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PEDESTRIAN DELAY AND TRAFFIC MANAGEMENT

by

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# PEDESTRIAN DELAY AND TRAFFIC MANAGEMENT

## ABSTRACT

The report summarizes a two-year study of the relationships between the delays to pedestrians crossing urban streets and traffic and layout characteristics. The aim of the study was to make explicit the influence of various types of traffic management on pedestrian delays.

A method for estimating pedestrian delays using a trained observer was developed and tested. This was used to record delays at sites where only few pedestrians crossed the road, while waiting times were observed directly at points with higher crossing flows. 423 surveys of delays, traffic, and layout characteristics were conducted in London streets. The sites were of five main types: kerbside points without crossing facilities, refuges, signalized junctions, zebra and pelican crossings.

Mean pedestrian delays were generally found to be below 8 seconds at flows of 1000 vehicles per hour, and below 20 seconds at 2000 vehicles per hour. Differences incurred at different types of location were marked, as were those between different age/sex categories of pedestrians.

Predictive equations for the mean delay and proportion of pedestrians delayed at the various types of location were developed, using multiple linear regression. In addition to traffic flow, the variables found to affect delays significantly were road width, signal timings, speed, composition, and the degree of bunching of the traffic. The correlation coefficients associated with the equations range from 0.72 to 0.96, and mean delays can be predicted with an accuracy of  $\pm 2$  seconds to  $\pm 6$  seconds, depending on the type of crossing situation. The possible applications of the equations are discussed in a concluding section.

## 1. INTRODUCTION

### 1.1 *Background*

The delays experienced by pedestrians wishing to cross urban streets are of practical interest in view of the time lost by delayed pedestrians, and because such delays, especially when prolonged, may be associated with risk-taking and higher accident rates. These delays may be said to comprise one aspect of the impact of traffic on the environment, which, together with noise, pollution etc, need to be taken into account in transportation planning studies.

In order to assess the overall impact of delay on pedestrians, it is necessary to know the waiting times imposed by traffic on people crossing the road. However, traffic flow is not the only factor affecting pedestrian delay. Other traffic characteristics, such as speed, composition, and bunching of vehicles, also play a part, as do layout characteristics such as carriageway widths and junction frequency. Furthermore, delay is affected by traffic management measures, particularly the phasing of traffic signals

and the installation of special pedestrian crossing facilities. An understanding of the underlying relationships is desirable since it may enable those management measures to be identified which, under given layout and traffic conditions, minimize pedestrian delay.

## 1.2 Objectives

This study sought to examine the relationships between levels of pedestrian delay and traffic, layout, and management factors, and to express these relationships in the form of practical predictive models to demonstrate how far, and in what ways, traffic management can contribute to the reduction of pedestrian delays.

## 1.3 Main approaches used in earlier studies

A detailed and realistic model of the interaction between pedestrians and traffic is difficult to establish, since it must take account of factors such as the distribution of gaps in the traffic and the pedestrian's judgement of whether a given gap in the traffic is long enough to permit safe crossing.

Early work on pedestrian delay has tended to concentrate on theoretical models. On the basis of simple hypotheses about pedestrian crossing behaviour and traffic flow distributions, abstract mathematical models of delay were constructed. The earliest of these was developed by Adams<sup>1</sup> who treated vehicle arrivals as a single random sequence of events in time, and assumed that pedestrians could cross the traffic stream whenever the gap between successive vehicles exceeded a constant critical time. Because of its simplicity, this model served as a useful reference point for the present study. The Adams model was refined by Tanner<sup>2</sup> who made allowance for the fact that, in two-way streets, pedestrians cross two separate streams of traffic. If the road could be crossed in two stages, delays would be reduced substantially.

Few studies have investigated how delays under conditions of random traffic flow differ from the delays associated with the types of interrupted or congested flow commonly found in busy urban streets. Dowell<sup>3</sup> indicated that non-random traffic flows lead to increased delays.

Empirical surveys, as well as simulation studies under controlled conditions, have been used to investigate the minimum length of gaps in the traffic which enable people<sup>4</sup> to cross. In a Manchester shopping street, Cohen, Dearnaley and Hansel<sup>4</sup> measured the time interval between the moment a pedestrian stepped off the kerb and the arrival of the nearest vehicle. They found that 25 per cent of pedestrians would accept gaps of 2 seconds or less, 50 per cent gaps of 3½ seconds or less, and 75 per cent gaps of 5 seconds or less. The gap length required by pedestrians decreased slightly as vehicle speeds increased.

Vehicular as well as pedestrian delays at pedestrian crossings have been studied in some detail. Jacobs, Older and Wilson<sup>5</sup> compared different crossing types, primarily with a view to economic evaluation.

A purely empirical investigation of delays to pedestrians in a range of shopping streets was carried out by Bowers as part of the Coventry

Transportation Study<sup>6</sup>. However, in that study total crossing times (including the walking as well as the waiting component) were recorded, so that the results are not strictly comparable with those of the present study. The Coventry results indicated that an increase in traffic flow of 100 vehicles per hour raised mean delays at points without crossing facilities by 0.6 seconds, at traffic signals by 0.9 seconds, and at pedestrian crossings by a negligible 0.05 seconds.

#### 1.4 Approach used in the present study

In the present study of delay, a largely empirical approach was adopted, though not without reference to analytical models. A number of typical pedestrian street crossing situations were identified, and for each situation the levels of delay associated with differing traffic conditions were ascertained. To this end, 423 surveys of approximately 15 minutes' duration were conducted in London streets. The sites chosen included random crossing points on ordinary one- and two-way streets, crossing facilities such as refuges, signalized junctions, pedestrian crossings, and a number of less common situations, such as bus lanes.

Simple and multiple linear regression were the main tools used to construct predictive equations for the delays incurred. The equations were developed with reference to a theoretical model of pedestrian delay, based on purely random traffic flow, but the mathematical form finally adopted was chosen for its simplicity. An attempt was made to quantify the effect which the bunching of vehicles can have on pedestrian delays, since many management measures affect pedestrian delays indirectly by altering traffic arrival patterns.

Although this study has concentrated on delay as if it depended on traffic and management conditions alone, waiting is an aspect of the pedestrians' response to these conditions. It cannot be seen in isolation from the individuals affected, nor from the alternative actions available to the pedestrian. A pedestrian trying to cross the road, but unable to do so immediately, may either wait at the kerbside until the road is clear, or he may walk along the kerb, continuously looking for a gap in the traffic, and then cross without stopping. Alternatively, he may decide to walk to a pedestrian crossing before attempting to cross. In extreme cases, he may adjust his route to avoid crossing the road altogether. Because of the difficulty involved in observing the detours pedestrians make when their intended paths are not known, this study has been restricted to measuring the time people spend standing at the kerb immediately prior to crossing the road.

The survey technique apparently most suitable for data collection was the direct observation of pedestrian waiting times. This would have had the advantage of allowing the delays experienced by different categories of pedestrians to be differentiated. However, observation is only practicable at sites where the numbers of pedestrians crossing the road are not too low. But to cover the necessary range of traffic, layout, and management conditions, surveys had to be conducted at sites where few, if any, pedestrians were present. Trained observers were therefore employed, making use of a continuous estimation method to record delays. This method was first validated and then used to measure delays at sites where pedestrians wishing to cross the road would not be able to affect the traffic by their presence. Where this condition was not met, especially at pedestrian crossings, direct observation was used.

