DETECTING STOPPAGE WAVES FOR FREEWAY CONTROL

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An experimental warning system has been installed on the inbound control section of the Gulf Freeway as a means of alerting drivers approaching crest vertical curves of stoppages downstream of the crest. Automatic control of the warning system dictated the need to identify measurable traffic parameters that indicate the presence of a stoppage wave. This paper presents an analysis of selected speed and energy parameters as indicators of stoppage waves. The results demonstrate that both the speed and energy parameters perform satisfactorily. Based on the results of the investigation, a digital computer control algorithm was structured for automatic control of the warning system. Recommendations are presented for detector placement.

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

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

Three overpasses were selected as sites for pilot installations to study the effectiveness of the warning system, to develop automatic control algorithms, and to further evaluate the design concepts. The system currently consists of a static sign with attached flashing beacons (Fig. 1) located upstream of each overpass crest and a flashing beacon mounted on the bridge rail on the top of each crest (Fig. 2). Although the warning signs can be controlled manually by remote switches located in the control center, automatic operation of the system by a computer is desired. Prior to the installation of the warning signs, double-loop detectors were installed on each lane and located on both sides of the three overpasses to study traffic characteristics relative to stoppage waves, to test automatic control algorithms, and to be used for real-time control. The primary function of the detectors downstream of the overpass is to sense stoppage waves so that the warning sign can be activated. The upstream detectors indicate when the sign should be turned off.

Several researchers have demonstrated the ability to identify major shock waves as they propagate upstream over detectors spaced at considerable intervals along a freeway lane (2, 3, 4, 5). Because traffic incidents can occur anywhere in the system (e.g., immediately downstream of an overpass), it was particularly important to evaluate the ability to detect or predict the passage of stoppage waves propagating across a single detector station. Automatic control of the warning system therefore dictated the need to identify measurable traffic parameters that indicate the presence of a stoppage wave.

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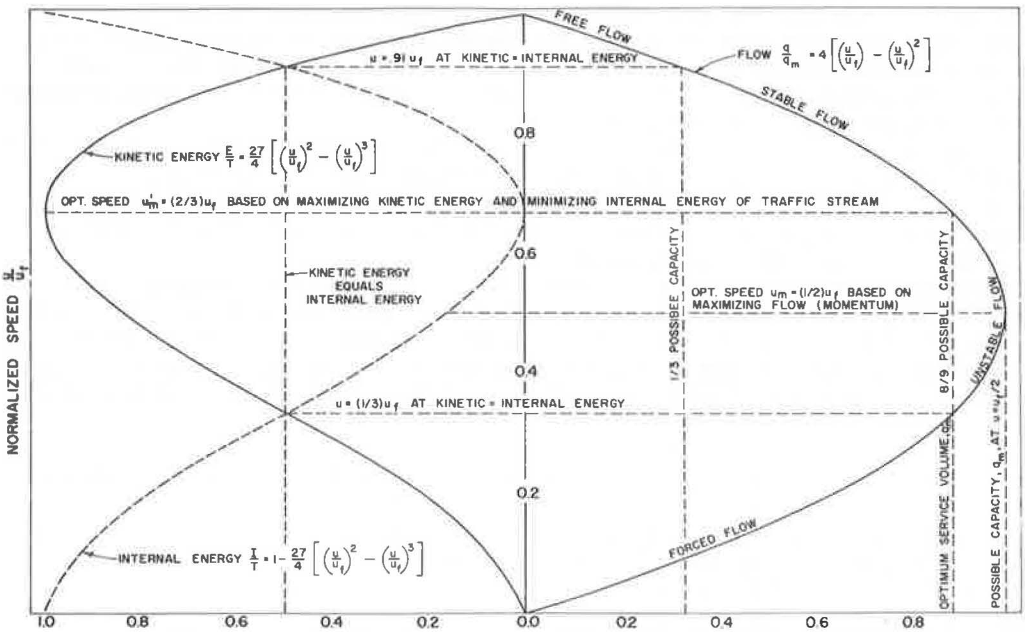
Figure 1. Warning sign with flashers.

Figure 2. Flasher unit at crest of overpass.

Figure 3. Quantitative approach to level of service using total energy-momentum analogy (7).



The selected parameter should minimize the probability that the system will not respond to a stoppage wave (type I error) and should minimize the number of false activations (type II error). This paper presents an analysis of selected speed and energy parameters as indicators of stoppage waves. Also included is the development of a digital computer control algorithm for the pilot system on the Gulf Freeway.

CONTROL VARIABLES

The traffic variables selected for analysis for automatic control of the warning system are speed and kinetic energy. The basic theory and the relation among speed, volume, and kinetic energy have been well documented in the literature (6, 7, 8). If we assume a linear function between speed and density, the normalized relationships of volume q and kinetic energy E_k can be written as a function of speed u:

$$q = k_j \left(u - \frac{u^2}{u_f} \right) \tag{1}$$

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

where

k_j = jam concentration and
u_f = free speed.

