A SURVEY OF RESEARCH INTO RELATIONSHIPS BETWEEN
TRAFFIC ACCIDENTS AND TRAFFIC VOLUMES

by

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A SURVEY OF RESEARCH INTO RELATIONSHIPS BETWEEN TRAFFIC ACCIDENTS AND TRAFFIC VOLUMES

ABSTRACT

Previous research into relationships between road accident frequencies and traffic volumes is reviewed. Methods used are assessed and the main conclusions of the soundest studies drawn together. Some researchers have deduced theoretical relationships between accident numbers and traffic volumes and checked these against data, while others have derived relationships more empirically.

In order to deduce an empirical relationship, it is necessary either to study different roads carrying different volumes of traffic, or to examine time-series data. Research of the former type has often shown that the number of single-vehicle accidents per unit of vehicle distance travelled tends to decrease with increasing traffic, while the number of collisions between two or more vehicles tends to increase. Knowledge about relationships between accidents and traffic volumes at intersections is less extensive but includes useful results. Time-series studies have usually shown that accident numbers have grown more slowly in the long term than have volumes of traffic, but, because of the many other time-dependent factors which affect the incidence of accidents, care must be taken in drawing conclusions from such studies about the underlying relationship between accidents and traffic volumes.

Comments are made concerning the data and methods likely to be useful in further research.

1. INTRODUCTION

It is certain that the number of opportunities for road accidents is closely related to the volume of traffic. However, only a very small proportion of these opportunities actually result in an accident. As the probability of an opportunity producing an accident may be related to the traffic volume and other factors, there may not be a close relationship between the frequency of accidents and the volume of traffic.

Many researchers have attempted to derive such a relationship from data on road accidents and traffic volumes, but in some cases no relationship has been apparent, while other studies have found contradictory results.
Over 80 studies are considered in this survey. The pieces of work have been grouped together according to the subject and the approach used. The grouping is not completely clear-cut and there is therefore some overlap between the different sections of the survey.

Several authors have tried to assimilate existing knowledge by studying the research of earlier workers, and Section 2 describes the literature reviews and surveys produced by these authors.

Some researchers have started from first principles and, without reference to any data, have derived theoretical expressions describing the way accident numbers would be expected to vary with amounts of traffic. These expressions have in some cases been afterwards validated with respect to data on accidents. Approaches of this type are reviewed in Section 3.

Most of the papers described in this report started with data on accidents and traffic volumes and proceeded to analyse these data in more or less appropriate ways. In order to deduce a relationship between accidents and traffic, it is, of course, necessary to have data on the numbers of accidents occurring at a range of traffic volumes. A range can be obtained by studying different roads carrying different amounts of traffic. Reports describing research of this type are reviewed in Section 4. Some workers have been able to isolate the effect of traffic volume by choosing road sections which are homogeneous in all other respects likely to influence accident frequency. Other researchers have sought to determine the effects of both traffic volumes and road design at the same time, often by deriving regression equations, and Section 5 describes some such pieces of work. Two factors which are likely to affect the occurrence of accidents but which receive relatively little explicit attention in the studies reviewed here are speed and the presence of pedestrians.

The problem of deducing a relationship between accidents and traffic at junctions, interchanges, ramps and so on is more complicated, as more than one traffic volume measure is required and it is not always clear which are the most appropriate measures. The basic problems of controlling for different design features are, however, the same as for road sections. Section 6 surveys previous research on this topic.
An alternative way to obtain a relationship between accidents and traffic is to concentrate on a particular road or set of roads and see how many accidents occur at different traffic flows. Section 7 looks at papers which have sought a relationship by observing how the accident rate changes when the amount of traffic using the road (or roads) changes in the short term, by considering volumes of traffic in different hours of the day. Section 8 deals with papers which look at the changes in accident numbers and accident rates over a longer period of time; many of these studies refer to accident statistics over a wide area. Some workers have fitted mathematical models to such time-series data, and some of these models have been used to predict numbers of accidents. Section 9 reviews these more mathematical treatments of time-series data.

2. PREVIOUS LITERATURE REVIEWS

A general review of research into relationships between accidents, traffic control and road design is given by the Automotive Safety Foundation in a chapter document. Chapter II, dealing with traffic volumes, gives a readable introduction to the subject and describes many of the most important studies of the relationship between accidents and traffic dating from before 1963. However, the number of relevant references in the chapter is limited to less than a dozen, and the authors do not deal with the subject in any great depth. There is an extensive list of references, over 700 in all, at the end of the book, including much unpublished material from the United States, and a subject index; however, the usefulness of these is limited by the time which has elapsed since their compilation.

Of a similar scope is a report from Chalmers Tekniska Hogskola. This report, which is in Swedish, is a survey of research on road accidents and the road and traffic environment. There are ten chapters, but the material relating to the influence of traffic volumes on accident numbers is contained in Section 2.3, which gives a straight description of the main results found by previous researchers. The number of relevant papers is limited to about fifteen, but the material is laid out clearly and well.

A dissertation by Thorson aims to discover correlations between road, traffic and accident data by computer analysis. A literature survey considers about 20 relevant references; the author goes on to deal with mathematical
models of accident occurrence and then sets out results of computer analyses of Danish accident data. Although the analyses include intersection accidents, previous work on these is not reviewed. Like the two reports mentioned above, the dissertation does not deal with time-series studies. The author gives a more thorough and thoughtful review than either of the above studies and has therefore produced a valuable contribution to the subject.