Six groups of surveys were conducted:

- a) pilot surveys using a single observer to develop the continuous estimation method;
- b) surveys with up to 5 observers operating the continuous estimation method simultaneously, at random points at the kerbside;
- c) comparison surveys using continuous estimation and direct observation simultaneously;
- d) continuous estimation surveys at random points, refuges and signalized junctions;
- e) continuous estimation surveys at special sites.

### 1.5 *Scope of the report*

This report first discusses measurement units for pedestrian delay, describes the survey methods used, and the tests carried out to ensure the validity of the continuous estimation method as a research tool. It then presents the survey results and predictive equations developed for five types of situations where pedestrians cross roads. Finally, it compares the delays incurred in the different situations and indicates how the results might be used in practice.

## 2. THE MEASUREMENT OF PEDESTRIAN DELAY

### 2.1 *Measurement units*

At a given location, the individual delays incurred by pedestrians crossing within minutes or even seconds of each other may differ widely, depending on the precise traffic configuration at the instant of the pedestrian's arrival at the kerb. For prediction purposes, some form of averaging out of short term fluctuations over a longer period is necessary. In this report, two units in common use have been adopted, namely the mean delay ( $d$ ) to all pedestrians crossing the road, and the proportion ( $p$ ) of all pedestrians crossing who are delayed. Values of  $d$  will always be measured in seconds.  $p$  is a number between 0 and 1, but, for convenience, values of  $p$  in the text and tables will frequently be expressed as percentages. This does not apply to the equations.

The choice of units to be adopted in an evaluation of delays can be critical since it will be shown that there are some types of management measures which increase mean delays while reducing the proportion delayed at the same time. The problem of deciding on the 'right' measurement units is discussed in Section 4.

### 2.2 *Survey method*

Data for use in a series of multiple regression analyses was collected in the six groups of surveys described in 1.4 above. The length of surveys was generally 15 minutes. This time was usually both long enough to identify mean pedestrian delays and traffic flows sufficiently accurately, and short

enough to avoid major changes in traffic conditions and loss of concentration on the part of the observers.

2.2.1 Continuous estimation of delays: At sites where pedestrian numbers were low, continuous estimation was used to measure delays without the need to observe pedestrians. Throughout the length of a survey, a trained observer standing at the roadside recorded the instants in time when, in his estimation, approaching vehicles made it impossible for him to cross the road, and the moments when the road became clear again. These estimates were recorded on a portable tape recorder, thereby giving a complete breakdown of the survey time into periods when the road was clear and 'delay blocks' during which crossing was impossible. From this survey record, delays to pedestrians were calculated on the assumption that pedestrians arrived at random intervals, ie that they were equally likely to arrive at any time during a survey:

The mean delay 
$$d = \frac{1}{2} \sum_{1}^n d_i^2 / t, \text{ and}$$

the proportion delayed 
$$p = \sum_{1}^n d_i / t,$$

where  $t$  = survey length (in seconds)

$n$  = number of delay blocks

$d_i$  = length of  $i^{\text{th}}$  delay block (in seconds),  $1 \leq i \leq n$ .

The proof of these formulae may be summarized as follows. Suppose that, on average,  $m$  pedestrians arrive per second. Then the number of pedestrians arriving during the  $i^{\text{th}}$  delay block is  $m d_i$ . Each of these pedestrians, being as likely to arrive near the beginning as near the end of the delay block, must wait for an average time of  $d_i/2$  seconds until the end of the delay block. Summing over all delay blocks in the survey,  $\sum m d_i$  pedestrians are delayed for a total of  $\sum m d_i \times d_i/2$  man-seconds. Since the number crossing during the entire survey is  $mt$ ,

$$p = \sum d_i / t \quad \text{and} \quad d = \frac{1}{2} \sum d_i^2 / t.$$

2.2.2 Direct observation of delays: Pedestrian delays were observed directly as part of the procedure for validating the continuous estimation method, and later at sites where the presence of pedestrians did, or at any rate could, affect the traffic. At such sites, continuous estimation would have been unrealistic. During most observation surveys, observers with stop watches and record sheets were employed. It was found that a single observer looking at a channelized crossing could notedown the waiting times, sexes and ages (in three broad groups) of about 30 to 40 pedestrians in 15 minutes. At many sites, pedestrian flows were higher than this, and a sampling system was tried. It proved difficult to avoid taking a biased sample containing a

higher proportion of pedestrians when conditions were quiet, and a lower proportion when several pedestrians arrived nearly simultaneously. The problem was solved by using sufficiently many observers to enable them to record all pedestrians. Except at a few exceptionally crowded pelican crossings, four observers were the maximum number needed.

2.2.3 Other variables recorded on surveys: On all surveys except the initial pilot series, the following information was recorded in addition to delays:

- type of site (random point at kerb/refuge/signalized junction etc),
- traffic count,
- heavy vehicle count (not obtained at some sites),
- estimated traffic speed on a four-point scale,
- one-way or two-way traffic,
- carriageway width,
- number of lanes,
- parking,
- traffic signal timings (where appropriate).

On continuous estimation surveys, the traffic arrival pattern in the form of successive 10-second traffic counts was also recorded.

A summary of the numbers of surveys conducted, broken down by type of crossing situation and traffic flow, is given in Table 1.

### 2.3 *Validation of the continuous estimation method*

2.3.1 Stability of estimated delays and differences between observers: A series of 50 pilot surveys was carried out, in which a single observer recorded delays by the continuous estimation method. Traffic flows between 600 and 1600 vehicles per hour were measured, and the estimated delays fell within the ranges quoted for random points at the kerbside in Tables 2 and 3. The first 32 surveys were conducted in one-way streets where the method is easiest to apply, and where the bunching of vehicles and the traffic arrival pattern generally are easiest to observe. The remaining surveys took place in a group of sites in two-way streets chosen for their similarity in all respects except traffic flow. The relationship between delay and traffic flow emerging from these surveys is discussed in section 3.1.1. In the present context, it is sufficient to note that the mean delays and the proportion delayed, as calculated from the continuous estimation surveys, were encouragingly predictable and consistent.

The main group of 37 surveys at random kerbside points, under freely flowing traffic conditions, was designed to test the extent to which different observers, faced with the same traffic and layout situation, would be consistent in their estimates of delay. Up to five observers were asked to estimate delays simultaneously at the same site, while two other team members measured traffic flow, composition, and speed. Most of the observers were aged between 20 and 30 years (which may explain why only minor differences between observers were detected), though an older man took part during the first few surveys.

For each survey, the mean and standard deviation of the various observers' estimates of  $d$  and  $p$  were calculated. If estimates made by the older

man are excluded, the standard deviation of estimates of  $d$  varied between surveys from 0.3 to 11 seconds, with an average deviation for all surveys of 1.7 seconds. The higher deviations were found on surveys where the mean of the estimates of  $d$  was high. The ratio of the standard deviation to the mean of the estimates was, therefore, a more meaningful measure. It varied from 0.10 to 0.50, with an average of 0.26.

The standard deviations of estimates of  $p$  ranged from 0.01 to 0.05, with an average of 0.03. They were apparently unrelated to the value of  $p$  itself which ranged from 0.23 to 0.89.

As an illustration, take a street with traffic flow of 1000 vehicles per hour, where 60 per cent of the pedestrians crossing have to wait, and where the mean delay is 5 seconds. Most likely, the observers' estimates of the proportion of pedestrians delayed would have ranged from 55 per cent to 65 per cent, and the estimates of mean delays from 3.5 to 6.5 seconds.

