
C DO LOOP TO CONSIDER UP TO 5 VALUES OF SENSOR SPACINGS
      DO 103 M = 1,5
      IF(SPACE(M).EQ.Z) GO TO 98
C CHECK BOUNDARY CONDITIONS AND COMPUTE PERCENTAGES
      IF(WTIME.LT.DETTM(J)) GO TO 70
      PCT(M) = WDIST/SPACE(M) * 100.
      IF(PCT(M).GT.100.) PCT(M)=100.
      GO TO 103
   70 SS100 = (WTIME - COMPRT) * WAVE * (-1.)
      PCT(M) = SS100/SPACE(M) * 100.
      IF(PCT(M).GT.100.) PCT(M) = 100.
  103 CONTINUE
   98 WRITE(6,202) FRESPD, ANCAP, AICAP, OPSPD(L), DETTM(J), (PCT(N),
     4SPACE(N), N = 1,M)
  102 CONTINUE
  101 CONTINUE
  100 CONTINUE
   50 FORMAT(1H1,5X,33HPERCENT OF INCIDENTS DETECTED OF,F5.1,2X,24HMINUT
     4ES OR MORE DURATION//)
   51 FORMAT(1H ,77X,8HINCIDENT/6X,10HFREE SPEED,6X,11HNORMAL CAP.,6X,13
     4HINCIDENT CAP.,6X,11HOPER. SPEED,6X,14HDETECTION TIME,7X,7HPERCENT
     4,8X,6HSENSOR/9X,5H(MPH),11X,5H(VPH),11X,5H(VPH),15X,5H(MPH),13X,6H
     4(MIN.),10X,8HDETECTED,5X,13HSPACING (MI.)/)
  202 FORMAT(1H ,6X,F5.0,11X,F5.0,12X,F5.0,13X,F5.0,15X,F5.1,12X,F5.1,10
     4X,F5.2/95X,F5.1,10X,F5.2/95X,F5.1,10X,F5.2/95X,F5.1,10X,F5.2/95X,
     4F5.1,10X,F5.2/)
   80 FORMAT(8F10.0)
   81 FORMAT(5F10.0)
   82 FORMAT(2F10.0)
   83 FORMAT(3F10.0)
   84 FORMAT (5F10.0)
   30 STOP
      END
```

PERCENT OF INCIDENTS DETECTED OF, 2.0 MINUTES OR MORE DURATION

FREE SPEED (MPH)	NORMAL CAP. (VPH)	INCIDENT CAP. (VPH)	OPER. SPEED (MPH)	INCIDENT DETECTION TIME (MIN.)	PERCENT DETECTED	SENSOR SPACING (MI.)
60.	5560.	2880.	30.	1.6	49.6	0.35
					36.9	0.47
					24.8	0.70
					12.4	1.40
					0.0	0.00
60.	5560.	2880.	33.	1.6	42.4	0.35
					31.6	0.47
					21.2	0.70
					10.6	1.40
					0.0	0.00
60.	5560.	2880.	36.	1.6	35.3	0.35
					26.3	0.47
					17.7	0.70
					8.8	1.40
					0.0	0.00
60.	5560.	2880.	39.	1.6	28.2	0.35
					21.0	0.47
					14.1	0.70
					7.0	1.40
					0.0	0.00
60.	5560.	2880.	42.	1.6	21.0	0.35
					15.7	0.47
					10.5	0.70
					5.3	1.40
					0.0	0.00
60.	5560.	2880.	45.	1.6	13.9	0.35
					10.3	0.47
					6.9	0.70
					3.5	1.40
					0.0	0.00
60.	5560.	2880.	48.	1.6	6.7	0.35
					5.0	0.47
					3.4	0.70
					1.7	1.40
					0.0	0.00
60.	5560.	2880.	50.	1.6	2.0	0.35
					1.5	0.47
					1.0	0.70
					0.5	1.40
					0.0	0.00
60.	5560.	2880.	30.	2.1	99.2	0.35
					73.9	0.47
					49.6	0.70
					24.8	1.40
					0.0	0.00
60.	5560.	2880.	33.	2.1	84.9	0.35
					63.2	0.47
					42.4	0.70
					21.2	1.40
					0.0	0.00
60.	5560.	2880.	36.	2.1	70.6	0.35
					52.6	0.47
					35.3	0.70
					17.7	1.40
					0.0	0.00
60.	5560.	2880.	39.	2.1	56.3	0.35
					41.9	0.47
					28.2	0.70
					14.1	1.40
					0.0	0.00
60.	5560.	2880.	42.	2.1	42.0	0.35
					31.3	0.47
					21.0	0.70
					10.5	1.40
					0.0	0.00