Chapman\(^4\) gives a wider survey of the literature, which examines relationships between accident frequency and exposure. Much of Chapman's own work on accident statistics is geared towards finding the most appropriate exposure measure, but some of his conclusions yield useful information on the accident situation, even though the methods used are elementary (with generally no mathematical models being derived), and the results often negative. Interspersed with the author's original analysis in this thesis of over 300 pages is a large body of comment on previous research. The criticism itself is limited, but some topics, such as exposure measures for intersection accidents, are investigated at length (see Section 6).

3. THEORETICAL EXPRESSIONS OF ACCIDENT INCIDENCE

This section considers research in which the worker starts from first principles and, before analysing accident data, develops equations expressing the way accident numbers might be expected to be related to traffic volumes. Models fitted empirically to accident data are not dealt with here but are examined in Section 9.

The various reports reviewed in this section use widely differing systems of notation, sometimes extremely cumbersome, but this has been simplified and standardised for the discussions here, in which \(y\) denotes the number of accidents and \(x\) signifies a measure of traffic volume. Much of the theory can be developed without being very specific about what counts as an accident, but in any application it is necessary to be clear whether, for example, fatal accidents only, or all injury accidents are being considered, and whether damage-only accidents are included. Still other studies relate to numbers of casualties of different severities rather than numbers of accidents.

At this stage it is necessary to distinguish between two closely related measures of traffic. Firstly there is the traffic flow past a point in a
given time - the units of this quantity are vehicles per unit of time, which may be an hour, a day or a year. The words 'flow' and 'volume' are normally regarded as synonymous in this connection. (The most frequently used measure of traffic carried by a road is average daily traffic (ADT).) Secondly there is the distance travelled by vehicles, which, for a particular section of road, is the flow of vehicles multiplied by the length of the section, and this is expressed in vehicle-miles or vehicle-kilometres per unit of time.

An obvious possible form of relationship between the number of accidents $y$ and the volume of traffic $x$ is the power function

$$y = ax^p$$

where $a$ is a constant. The accident rate per unit volume of traffic, $y/x$, has a similar form

$$\frac{y}{x} = ax^{p-1}$$

Thorson (1967) gives a more general form of (1),

$$y = a((x+r)^p - r^p)$$

where $r$ is a constant, and he illustrates the possible shapes that such curves can have. This form solves the problem created by formula (1), namely that, in that case, as the traffic approaches zero, the accident rate tends to either zero or infinity (except in the special case $p = 1$). However, form (3) is a good deal less natural than the simpler form.

Pfundt also considers accidents as power functions of traffic and how such a relationship can be used in before-and-after studies. If, before, say, a road safety measure,

$$y_1 = a_1 x_1^p$$

and, after the change,

$$y_2 = a_2 x_2^p$$
then the effectiveness of the change can be measured by

\[ k = \frac{a_2}{a_1} = \frac{y_{2}x_1^p}{y_1x_2^p} \]  \ldots \ldots (6)

Smeed argues from first principles that the number of deaths from accidents involving just one vehicle should, if nothing else changed, vary in direct proportion to the number of vehicles \( N \) on the road. Similarly, the number of deaths from collisions between two vehicles should be proportional to the square of the number of vehicles, and the number of deaths from single-vehicle accidents involving a pedestrian should vary in proportion to the product of the numbers of vehicles and the population \( P \). The total number of deaths \( D \) would then be expressible in the form

\[ D = \alpha N + \beta N^2 + \gamma NP \]  \ldots \ldots (7)

where \( \alpha, \beta, \gamma \) are constants and accidents involving more than two traffic units (vehicles or pedestrians) are neglected.

Smeed returns to a similar theme in later years, but, with more detailed accident and traffic flow data available, he is able to formulate his hypotheses more precisely and to test them. The simple idea expounded in his later work is that the number of single-vehicle accidents not involving pedestrians should be proportional to the distance travelled by vehicles of the appropriate type, and that the number of collisions between two vehicles should be proportional to the product of the distances travelled by the two types of vehicle concerned. When time-series data on British accidents are analysed, it is found that the numbers of accidents do not vary in the way expected, but Smeed makes further analyses of the data, resulting in equations of the form

\[ y_{ij} = a_{ij}x_i^p x_j^p \]  \ldots \ldots (8)

where \( y_{ij} \) = accidents between vehicles of types \( i \) and \( j \) and \( x_i, x_j \) = distances travelled by vehicles of types \( i, j \). These models are discussed in Section 9.

Thorson reviews Smeed's model and also that of McKerral, who fits curves of the form
\[ y = ax^2 + bx + c \] \hspace{1cm} \text{...... (9)}

to accident and traffic data. The latter work is of a more empirical nature and is therefore dealt with in Section 4.

A report from the Dutch Central Bureau of Statistics\(^9\) adopts an approach similar to Smeed's: the number of collisions between two vehicles is assumed to be proportional to the product of the distances travelled by vehicles of the types involved. Each type of vehicle \(i\) is assumed to have an accident liability \(\lambda_i\) associated with it, so that the number of accident involvements \(z_{ij}\) incurred by vehicles of type \(i\) with vehicles of type \(j\) is given by

\[ z_{ii} = \lambda_i x_i^2 \] \hspace{1cm} \text{...... (10)}

\[ z_{ij} = (\lambda_i + \lambda_j) x_i x_j \quad (i \neq j) \] \hspace{1cm} \text{...... (11)}

The additive nature of the coefficient in (11) is perhaps less plausible than a multiplicative form \(\lambda_i \lambda_j\), and the report fails to relate accident numbers to involvement numbers correctly. A further fault of this report is that the authors choose to neglect single-vehicle accidents.