In order to investigate the possibility of systematic differences between observers, the ratio of each observer's estimate of  $d$  to the mean of all observers' estimates of  $d$  was calculated for each observer and each survey. Let this ratio be denoted by  $r_{ij}$ , where  $i$  identifies the observer and  $j$  the survey. For each observer, the set  $R_i = \{r_{ij}\}$  where  $j$  ranges over all surveys in which the observer took part, was formed: the mean of  $R_i$  provides a measure of the systematic differences between the  $i^{\text{th}}$  observer's estimates of  $d$  and the average of the group. It was found to vary between 0.8 and 1.4 for all observers with the exception of the older man who estimated  $d$  to be twice as high as the other observers. This may be a freak result since he was present at only three of the surveys. The standard deviation of the set  $R_i$  provides a measure of the consistency of an individual's estimates of  $d$ . It was found to vary between 0.17 and 0.30 for the different observers and tended to be low for the observers with the greatest experience in the group.

It was concluded that differences between observers in the 20-30 year age group were noticeable, though not statistically significant when compared with the likely variation in any single observer's estimates. A person's successive estimates of  $d$  under identical survey conditions are likely to vary by up to 30 per cent. For an experienced observer, the expected variation is rather lower at about 20 per cent.

2.3.2 Comparison between observed and estimated delays: Once the consistency of measurements by the continuous estimation method was established, it was necessary to confirm that the quantity measured did in fact correspond to actual kerbside delays experienced by pedestrians. For this purpose, eight separate surveys were carried out at sites with high pedestrian crossing flows of between 250 and 1000 per hour, and traffic flows of between 400 and 1250 vehicles per hour. During these surveys, pedestrians were filmed with a time-lapse camera mounted approximately three metres above the ground on a parked van. Simultaneously, an observer recorded delays by the continuous estimation method. In the analysis of the films, a pedestrian's delay was defined as the time spent standing at the kerb immediately prior to crossing, plus any stops in the middle of the road. For each survey, the difference between the observed and the estimated delay was calculated. The table below summarizes these differences:

Comparison of estimated and observed delays

Measure of delay	Range of recorded values	Mean difference (observed minus estimated)	Standard deviation of differences
Proportion delayed (%)	30-89	2.9	7.5
Mean delay (seconds)	1- 7	0.0	1.4

To see these differences in perspective, they may be compared with the differences between the various categories of pedestrian. On the same set of surveys, for instance, the mean delay to women crossing was 1.7 seconds higher than that to men. It was concluded that the continuous estimation method produces results broadly consistent with observed kerbside delays, free from significant bias, and sufficiently accurate to be used as a tool in the study.

3. PEDESTRIAN DELAYS ASSOCIATED WITH DIFFERENT ROAD CROSSING SITUATIONS

3.1 *Delays at random crossing points*

Before studying the delays associated with specific traffic or pedestrian management measures, it is necessary to quantify the delays associated with crossing the road at normal, unmarked points at the kerbside, in order to establish a base for comparison.

3.1.1 Pilot surveys: At the sites of the pilot surveys, layout conditions were held fairly constant. Consequently, the analysis concentrated on the effects of traffic flows and arrival patterns. The analysis took the form of a comparison between the estimated delays and the delays predicted by Adams' theoretical model.

The Adams model assumes that vehicles arrive at random, and that pedestrians can cross the road whenever the gap between vehicles exceeds a constant critical value. The model predicts that

the proportion of pedestrians delayed is  $p = 1 - e^{-qT}$  ..... (1)

and the mean delay is  $d = \frac{1}{q} (e^{qT} - qT - 1)$  ..... (2)

where  $q$  is the traffic flow (in vehicles per second), and  $T$  is the critical gap (in seconds).

The results of the pilot surveys were found to match the predictions of the model reasonably well if the parameter  $T$  was set to 3-4 seconds in the case of the proportion delayed, and to 4-5 seconds in the case of the mean delay. It is interesting to note that the value of  $T$  which produced the

best agreement between prediction and survey results was consistently higher for the mean delay than for the proportion delayed. This indicates that the model, while useful as a reference point, is insufficiently realistic.

By substituting the surveyed values of  $p$  and  $q$  in equation (1) and solving for  $T$ , the relation between the theoretical model and reality was examined in more detail. It was found that

$T$  was independent of traffic flow, and  
 $T$  was sensitive to the pattern of vehicle arrivals.

As a measure of the traffic arrival pattern, the index of dispersion ( $I$ ) was calculated.  $I$  was defined as the ratio of the variance to the mean of successive 10-second traffic counts. In theory,  $I = 1$  for random traffic, and  $I$  increases as the traffic becomes more bunched. Typical values of  $I$ , as measured on the surveys, were around 1.2 away from traffic lights, and between 1.8 and 2.5 near traffic lights. A strong negative correlation between the values of  $I$  and of  $T$  was found. If one assumes that the critical gap actually accepted by pedestrians is independent of  $I$ , it follows that, at a given traffic flow, the proportion of pedestrians delayed is lower, the more bunched the traffic.

It seems quite obvious that the parameter  $T$  of the Adams model, which decreases as traffic becomes more bunched, does not represent the pedestrians' actual gap acceptance. This is confirmed by the fact that solving equations (1) and (2) to match the survey data leads to different values of  $T$ .

3.1.2 Main surveys: The main group of surveys at random kerbside points without crossing facilities, using up to five observers at each site, provided the material for the first practically useful set of predictive equations. For each survey, the averages of the various observers' estimates of the proportion delayed ( $p$ ) and of the mean delay ( $d$ ) were calculated. These averages were, of course, statistically more reliable and did, in fact, show less random variation than any single observer's estimates. The ranges of traffic flows and delays recorded on these surveys are summarized in Tables 1 (random points at kerbside - free flow), 2, and 3 (random points at kerbside).

A standard multiple linear regression program\* with facilities for transforming variables was used to set up the predictive equations. For the prediction of  $p$ , the negative exponential form of the Adams model ( $p = 1 - e^{-qt}$ ) was adhered to, but the equation for  $d$  was kept as mathematically simple as possible. From the full range of survey variables recorded, the program selected those which significantly affected the values of  $p$  and  $d$ . Quite strikingly, the only variables found to be significant were those relating to the traffic flow. Road width, the number of lanes of traffic, one-way or two-way traffic, and speed were rejected as insignificant. The reason may lie in the restricted range of these variables; most of the streets surveyed were between 6 and 10 metres wide, and traffic speeds were concentrated between 22 and 35 miles per hour.

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\*BMD O2R stepwise regression program, Health Services Computing Facility, UCLA, 13 April 1965

The following equations were obtained:

$$p = 1.01 - e^{-(1.25 - 0.19I) \times 10^{-3}Q} \dots\dots\dots (3)$$

$$R = 0.96, \text{ S.E.} = 0.029$$

$$d = 1.00 + 4.70 \times 10^{-6}Q - 0.77 \times 10^{-3}QL + 0.21 \times 10^{-3}QL^2 \dots\dots\dots (4)$$

$$R = 0.94, \text{ S.E.} = 1.22 \text{ sec}$$

where Q = traffic flow in vehicles per hour,  
 I = index of dispersion, as defined in Section 3.1.1,  
 L = indicator of distance from the nearest traffic lights, ranging from  
 0 (= away from lights) to 3 (= near lights).

Equations obtained after only one stage of the regression, with Q as the only independent variable, are

$$p = 1.01 - e^{-1.03 \times 10^{-3}Q} \dots\dots\dots (5)$$

$$\text{and } d = 1.26 + 4.54 \times 10^{-6}Q^2 \dots\dots\dots (6)$$

$$R = 0.93, \text{ S.E.} = 1.28 \text{ sec.}$$

The accuracy of equation (3) is very satisfactory since its standard error is no greater than the standard deviation of different observers' estimates at a single survey. Equation (5) is consistent with the results of an earlier study of the estimated proportion delayed in Edinburgh\*. Equation (4) for the mean delay is less satisfactory. It shows that some measure of the bunching of traffic near signals would certainly go towards explaining differences in mean delays in streets with similar traffic flows, but that the simple indicator L is insufficient. Rather surprisingly, I is not significant. The standard error of 1.22 seconds is less than the standard deviation of different observers' estimates of d at a single survey (1.7 seconds).

