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TRAFFIC ACCIDENT RESEARCH UNIT

DEPARTMENT OF MOTOR TRANSPORT N.S.W.

A TRAFFIC SIGNAL SYSTEM FOR HIGH-SPEED ROADS

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B.Sc. (Tech.)

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The Traffic Accident Research Unit was established within the Department of Motor Transport, New South Wales, in May 1969 to provide a scientific approach into traffic accident prevention.

The Unit brings together a team of medical practitioners, scientists, statisticians, psychologists, sociologists and engineers engaged full time on research into all facets of road accident causation.

This paper is one of a number which report on their research and is published for the information of all those interested in the prevention of traffic accidents.

D. R. Coleman

Commissioner.

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ABSTRACT

Even at suburban intersections controlled by traffic signals where the speed limit is 35 m.p.h. most drivers will at some time have found themselves in the so called "dilemma zone". On the approach to traffic signals, this zone is where most drivers, at the onset of the amber signal, find themselves in the predicament of being too close to the intersection stop line to stop safely or comfortably, and yet too far from it to clear the intersection before the red signal is displayed.

The length of and distance from the stop line of this dilemma zone are functions of driver reaction time, vehicle stopping distance and the duration of the amber signal. Therefore, where the driver's dilemma is enhanced by high vehicle speeds on the approach to traffic signals, the risk of serious driver error with the resultant possibility of an accident is increased dramatically.

This report describes the development of a traffic signal system for use on high speed roads. The aim of the system is to reduce the risk of driver error by minimising the chance of the traffic signals changing from green to amber while a vehicle is within the dilemma zone associated with its approach speed. The equipment developed consists of a series of conventional vehicle loop-detectors installed in the roadway on the high speed approach to the signals. These detectors are coupled to a standard traffic signal controller through a timing and detector output control device which renders the detectors sensitive to vehicles in certain speed ranges. The relationship between the distance of each detector from the stop line and the range of its speed sensitivity are derived from Crawford's experimental results on driver judgment and error during the amber period at traffic lights (Ergonomics, 5(4) : p513)[1].

INTRODUCTION

The need for traffic signals on a high speed road first arose in New South Wales on the Berowra-Hawkesbury section of the Sydney to Newcastle Tollway. The interim traffic arrangements pending the completion of a new bridge across the Hawkesbury River necessitated the north-bound traffic lanes of the Tollway meeting the Pacific Highway at a junction just south of the existing bridge. A plan of the junction is shown in Figure 7 and photographs of the location are shown in Figures 8 and 9.

This junction at Hawkesbury occurs at the end of a section of expressway several miles long, with a speed limit of 65 m.p.h. and a considerable average down gradient. It was considered that in this situation, the control of traffic by conventional signals could create hazardous conditions.

Webster and Ellson[2] have investigated the problems associated with traffic signals on high speed roads and in their report they describe a signal system developed for these roads. However, the equipment, although in commercial production in the U.K., could not be made available in time for the opening of the new Tollway section on 12th December, 1968. As an alternative, a signal system was developed which utilized as much conventional equipment as was practicable.

The system developed to obviate the dilemma zone employs a standard two phase traffic-actuated controller with a speed-sensitive multiple detection system for high speed traffic on the Tollway. Apart from the simple timing and detector output control device, all equipment is standard traffic signal equipment.

Prior to the opening of the Berowra-Hawkesbury section of the Tollway, the system developed was installed and tested to prove the design. The system was commissioned concurrently with the opening of the new section of the Tollway on 12th December, 1968.

THE DILEMMA ZONE

On the approach to traffic signals a driver will at some time find himself in the so-called "dilemma zone". This zone is where most drivers, at the onset of the amber signal, find themselves in the predicament of being too close to the intersection stop line to stop safely or comfortably, and yet are too far from it to clear the intersection before the red signal is displayed (See Figure 1). The determination of the dilemma zone and the problems associated with it have been the subject of several studies.

Gazis et al[3] examined this problem on the basis that under the law in certain States of the U.S.A., many drivers were faced with a decision-making situation that could not be solved. This situation is enhanced by the practice of using "fixed time" traffic signal controls, because with these controllers every change of phase is independent of approaching traffic.

The law in New South Wales regarding the amber signal states that a driver facing this signal shall not proceed beyond the stop line or enter the intersection, unless his vehicle is so close to the stop line or the intersection when the amber signal first appears that he cannot safely stop his vehicle before passing the stop line or entering the intersection. This law attempts to provide an operational definition of the meaning of the amber signal with specific instructions to drivers as to when they may drive on. Although not providing a real solution to the driver's dilemma the law is supported by the practice of using traffic-actuated controllers which materially reduce the dilemma zone problems. It was concluded by Gazis that the correct resolution of the problem may be found in the following:

(i) Design the duration of the amber phase according to some realistic criterion in order to guarantee that a driver can always be in a position to obey the law;

(ii) If the amber phase is to be kept short in apparent contradiction with the crux of the problem, then the law should be stated in such a way as to make it compatible with the driver, car, road and signal characteristics.