Belmont\(^{10}\) goes into more detail when proposing models relating accident numbers to traffic volumes. He begins with a relation similar to those described above, namely

\[ y = ax^2 + bx \] \hspace{1cm} \text{...... (12)}

where the first term accounts for collisions between two vehicles or more and the second term refers to single-vehicle accidents. However, the preliminary analyses show a poor agreement between theory and reality in some respects, notably at very high and low flows, so Belmont refines his hypothesis by considering different types of accident separately and by introducing speed into his equations.

For single-vehicle accidents, he argues heuristically, considering braking distances and reaction times, and arrives at the relationship

\[ y = k_1 v^{1.5} x \] \hspace{1cm} \text{...... (13)}
where $v$ is the average speed of traffic. Although data are not available to validate this theory, the observation that at high volumes both speed and single-vehicle accident rates per vehicle-kilometre fall suggests that Belmont's ideas may contain at least an element of truth.

His theoretical treatment of head-on collisions is rather more complicated and rests on the assumption that the probability of two vehicles colliding is proportional to a power of the sum of their approach speeds. A power of 2 seems to give a reasonable agreement with observation, and (after some simplification which affects the power of $v$ appearing in the resulting expression) this leads to the formula

$$y = k_2 v x^2 \quad \ldots \ldots \quad (14)$$

Belmont divides rear-end collisions into those which resulted from vehicles travelling at less than a safe distance and other collisions. The expected number of accidents of the first type is worked out using the implausible assumption of random vehicle headways, and the expression which results can be approximated as

$$y = (k_3 + k_4 v) x^2 \quad \ldots \ldots \quad (15)$$

It is argued that collisions of the second type are of a similar nature to single-vehicle accidents and therefore their numbers are governed by an equation of form (13). Belmont's rear-end collision data agree well enough with his theory except at high flows (over 700 vehicles per hour on 2-lane roads), when the number of accidents is much fewer than expected.

It is very unlikely that Belmont's theories could ever be checked effectively. It is difficult enough to observe accident numbers at different flows while keeping other sources of variation under control; to allow flow and speed to vary independently while controlling for the other variables is doubly difficult. The necessary data on the traffic speed at times and sites representative of those of the accidents would be hard to obtain.

Thorson considers head-on collisions, pointing out that, if traffic is moving in platoons, the probability of a collision is much higher for a vehicle at the head than for a vehicle in the queue behind. If one neglects
the latter probability and assumes, as is suggested by theoretical traffic models, that the number of platoons is proportional to $x^{0.6}$, where $x$ is the traffic volume, then one reaches the conclusion that the number of head-on collisions should be proportional to $x^{1.2}$ (as opposed to $x^2$ in the more basic models).

There are numerous theoretical studies which express the number of conflict situations at intersections as mathematical functions of the traffic flows; some of these studies do not attempt to assess the usefulness of their formulae by examining real data. On the whole this kind of work is of limited relevance to the discussion here, and so only a few of the papers are mentioned; Chapman\(^4\) reviews the literature more fully. Analyses of data on intersection accidents and traffic are described below, in Section 6.

Chapman\(^4\) looks at streams of traffic crossing at right angles and finds that, for low flows, the number of potential conflicts is proportional to the product of the flows. Surti\(^\text{11}\) looks in more detail at points at which traffic streams cross at a four-way intersection and derives lengthy formulae giving exposure indices (basically the sum, over all the conflict points, of the products of the conflicting traffic flows). Indices are computed for four intersections.

Underwood\(^\text{12}\) considers low-volume Y-junctions and again deduces that the number of conflicts is, in theory, proportional to the product of the flows. Thorson\(^\text{3}\) examines T-junctions and divides the headways in the main road traffic into 'blocks' (headways too small for a vehicle to emerge from the side road) and 'antiblocks' (large enough headways for a vehicle to enter the traffic). He deduces that a correction term is needed in addition to the simple product-of-flow relationship, so that

$$C = a_1 Q q - a_2 Q^2 q$$

where $C$ is the number of conflicts, $Q$, $q$ are the major road and side road flows and $a_1$ and $a_2$ are constants. No data are examined.

Breuning and Bone\(^\text{13}\) deduce that the exposure index of two weaving streams of traffic should be the product of the two flows. They derive, in a similar manner to Surti, expressions for the total exposure at a cloverleaf...
interchange, and the exposure indices at two interchanges of different design are compared with the accident statistics.

The following sections describe various ways in which relationships between measures of accident occurrence on the one hand, and measures of traffic volume and other relevant parameters on the other, have been examined by the analysis of data. In comparing and using the results of such analyses it should be remembered that a relationship fitted for one independent variable cannot always be transformed algebraically into a valid relationship for another independent variable, even when the two variables are simply related theoretically. For example, a relationship for accident rate, when multiplied through by the flow, may yield a relationship for accident frequency very different from that which would be obtained by fitting a relationship of the same form directly to the accident frequencies.

4. ACCIDENT RATES ON DIFFERENT ROADS CARRYING DIFFERENT TRAFFIC VOLUMES

It is known (see Table 15 of Johnson and Garwood\textsuperscript{14}) that, in Britain, the different classes of road, which carry very different traffic volumes, tend to have accident rates (per vehicle distance travelled) of a similar order of magnitude. The implication is that the relationship between accident rates and traffic amounts is not a strong one or perhaps that it is being masked because of systematic differences (between busy and quiet roads) in physical factors which are affecting the accident rate in the opposite direction.

To isolate the underlying relationship between accidents and traffic volumes by studying different roads, it is necessary to allow for these other factors in some way. Conversely, a researcher who wishes to investigate a relationship between accident numbers and a physical feature of the road (such as carriageway width) has generally to eliminate the effect of traffic volume on the accident data in order to reach an assessment of the effect of the road feature; indeed, many of the pieces of work described below are aimed at finding such an effect, and the role of traffic volume is explored merely as a means to an end.