Equation (5) is nearly identical to equation (1) of the Adams model, with the parameter T set to 3.7 seconds. Equation (6) is almost identical to equation (2) over the traffic flow range from 500 to 1200 vehicles per hour, if a value of T = 4.9 seconds is substituted. Figures 1 and 2 show how well equations (5) and (6) fit the data.

\*143 ten-minute surveys were conducted in Edinburgh streets using the continuous estimation method to record the proportion of pedestrians delayed. The regression equation obtained then was equivalent to

$$p = 0.98 - e^{-1.03Q} \quad (R = 0.79). \quad \text{Reference: Crompton and Gilbert}^7.$$

Both the pilot and the main surveys were conducted in a mixture of one-way and two-way streets. At a given total traffic flow, no significant difference between delays in one-way and in two-way streets was found. Since none of the sites had crossing facilities, it was assumed that pedestrians would cross the whole road without stopping in the middle. However, if a refuge were to be provided, pedestrians would be able to cross in two stages, in which case each half of the road could be treated as a one-way street with half of the two-way traffic flow. In that case equation (6) could be applied to each half of the road separately. An evaluation of the equation for the one-stage and two-stage crossings shows that the provision of a refuge will reduce mean delays at flows above 800 vehicles per hour. At a two-way flow of 1500 vehicles per hour, the reduction in the mean delay will be as high as 3.8 seconds.

3.1.3 Surveys at congested sites: A separate series of surveys was conducted at random kerbside points on a number of streets which were prone to congestion. The range of traffic flows encountered is summarized in Table 1. The recorded mean delays and proportion of pedestrians delayed were, on the whole, consistent with those of the main surveys.

Again, multiple regression was used to select the significant explanatory variables, and to develop the following equation for the mean delay:

$$d = 1.13 + 4.28 \times 10^{-6} Q^2 / I_n \quad \dots\dots\dots (7)$$

$$R = 0.86, \text{ S.E.} = 1.41 \text{ sec.}$$

Here,  $I_n$  is a new attempt at measuring the traffic arrival pattern in a way which might reflect the effect of bunching on delay somewhat better.  $I_n$  is defined as  $\frac{1}{2} \sum (n_i - n_{i-1})^2 / \sum n_i$ , where  $n_i$  is the  $i^{\text{th}}$  10-second traffic count. In the case of purely random vehicle arrivals,  $I_n = 1$ .

Speed was estimated on a simple scale from 1 (congested stop/start driving) to 4 (over 30 mph). The speed index has not yet been incorporated in a practically useful equation, but the survey results indicate that pedestrian delays due to very slow-moving traffic are longer than when vehicles move faster. An increase in speed from 1 to 3 (ie normal, 20-30 miles per hour) is associated with a reduction of  $d$  by 0.4 seconds.

### 3.2 Delays at 'managed' locations

In the previous sections, the delays to pedestrians crossing the road at random locations have been described. It is now possible to test how pedestrian delays are affected by the presence of traffic signals at junctions, zebra crossings, signal-controlled pedestrian crossings, and by the provision of simple refuges. The continuous estimation method produces false estimates of delay at sites where pedestrians wishing to cross the road can force drivers to slow down or stop. This applies at crossings where pedestrians are specifically given priority, as well as at sites where their sheer weight of numbers forces the traffic to give way. Consequently, the surveys conducted at signalized junctions with low pedestrian flows employed the continuous estimation method, while surveys at signalized junctions with high pedestrian flows, at pedestrian crossings, and at refuges were based on the direct observation of pedestrian waiting times.

3.2.1 Signalized junctions: At signalized junctions, a total of 93 surveys was conducted. On 27 of these, direct observation was employed, though these surveys will not be referred to in detail. On the whole, the results were consistent with those obtained by estimation, though the observed delays did tend to be somewhat higher than estimated delays when traffic flows were low, and lower than estimated delays when traffic flows were high.

On the remaining 66 surveys, continuous estimation was used. The recorded ranges of traffic flows, of mean delays, and of the proportion of pedestrians delayed are summarized in Tables 1, 2 and 3. For delays at signalized junctions, the following regression equations were derived:

$$d = 0.68 + 5.84 \times 10^{-5} Q^2/W - 1.12 \times 10^{-4} Q^{3/2} + 0.071 G \dots\dots\dots (8)$$

$$R = 0.96, \text{ S.E.} = 1.49 \text{ sec.}$$

$$p = 0.095 + 0.018 \sqrt{Q} - 0.048 I \dots\dots\dots (9)$$

$$R = 0.93, \text{ S.E.} = 0.059$$

where Q = hourly traffic flow,  
W = road width in metres,  
G = length of green signal phase in seconds (driver aspect),  
I = index of dispersion of the traffic, as defined in Section 3.1.1.

The mathematical form of these equations is purely empirical, and probably needs further development. In the equation for the proportion of pedestrians delayed, the negative exponential form of equation (1) was abandoned since there is no theoretical reason to expect that the proportion delayed will approach unity as traffic flows rise, because of the finite length of the red signal phase. The equation for the mean delay shows that the dependence of d on traffic flow is non-linear, but that a quadratic function rises somewhat too fast. Road width is significant, probably as a proxy for the number of lanes in which traffic moves, and the corresponding queue discharge rate. Changes in signal timings are significant, but do not appear to have the overwhelming effect that theoretical considerations would indicate.

In a supplementary group of surveys in three streets, it was decided to examine how the delay changed as a function of the distance of the pedestrian's crossing point from the traffic lights. This was one of the few occasions where a difference between the influence of one-way and of two-way traffic on delays became apparent. In the two-way street, both the mean delay and the proportion of pedestrians delayed were lowest directly at the lights, rose significantly as the position of the crossing point was moved to a distance of 50 m from the lights, and then stayed approximately constant as the distance was further increased. In the two one-way streets, the proportion delayed was noticeably lower on the upstream side than on the downstream side of the junctions, but then stayed virtually constant as the position of the crossing point was moved further downstream. The mean delay was slightly higher on the upstream side of the junctions than on the downstream side. Over the next 100 m downstream of the junction it fell further,

then levelled out. The effect of platooning on delays, giving rise to long delay blocks followed by long clear periods, was much more marked in the presence of one-way traffic than of two-way traffic.

3.2.2 Refuges: Pedestrian delays were observed at 17 sites with refuges on roads with generally high, but freely moving, traffic flows. Tables 1 to 3 summarize the ranges of traffic flows and delays encountered. The pedestrian delays recorded on the surveys included waiting times at the kerb, as well as on the refuge. The following regression equations for the mean delay and the proportion of pedestrians delayed were obtained:

$$d = 4.21 + 1.56 \times 10^{-6} Q^2 \quad \dots\dots\dots (10)$$

$$R = 0.80, \text{ S.E.} = 2.20 \text{ sec.}$$

$$p = 1.0 - e^{-1.06 \times 10^{-3} Q} \quad \dots\dots\dots (11)$$

If these results are compared with equations (5) and (6) for sites without refuges, it becomes apparent that the proportion of pedestrians delayed is unaffected by the provision of refuges, while the rise in mean delays as a function of traffic volume is made much less steep. Indeed, on the assumption of equal one-way traffic flows on each half of a road, equation (10) may be converted into  $d = 2.1 + 3.12 \times 10^{-6} Q^2$  for the delay incurred in crossing a single carriageway. For flows between 400 and 1500 vehicles per hour, this agrees well with equation (6).