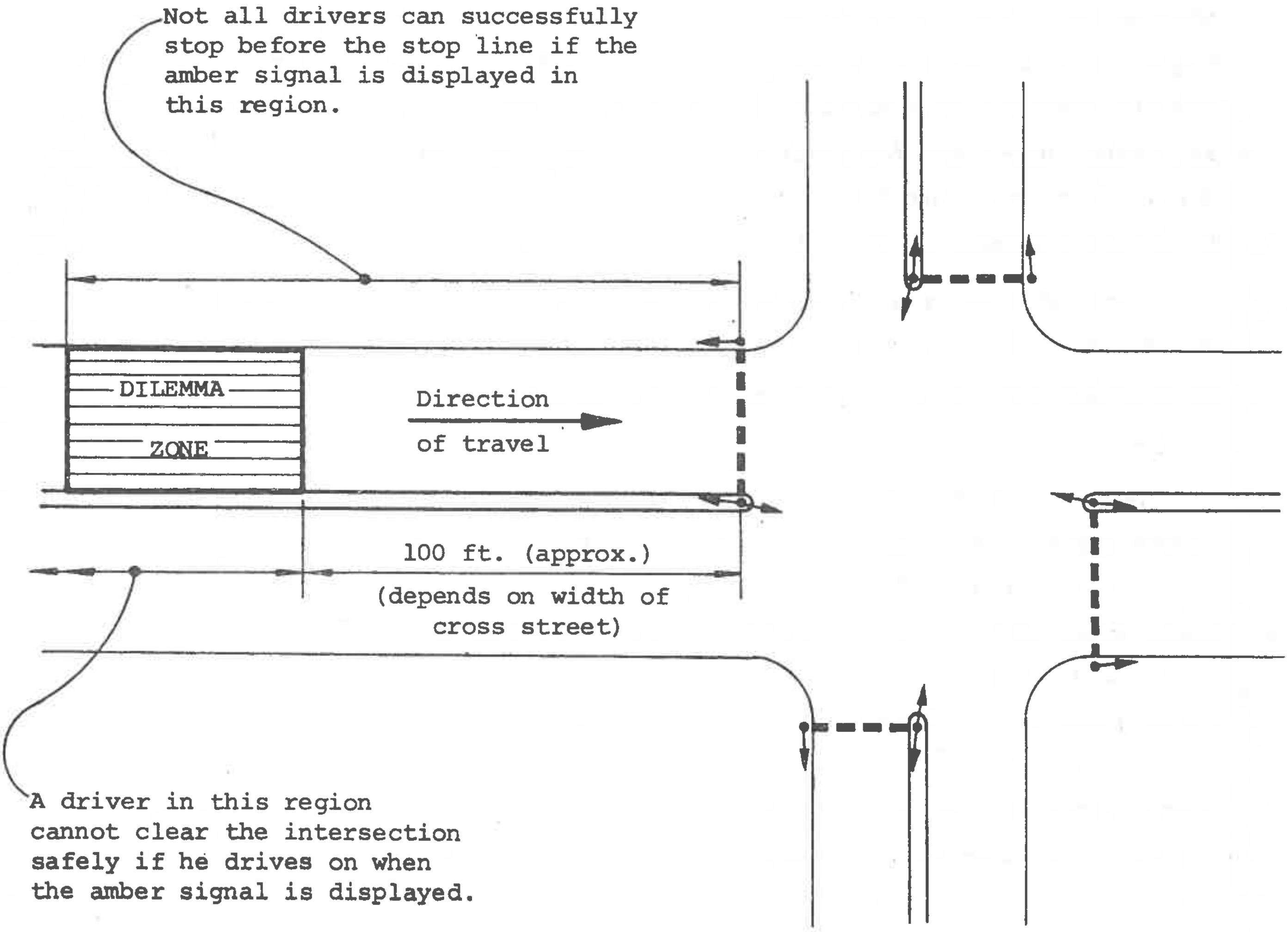


FIGURE 1

Diagrammatic representation of the driver's dilemma zone at traffic control signals for an approach speed of 35 m.p.h. and a three second amber signal duration.

In either case it is considered very advisable to educate both the driving public and law enforcement agencies as to the exact operational definition of the amber light.

Gazis also derives a formula for the minimum amber phase duration that would eliminate the dilemma zone. The use of this formula, however, requires assumptions concerning the reaction-decision times of drivers and the constant deceleration used to stop. Both of these parameters are rather uncertain for practical usage and as a result Olson and Rothery[4] derived a formula based on empirical data, obtained in the field, relating to driver response to the amber signal.

Both of these studies were carried out in the U.S.A., presumably on fixed time traffic signals, and both indicated the need for an amber phase of somewhat longer duration than the standard three seconds (as used in N.S.W.).

Several experiments have also been carried out at the Road Research Laboratory to investigate the performance of drivers during the amber phase at traffic signals. All of these experiments were carried out on a test track arranged to simulate a signal-controlled intersection on a high speed road. These experiments were similar in that a number of drivers driving several different vehicles made numerous runs through the signal-controlled intersection. Approach speeds were varied over a considerable range, and the onset of the three second signal was controlled in such a way that any combination of approach speed and distance from the intersection when the amber signal was displayed could be examined. A randomised and balanced programme of runs was carried out, and included combinations of circumstances for which the decision to stop or go on was simple, and a proportion of runs when the signals were kept on the green phase. The proportion of successful stopping runs and the distance from the stop line when the amber signal was displayed in these cases was then examined in detail.

From the experimental results it was concluded that the differences due to driving the different vehicles were not significant and hence the results for the different vehicles were combined. From a regression analysis of the data, these experiments produced, for the various speeds examined, percentile values of the distances from the stop line from which satisfactory stops were made at the onset of the amber phase. Two of the experiments produced slightly different results (See Tables 1 and 2) but no attempt has been

TABLE 1

(From Crawford and Taylor[5])

Approach speed (m.p.h.)	Distance of vehicle from stop line at the onset of the amber signal (ft.)		
	Percentage of successful stops		
	50%	80%	95%
20	47	58	70
30	90	111	134
40	143	175	213
50	204	250	304
60	273	335	407

TABLE 2

(From Webster and Ellson[2])

Approach speed (m.p.h.)	Distance of vehicle from stop line at the onset of the amber signal (ft.)			
	Percentage of successful stops			
	10%	50%	90%	95%
30	80	105	135	145
40	125	160	205	220
50	185	235	300	320
60	275	345	440	460
70	400	525	650	700

made in this investigation to analyse these differences. The Webster and Ellson data from Table 2 is plotted in Figure 2 to show graphically the dilemma zone between the 95th percentile successful stopping threshold and the amber phase clearance distance.

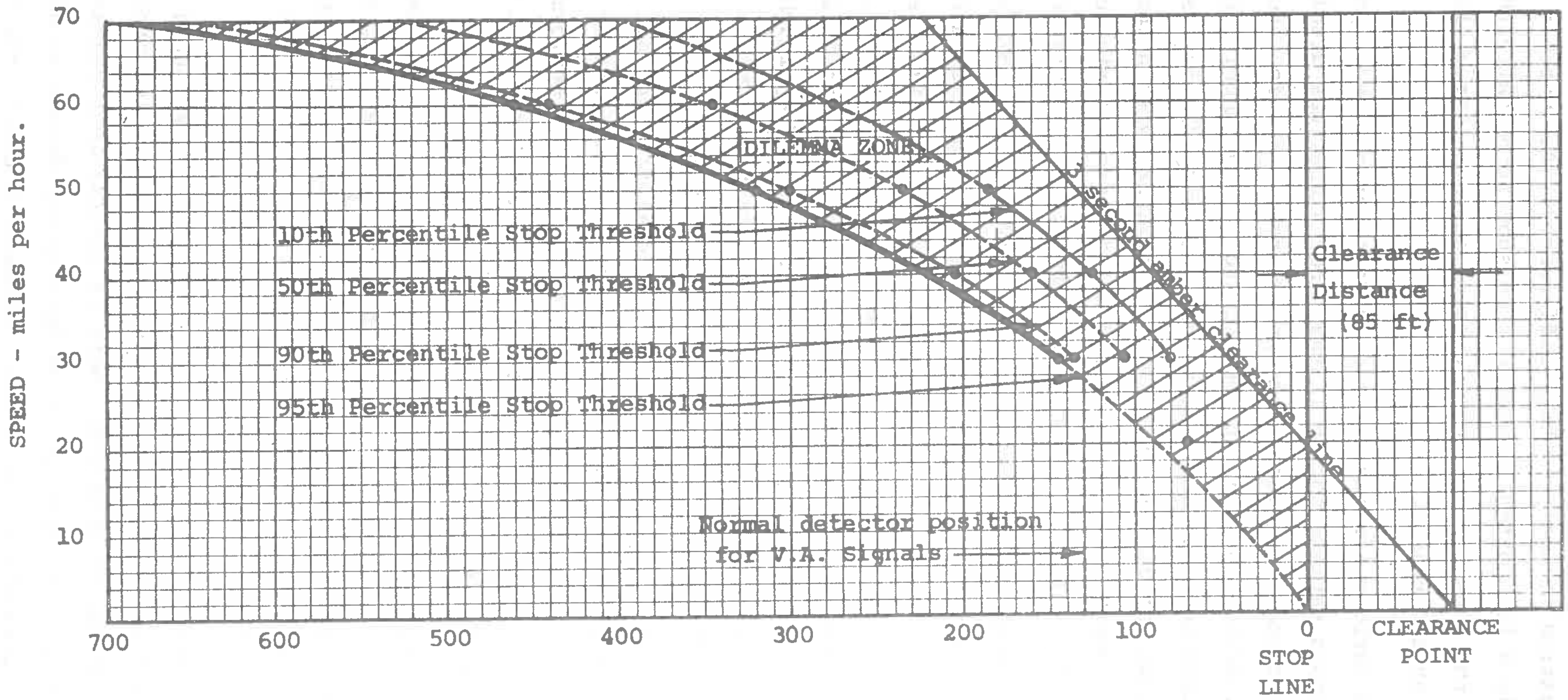
As expected, the various experiments showed that for a given approach speed all drivers stopped satisfactorily if the amber signal was displayed before they reached a certain distance from the intersection; for the same speed of approach all drivers made no attempt to stop if the amber signal was displayed after they had passed a certain distance from the intersection. Between these two points the dilemma zone existed, that is, within this zone, some drivers stopped, some drivers drove on and all drivers experienced some degree of dilemma. This situation is shown diagrammatically in Figure 1.