The methods used to separate out the effects of the different factors vary from study to study. Some researchers fit equations to the accident
data, requiring assumptions about the form of the relationship, while others give quite involved cross-tabulations, which, although not requiring any basic assumptions, may well be difficult for the reader to follow. Other authors ignore the problem and assume that all the 'nuisance' variables balance out over the different traffic volume classes. Some papers give a combination of these different methods, often starting with an elementary treatment and continuing with a more sophisticated analysis.

Most of the studies described here consider a number of road sections and begin with certain data on each section i, including the vehicle-distance travelled \( X_i \) and the number of accidents \( Y_i \) (or, equivalently, the traffic volume and accident 'density', each formed from the original variables by dividing by the section length). The usual approach is to use as the dependent variable the accident rate \( Y_i / X_i \) and relate it to the traffic flow and other factors.

One of the earliest workers to present data relevant to the problem is Vey\(^{15}\) who plots accident rates against ADT on 2-lane state highways in New Jersey. A curve fitted through the data shows the accident rate to rise from zero at zero traffic to a maximum and then to decline. However, the shape of the curve appears to be somewhat arbitrary and not to fit the data very closely, even though Vey describes the relationship as 'definite'. No control of any design variables is acknowledged.

A much more thorough analysis is carried out by Raff\(^{16}\) whose paper remains one of the standard works of reference on the influence of traffic volumes and road design features on accident rates. The study covers accident data from main rural highways in 15 states of the USA, mostly in 1941. The 5,000 miles of road are divided into short, homogeneous sections. Raff tries three methods of dealing with the problem of differential reporting levels in the different states, and the resulting three analyses are carried out in parallel throughout his report. As well as traffic volumes, the report considers numbers of lanes, divided/undivided roadways, straight/curved sections, roadway and shoulder widths and many other variables. The analysis proceeds by cross-tabulating accident rates against two or three variables at a time, so that it is not possible to control for all the variables simultaneously. The effect of traffic volumes on accident frequency does not emerge especially clearly, but the general trend is that accident rates
increase with increasing traffic up to a certain point, after which there is a decrease; the exception to the rule is for two-lane curves, where accident rates seem to decrease as traffic increases. The two main drawbacks of this study (except for its age) are that no division of accidents into types is made and that the author tries to investigate too many effects at once. But the report illustrates the complexity of the problem and gives a guide for later authors as to the sort of relationships they should expect to find.

On a much smaller scale is a study by Coburn\textsuperscript{17} of accident rates on rural roads in Buckinghamshire in the years 1947-50. Like Raff, Coburn attempts to evaluate the effects of design variables as well as traffic volumes. Simple tabulations are given and regression methods used, but the author acknowledges his failure to control fully for the design variables, so that definite conclusions cannot always be reached. For further investigations, Coburn recommends limiting attention to a few variables at a time; roads should be chosen to be similar in all respects except those to be investigated - this is undoubtedly correct. Despite this lack of control, the author observed some definite trends in the rates of different types of accident: the single-vehicle accident rate decreases with increasing traffic, the two-vehicle accident rate increases and the rate of accidents involving more than two vehicles increases sharply. However, the total injury accident rate does not appear to vary much with the amount of traffic, although Smeed\textsuperscript{18} fits a line with a small positive slope through the points. The data show that the damage-only accident rate increases with the traffic volume much more rapidly than the injury accident rate.

A particularly thorough piece of research is described by Kihlberg and Tharp\textsuperscript{19}. Data on accidents on rural highways in five American states in 1961-64 are analysed using regression models. The roads are divided into homogeneous segments of length 0.3 miles, and many different regressions carried out according to the number of lanes, the degree of access control and whether the highway is divided, as well as grade, curvature and the presence or otherwise of intersections and structures. Thus an attempt is made to control a fair number of physical factors in the analyses. The conclusions reached about traffic volumes are similar to those of Coburn, namely that single-vehicle accident rates decrease with increasing ADT and that collision rates increase with increasing traffic. However, the
relationship between the rates for all accidents and traffic is indeterminate—in some cases the rate increases and in other cases it decreases, perhaps because different proportions of single-vehicle accidents and collisions are included in the different cases.

The studies described above, which are among the most carefully executed pieces of research on the subject, imply relationships between accident rates and traffic of the general forms shown in Figures 1 and 2.

The shape of the relationship between total accident rates and traffic will depend on the proportions of the different types of accident. One possible form is that given by Yu showing curves fitted to accident data from highways in Virginia. While his paper gives few details of the analyses carried out, the form of the curves shown (Figure 3) is certainly consistent with the above findings—with single-vehicle accidents dominating at low flows and collisions becoming important at higher traffic volumes.

Pfundt shows curves fitted to accident data on rural roads in West Germany. Again few details of the analysis are given, but different types of accident are considered. Whilst turning accident rates increase with traffic volume, single-vehicle accident rates decrease sharply, as found by other researchers, and the rate of rear-end type accidents decreases slowly with traffic. The total accident rate is found to decrease with traffic volumes, and, as the roads being considered are quite lightly trafficked, this finding is quite consistent with Figure 3.

The results of Nilsson are in broad agreement with other findings. Nilsson's findings, based on data from rural main roads in Sweden in 1962-64, are, again, that the single-vehicle accident rate decreases with ADT and that the collision rate increases with ADT. The regression lines fitted control for roadway width and shoulder width in that different lines are calculated for the various width groupings. A later report by Nilsson does not distinguish between different types of accidents. Using the same data as the previous report, Nilsson carries out multiple regressions and correlation analyses (using both total and partial correlations). The general trend exhibited by the results is that accident rates are correlated negatively with traffic volumes, but variables describing sight distance prove to be most closely correlated with accident rates.
Crosby's observations from accident data on the New Jersey Turnpike are in line with other research. It is noted that the proportion of single-vehicle accidents decreases with increasing flow, while the proportion of overtaking accidents increases. However, no relationship is found between the total accident rate and ADT. This is perhaps hardly surprising in view of the limited scope of the data.