3.2.3 Pedestrian crossings: Pedestrian delays were observed on 67 surveys at zebra crossings and 40 surveys at crossings with pedestrian-actuated signals. In the analysis, pelican crossings and signalized crossings without a flashing pedestrian green phase were treated as one group, since their effect on pedestrian delay was found to be broadly similar. Tables 1 to 3 summarize the survey results. The following regression equations were derived:

At zebra crossings:

$$d = 0.97 + 0.0023Q \quad \dots\dots\dots (12)$$

$$R = 0.69, \text{ S.E.} = 1.84 \text{ sec.}$$

$$d = -0.95 + 0.38 \sqrt{H} \quad \dots\dots\dots (13)$$

$$R = 0.80, \text{ S.E.} = 1.51 \text{ sec.}$$

$$p = 0.17 + 0.032 \sqrt{H} \quad \dots\dots\dots (14)$$

$$R = 0.77, \text{ S.E.} = 0.14$$

At pelican crossings:

$$d = 5.89 + 1.86 \times 10^{-6} Q^2 \quad \dots\dots\dots (15)$$

R = 0.78, S.E. = 4.30 sec.

$$d = 6.99 + 2.28 \times 10^{-6} Q^2 - 0.51 F \quad \dots\dots\dots (16)$$

R = 0.82, S.E. = 3.93 sec.

$$p = 0.44 + 0.092S + 0.0019M \quad \dots\dots\dots (17)$$

R = 0.72, S.E. = 0.10

- where Q = hourly traffic flow
- H = hourly flow of medium and heavy goods vehicles
- F = length (in seconds) of the flashing pedestrian green phase at pelican crossings
- M = length (in seconds) of minimum pedestrian red phase
- S = estimated vehicle speed on a scale from 1 (congested stop/start driving) to 4 (over 30 miles per hour)

An examination of the equations indicates that delays at zebra crossings are more highly correlated with flows of heavy vehicles than with total traffic flows. This may reflect a reduced willingness on the part of drivers of large vehicles to stop for pedestrians, as well as a degree of intimidation of the pedestrian. At pedestrian-actuated traffic signals, large constant terms dominate the equations, reflecting the generally slow response of the lights after a pedestrian has registered his demand. Lights with a fixed-length pedestrian green phase (ie F = 0) appear to give rise to mean delays approximately four seconds shorter than at pelican crossings. The proportion of pedestrians delayed appears to depend on vehicle speeds and signal timings, rather than on traffic flows. It should be borne in mind, however, that the sites with higher vehicle speeds also tended to be those with higher traffic flows (the correlation between Q and S being R = 0.57).

Both zebra and pelican crossings are designed to enable pedestrians to cross busy streets safely and quickly. However, a comparison of the mean delays incurred at the two types of crossing shows that pedestrians have to wait two to three times longer at pelican crossings than at zebra crossings. Why should this be so? The operation of zebra crossings is very simple. When the road is clear, a pedestrian can cross immediately. When vehicles are approaching, he needs to wait until a driver abides by the rules and stops. The action required by pedestrians at pelican crossings is far less obvious. They are supposed to press a switch and wait for the signals to change before crossing, even when the road is clear. Once the signals change, without an amber warning period for pedestrians, people wishing to cross the road must react quickly before their short green period changes to the flashing phase during which drivers have priority over any pedestrians not already on the road. In order to limit vehicular delays, pelican crossings are designed with a minimum separation period, often lasting longer than 40 seconds, between successive pedestrian green phases. Consequently, the response of the signals to the pedestrian's demand is generally slow.

Even at pedestrian flows as low as one per minute, less than half the pedestrians arriving could expect an immediate response. Consequently, many people, particularly men, were observed to cross before the lights changed. Conversely, a significant minority of largely elderly people were unable to cross sufficiently quickly when the lights did change, and were consequently left stranded for extended periods.

3.2.4 Supplementary surveys at other locations: A separate group of surveys was carried out to examine the effects of selected types of traffic management on pedestrian delays. These types included mini-roundabouts, carriageways which have been narrowed to facilitate pedestrian movements, and bus lanes.

The results were generally negative, since it was not possible to demonstrate that these measures had a significant impact on pedestrian delays. In the case of mini-roundabouts and narrowed carriageways, the delays at these points were compared with delays at points further along the same streets. Mini-roundabouts appeared to have a negligible effect, since they did not greatly alter the fairly random traffic arrival pattern on the streets surveyed. (This applies to larger roundabouts as well.) Where roads were narrowed, the reduction in the time needed for pedestrians to walk across the road was balanced by the increase in the length of platoons of vehicles as the number of lanes was reduced. Consequently, the mean delay was left unchanged. Lastly, on streets with bus lanes, surveys were carried out both during the times when restrictions on the use of the bus lanes were in operation, and when they were not. Comparisons were made difficult by changes in traffic flows, and by the reluctance of drivers to use bus lanes during off-peak hours, even when it was legally permitted to do so, and no changes in delays due to the presence of the bus lanes could be demonstrated.

### 3.3 *The accuracy of the predictive equations*

The standard errors of the equations predicting delays at traffic lights, refuges, and pedestrian crossings are greater than those of the equations predicting delays at random locations. Part of the explanation may be that the most suitable mathematical forms of the equations have not yet been found. Another part lies in the random nature of the data collected on delay. Equations (3) to (6) are based on the means of up to five observers' estimates of delay. Equations (8) and (9) are based on a single observer's estimates of delays at traffic signals. Using the estimate of an observer's accuracy given in section 2.3.1, it is possible to calculate how much of the standard error in equation (8) can in fact be attributed to observer variation. If this is taken into account, the remaining unexplained error is reduced to less than that of equation (6).

In order to get an estimate of the accuracy of the mean delays calculated from surveys of observed pedestrian delays, the distribution of the individual pedestrian waiting times needs to be examined. On the whole, the standard deviation of individual waiting times was found to be roughly equal to the mean delay. Consequently, a large number (approximately 100) pedestrians would have had to be surveyed at each site to determine the mean delay to an accuracy of  $\pm 20$  per cent. However, it was impossible to observe such high numbers of pedestrians will still covering the variety of sites and of traffic flows needed to set up predictive models. The mean number of pedestrians observed on each survey was 67. As a result, the equations based

on observation have standard errors which are generally larger than those of the equations based on estimation.

### 3.4 *Comparison of delays associated with different crossing situations*

The analysis in this section relates to the dependence of pedestrian delay on traffic flow only, since this is the only variable which has been found to affect delays at all types of site studies. A comparison of different types of site is complicated by the fact that traffic flows at the random crossing locations tended to be lower than at traffic lights and pedestrian crossings. This is inevitable and underlines the fact that the choice of possible crossing facilities on a road is circumscribed by the prevailing traffic and layout conditions.

Tables 2 and 3 permit the ranges of mean delays and of the proportion of pedestrians delayed to be compared for different crossing types. Despite the considerable overlap between the recorded ranges of delays for different types of site, differences are discernible.

Figure 3 and Table 4 bring together the best available predictions of the mean delay, and of the proportion of pedestrians delayed, as a function of traffic flow.\* The accuracy of the prediction of mean delay is greatest at random crossing points ( $\pm 2.1$  seconds at 90 per cent confidence level), and least at pelican crossings ( $\pm 6.4$  seconds).