Crawford[1] carried out a detailed investigation of driver judgment and error during the amber period at traffic lights based upon data obtained in another experiment[5]. The results of this research provide a rationale for the choice of traffic signal control design criteria, that is, the choice of P, where P is the proportion of drivers who will stop satisfactorily at the onset of the amber period for the various combinations of approach speed and distance from the intersection. This proportion determines the location and extent of the dilemma zone for design purposes.

Because it is not practicable to cater for all drivers under all conditions, the criteria of design for the signal system developed by the author is based on the recommendation by Crawford that optimal performance could be achieved when P = 95%. This implies that 5% of drivers will be "unsafe" at the onset of the amber signal.

The recommendation by Crawford to use P = 95% is based upon a measure of task difficulty: $\log \frac{d}{D} = 0.2$ where d is the distance available to stop and D is the driver's judgment threshold at the particular approach speed. For this value only a small proportion of decisions to stop result in changes of mind or stopping errors.

Using the recommended design criterion of P = 95%, the remaining 5% of drivers who are potentially at risk can be subdivided into two groups: (1) those drivers who decide to stop when there is insufficient distance available before the stop line, and (2) those drivers who decide to drive on when it will not be possible to clear the intersection before the red



DISTANCE FROM STOP LINE - feet

FIGURE 2

Graph showing sections of the approach to traffic signals where drivers may be in a dilemma.

Plotted from data obtained by Webster and Ellson[2]. See Table 2 light appears. Crawford and Taylor[5] found that of the decisions to stop from the 95% threshold distance, less than 1% resulted in errors, hesitations, etc., indicating that the hypothetical group (1) described previously is of negligible size and therefore most of the "unsafe" drivers will be in group (2). The duration of the "all red" period necessary to ensure the safety of this second group of drivers can be determined by the method derived by Olson and Rothery for calculating the duration of the amber phase and then subtracting three seconds (the N.S.W. standard amber duration).

Crawford observed some interesting characteristics of drivers in the environment of the experiment. He found that although drivers would be expected to apply an average deceleration to their vehicles of 0.36 g when stopping from the 95% stopping threshold, most drivers waited before applying the brakes. Hence the average deceleration required was somewhat higher than would have been necessary if the brakes had been applied with the minimum reaction time. The delay in application of the brakes resulted in the average deceleration being an almost linear function of the difficulty of the task of stopping. The results also suggest that there is a minimum level of deceleration which drivers use, as well as a maximum which is governed by the brakes, tyres, surface characteristics etc. (Figures 3 and 4).

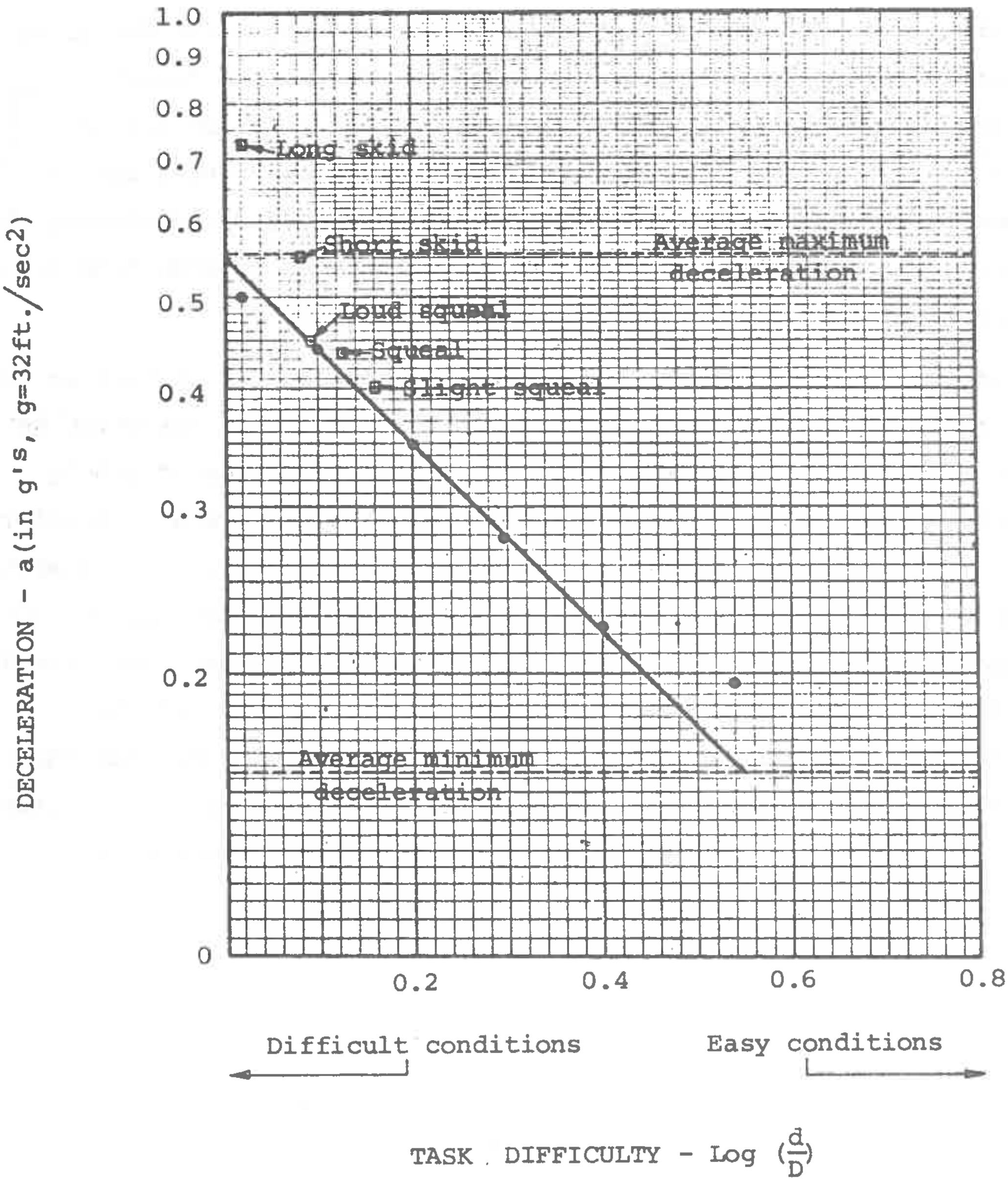


FIGURE 3

Mean deceleration according to task difficulty with straight line fitted to middle four points (the most controllable range).

Co-ordinates shown thus ⊡ are the average of the runs at 40, 50 and 60 m.p.h. in which the tyres squealed and skidded.