The relation between q and E_k is shown in Figure 3. Optimum service volume, based on maximizing kinetic energy and minimizing acceleration noise, corresponds to a level of flow that is less than capacity. Operating speed, on the other hand, is higher than the speed realized at capacity. The right side of Figure 3 shows that a small increase in demand above the volume at maximum energy tends to greatly increase the density of the traffic stream, accompanied inevitably by a sharp decrease in operating speed.

An examination of the relationship between energy and momentum reveals that the lower intercept of the energy and acceleration noise curves identifies forced flow conditions (level of service F) on the freeway. Flows are below capacity, and storage areas consisting of queues of vehicles form. This type of operation is indicative of stop-and-go traffic stream motion. The transition to the forced flow condition occurs rather rapidly (9). The intercept of the energy and acceleration noise curves occurs when the energy is one-half the maximum energy (E_m') of the stream. Based on this premise, it would appear initially that shock waves could be detected by measured energy less than one-half of maximum energy. This energy level can be referred to as the critical energy, E_c.

$$E_c = \tfrac{1}{2} E_m' \tag{3}$$

Associated with the critical energy parameter is a speed that might be referred to as critical speed u_c, which is equal to one-third of the free speed.

$$u_c = \tfrac{1}{3} u_f \tag{4}$$

Thus, the critical speed parameter might also serve as an initial parameter for evaluation.

It is emphasized that the energy will also be less than one-half maximum energy when the freeway is operating at level of service A. Therefore, it would be necessary to ascertain the level of service by measuring the speed characteristics. One reason for evaluating both energy and speed parameters even though they represent the same operating point in Figure 3 is to determine whether one variable is more sensitive and responsive than the other.

STUDY PROCEDURES

Equipment

Double-loop detectors are positioned on each lane of the inbound Gulf Freeway both upstream and downstream of three overpasses selected as the sites for the prototype safety warning devices. The locations of the three subsystems are shown in Figure 4. Traffic flow data from detectors are transmitted to an IBM 1800 digital computer located in the surveillance and control center. The data are then processed to compute traffic variables that can be used for control and then may be stored on disk, printed, or punched on cards.

Data Collection and Reduction

A computer program was written to collect data from the subsystem detectors, compute the desired traffic flow variables, and store the information at 30-sec intervals. Speed and volume were determined for each lane at both the upstream and downstream stations for the three subsystems. Speed was computed from the travel time of each vehicle between the two detectors. When an incident was observed on the study section, the computer stored the incoming data from the subsystem detectors on remote disk units for later analysis and processing. Simultaneously, a video tape recording was made to provide a visual record of traffic conditions during the incident. This provided the capability for later evaluation of traffic flow that could not be easily accomplished as it occurred. Video tape recordings of incidents were examined, and specific information on the origin of freeway shock waves and the time shock waves were observed to cross individual detectors were noted.

The quantitative computer data were examined, and the traffic flow condition based on speeds and flow rates prior to the shock wave passage was noted. The computer data and the video tape recording were synchronized in time, which permitted comparison of the two types of data.

Several computational time bases ranging from 10 sec to 2 min were considered for the program. Based on a preliminary study of the sensitivity of several traffic variables using different time bases within this time range and the results of freeway control research in different parts of the country, a time base of 1 min with data updated every 30 sec was selected. In other words, the traffic variables were computed for 1 min, and the values were updated every 30 sec by adding the most recent 30 sec of data and dropping the oldest 30 sec.

RESULTS

Critical Energy and Critical Speed

Least squares regressions were performed on kinetic energy-speed data consistent with the basic relationship

$$E_k = b_1u^2 - b_2u^3 \tag{5}$$

(where b_1 and b_2 are constants) by using base data collected at each detector station. Statistical tests of the regression coefficients were found significant in all cases at the 0.01 level. In addition, the R^2 values for each regression were all above 0.92, indicating good correlation between kinetic energy and speed.

Once the relationships between energy and speed were established, the maximum energy E_m', critical energy E_c, and critical speed u_c were calculated for each detector station (Table 1).

Detection of Stoppage Waves

Using the E_c and u_c as indicators of stoppage waves allowed us to compare, on an individual lane basis, the actual observation of 142 stoppage waves crossing one of the detectors and the time that the critical energy and speed parameters registered the presence of a wave. The observations were made when the freeway was operating at levels of service B, C, and D prior to the occurrence of a stoppage wave. The results of the analysis are shown as performance curves in Figure 5.

The values presented in the figure represent the difference in seconds between the time when the variable on the lane dropped below the critical value and the actual observed time of the stoppage wave moving over the detector. A positive value indicates that the energy or speed dropped below E_c or u_c before the wave was observed to cross the detector station. A negative value represents a late response by the parameter.

The results indicate that critical energy and speed are good parameters for the identification of a stoppage wave under levels of service B, C, and D. Generally, the parameters were able to predict the presence of a downstream stoppage wave. In general, there was little difference in the response between the energy and speed parameters.