60.	5560.	2880.	45.	2.1	27.8	0.35
					20.7	0.47
					13.9	0.70
					6.9	1.40
					0.0	0.00
60.	5560.	2880.	48.	2.1	13.5	0.35
					10.0	0.47
					6.7	0.70
					3.4	1.40
					0.0	0.00
60.	5560.	2880.	50.	2.1	3.9	0.35
					2.9	0.47
					1.9	0.70
					1.0	1.40
					0.0	0.00
60.	5560.	2880.	30.	3.1	100.0	0.35
					100.0	0.47
					99.2	0.70
					49.6	1.40
					0.0	0.00
60.	5560.	2880.	33.	3.1	100.0	0.35
					100.0	0.47
					84.9	0.70
					42.4	1.40
					0.0	0.00
60.	5560.	2880.	36.	3.1	100.0	0.35
					100.0	0.47
					70.6	0.70
					35.3	1.40
					0.0	0.00

60.	5560.	2880.	39.	3.1	100.0	0.35
					83.9	0.47
					56.3	0.70
					28.2	1.40
					0.0	0.00
60.	5560.	2880.	42.	3.1	84.1	0.35
					62.6	0.47
					42.0	0.70
					21.0	1.40
					0.0	0.00
60.	5560.	2880.	45.	3.1	46.5	0.35
					34.7	0.47
					23.3	0.70
					11.6	1.40
					0.0	0.00
60.	5560.	2880.	48.	3.1	16.4	0.35
					12.2	0.47
					8.2	0.70
					4.1	1.40
					0.0	0.00
60.	5560.	2880.	50.	3.1	3.9	0.35
					2.9	0.47
					1.9	0.70
					1.0	1.40
					0.0	0.00
60.	5560.	2880.	30.	4.1	100.0	0.35
					100.0	0.47
					100.0	0.70
					74.4	1.40
					0.0	0.00
60.	5560.	2880.	33.	4.1	100.0	0.35
					100.0	0.47
					100.0	0.70
					63.7	1.40
					0.0	0.00
60.	5560.	2880.	36.	4.1	100.0	0.35
					100.0	0.47
					100.0	0.70
					53.0	1.40
					0.0	0.00
60.	5560.	2880.	39.	4.1	100.0	0.35
					100.0	0.47
					84.5	0.70
					42.2	1.40
					0.0	0.00
60.	5560.	2880.	42.	4.1	99.7	0.35
					74.2	0.47
					49.8	0.70
					24.9	1.40
					0.0	0.00
60.	5560.	2880.	45.	4.1	46.5	0.35
					34.7	0.47
					23.3	0.70
					11.6	1.40
					0.0	0.00
60.	5560.	2880.	48.	4.1	16.4	0.35
					12.2	0.47
					8.2	0.70
					4.1	1.40
					0.0	0.00
60.	5560.	2880.	50.	4.1	3.9	0.35
					2.9	0.47
					1.9	0.70
					1.0	1.40
					0.0	0.00
60.	5560.	2880.	30.	5.1	100.0	0.35
					100.0	0.47
					100.0	0.70
					99.2	1.40
					0.0	0.00
60.	5560.	2880.	33.	5.1	100.0	0.35
					100.0	0.47
					100.0	0.70
					84.9	1.40
					0.0	0.00
60.	5560.	2880.	36.	5.1	100.0	0.35
					100.0	0.47
					100.0	0.70
					70.6	1.40
					0.0	0.00
60.	5560.	2880.	39.	5.1	100.0	0.35
					100.0	0.47
					99.4	0.70
					49.7	1.40
					0.0	0.00
60.	5560.	2880.	42.	5.1	99.7	0.35
					74.2	0.47
					49.8	0.70
					24.9	1.40
					0.0	0.00
60.	5560.	2880.	45.	5.1	46.5	0.35
					34.7	0.47
					23.3	0.70
					11.6	1.40
					0.0	0.00
60.	5560.	2880.	48.	5.1	16.4	0.35
					12.2	0.47
					8.2	0.70
					4.1	1.40
					0.0	0.00

PERCENT OF INCIDENTS DETECTED OF, 4.0 MINUTES OR MORE DURATION

FREE SPEED (MPH)	NORMAL CAP. (VPH)	INCIDENT CAP. (VPH)	OPER. SPEED (MPH)	INCIDENT DETECTION TIME (MIN.)	PERCENT DETECTED	SENSOR SPACING (MI.)