Duncan analyses British accident data from 30-foot carriageways (main roads in predominantly rural areas). He groups the road sections into flow categories and fits simple regression equations to the accident rates and flows. The data are of limited extent, and no attempt is made to control for design variables. It is found that accidents involving two vehicles or more are positively correlated with ADT, but the correlation between single-vehicle accidents and ADT is insignificant.

Thorson does not distinguish between accident types in his regression analyses of accident data from rural roads in Denmark in 1962. Control of certain variables is achieved by fitting different curves for different types of road - according to width, number of lanes, whether the road is divided or undivided and whether there is any development. The power curves fitted to the data imply an accident rate uncorrelated with traffic on 3-lane roads and correlated negatively with traffic on 2-lane roads. These analyses are also described by Jørgensen. Thorson and Mouritsen use the same methods to fit a wider variety of power curves to similar data from 1962 to 1966; some curves show a positive, and some a negative, relationship between accident rate and traffic volumes.

An analysis by Lundy of accident data on Californian freeways regresses accident rates against ADT. Different regressions are calculated for roads with different numbers of lanes, but otherwise there is no control of design variables. The analyses show the accident rate increasing with traffic.

Large-scale surveys of accident rates on roads in Belgium and France are reported respectively by Claes and Goldberg. Neither of these researchers control very well for design differences between roads, and only simple tabulations and graphs are given, but both studies show some evidence of a U-shaped relationship between accident rates and traffic volumes.
Billion and Parsons\textsuperscript{30} consider accidents on divided urban highways on Long Island, New York between 1955 and 1959. Although the accident data are quite extensive, the length of road studied is very limited, so it is quite impracticable to control for design variables. The authors have to assume that these factors balance out over the various traffic volume classes, but, with such a small set of roads, this assumption is doubtful. Thus the finding that accident rates increase with traffic is not very soundly based.

McKerral\textsuperscript{8} analyses accident data from New South Wales in 1961. He fits curves of the form

\[ y = a + bx + cx^2 \] \hspace{1cm} (17)

where \( y \) is the number of accidents per year per mile and \( x \) is the ADT. The constant \( a \) proves to be close to zero, which is correct, and both \( b \) and \( c \) are found to be positive (147x10\textsuperscript{-5} and 238x10\textsuperscript{-10} respectively for all accidents), implying an increasing accident rate with increasing traffic. But McKerral does not control for any design variables.

Silyanov\textsuperscript{31} also fits a curve of form (17), but his data are secondhand and come from a wide variety of sources, so that, in the absence of any attempt to control for any of the basic differences between the sets of data, his curve cannot be taken very seriously.

The analyses of Jacobs\textsuperscript{32}, dealing with rural roads in Kenya and Jamaica, do not directly set out to find a relationship between the accident rate and the amount of traffic. Jacobs simply performs a linear regression of accident density on traffic, and, of course, the slope proves to be positive. This implies a relationship between the accident rate \( y \) and the traffic \( x \) of the form

\[ y = a + \frac{b}{x} \] \hspace{1cm} (18)

where \( a > 0 \). \( b \) also turns out to be positive, so that the implication is a decrease in accident rate with increasing traffic, which is in line with other results because of the light traffic carried by the roads considered.
Chapman\textsuperscript{4} gives the results of several analyses, which do not control for any design differences. The data are from Britain, New Zealand and Israel, and, generally, no strong relationship between accident rate and flow is found, although there is a tendency for the correlation to be negative.

Moskowitz and Schaefer\textsuperscript{33} analyse accident rates on highways in California. They reach the rather unexpected conclusion that the form of the relationship depends on the type of median: with traversable medians, the rate goes up with increasing traffic, and the opposite is true for roads with non-traversable medians. However, the effect of design differences between individual roads may be influential here, as no attempt is made to control for these other factors.

Sitzel\textsuperscript{34} can find no relationship between accident rates and ADT on West German motorways, but, here again, there is no control of design variables.

Rykken\textsuperscript{35} analyses data from Minnesota, and uses an approach somewhat different from the pieces of work described above. He does not analyse traffic volumes as such, but, for each road section, he calculates a congestion index, which is the quotient of the 30th highest hourly traffic (per year) and the practical hourly capacity. Rykken plots accident density against the congestion index and fits two straight lines to the data (one each for congestion indices below and above unity). The data show that the number of accidents increases linearly with the congestion index and that the rate of increase is greater when the index exceeds unity. The implication is that, for a particular type of road, the accident rate remains constant until congested conditions are reached and then begins to rise.

A different but related topic is explored by Chatfield\textsuperscript{36}, who compares the different states of the USA and plots the fatal accident rate against the 'travel density', which is actually the average traffic volume over the whole of the road network. Not surprisingly, there is a great deal of scatter, but the author fits hyperbolic curves to the data. This analysis does not reveal much about the relationship between accidents and traffic but provides a yardstick for assessing the accident record of particular road systems. Peltzman\textsuperscript{37} fits regression models to accident data from different American states, using a curious mixture of economic and traffic variables, but no definite conclusions about the underlying relationship with traffic volumes.
can be safely reached from a study of this kind.

Most of the studies referred to in this section relate to rural roads. It is understandable that relationships between accident occurrence, and traffic volume should have been sought first on rural rather than on urban roads, because the pattern of other factors likely to affect the occurrence of accidents is less complicated in the former.