Each parameter detected the presence of a stoppage wave either at the time the wave was moving over the detector or several seconds before the wave reached the detector stations in 131 of the 142 cases (93 percent). A total of 141 observations fell within the expected limits of the control logic. Because the 1-min values of energy and speed were updated every 30 sec, it was expected that a stoppage wave in some cases could conceivably pass over the detectors 30 sec before the computed energy or speed fell below the critical value. Therefore, a few late responses as high as 30 sec (-30) might be expected. In only one case did the parameters respond late by more than 30 sec (type I error). The reason for the lack of agreement for the one case could not be ascertained from the data and can only be conjectured at this time. However, the critical energy and speed parameters have been shown to possess a predictive characteristic for stoppage waves.

One-Lane Detection Criterion

Experience has shown that, although there is a degree of sympathy of speed between lanes regardless of volume, stoppage waves do not necessarily move in unison on each lane of a freeway (10). Generally, there are differences in the time that the waves on the individual lanes will reach a certain point on a freeway. An analysis of the relative movement of waves between lanes on the Gulf Freeway was made and is presented later. Because detectors for the safety warning device were placed on each lane, any one of the lanes could serve as the control lane. That is, the system was activated when a stoppage wave was sensed on any one of the lanes. An analysis was therefore made to test the responsiveness of detector stations having detectors in all three lanes to the occurrence of a stoppage wave. Forty-two stoppage waves resulting from incidents were evaluated as they crossed one of the five detector stations. The results of the analysis are shown in Figure 6.

The advance warning of a stoppage wave shown in the figure represents the difference between the time that the energy or speed dropped below the critical value on any one of the lanes and the time that the first stoppage wave was observed to cross one of the detectors. Again, positive values represent advance warning; negative values represent late responses.

The results clearly show that there was essentially no difference in response between the energy and speed parameters. In addition, with a three-lane detection station, adequate advance warning of stoppage waves is achieved within the limitations of the measurement technique. This is accomplished by allowing any one of the three lanes to predict the occurrence of a stoppage wave. In only one case did the wave pass over the detectors before the variable fell below the critical value on any one of the lanes. However, the difference was only 17 sec, well within the limit because of the 30-sec update of the data base.

A review of the data also revealed that, for the incidents studied, the stoppage waves were first detected on either the median or the middle lanes, or both, in 98 percent of the cases. An explanation of this result can be surmised. Because of the traffic leaving the shoulder lane via the off-ramps, the stoppage wave at times is interrupted and, therefore, will take longer to travel upstream. Earlier research on the Gulf Freeway by Drew (10) indicated that there does not seem to be any transverse pattern of failure

Figure 4. Location of test equipment.

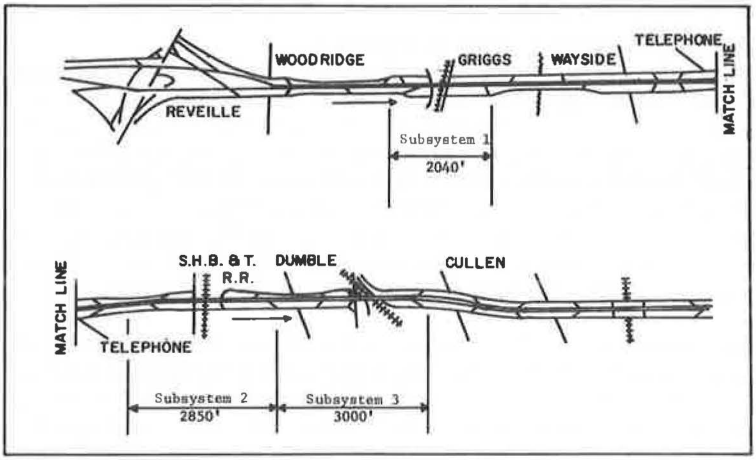
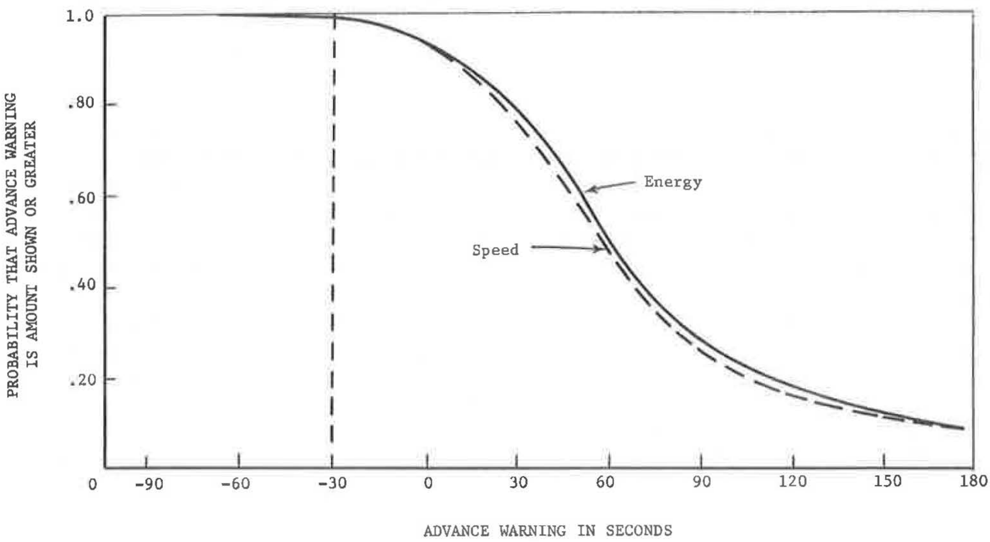


Table 1. Traffic parameters.