(From Crawford[1])

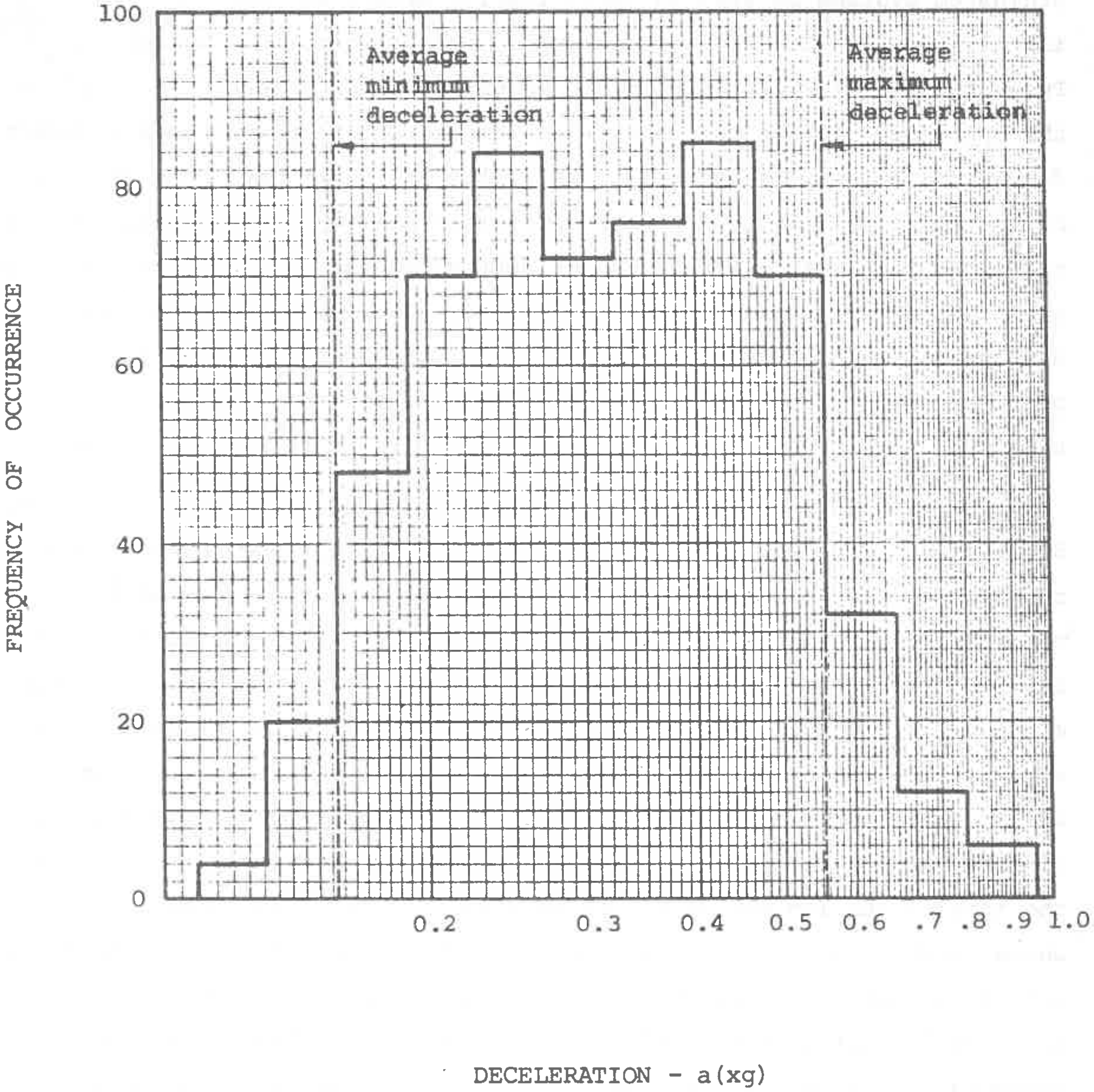


FIGURE 4

Distribution of the average decelerations incurred in stopping at traffic lights (From Crawford[1])

OPERATIONAL CHARACTERISTICS OF TRAFFIC CONTROL SIGNALS WITH TRAFFIC ACTUATED CONTROLLERS

Except for isolated mid block signals for pedestrians and the co-ordinated systems as used in dense traffic areas, all traffic signal installations in New South Wales employ traffic-actuated controllers. These controllers respond to vehicles passing over detectors located on the approaches to the intersection. When a vehicle passes over a detector during the display of the red signal, provided there have been no actuations of the detectors on the opposing approaches for a preset period, the amber signal is displayed on the opposing approaches for a standard duration of three seconds, followed by the red signal. The green signal is then displayed simultaneously except that if a preset "all red" period is provided red signals are displayed on all approaches. The duration of the green signal varies according to the traffic passing over the detectors.

The green period, called the "traffic running period", is effectively divided into two parts, the "initial running period" and the "maximum running period". The initial running period is increased from the minimum preset time necessary for one vehicle to start up and cross the intersection by one or more set increments, the number of which is determined by the number of vehicles that cross the detector before the green signal is displayed. This ensures that all vehicles stationary between the stop line and the vehicle detectors will have time to move off and clear the intersection before the termination of the phase. At the end of the initial running period the green phase will continue indefinitely unless a vehicle arrives on the opposing approach. When that happens, the vehicle actuates the detector on the opposing approach, and the green phase then running enters its "maximum running period". This period can be extended by a preset amount called the "traffic extension" whenever a vehicle crosses the detector on the running approach. If a time "gap" greater than the traffic extension occurs between successive vehicles at any time during the maximum running period, the green signal of the running phase will be terminated, thus allowing a green signal to be displayed to opposing traffic. Change of phase in this way from one approach to the opposing approach is termed a "gap change".

It is obvious that under heavy traffic conditions the "gaps" between successive vehicles are smaller and hence overlapping "traffic extensions" would prevent a gap change occurring. To avoid the inordinately long green periods that would result, a maximum period is timed from the arrival of the first vehicle on an opposing approach. At the end of this maximum period regardless of the traffic requirements the green phase is terminated. Change of phase in this way is termed a "maximum change".

The normal location of vehicle detectors is 130 feet from the stop line, but is varied depending on the gradient of the approach and the geometry of the intersection. The duration of the traffic extension period is set such that vehicles travelling at their normal running speed would have sufficient time at that speed to reach a point just beyond the stop line. Because of the location of these detectors it is apparent that even at moderate speeds of up to the suburban general speed limit of 35 m.p.h. the dilemma zone problem exists. It has been shown by Crawford[1,5] and Webster[2] that the start of the dilemma zone can be up to 165 feet from the stop line at these speeds (Tables 1 and 2). This means that a vehicle would not be detected until it had travelled a minimum of 35 feet in its dilemma zone and hence a gap change could occur during this time with the resultant chance of serious driver error.

ALLEVIATING THE DILEMMA ON HIGH SPEED ROADS

For high speed roads the shortcomings of the normal signal equipment and detector locations become more obvious than for roads subjected to the 35 m.p.h. suburban speed limit. For example, at 50 m.p.h. the dilemma zone, for some drivers, starts some 300 feet from the stop line. Hence a vehicle would be in the dilemma zone associated with this speed for over 170 feet or two seconds of travel. The chances of driver error would therefore increase alarmingly at high speeds if conventional signal control equipment were used.

It would seem that the solution to the problem is simply to relocate the detectors in the high speed approaches so that an approaching vehicle would be detected before it entered its dilemma zone, that is, for an approach with speeds up to say 60 m.p.h. the detectors would need to be located approximately 460 feet from the stop line (assuming the approach to be level). The problems associated with a single detector this distance from the stop line become immediately apparent. For example, vehicles travelling at speeds somewhat lower than 60 m.p.h. could need a traffic extension time of up to 10 seconds. Obviously, with an extension setting of this magnitude, very few gap changes would occur; that is, most phases would be terminated by the maximum timer and hence would occur arbitrarily.

Under the conditions of a maximum change, a vehicle, although having reset the extension timer by passing over the detector, can still be within its dilemma zone when the phase is terminated in this arbitrary manner. Another shortcoming of locating the detector at this distance from the stop line is that the control equipment is normally designed to provide an initial green period related to the number of vehicles arriving during the preceding red period and waiting between the detector and the stop line. Extreme difficulty would arise in attempting to extend this method with sufficient accuracy to meet the requirements of a signal system having a single detector so far from the stop line. Because of the inadequacies inherent in conventional signal equipment, if used on high speed roads, it was necessary to revise the normal methods of control employed in suburban areas.