5. REGRESSION STUDIES OF ACCIDENT RATES AND ROAD DESIGN VARIABLES

Some researchers seek to determine simultaneously the influence of traffic volumes and road features by fitting regression models. Usually the main aim of such studies is to explore the influence of some aspects of the road design on the number of accidents. The methods employed vary somewhat, but the main differences between the different studies involve the choice of the dependent and the independent variables. The dependent variable may be the number of accidents, the accident rate or the accident density or a transformation of any of these, and the condition given at the end of Section 3 is particularly relevant here. The independent variables commonly include width, measures of vertical and horizontal alignment, type of development and the number of intersections and openings. In the following discussion, values of the multiple correlation coefficient \( R^2 \) are quoted as an indication of the effectiveness of different models in explaining variation in the data. The values of \( R^2 \) in different studies should, however, only be compared with caution, because of the different nature of variability in the different sets of data.

Belmont\(^{38}\) investigates the effect of shoulder width on accidents on straight two-lane road sections in California and fits a curious equation, whose terms are different depending on whether the shoulder width is greater or less than 6 feet and whether the ADT is greater or less than 5,000. As his dependent variable Belmont chooses the square root of the number of accidents. (The square root transformation has the theoretical advantage that the variance of the dependent variable is more homogeneous, and least squares regression techniques are strictly only applicable when the variance is homogeneous.) The form of the equation fitted is

\[
\sqrt{y} = a + b \sqrt{1} + c \sqrt{x} \quad \ldots \ldots \ (19)
\]
where \( y \) is the number of accidents, \( x \) is the vehicle mileage and \( l \) is the section length. Despite the unusual form of equation, a multiple correlation coefficient \( R^2 \) of 0.90 is quoted, which is very high for an analysis of this type. Probably the large size of \( R^2 \) is partly a reflection of the wide spread of \( y \), which ranges from 1 to 138.

In a later paper, Belmont\(^3^9\) returns to a similar theme but takes sections of uniform length - one mile. Grouping the data, he develops equations of the form

\[
y = a + bS + cx + dSx \quad \ldots \ldots (20)
\]

where \( S \) is the shoulder width and \( x \) is the ADT. The value of \( R^2 \) found is very high, 0.946. The success of the studies of Belmont no doubt depends on the very careful selection of roads, excluding any sections with curves, structures or intersections. Not surprisingly, the coefficients \( c \) in equations (19) and (20) are found to be positive.

The analyses of Nilsson\(^2^1,2^2\), relating to accidents on rural main roads in Sweden, show a sensible and thoughtful approach to the problem. Rather than introduce a large number of independent variables from the beginning, the author gradually builds up his equations, starting with ADT, measures of sight distance, section length and width\(^2^1\). These variables are tried in various combinations, and three different dependent variables are used: number of accidents, accident density and accident rate. The equations obtained are not particularly reliable, with \( R^2 \) reaching only about 0.3, probably because of the lack of control of other variables. Traffic volume is not found to have an important influence on accident rates, the sight distance variables being more important. Nilsson\(^2^2\) later extends his list of independent variables to give nine in all, and different regression techniques are tried - unweighted, weighted and stepwise multiple regressions. Despite the extra sophistication, these regressions give poor values of \( R^2 \), only up to 0.34, probably owing to excessive variation, between the road sections, of factors not allowed for in the regressions. As in his previous report, Nilsson does not find that ADT has much effect on accident rates.

Coburn\(^1^7\) also attempts to develop multiple regression equations using a heterogeneous selection of roads. He uses as his dependent variable the
The equations developed, by several methods, are poor predictors, with $R^2$ less than 0.2, and all the regression parameters are insignificantly different from zero.

Head\textsuperscript{40} gives a large number of regression coefficients, obtained from data on State Highways of Oregon, relating the accident rate to ADT and several design variables. Head begins with only 426 road sections and proceeds to divide his data into quite small groups of sections, as small as 2 or 3 in some cases. Different regressions are calculated for the different subgroups, and it is hardly surprising that, with such small samples of roads, the different equations show little consistency. The small sample size no doubt accounts for the good multiple correlations obtained in some cases.

Cribbins, Arey and Donaldson\textsuperscript{41} use accident density per mile of road as the dependent variable in their analysis of accidents on multi-lane highways in North Carolina. Eight independent variables are used, including ADT and several describing access points and median characteristics. Stepwise regressions are carried out for numerous accident types, and, as the dependent variable is accident density, it is not surprising that the coefficient of ADT proves to be positive in many cases. A good value of $R^2$, 0.69, is obtained with the analysis of all accidents, indicating a well-fitting model, but the fact that accident density is the dependent variable means that, for reasons given at the beginning of this section, little can be concluded directly about the relationship between accident rates and traffic. Similar comments apply to the paper by Cribbins, Horn, Beeson and Taylor\textsuperscript{42}, who set out to investigate the effect of median openings on the accident rate.

Schoppert\textsuperscript{43} analyses data from the Oregon State Highways and develops simple regression equations relating the numbers of accidents on mile sections of road to seven independent variables, including ADT. Different equations are calculated for different ADT ranges, so that the effect of traffic volume is given both in the equations themselves and in the differences between the various equations. The coefficients of ADT are all positive but not all significant; the positivity is to be expected in view of the dependent variable used, and it does not yield any information about the
relationship between accident rates and traffic.

Dart and Mann\textsuperscript{44} attempt to relate accident rates on rural highways of Louisiana to highway geometry. They employ 11 independent variables plus first order interactions formed as products of pairs of the original variables, and the dependent variable is the accident rate. Curiously, the most important predictor variables appear to be the first order interactions, several of which involve ADT as one of the constituent factors. This makes it practically impossible to isolate the effect of ADT on accident rates.