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

[a]1 = shoulder, 2 = middle, and 3 = median.

Figure 5. Performance curves for individual lanes.



prompted by the spread of congestion from any one lane to the shoulder lane. He suggested that drivers seem to compensate for turbulence in the shoulder lane.

Type II Errors

The preceding section has shown that, for the incidents studied, a one-lane criterion was acceptable. The results revealed that there were no type I errors. This section discusses the results of an analysis for type II errors, false activations when a stoppage wave does not exist.

One of the assumptions made in selecting energy as one control variable is that the freeway will not be operating at level of service A during the normal periods of control (6 a.m. to 6 p.m.) because of the demands normally experienced on the freeway at these times. However, if for some reason short-period demands become light at a detector station, the energy values could conceivably drop below E_c, resulting in false activation of the safety warning device. Several hours of data, collected during off-peak and peak periods when no incidents occurred within the study section, were evaluated for the possibility of type II errors.

The results revealed that, generally, the operation of the device was satisfactory. However, it was observed that in some instances during the off-peak periods, particularly during the summer months, a reduction in freeway demand would cause false activations by using energy. Although not a frequent occurrence, the data indicated that the type II error was indeed a problem particularly during the summer and, therefore, would require attention. This was particularly true at subsystem 1 (Mossrose-Griggs).

The detector station at Griggs is located about 4,000 ft downstream of a major interchange and immediately downstream of a high-volume off-ramp. It appeared that the influence of the off-ramp coupled with motorists' desires to assume a comfortable headway after merging at the major interchange resulted in intermittent low-volume, high-speed measurement periods, particularly in the shoulder lane. The conditions were sufficiently severe to cause the energy to fall below E_c. This would give the indication of a stoppage wave.

There are at least two approaches that can be taken to circumvent this problem. One approach is to maintain a check of the speed and volume of the downstream detectors. Because the middle lane will carry a higher volume than the other two lanes during the off-peak periods, this lane can be used in the decision process. If the speeds remain above a threshold value, say 35 mph, while the volume in the middle lane stays above a threshold volume, say 8 vehicles per minute, this is an indication of random light flow on the affected lane. The safety warning device then would not be activated.

A second approach is to maintain the same control logic but increase the sampling time base. This would in effect smooth the energy function and reduce the severe peaking characteristic of the variable.

Each of these approaches was analyzed to determine its merits. Off-peak data, which indicated the highest frequency of type II errors, were used as the basis for the analysis. Thus, the approaches were evaluated under the worst noticeable conditions. Data from 414 sampling periods (30-sec periods) collected at the Griggs detector station on July 28 and 30 and August 3 and 4, 1971, were used as the base. The results of the analysis are shown in Figure 7.

The results indicate that using the basic control logic with an increased time base of up to 5 min reduces the frequency of false activations, but the reduction is not sufficient to be acceptable. The results also show that the approach wherein the middle lane at the downstream station is given a volume and speed check to determine the need to activate the safety warning device appears to be an acceptable solution. When a 1-min sampling period is used, a false activation would have occurred less than two-tenths of 1 percent (virtually zero) of the time under the worst possible conditions.

System Stability

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

Figure 6. Performance curve for one-lane criterion.

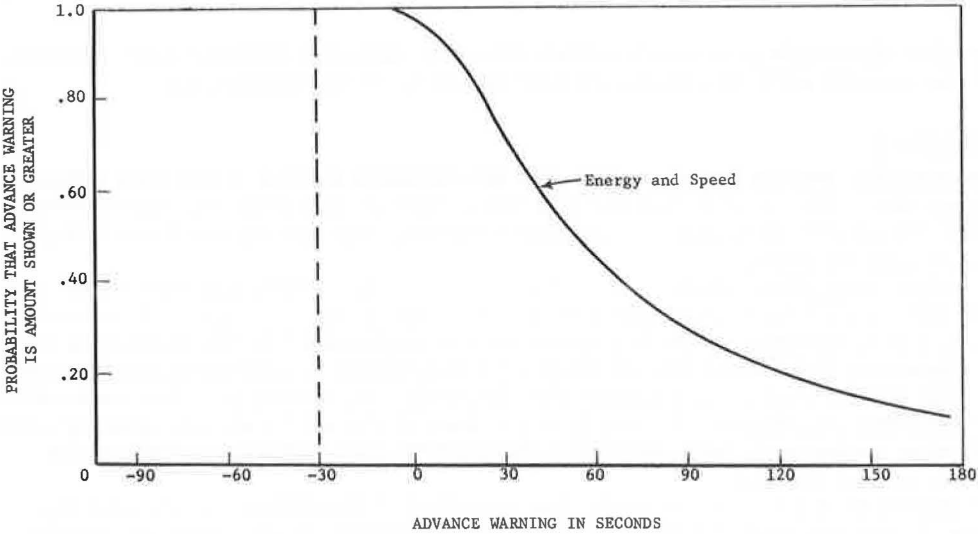


Figure 7. Effect of time base on type II errors.