Rather than add to the existing complexity of the driving task, particularly in the potentially hazardous environment of an at-grade intersection on a high speed road, it was decided that from the driver's viewpoint the proposed signal installation should not differ significantly from other signal controlled intersections in New South Wales. On this basis some of the methods examined of alleviating the driver's dilemma when approaching traffic signals at high speed were considered to be unsatisfactory. Webster and Ellson[2] outline these methods:

(i) Increasing the duration of the amber period;

(ii) Flashing or pulsating the signal lanterns at a predetermined time before the onset of the standard three second amber;

(iii) Display of a signal some distance in advance of the intersection to warn of an impending change;

(iv) Display of speed advisory signals;

(v) Display indication of the amount of green time remaining.

They also outline several objections to each of these methods, the most important of which is common to all of the above methods. This objection is that the flexibility of the traffic actuated controller would be substantially reduced because of the additional delay in effecting a change of phase arising from a demand from opposing traffic, which would in turn increase delays to traffic passing through the intersection.

Two other methods were examined:

(i) Reduction of vehicle speeds on the approaches to the intersection to at least 35 m.p.h. (the suburban speed limit applying to normal signal installations) by speed zoning;

(ii) Addition of an "all red" period after the standard three second amber to ensure adequate clearance time for vehicles unable to stop because of their higher approach speeds.

It should be noted that "all red" periods are already used extensively in this State to provide safe clearance of intersections. However, in a high speed environment, the all red period would be of necessity excessively long.

The first of these methods was considered impracticable because the signal-controlled junction under examination is preceded by several miles of high quality expressway with a legal speed limit of 65 m.p.h. The last mile of this expressway has an average 6% down gradient, of which approximately the last 1,000 feet has almost a 9% down gradient. These down gradients, together with the phenomenon of "velocitization", were considered to make the observance of reduced speed limits highly unlikely in this high speed road environment.

The second method, although solving the problem of possible collisions between the two opposing flows, does nothing to assist the driver in his dilemma. It also adds significantly to delays caused by the time lost between successive green phases.

Because of the difficulties associated with the methods previously discussed, it was concluded that the most appropriate method of alleviating the driver's dilemma was to modify the conventional vehicle detection system. These modifications were designed to ensure that the amber signal would not be displayed to any driver should he be within the dilemma zone associated with his approach speed.

Webster and Ellson achieve this by ensuring that extensions of the green period are provided whenever a vehicle is within this zone, and they employ an elaborate computing device coupled to a traffic actuated controller. A detailed description of its operation is given in R.R.L. Technical Paper No. 74[2]. The system developed by the present author provides similar operational characteristics but uses a method of speed-sensitive multiple detection.

DESCRIPTION OF THE SPEED-SENSITIVE MULTIPLE DETECTION SYSTEM

The detection system developed consists basically of a series of conventional loop detectors sensitive to various speed ranges, by which an extension of the green period is ensured while any vehicle is within its dilemma zone. Each of these detector systems is able to sense whether a vehicle is travelling at a speed greater than or less than a predetermined speed. This speed sensitivity is achieved by providing a timing detector "upstream" from the "extending" detection and comparing the time taken for a vehicle to travel between this pair of detectors with a preset timer (0.5 seconds). If the vehicle speed is such that it takes less than this time to travel between the pair of detectors, the traffic extension pulse is transmitted as the vehicle passes the extending detector. Conversely, if the time taken is greater than 0.5 seconds no extension pulse is transmitted.

The location of each extending detector is at the start of the driver's dilemma zone for that speed, and if a vehicle passes the detector at a speed greater than the predetermined speed a "traffic extension" pulse is transmitted to the controller. This signal resets the extension timer which holds the controller in the green period for the time set. The detectors are located in the high speed approach at intervals such that on passing the first extending detector at a speed just greater than its preset value, the length of the traffic extension period is just sufficient to allow the vehicle to reach the next extending detector if a constant speed is maintained.

To fix the locations of the extending detectors it was necessary to determine the limits of the driver's dilemma zone for various approach speeds. The delineation of this zone shown in Figure 2 is derived from the data of Table 2 which were obtained on a level test track. To allow for the down gradient on the high speed approach at the Hawkesbury site this zone was extended as shown in Figure 6.

The extension of this zone was based upon Crawford's criterion for design, that is, the probability of stopping (P) derived from a task difficulty ($\log \frac{d}{D}$) value of 0.2. For this value of $\log \frac{d}{D}$, Figure 3 shows a deceleration value of 0.36 g and Figure 5 shows a brake response time of approximately 0.9 seconds. From these data values of stopping distances