The regression analyses of Crowther and Shumate\textsuperscript{45} are of a rather different type to those described above. The dependent variable is accident density, but the independent variables are of an unusual type, intended to measure different kinds of exposure. Such measures as the number of headways less than 2 seconds and the number of meetings of vehicles are obtained from films of traffic at 57 sites. One of the 19 exposures measured is the traffic volume, but there is no doubt that many of the other exposure measures are intimately connected to the amount of traffic, so that the multiple regression equations do not say much about the relationship between accidents and traffic. Indeed, all the regressions give a negative coefficient for ADT, and this, if viewed in isolation, may be very misleading.

Placed in this section for convenience is the study of Versace\textsuperscript{46}, who performs a factor analysis of accident and road data from Oregon. Four factors are extracted, including one with large coefficients for accidents, traffic volumes, driveways and intersections. It is hard to come to any firm conclusions from a study of this type.

6. ACCIDENTS AND TRAFFIC VOLUMES AT JUNCTIONS

In Great Britain more than half the injury road accidents occur at or near junctions or intersections of some kind, and so the question of junction design is an extremely important safety problem. In order to evaluate the safety of different designs of junction it is necessary to know something about the underlying relationship between accidents and traffic volumes at junctions. The derivation of such a relationship has proved a complex and difficult problem, and few researchers have been able to give a satisfactory treatment of the subject. Although the majority of accidents at junctions
occur in urban areas, relationships between accident occurrence and traffic volumes were sought first at rural junctions, where the effects of other factors, such as the presence of pedestrians, are less complicated.

Tanner\textsuperscript{47} analyses data on accidents at rural three-way junctions in eight counties of England and Wales, and deduces the following relationships:

\[
\begin{align*}
A_r &= R_r q_r^{0.56} Q^{0.62} \quad \text{......... (21)} \\
A_l &= R_l q_l^{0.36} Q^{0.88} \quad \text{......... (22)}
\end{align*}
\]

where \(Q, q_r, q_l\) are the flows shown in the figure and \(A_r\) is the number of accidents between vehicles in the \(Q\) and \(q_r\) traffic streams, \(A_l\) the number of accidents between the \(Q\) and \(q_l\) streams and \(R_r, R_l\) are constants. As three of the four powers do not differ significantly from 0.5, Tanner replaces (21) and (22) by the simpler forms

\[
\begin{align*}
A_r &= R_r (q_r Q)^{0.5} \quad \text{......... (23)} \\
A_l &= R_l (q_l Q)^{0.5} \quad \text{......... (24)}
\end{align*}
\]

As was explained in Section 3, theoretical considerations would lead one to expect powers of 1 rather than 0.5, and Tanner's findings show that accident risk at three-way rural intersections does not increase as rapidly as would be expected when traffic volumes increase.

Colgate and Tanner\textsuperscript{48} analyse similar but more recent data, and, while the data are insufficient to check the mathematical form of the relationships, equations (23) and (24) are again found to provide an adequate description.

Roosmark\textsuperscript{49} studies data from three-way junctions in Sweden and deduces the equations

\[
\begin{align*}
A_r &= R_r q_r^{0.42} Q^{0.71} \quad \text{......... (25)} \\
A_l &= R_l q_l^{0.42} Q^{1.02} \quad \text{......... (26)}
\end{align*}
\]
Like Tanner, he rounds the powers of the turning flows to 0.5, but he rounds the powers of $Q$ to unity, so that

$$A_r = R_r q_r^{\frac{1}{2}} Q$$  \hspace{1cm} \text{......... (27)}

$$A_l = R_l q_l^{\frac{1}{2}} Q$$  \hspace{1cm} \text{......... (28)}

McDonald $^{50}$ deals with accident data from intersections on divided highways in California and derives an equation giving the number of accidents

$$A = R q^{0.63} Q^{0.45}$$  \hspace{1cm} \text{......... (29)}

where $Q$, $q$ are the major and minor road traffic volumes respectively and $R$ is a constant. The similarity of the equation to those found by Tanner is noteworthy. The data analysed relate to a variety of very different intersections types, no attempt being made to sort the intersections by type, and this perhaps detracts from the value of the result.

Another analysis of accident data at intersections on divided highways is given by Priest $^{51}$. He adopts an unusual approach, obtaining regression equations giving exposure (essentially the product of the two flows) as a quadratic function of accident frequency, and deriving charts showing the way exposure, primary and secondary traffic volumes and accident frequency are inter-related.

Syrek $^{52}$ aims to compare the accident experience at intersections in Los Angeles with three different types of traffic control. He finds that the number of accidents per million vehicles increases with minor street volume whatever the type of control, but the relationship with major street volume depends on the type of control - there is an increase at junctions with stop signs at all four approaches and a decrease at those with stop signs on the minor street only. A much more sophisticated treatment of the same problem is given in a report from Leisch, Pfefer and Moran $^{53}$ who fit multiple regression equations, with many independent variables describing both the layout and the usage of the intersections. The regression equations are not easy to interpret, but they seem to imply an increase in the accident rate per million vehicles entering the junction with an increase in either major or minor street traffic, which is not in line with other findings.
Raff\(^{16}\) gives some cross-tabulations of accident rates at intersections by the total traffic volume and the proportion of cross-traffic. No consistent relationship is observed between accident rates and traffic volumes, but there is a clear tendency for rates to be higher when there is a high proportion of cross-traffic. Underwood\(^{12}\) comments on Raff's findings, but his own data on low volume rural Y-junctions are so limited that very little can be concluded.