60.	5560.	2880.	30.	1.6	49.6	0.35
					36.9	0.47
					24.8	0.70
					12.4	1.40
					0.0	0.00
60.	5560.	2880.	33.	1.6	42.4	0.35
					31.6	0.47
					21.2	0.70
					10.6	1.40
					0.0	0.00
60.	5560.	2880.	36.	1.6	35.3	0.35
					26.3	0.47
					17.7	0.70
					8.8	1.40
					0.0	0.00
60.	5560.	2880.	39.	1.6	28.2	0.35
					21.0	0.47
					14.1	0.70
					7.0	1.40
					0.0	0.00
60.	5560.	2880.	42.	1.6	21.0	0.35
					15.7	0.47
					10.5	0.70
					5.3	1.40
					0.0	0.00
60.	5560.	2880.	45.	1.6	13.9	0.35
					10.3	0.47
					6.9	0.70
					3.5	1.40
					0.0	0.00
60.	5560.	2880.	48.	1.6	6.7	0.35
					5.0	0.47
					3.4	0.70
					1.7	1.40
					0.0	0.00
60.	5560.	2880.	50.	1.6	2.0	0.35
					1.5	0.47
					1.0	0.70
					0.5	1.40
					0.0	0.00
60.	5560.	2880.	30.	2.1	99.2	0.35
					73.9	0.47
					49.6	0.70
					24.8	1.40
					0.0	0.00
60.	5560.	2880.	33.	2.1	84.9	0.35
					63.2	0.47
					42.4	0.70
					21.2	1.40
					0.0	0.00
60.	5560.	2880.	36.	2.1	70.6	0.35
					52.6	0.47
					35.3	0.70
					17.7	1.40
					0.0	0.00
60.	5560.	2880.	39.	2.1	56.3	0.35
					41.9	0.47
					28.2	0.70
					14.1	1.40
					0.0	0.00
60.	5560.	2880.	42.	2.1	42.0	0.35
					31.3	0.47
					21.0	0.70
					10.5	1.40
					0.0	0.00
60.	5560.	2880.	45.	2.1	27.8	0.35
					20.7	0.47
					13.9	0.70
					6.9	1.40
					0.0	0.00
60.	5560.	2880.	48.	2.1	13.5	0.35
					10.0	0.47
					6.7	0.70
					3.4	1.40
					0.0	0.00
60.	5560.	2880.	50.	2.1	3.9	0.35
					2.9	0.47
					2.0	0.70
					1.0	1.40
					0.0	0.00
60.	5560.	2880.	30.	3.1	100.0	0.35
					100.0	0.47
					99.2	0.70
					49.6	1.40
					0.0	0.00
60.	5560.	2880.	33.	3.1	100.0	0.35
					100.0	0.47
					84.9	0.70
					42.4	1.40
					0.0	0.00
60.	5560.	2880.	36.	3.1	100.0	0.35
					100.0	0.47
					70.6	0.70
					35.3	1.40
					0.0	0.00

60.	5560.	2880.	39.	3.1	100.0	0.35
					83.9	0.47
					56.3	0.70
					28.2	1.40
					0.0	0.00
60.	5560.	2880.	42.	3.1	84.1	0.35
					62.6	0.47
					42.0	0.70
					21.0	1.40
					0.0	0.00
60.	5560.	2880.	45.	3.1	55.5	0.35
					41.3	0.47
					27.8	0.70
					13.9	1.40
					0.0	0.00
60.	5560.	2880.	48.	3.1	26.9	0.35
					20.1	0.47
					13.5	0.70
					6.7	1.40
					0.0	0.00
60.	5560.	2880.	50.	3.1	7.9	0.35
					5.9	0.47
					3.9	0.70
					2.0	1.40
					0.0	0.00
60.	5560.	2880.	30.	4.1	100.0	0.35
					100.0	0.47
					100.0	0.70
					74.4	1.40
					0.0	0.00
60.	5560.	2880.	33.	4.1	100.0	0.35
					100.0	0.47
					100.0	0.70
					63.7	1.40
					0.0	0.00
60.	5560.	2880.	36.	4.1	100.0	0.35
					100.0	0.47
					100.0	0.70
					53.0	1.40
					0.0	0.00
60.	5560.	2880.	39.	4.1	100.0	0.35
					100.0	0.47
					84.5	0.70
					42.2	1.40
					0.0	0.00
60.	5560.	2880.	42.	4.1	100.0	0.35
					93.9	0.47
					63.1	0.70
					31.5	1.40
					0.0	0.00
60.	5560.	2880.	45.	4.1	83.3	0.35
					62.0	0.47
					41.6	0.70
					20.8	1.40
					0.0	0.00
60.	5560.	2880.	48.	4.1	40.4	0.35
					30.1	0.47
					20.2	0.70
					10.1	1.40
					0.0	0.00
60.	5560.	2880.	50.	4.1	11.8	0.35
					8.8	0.47
					5.9	0.70
					3.0	1.40
					0.0	0.00
60.	5560.	2880.	30.	5.1	100.0	0.35
					100.0	0.47
					100.0	0.70
					99.2	1.40
					0.0	0.00
60.	5560.	2880.	33.	5.1	100.0	0.35
					100.0	0.47
					100.0	0.70
					84.9	1.40
					0.0	0.00
60.	5560.	2880.	36.	5.1	100.0	0.35
					100.0	0.47
					100.0	0.70
					70.6	1.40
					0.0	0.00
60.	5560.	2880.	39.	5.1	100.0	0.35
					100.0	0.47
					100.0	0.70
					56.3	1.40
					0.0	0.00
60.	5560.	2880.	42.	5.1	100.0	0.35
					100.0	0.47
					84.1	0.70
					42.0	1.40
					0.0	0.00
60.	5560.	2880.	45.	5.1	100.0	0.35
					82.7	0.47
					55.5	0.70
					27.8	1.40
					0.0	0.00
60.	5560.	2880.	48.	5.1	47.5	0.35
					35.4	0.47
					23.8	0.70
					11.9	1.40
					0.0	0.00