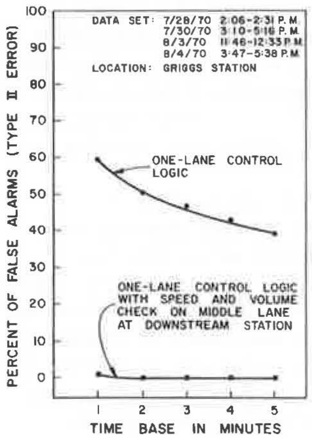


Figure 8. Relationship of stoppage wave differences between first and second waves.

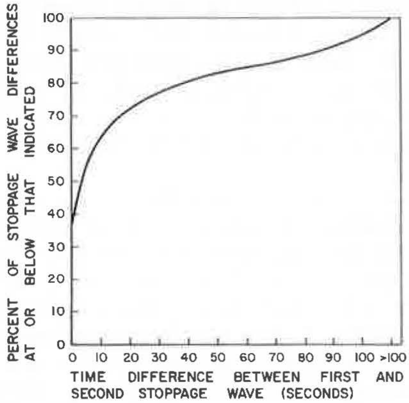
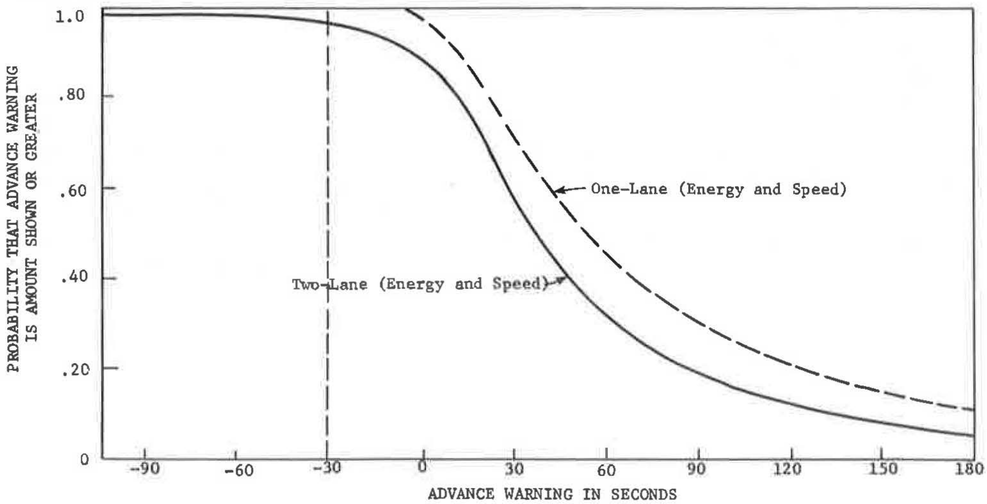


Figure 9. Performance curves for one-lane versus two-lane criterion.



The results of a system stability analysis revealed that, because of the fluctuations of traffic flow, there is some system instability when a 1-min data base is used. It was observed that the variation of traffic characteristics at the downstream detector stations would occasionally cause the safety device to turn off and on intermittently before the stoppage wave reached the upstream detector stations.

One solution to the problem is to require that the unit continue to operate for a fixed time following the initial period that resulted in energy values that called for system activation. An analysis of the data indicates that a hold time of six sampling periods (3 min) would be adequate to compensate for the possible instability of on-off cycling. This minimum time period can be reduced if the stoppage waves propagate over the upstream detectors sooner than 3 min. The minimum time can also be reduced when the sign is activated by slow vehicles (e.g., trucks and funeral processions).

Detector Problems

During the course of this research a rather high frequency of detector malfunctions was noted. This appears to be a problem common to operational freeway control systems. Because of the nature of the electronics associated with automatic traffic detection equipment, a particular detector may possibly become defective and thus transmit erroneous data to the computer or perhaps transmit no data at all. The problem is perplexing because a detector may become defective at any instant in time. Therefore, even though the detection equipment is thoroughly checked prior to control, there is no assurance that every detector will perform satisfactorily throughout the day.

The consequential effects of a defective detector in an automatic warning system for motorists are apparent. However, there are safeguard features that can be designed into the system to minimize their effects. One approach is to employ redundant detectors. Another approach is to rely on detectors on two lanes to give the alert of a major discontinuity in flow. That is, the safety warning device would not be activated unless the energy or speed on two lanes dropped below E_c or u_c. This approach, in effect, uses information from a detector on a second lane to verify the reliability of the data from the first. To test the feasibility of a two-lane control criterion required that an analysis be made of the relative movements of stoppage waves between lanes and the performance of this concept. These are discussed in the following sections.

Relative Movement of Stoppage Waves

The cumulative frequency of the time difference between the arrival of the first and second stoppage waves at the detector stations is shown in Figure 8. The plot reveals that, in approximately 23 percent of the cases studied, the second wave reached the detector station more than 30 sec after the first wave. Ten percent of the cases resulted in a time difference of 97 sec or more.