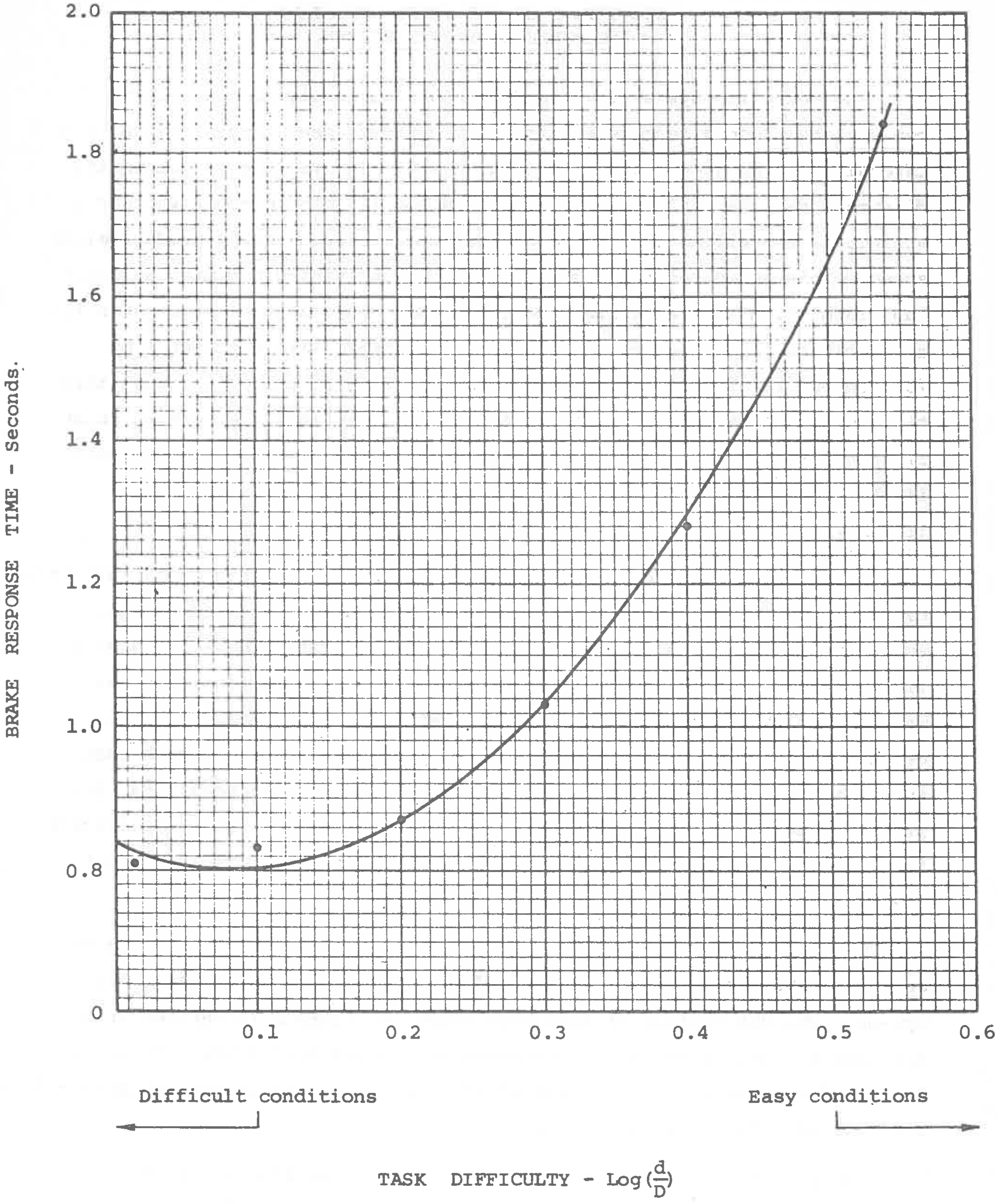
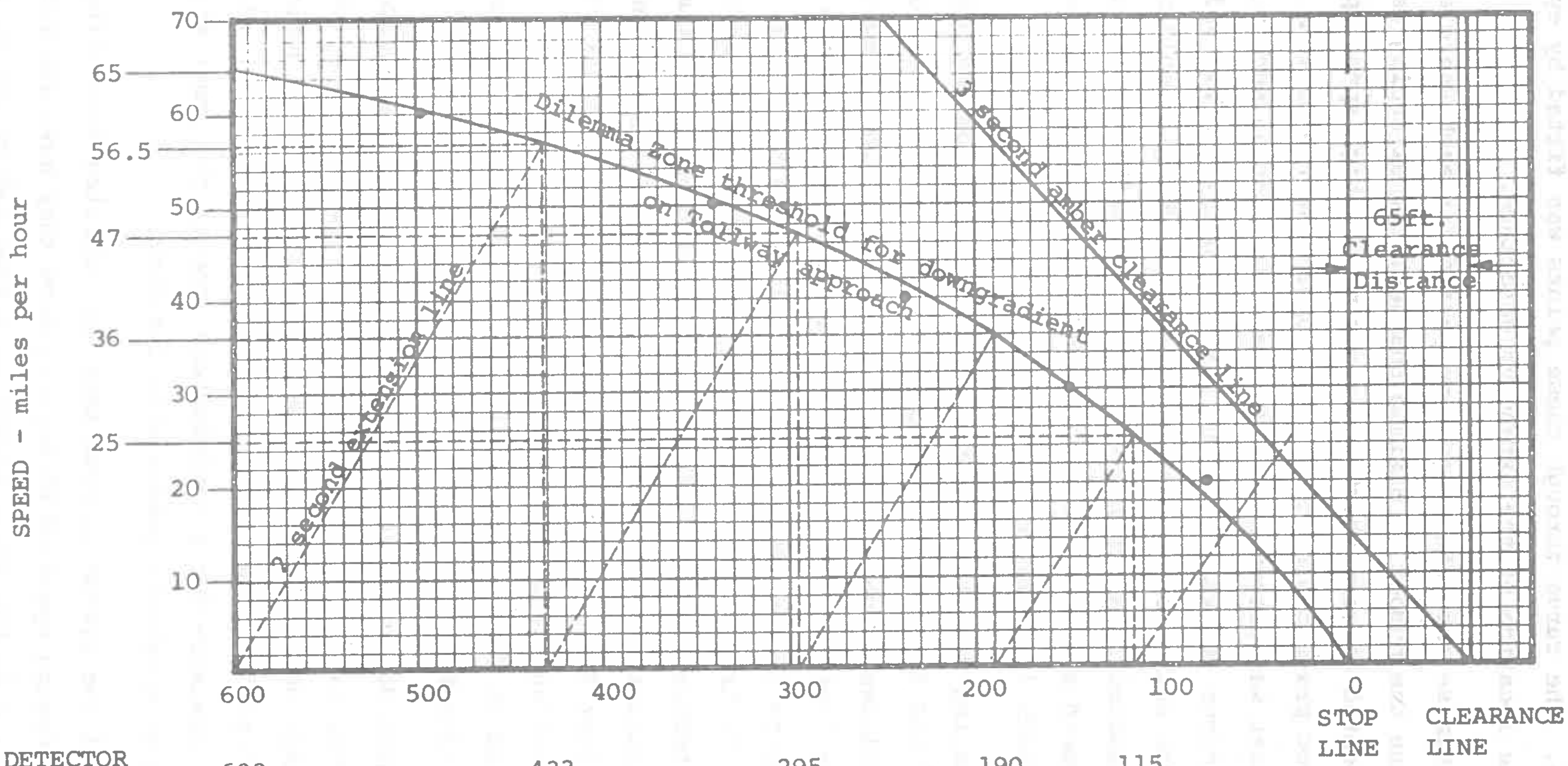


FIGURE 5

Mean brake response time grouped data according to task difficulty
(From Crawford[1])



DETECTOR LOCATION	600	433	295	190	115
SPEED SENSITIVITY	>56.5mph	>47mph	>36mph	>25mph	Normal Detector

FIGURE 6

Graphical determination of detector location and detector speed range sensitivity.

for various speeds with allowance for down gradient were calculated and plotted in Figure 6. The curve through these points was fitted by eye and is the basis for the location of the extending detectors.

In order to minimise the total extension period for each vehicle (a necessity to minimise the number of maximum changes) the extending detectors would need to be located at very short intervals on the high speed approach. This is obviously not practicable and so as a compromise the minimum number of extending detectors was determined by an iterative process such that under traffic conditions equivalent to the maximum hourly traffic volumes normally expected the estimated proportion of maximum changes would not exceed 1%. This resulted in a controller traffic extension setting of two seconds with four speed sensitive detectors and one normal detector along the high speed approach (See Figure 7).

The first extending detector encountered by a vehicle on the high speed approach is located 600 feet from the stop line which is the start of the dilemma zone for vehicles travelling at 65 m.p.h. (the design speed of the system and the speed limit on the Tollway). This detector transmits a traffic extension pulse if the speed of the vehicle is in excess of 56.5 m.p.h. A vehicle travelling at this speed will just reach the next extending detector before the expiration of the traffic extension time setting of the controller (two seconds). The location of the next detector encountered is 433 feet from the intersection stop line, the start of the dilemma zone for vehicles travelling at 56.5 m.p.h. The next three detectors are located at further intervals also of two seconds at the appropriate speeds (See Figure 6).

The last of these detectors is a normal detector which is located 115 feet from the stop line. At speeds in excess of 25 m.p.h., a vehicle could travel from this detector to the amber clearance distance during the two seconds of green period extension. At speeds less than 25 m.p.h. there would be sufficient distance for a satisfactory stop if the amber signal were displayed just as a vehicle passed this detector.

The operation of the system is such that for vehicles travelling at any speed up to the design speed of 65 m.p.h., once they have entered their dilemma zone, extension of the green period is guaranteed by the successive resetting of the traffic extension timer in the controller as the vehicle passes each extending detector. As the distance between the extending detectors decreases as the stop line is approached, the duration of the