The most conspicuous feature of Figure 3 is that zebra crossings gave the lowest mean delay at all levels of traffic flow, rising slowly from 2 seconds at 500 veh/h to 8 seconds at 3000 veh/h. At random points, with no crossing facilities, mean delay rose rapidly from 2 seconds at flows below 500 veh/h to nearly 20 seconds at 2000 veh/h. The provision of refuges was beneficial at all flows above 1000 veh/h: they always gave a lower mean delay than that at pelican crossings, which gave the highest delays of all crossing situations at low flows. Delays at signalized junctions were low at low flows but rose rapidly.

At 1750 veh/h, about the midpoint of the range of flows encountered, the mean delay was 15 seconds at random points,  $11\frac{1}{2}$  seconds at pelican crossings,  $10\frac{1}{2}$  seconds at signalized junctions, 9 seconds at refuges, and 5 seconds at zebra crossings.

## 4. CONCLUSIONS

### 4.1 *Summary of results*

The task of the present study has been firstly to develop and test a method of estimating pedestrian delays at sites where pedestrian flows are too low to make direct observation practicable, and secondly, to quantify and compare the delays associated with various types of crossing situations.

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\*Note that the flows quoted are two-way totals (except, of course, for one-way streets), and the delays are as defined in Section 2.3.2.

The continuous estimation method has been shown to produce reliable results which are in agreement with the delays incurred by pedestrians crossing roads. The mean delays obtained by continuous estimation are less subject to random error than those obtained by direct observation of pedestrians in the present study.

Predictive equations for mean delays and for the proportion of pedestrians delayed have been developed for a number of distinct crossing situations. Generally, the resulting correlation coefficients are surprisingly good for the models based on continuous estimation, ranging from 0.86 to 0.96, and mean delays can be predicted to within  $\pm 2.5$  seconds. The correlation coefficients for models based on observed delays range from 0.72 to 0.82, and mean delays can be predicted to within  $\pm 2.5$  to  $\pm 6$  seconds, depending on the type of crossing situation.

The models do, of course, refer to an 'average' pedestrian, and would need to be modified if, for example, it was desired to predict delays at a site used mainly by old people. It was observed that old people had to wait between 20 and 40 per cent longer, and children between 0 and 35 per cent less long than adults aged under 60. Such differences need to be taken into account when judging whether the accuracy of the models is acceptable.

In addition to traffic flow, delays have been shown to be affected by the traffic arrival pattern, the number of heavy vehicles, traffic speed, and road width. The influence of each of these variables depends on the type of crossing situation, and on the measure of delay used. The effect of altering the traffic arrival pattern, in particular, is potentially great, since delays are strongly dependent on the distribution of vehicle platoons and clear gaps in the traffic stream. A supplementary theoretical study, not included in the present report, indicates that, with close control over the pattern of vehicle flow, mean delays at a given traffic flow might be altered by a factor of 3 or more. The field surveys, however, did not identify such a strong effect.

Before the predictive equations can be applied in any particular street, it must be possible to determine the values of the explanatory variables used in the equations. This presents no problem in the case of street widths and signal timings. Information on traffic flows and composition is frequently available for the busy streets where pedestrian delay is likely to cause concern, and it should be relatively easy to estimate speed in the crude form required. But the traffic arrival pattern presents a problem since no entirely satisfactory unit for its measurement has yet been established, and since the index of dispersion used in the present study is difficult to predict. For practical applications it is therefore preferable to use the best available equations which make no explicit reference to the traffic arrival pattern. A list of these equations is provided in the Appendix.

Different types of road crossing situations have been compared in terms of the delays they cause to pedestrians at various traffic flows. Although traffic signals seem to minimize the proportion of pedestrians delayed at all traffic flows, they lead to a mean delay higher than that at random points when traffic flows are low. This underlines the importance of using the most appropriate measurement units when evaluating pedestrian delay, since traffic management may minimize delay by one measure, while increasing it by another.

The results of the study suggest that the proportion of pedestrians delayed is sensitive to changes in the traffic when traffic flows are low. However, more than half of all pedestrians crossing are delayed when flows reach 800 vehicles per hour, and at flows above 1000 vehicles per hour, when the problem of delay becomes most severe, the proportion delayed becomes rather insensitive to changes in the traffic. This throws some doubt on the usefulness of the proportion of pedestrians delayed as a measure of delay. The mean delay may not give an accurate reflection of the pedestrian's concern about being delayed, either. After all, mean delays are generally quite short: below 8 seconds at 1000 vehicles per hour, and below 20 seconds at 2000 vehicles per hour. Nevertheless, mean delays have the advantage of being sensitive to changes in conditions at high traffic flows, and of allowing the total time lost through delay to be calculated.

#### *4.2 Implications and applications*

The results of the present study are limited in two important respects. Firstly, the study has examined kerbside delays only and has left aside the wider problem of pedestrian trip diversion and trip suppression as a result of difficulties in crossing the road, and secondly, the study gives no answer as to what measure of delay is most meaningful to the pedestrian, nor which levels of delay might be identified as negligible, reasonable, or unacceptably high.

In spite of these limitations, there seem to be three ways in which the models developed in this study could be put to practical use, once it was decided which measure of delay was the most appropriate. Firstly, given that a certain hourly traffic flow must use a road, the practical question would be to determine the pedestrian crossing arrangements which would be most likely to minimize pedestrian delay.

Secondly, traffic flow assignments might be available for a road network or a series of alternative networks, where all the layout and pedestrian crossing facilities were already well established and where the numbers of pedestrians likely to cross the various roads of the network were known. In this case, the models could be used to compare the performance of the alternative road networks in terms of the delays they imposed on pedestrians. If mean delay were used in such an evaluation, total man-hours of delay could be calculated, for instance for use in cost-benefit analyses.

Thirdly, once provisional environmental standards for pedestrian delay were formulated, the models could be used to determine the degree of traffic restraint necessary to achieve such standards. Alternatively, the models could be used in conjunction with such environmental standards as part of the environmental input in the network design process.

A new TRRL-supported study now being conducted at Imperial College aims to relate the delays incurred by pedestrians to their subjective response in terms of annoyance and risk-taking. If successful, that study will help to decide how serious a problem pedestrian delay is, what levels of delay matter to the public, and how delay is most meaningfully measured. In the light of such information, a fuller evaluation of delays will be possible.

## 5. ACKNOWLEDGEMENTS

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TABLE 1

Summary of numbers of surveys conducted, broken down by type of crossing situation and traffic flow

Traffic flow range (vph)	Random points at kerbside*		Signalized junctions*	Refuges <sup>+</sup>	Zebra <sup>+</sup> crossings	Pelican <sup>+</sup> crossings
	Free flow	Congested				
All flows	37	21	66	17	67	40
0 - 500	2	2	11	-	17	-
501 - 1000	17	16	31	6	19	10
1001 - 1500	14	2	15	1	13	12
1501 - 2000	3	1	4	3	9	9
Over 2000	1	-	5	7	9	9

\* survey method: continuous estimation

+ survey method: direct observation

TABLE 2

Recorded ranges of mean delays (in seconds) to all pedestrians, by type of crossing situation

Traffic flow range (vph)	Random points at kerbside	Signalized junctions	Refuges	Zebra crossings	Pelican crossings
0 - 500	0.5 - 2	1 - 4.5	-	0.5 - 3.5	-
501 - 750	1.5 - 6	2 - 8.5	2 - 5	0.5 - 3	5 - 7.5
751 - 1000	3 - 10	3 - 10	1.5 - 8	2 - 4	3.5 - 9
1001 - 1500	4 - 14.5	3 - 15	3 - 8	2.5 - 6	5 - 18
1501 - 2500	12 - 21	3 - 11.5	6.5 - 15.5	3 - 11.5	7.5 - 18
Over 2500	-	11 - 33	12 - 26	5 - 8.5	18 - 27