It would appear at the outset that a great degree of efficiency might be lost when using a two-lane control criterion. However, because the critical energy and speed parameters did exhibit predictive qualities, the effect of the parameters might compensate for some of the large time differences between stoppage waves. The extent of the change in performance relative to the one-lane criterion was evaluated and is discussed in the following section.

Two-Lane Control Criterion

The response times using a two-lane control criterion are shown in Figure 9. The results indicate that, generally, the system using a two-lane control criterion would respond within the expected limits. In only two cases out of 47 observed did the system respond later than 30 sec after the initial stoppage wave crossed the downstream detector station. In one extreme case, the system would not have sensed the presence of a major discontinuity in flow until 180 sec after the initial stoppage wave reached the detector station. A study of the video tapes revealed that in this one case the response would have been too late to warn motorists approaching the grade.

Comparisons of response times between the one-lane and two-lane criteria for critical energy and speed are also shown in Figure 9. As was expected, the results show that the two-lane criterion is less responsive to stoppage waves than the one-lane control criterion.

Trade-offs must be made in deciding the alternative course of action for an operational system. The one-lane criterion was shown to be acceptable. However, with this type of operation a defective detector on a lane can cause the warning sign to activate erroneously. The two-lane control criterion can compensate for the probability of a detector failure and appears to produce satisfactory results 96 percent of the time.

APPLICATIONS

This paper was concerned with a study of stoppage wave detection methods by using either critical speed or critical energy threshold values. Both parameters were found to be acceptable for application to digital computer control of the warning system.

Detector Location

Because the speed and energy parameters were computed from 1-min data updated every 30 sec, the response to a stoppage wave in some instances would be expected to be late by as much as 30 sec. The detectors located downstream of the overpasses must, therefore, be located a sufficient distance downstream of the critical freeway section to cope with this possibility. Observations in Houston have shown that the speed of stoppage waves will reach as much as 26 fps. Thus, it is possible that a wave could travel at least 720 ft (26 fps × 30 sec = 720 ft) before the logic responds to it. To ensure a factor of safety in the design, we selected a design travel distance of 800 ft. To ensure that the system responds to a stoppage wave before the wave reaches the foot of the vertical curve required that a suggested placement for the basic set of downstream detectors be developed (Fig. 10). It may at times be desirable to place some additional detectors downstream of this basic set to allow for a greater degree of advanced warning. The desirability of these additional detectors would be dictated by the specific problem location.

One function of the upstream detectors is to signify whether the conditions upstream of the overpass are such that a stoppage wave propagating on the far side of the overpass would result in hazardous conditions for approaching motorists. A second function is to turn the sign off once the stoppage wave has passed over the upstream detectors. The detectors should be located downstream from any bottlenecks existing in the immediate area. In some cases, a high-volume ramp may cause some congestion on the shoulder lane. The probability of not being responsive to a stoppage wave in the shoulder lane is reduced by positioning the detectors downstream from the ramp. The results of the analysis on the Gulf Freeway indicated that detectors placed at distances shown in Figure 10 appear to work satisfactorily, barring the influence of a ramp.

Control Logic

Based on the results of this study, a control logic was developed for digital computer control of the warning system. The logic assumes that a one-lane criterion is used at the downstream station and a two-lane criterion is used at the upstream location. Additions were made to permit 24-hour a day operation for 7 days each week. It should be understood, however, that the program is not overly sensitive to incidents occurring during periods of extremely light flow as would be experienced during the early morning hours. This is due to the limitations of detector placements in addition to the fact that the logic responds to the effects of incidents. As long as stoppage waves are present, the program will be responsive. However, the program is not capable of responding to incidents occurring between the upstream and downstream detector stations during these early morning hours. A flow chart for the control logic using energy as a control variable is shown in Figure 11. A comparable program can be structured for speed. The following list refers to the notation used in the figure and represents variables computed on a per-lane basis:

Figure 10. Suggested detector locations.