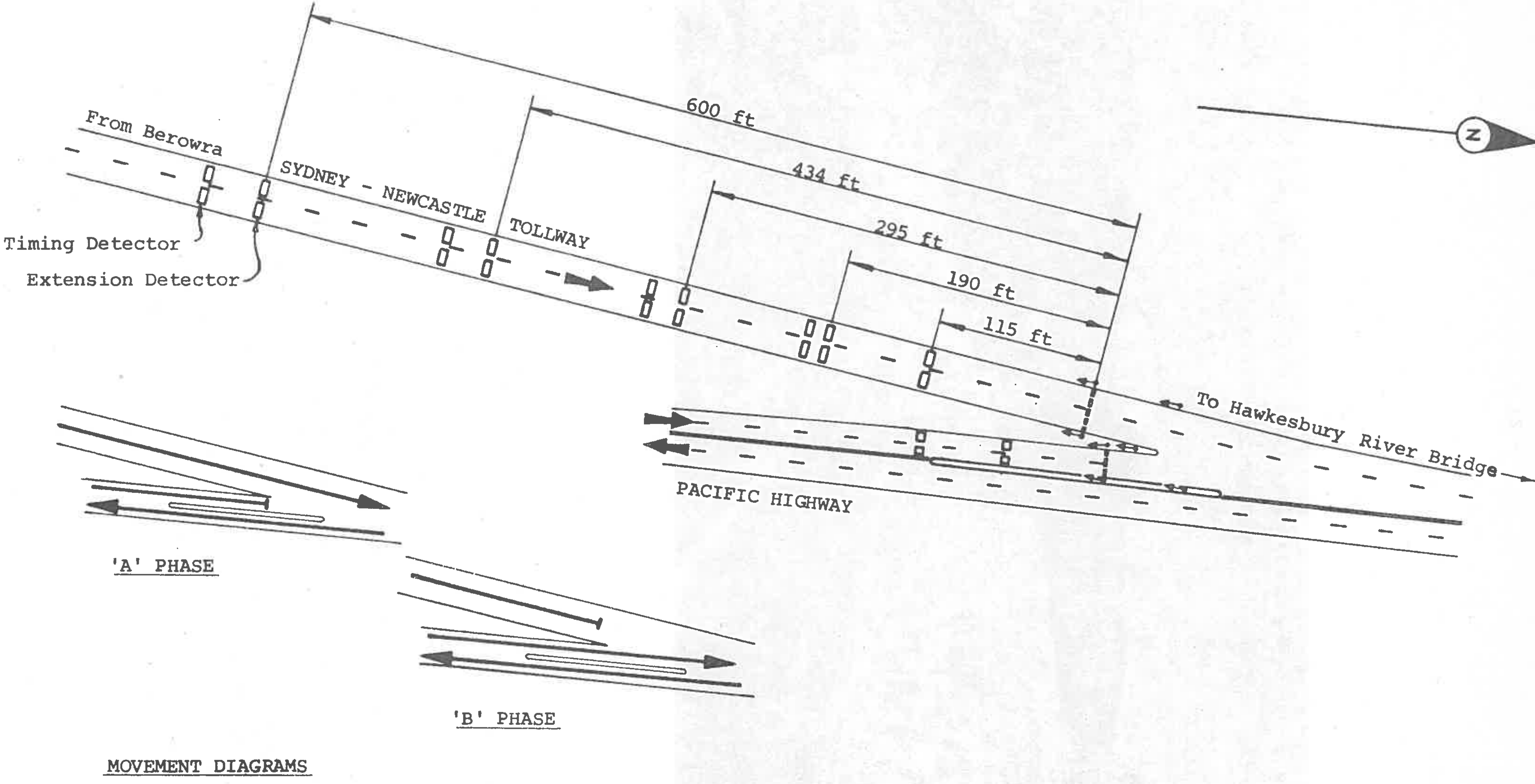


FIGURE 7

Plan of Signal Controlled Junction

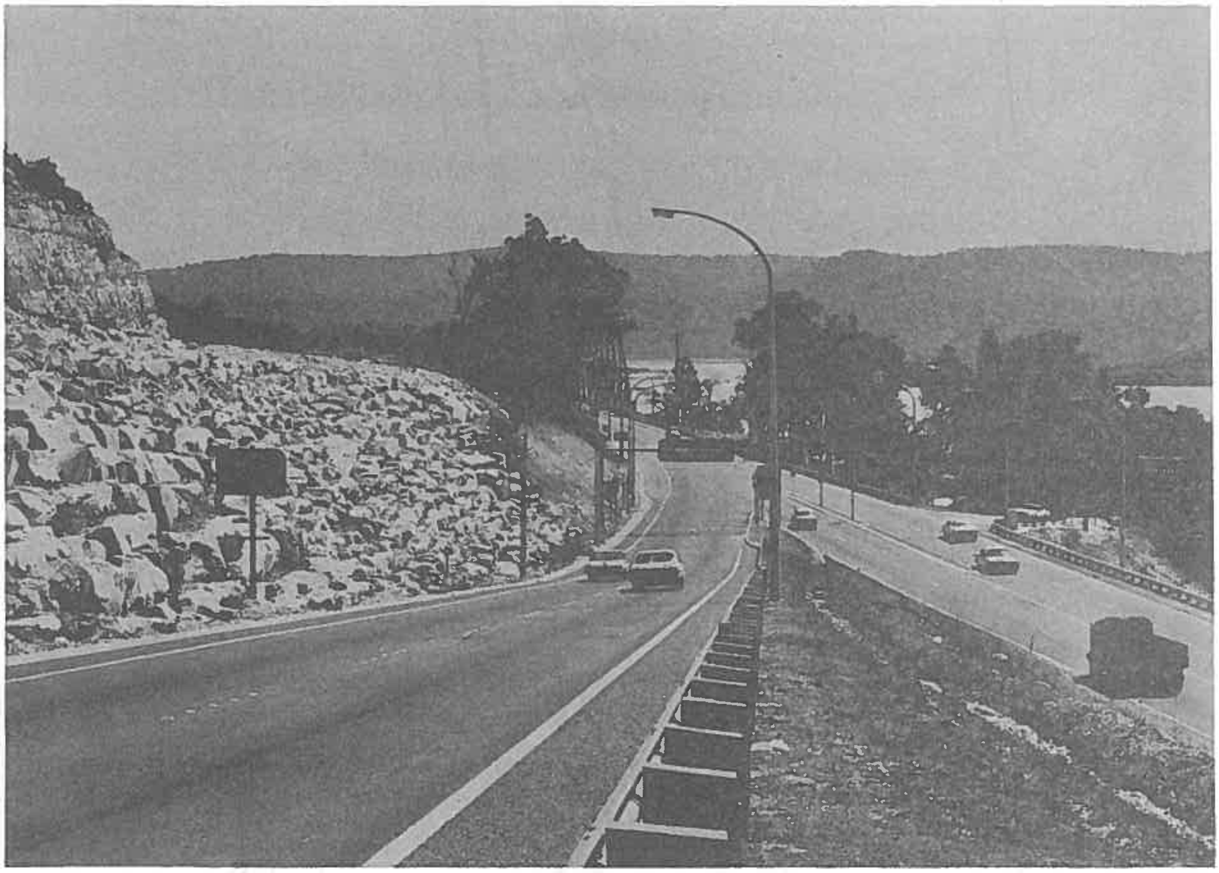


FIGURE 8

View towards junction from Tollway approach

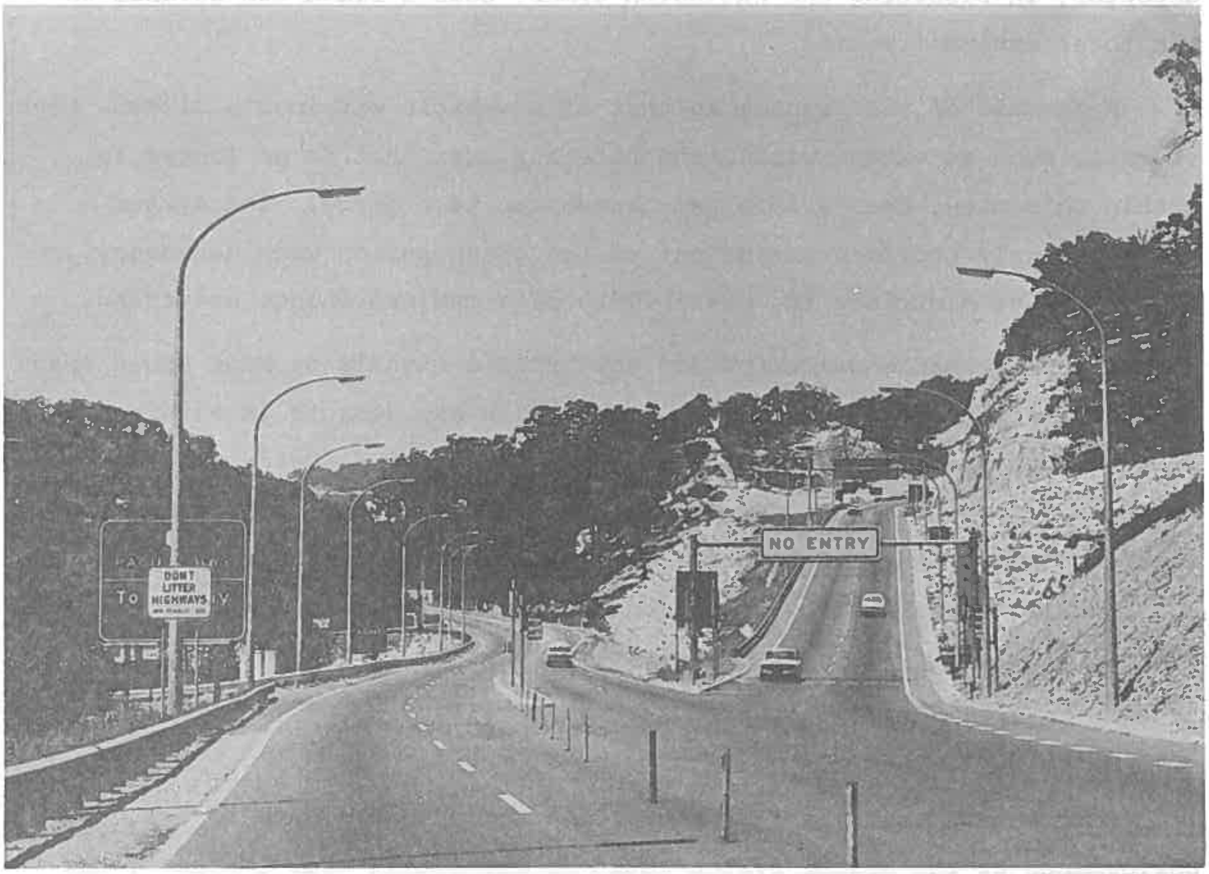


FIGURE 9

View of junction from Pacific Highway

extended period provided to reach the normal detector varies according to the requirements of the approach speed of the vehicle. The normal detector, in resetting the extension timer, adds a fixed two seconds to the total extended period.

A feature of this system is that if a vehicle within its dilemma zone slows to such an extent within the detector area that it no longer is within this zone, then a safe gap change can take place. The system therefore only provides extensions of the green period when necessary, and hence further minimises the possibility of a maximum change occurring.

The performance criterion set for traffic signals on high speed roads is that the signals should remain green while any vehicle is within the dilemma zone associated with its approach speed. The speed-sensitive multiple detection system developed ensures this, except when a maximum change occurs. Since it is not feasible to ensure that no maximum changes occur during heavy traffic conditions, a practical limitation must be set. This limitation is that the percentage of maximum changes during traffic flow conditions equivalent to the design hourly volume should be less than 1%.

For the Hawkesbury site, several assumptions were made so that the performance of the signal system could be predicted. For instance, the design hourly traffic volumes used in the prediction of performance were 1500 vehicles per hour on the Tollway approach and 400 vehicles per hour on the Highway approach. These are estimates of the 30th highest hourly volumes for 1972, the year of the scheduled completion of the new Hawkesbury River Bridge. The distribution of traffic speeds assumed was based on a survey of spot speeds measured in an equivalent situation on the existing section of the Tollway, the distribution of which approximated the normal distribution with mean 45 m.p.h. and standard deviation 6.5 m.p.h. It was also assumed that traffic speeds remained constant through the detection system area. For the traffic volumes expected it was assumed that the time headways of traffic were distributed exponentially and the durations of each green phase were similarly distributed.

The performance of the system installed was predicted by estimating the average extension period resulting from the assumed speed distribution of the Tollway traffic and the speed sensitivity ranges of the detectors and assuming this to be provided from a fixed point in space (the stop line).

The estimate of the average extension period was 5.4 seconds and using this value in Adam's formula, the average duration of the extended or running period of the Tollway green phase was calculated, that is, for $\tau = 5.4$ seconds

$$\overline{W} = \frac{1}{q} \exp. (q\tau) - \frac{1}{q} - \tau$$

$$\fallingdotseq 15 \text{ seconds}$$

This is the average wait for a time gap of greater than 5.4 seconds in a traffic stream flowing at a volume q = 1500 vehicles per hour with exponential time headways.

From the average running periods for each phase plus the appropriate initial periods to clear vehicles that have stopped, the average cycle length during the design hourly conditions was calculated as 40 seconds and the average duration of the green phase for the Tollway approach as 23 seconds.

With the assumption that the Tollway green phase duration ϕ is distributed exponentially with mean $\overline{\phi} = 23$ seconds, the probability of a maximum change occurring during the running period of this phase is

$$P_m = P\left[\phi > g_a \text{ (max.)}\right]$$