TABLE 3

Recorded ranges of the proportion of pedestrians delayed (%),  
by type of crossing situation

Traffic flow range (vph)	Random points at kerbside	Refuges	Signalized junctions	Zebra crossings	Pelican crossings
Under 500	24 - 48	-	23 - 31	5 - 49	-
501 - 750	41 - 57	26 - 76	32 - 55	20 - 46	35 - 69
751 - 1000	42 - 63	26 - 76	26 - 70	44 - 81	56 - 100
1001 - 1500	57 - 77	80 - 82	48 - 70	46 - 81	66 - 81
1501 - 2500	78 - 89	72 - 82	60 - 73	64 - 100	71 - 100
Over 2500	-	90 - 100	62 - 95	66 - 90	85 - 100

TABLE 4

Comparison of predicted mean delays (d, sec) and proportion delayed\* (p, %),  
by type of crossing situation

Traffic flow (vph)	Random points at kerbside		Refuges		Signalized junctions		Zebra crossings		Pelican crossings	
	d	p	d	p	d	p	d	p	d	p
500	2.4	40	-	-	3.0	32	2.0	35	-	-
750	3.9	54	5.1	50	3.8	45	2.7	48	6.9	60
1000	5.8	66	5.8	60	5.0	55	3.3	60	7.8	70
1500	11.5	79	7.7	78	8.3	65	4.4	70	10.1	75
2000	19.5	87	10.5	80	13.0	70	5.6	75	13.3	80
2500	-	-	14.0	85	-	-	6.7	80	17.5	85
3000	-	-	18.2	90	-	-	7.9	80	22.6	90
Accuracy of prediction of mean delay (at 90% confidence level)	± 2.1 sec		± 3.6 sec		± 3.6 sec		± 3.0 sec		± 6.4 sec	