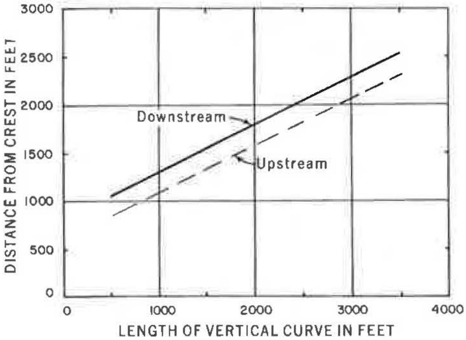
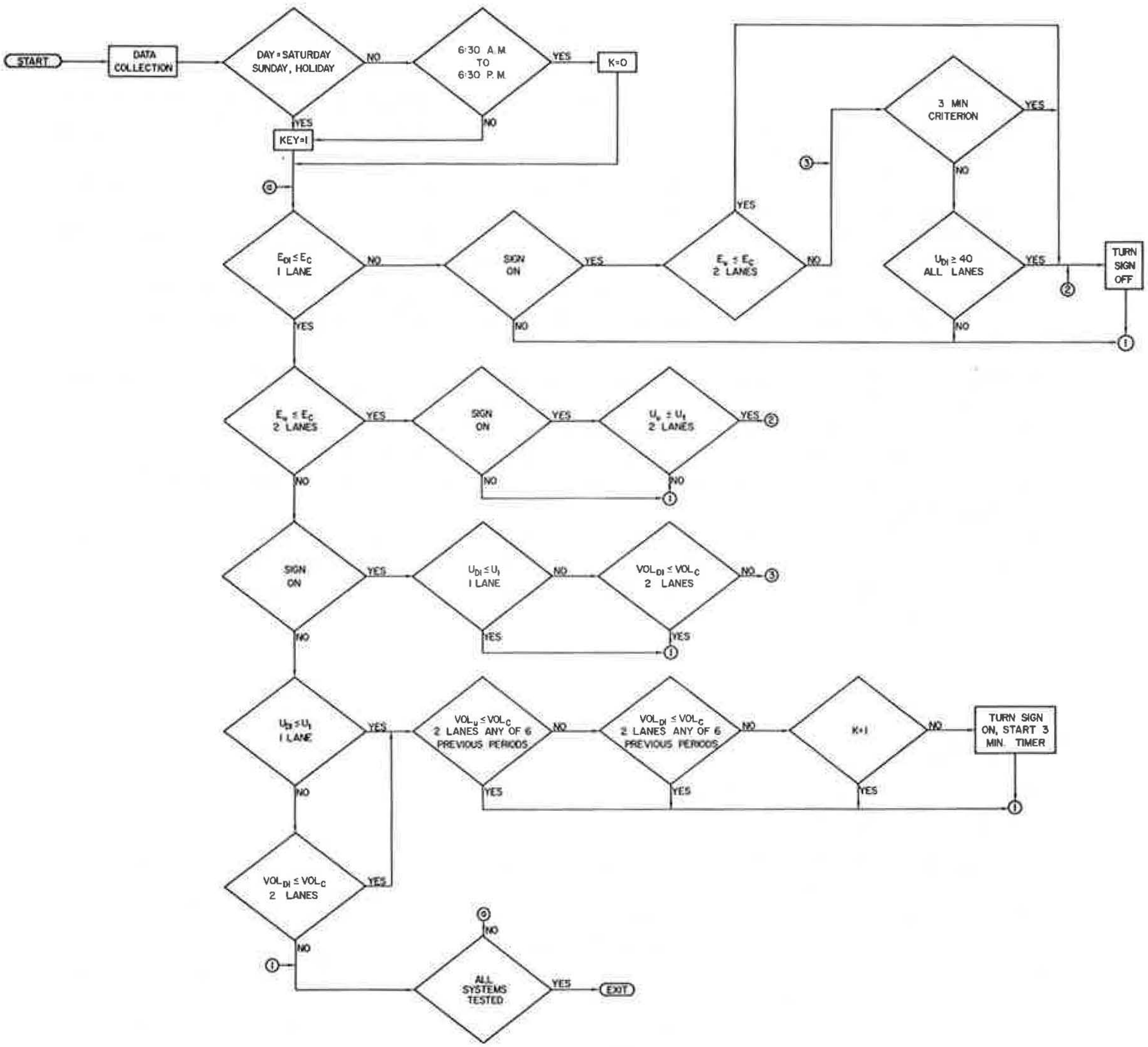


Figure 11. Flow chart of control logic.



E_u = energy upstream
E_{D1} = energy downstream
Vol_c = threshold volume (8 vpm)
Vol_u = volume upstream
Vol_{D1} = volume downstream
u_t = threshold speed (35 mph)
u_u = average speed upstream
u_{D1} = average speed downstream

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DISCUSSION

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The authors have presented the development and preliminary testing of a very interesting driver information system. The system detects queues or stoppage waves in the freeway traffic stream and activates upstream beacons to warn the motorists of a forthcoming speed reduction. This system has the potential of accomplishing a great reduction in the frequency of rear-end accidents and other accidents caused by shock wave propagation in a traffic stream.

One area of potential application of a warning system of this type is the situation described by the authors, namely, areas in which there are sight distance restrictions caused by geometric design deficiencies. There is a more general area of potential application, however. This would be the warning of shock waves on any urban freeway during peak periods. When traffic densities are high, sight distance can be severely limited on a freeway of any geometric design. At operating conditions near capacity, headways are small, and this combination produces a potentially hazardous situation if a shock wave develops in the stream.

Another area of application would be freeway or tollroad situations in which traffic volumes are moderately high. In these cases, shock waves would be generated at irregular times and would be propagated through the traffic stream. An advanced warning of this situation would provide a definite safety benefit.

One must commend the authors for proposing a system that is inexpensive and easily understood by the drivers. At a time when most considerations are given to large, expensive, complex, sophisticated, and more glamorous systems, it is refreshing to note the authors' presenting a straightforward solution to a driver communication problem. A system that included a similar concept was proposed for the City of Baltimore after a cost-effectiveness analysis ruled out more elaborate alternatives (11).