That is, P_m is the probability that the Tollway traffic will attempt to extend the green phase beyond g_a (max.), the maximum possible time set at the controller, which in this case is 130 seconds.

$$P_m = \exp\left(-\frac{130}{23}\right)$$

$$\fallingdotseq 0.004$$

This means that under the assumed conditions only 0.4% of phase changes would be maximum changes.

Recording apparatus installed after the commissioning of the signal system has shown that the actual operational performance follows reasonably well that predicted for actual volumes up to 1300 vehicles per hour on the Tollway approach and 300 vehicles per hour on the Highway approach.

In the event of a maximum change occurring, the intergreen period must be at least sufficient to ensure safe clearance of the intersection for any vehicle in the dilemma zone associated with its approach speed. The minimum period required was determined by calculating the time required for a vehicle travelling at 65 m.p.h. to cover the distance from the dilemma zone threshold to the point where the vehicle would be safely clear of any vehicle approaching on the opposing phase. The total time was calculated as approximately eight seconds, thus, with the standard three second amber period, the necessary all red setting is five seconds.

CONCLUSION

This report describes the development of a simple traffic detection and signal system utilizing a minimum of non-standard equipment and which is capable of safely controlling traffic on high speed roads. The performance of this system followed that predicted for traffic volumes up to the maximum recorded of 1300 vehicles per hour on the high speed approach.

As a traffic accident countermeasure this system is considered to be very successful. During the two years since the commissioning of the system at the Hawkesbury site only six relatively minor accidents have been reported as having occurred at or on the approaches to the traffic signals, none of which was attributable to the operational characteristics of the traffic signals.

While this system was designed specifically for a maximum volume of 1500 vehicles per hour on a two lane approach, the application of the principle to other volumes would be appropriate. However, for somewhat higher volumes, the time duration between gaps suitable for a safe termination of the green phase may be so long that either the delays to the opposing traffic become intolerable or the number of maximum changes is in excess of that considered acceptable. The choice of maximum green time possible provides the balance between these two alternatives.

Nevertheless, some recompense is available in the relationship between the speed and volume of a traffic stream, for, as the volume increases, the average speed decreases as also does the variance of the distribution of speeds. Thus, some measure of self-compensation comes into operation, and reduces the length of the time gap necessary for a safe change of phase.

The interaction between human, vehicle and environmental factors in the road-use system makes it essential that compatibility is maintained between all elements of the system. The management of traffic within the road-use system entails the use of a combination of what may be termed "hardware" such as signals, signs and roadmarkings, and "software", the rules or laws governing operation of traffic within the system. The detection and signal system described in this report overcomes the problem of system incompatibility arising on the approach to traffic signals on high speed roads by providing that as far as possible drivers will not be required to make a decision as to whether to stop or carry on if there is likely to be any significant chance of their making a serious error.

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