\* based on scatter diagrams where no predictive equation available

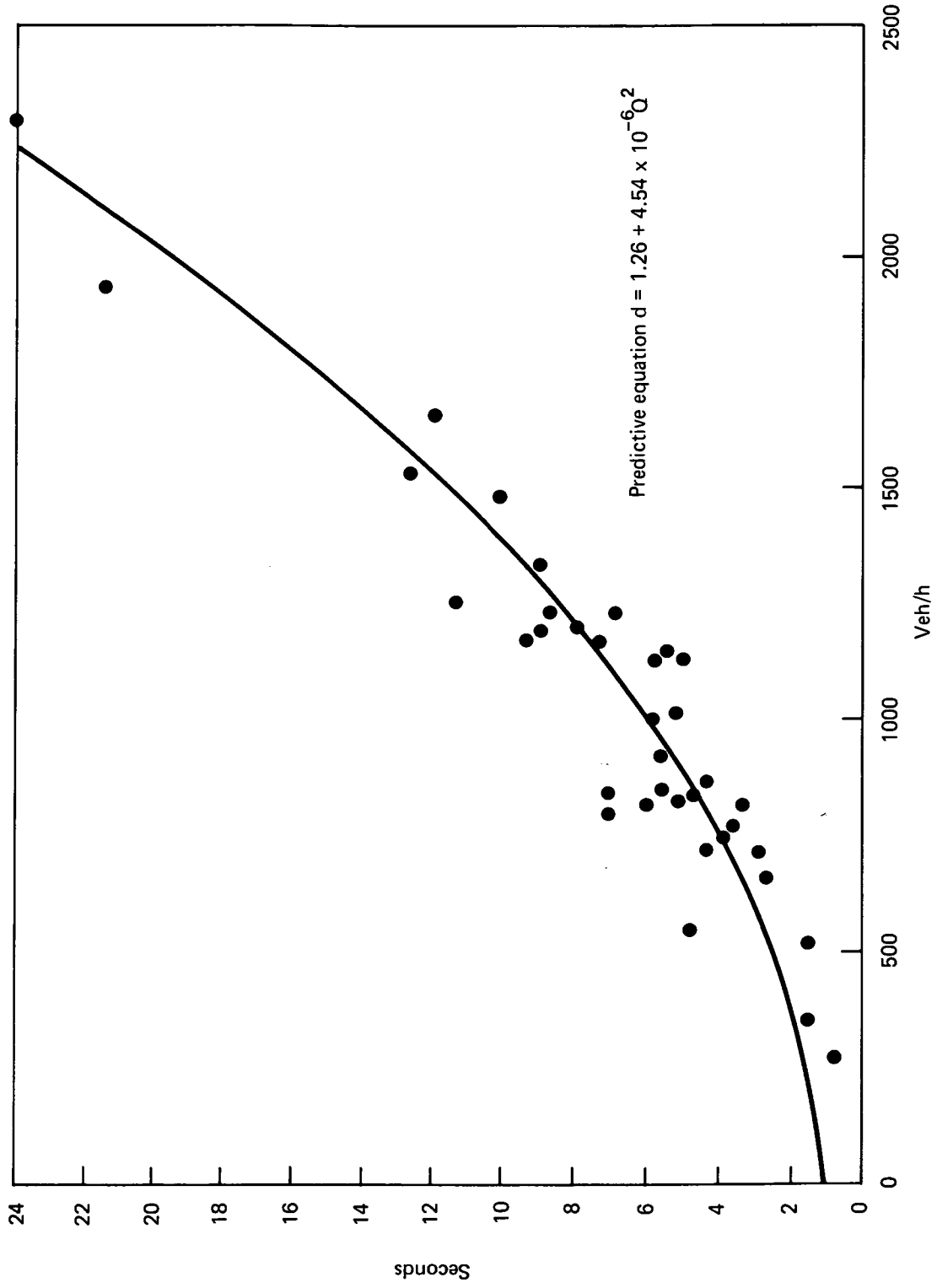


Fig.1 MEAN PEDESTRIAN DELAYS AT RANDOM CROSSING POINTS

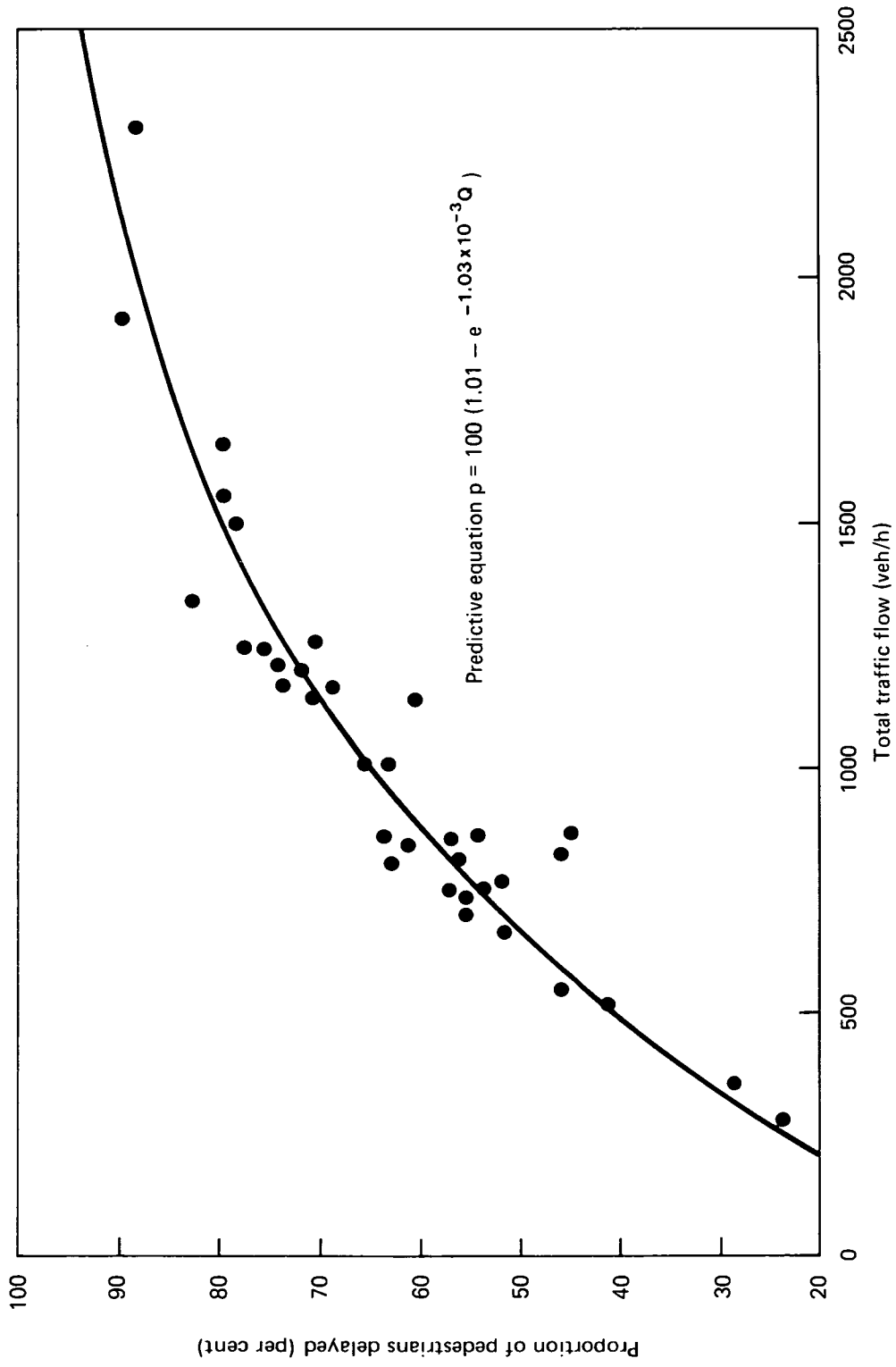
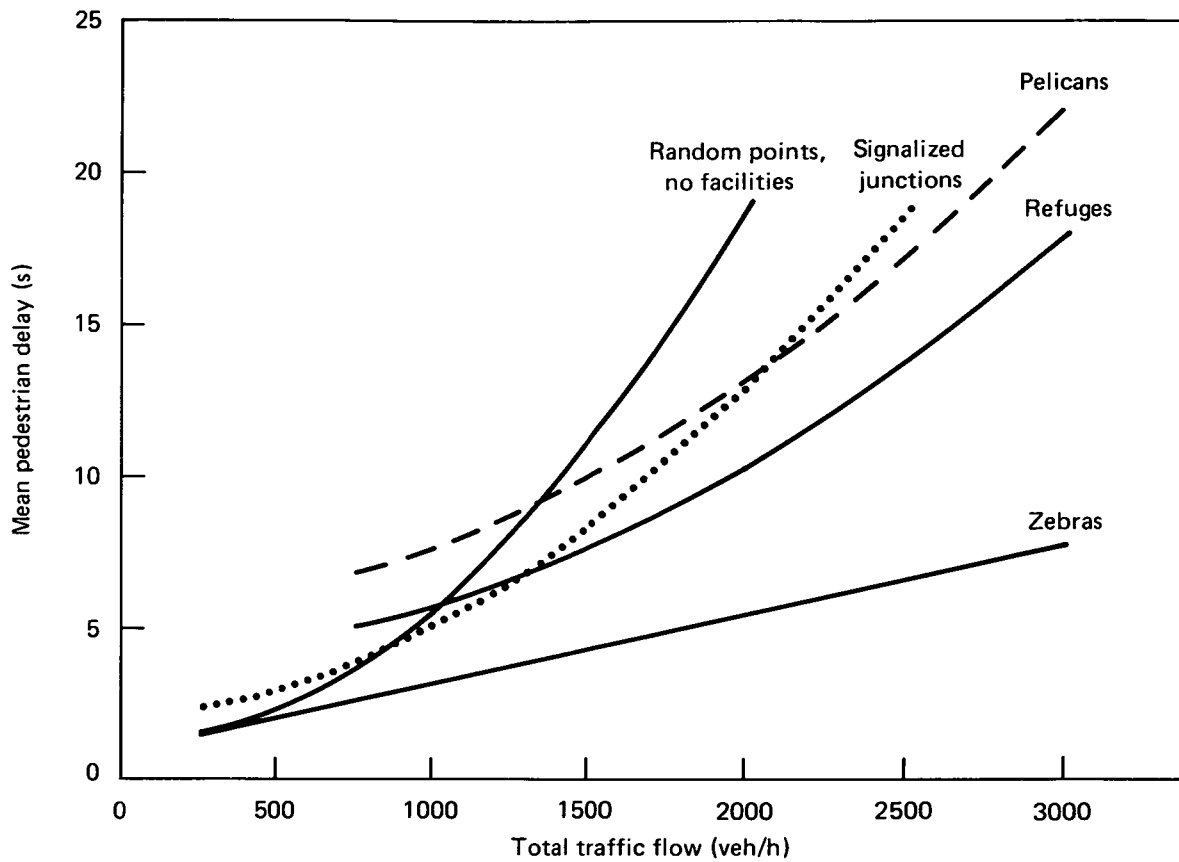


Fig.2 PROPORTION OF PEDESTRIANS DELAYED, AT RANDOM CROSSING POINTS



**Fig. 3 MEAN PEDESTRIAN DELAYS ASSOCIATED WITH DIFFERENT ROAD CROSSING SITUATIONS**

## ABSTRACT

PEDESTRIAN DELAY AND TRAFFIC MANAGEMENT: *J Goldschmidt*: Department of the Environment Department of Transport, TRRL Supplementary Report 356: Crowthorne, 1977 (Transport and Road Research Laboratory). The report summarizes a two-year study of the relationships between the delays to pedestrians crossing urban streets and traffic and layout characteristics. The aim of the study was to make explicit the influence of various types of traffic management on pedestrian delays.

A method for estimating pedestrian delays using a trained observer was developed and tested. This was used to record delays at sites where only few pedestrians crossed the road, while waiting times were observed directly at points with higher crossing flows. 423 surveys of delays, traffic, and layout characteristics were conducted in London streets. The sites were of five main types: kerbside points without crossing facilities, refuges, signalized junctions, zebra and pelican crossings.

Mean pedestrian delays were generally found to be below 8 seconds at flows of 1000 vehicles per hour, and below 20 seconds at 2000 vehicles per hour. Differences incurred at different types of location were marked, as were those between different age/sex categories of pedestrians.

Predictive equations for the mean delay and proportion of pedestrians delayed at the various types of location were developed, using multiple linear regression. In addition to traffic flow, the variables found to affect delays significantly were road width, signal timings, speed, composition, and the degree of bunching of the traffic. The correlation coefficients associated with the equations range from 0.72 to 0.96, and mean delays can be predicted with an accuracy of + 2 seconds to + 6 seconds, depending on the type of crossing situation. The possible applications of the equations are discussed in a concluding section.

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