The authors presented the results of studies of the practicability of detecting freeway stoppage waves and predicting their arrival at an upstream location. They used both speed and kinetic energy measures and found that they were about equal as far as their detection of shock waves is concerned. The kinetic energy measure was found to produce some false alarms under low-volume conditions, whereas the speed measures did not create this problem. This would lead the discussant to conclude that, for an operational system, speed measures would be preferable to energy measures.

Finally, the authors echo the need for more reliable detectors. Anyone who works in the field of traffic control issues the same plea from time to time. Perhaps someday manufacturers will find it important enough to respond to.

In summary, the authors have described a very good and useful safety warning system for freeways and have adequately developed and tested the concepts. We look forward to a wider application of this type of system.

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DISCUSSION

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The authors should be commended for research and implementation of a system designed to indicate stoppage waves by algorithms by using speed and kinetic energy parameters. Their effort was aimed at some specific problem locations characteristic of the roller-coaster type of design of an outmoded freeway. In this research the stoppage waves were generated out of sight (over the crest) of approaching motorists, and a warning system was needed to reduce the number of rear-end collisions. My experience has been that the stoppage wave development is usually on the upgrade or foot portion of the vertical curve rather than on the downgrade portion past the crest. With this in mind, it would have been helpful for the authors to have given more details on the experimental sites, including both traffic and geometric features. For example, I received the impression that some stoppage waves were generated by excessive demand. However, there were off-ramps in the study sections; exiting traffic was given as a reason for the right lane stoppage waves moving slowly upstream.

The generalized suggested locations of detectors (Fig. 10) are a useful aid. Here again, I would have preferred more detail on the detector placement for the individual study sections and the associated geometrics of the vertical curves.

The authors did not stray from their subject area in presenting this research. Beyond the suitability of the parameters, I am curious about the actual effect on the motorist and the effects on accident statistics. Even a preliminary subjective evaluation would be helpful although I suppose an evaluation of system effectiveness is taking place; in the case of accident statistics, this requires patience over a longer period of time. Past research by others on similar traffic warning devices has been curiously devoid of the human factors element. I do not think it is enough to measure and analyze traffic variables without determination of the devices' alerting effects, which might not show so significant in speed measurements yet might prove important in accident statistics or more subtle aspects of traffic stream flow stability. There have been past weaknesses in not identifying motorists' reactions to the presented information and use thereof. I hope that future research will be more cognizant and attempt to rectify these shortcomings.

At this point, I would like to digress to a topic closely related to the paper presented at this session, that of sight distance on freeways. Our present sight distance criteria might be perfectly adequate for rural freeways but, for those freeways carrying traffic at levels of service C, D, and E, it should be apparent that present sight distance criteria are hardly applicable. Sometimes we see only the back of the car ahead of us. Other times, when at the crest of a vertical curve and looking out over a curving downward section, we can see traffic stream characteristics for a great distance ahead. Perhaps there should be research undertaken to more adequately describe in quantitative terms what the real sight distances are for traffic streams of high density. Conceptualization of a research approach leading to development of applicable sight distance criteria seems to me a very difficult problem in itself.

In summary, I think the authors have done a fine job, and my comments are based more on what they did not tell me rather than what they did tell me. And I am glad I had the opportunity to make a few remarks on sight distance criteria.

AUTHORS' CLOSURE

The authors are appreciative of the excellent reviews by Wattleworth and Hess. Their comments are very appropriate and will be of assistance in developing techniques for improving the safety and efficiency of existing freeway systems.

The prototype safety warning system on the Gulf Freeway has been under digital computer operation since February 1972. We are very confident in the hardware and software operation and feel that the system can be implemented at other locations. As of this writing, however, we have not fully evaluated motorist response to the system. Evaluation studies are in progress, and the results will be available when the studies are completed.

The control algorithm presented in the paper is responsive to stoppage waves generated from both freeway incidents and excessive demand conditions under moderate to heavy flow conditions. Modifications to both the algorithm and detector configuration may be necessary to make the system responsive during extremely low-volume conditions.

Although the speed parameter was shown to be as responsive as the energy parameter, there have been unexpected spin-offs resulting from the latter. First of all, the energy parameter is responsive to slow-moving vehicles such as trucks or funeral processions during the off-peak periods, whereas the speed parameter is not. Secondly, whenever we receive a false alarm during the off-peak periods, we are almost assured that a detector is transmitting erroneous data. We have computer software that allows us to locate detectors that fail completely. However, when a detector fluctuates into a "gray" area without complete failure, this is more difficult to isolate. The energy parameter, however, assists us in spotting those detectors that are operating in the gray area.

It must be emphasized that the computer algorithm for the warning system is not an incident detection scheme. The algorithm is responsive to stoppage waves only and does not necessarily indicate the presence of a freeway incident. We are in the process of developing incident detection logic that will be an add-on to the stoppage wave program. Utilization of this logic in conjunction with travel time prediction techniques (12) will permit real-time evaluation of freeway conditions so that appropriate changes in ramp control strategies can be made and appropriate information can be relayed to the driver for effective diversion within a corridor.

REFERENCE

12. Messer, C. J., Dudek, C. L., and Friebele, J. D. A Method for Predicting Travel Time and Other Operational Measures in Real-Time During Freeway Incident Conditions. Highway Research Record 461, 1973.