Several other papers investigate accident rates on entrance and exit ramps in the United States. Fisher\(^{54}\) gives a graph suggesting that the accident rate increases with traffic volume on left-hand ramps in New Jersey, but this is inconclusive, being based on just ten sites. Lundy's\(^{55}\) much more extensive study of freeway ramps in California, on the other hand, finds a negative correlation between accident rate and daily traffic on ramps, but he suggests that much of this apparent effect may be due to the more heavily-trafficked ramps being better designed. Worrall et al\(^{56}\) look at ramps on urban freeways in the Chicago area but fail to find any relationship between the accident rate and the traffic volume on either the freeway or the ramp.

Thorson\(^{3}\) includes some analyses of intersection accidents in his study of rural roads in Denmark, but he, too, fails to find any relationship between the accident rate per vehicle and the volume of traffic.

Chapman\(^{4}\) discusses at some length the choice of exposure measures for intersection accidents. He considers three possible measures: the sum of the two conflicting flows, the product of the flows, and the square root of the latter. It is shown, using data on intersection accidents from Denmark, that the accident rate formed using the product of the flows as the exposure tends to be negatively correlated with traffic volumes.

7. ACCIDENT RATES ON THE SAME ROADS CARRYING DIFFERENT TRAFFIC VOLUMES

To determine the form of the relationship between accident rates and traffic volumes it is necessary to compute accident rates at a range of different volumes. Section 4 described studies which obtained a range of flows by looking at different roads, but, generally, the traffic volume used was the ADT, which, while it expresses the average traffic carried by the road at all times, does not give direct information about the traffic volumes at which
the accidents did, or did not, occur. An alternative approach is to compare hourly accident frequencies with hourly traffic volumes. Several authors provide such a treatment; some deal with single roads, some a set of roads and others take a macroscopic viewpoint.

Tanner\textsuperscript{57} and Foldvary\textsuperscript{58,59} look at macroscopic accident data (from Britain and Queensland respectively) and compare the proportions of accidents occurring at different times of day with the proportions of vehicle mileage, estimated from traffic counts. It is generally found that hours with the lightest traffic tend to have the highest accident rates, but, as these are nearly always the night hours, this evidence is inconclusive, because of the probable influence of poor light conditions, fatigue and alcohol. Probably the fullest analysis of this kind of data is given by Smeed\textsuperscript{60}, who divides accidents up according to the numbers and types of vehicles involved. He plots the hourly totals of single-vehicle accidents against the estimated mileages travelled by the different vehicle types and the hourly two-vehicle accident numbers against the products of the estimated mileages by vehicles of the types involved. Although the graphs show a good deal of scatter, he concluded that the points for daylight hours lay approximately on straight lines through the origin, indicating that accident numbers in daylight varied roughly in the way Smeed expected. The implication of this would be that, contrary to the findings discussed in Section 4 and illustrated in Figures 1 and 2, the single-vehicle accident rate is independent of the traffic flow but that the two-vehicle accident rate increases in proportion to the volume of traffic.

Belmont\textsuperscript{10} examines accident data from two-lane roads in California and compares accident rates per vehicle mile with hourly traffic volumes. Whilst the single-car accident rate tends to decrease with traffic, the head-on accident rate does not vary much with traffic volume, but multi-car and rear-end accident rates increase sharply until an hourly volume of 600-700 vehicles is reached and then decline. The total accident rate reaches a peak of 80 per 10\textsuperscript{8} vehicle miles before declining. Unlike those of Smeed these findings are broadly in line with many of the studies described in Section 4.

Several workers look in detail at accident rates on a single road when carrying different traffic volumes. One such study is by Mothe\textsuperscript{61}, who
investigates accident rates on the Paris Autoroute de l'Ouest on Sundays. The accident rate appears to reach a peak at an hourly flow of between 4,000 and 5,000 and then decreases. The general shape of the relationship is not dissimilar from that shown in Figure 3.

Gwynn\textsuperscript{62} analyses accident data from a four-lane divided highway in New Jersey. The relationship between accident rates and hourly volumes does not emerge very clearly, but a U-shaped curve is suggested. A later report by Gwynn and Baker\textsuperscript{63} analyses similar data from a different highway in New Jersey. This time separate analyses are done for weekday/weekend, day/night hours, and, while the large accident rate at low flows is again found, the data do not show any upturning at the higher volumes.

Chapman\textsuperscript{4} also compares accident frequencies on single stretches of road with hourly traffic volumes. His data relate to roads in New Zealand and Israel. No very clear tendency is observed, except that high accident rates occur in hours with low flow.

Some valuable research has been carried out on this topic in West Germany. This is reported in papers by Pfundt\textsuperscript{5}, Leutzbach, Siegener and Wiedemann\textsuperscript{64} and Brilon\textsuperscript{65,66}. There is some overlap in the subject matter of these reports, of which only the first of Brilon's\textsuperscript{65} is in English. Automatic counters installed at 15 points on motorways and two-lane rural roads enable the researchers to compare the numbers of accidents with the hourly traffic volumes. For both the motorways and the other roads the clear conclusion emerges that rear-end accident rates increase with hourly traffic and single-vehicle rates decrease; the curve giving total accident rate against volume is U-shaped. These results are particularly convincing because of the extent of the data used - over 6,000 accidents in all.

8. LONG-TERM TRENDS IN ACCIDENT RATES

In order to have some idea about the number of road accidents to be expected in the future, when traffic levels may well be higher than at present, it is necessary to study accident experience in the past and see how the number of accidents has altered as the volume of traffic has changed over previous years. In doing so, it has to be borne in mind that changes over the years are by no means confined to traffic volumes; they also extend to traffic.
composition, the application of safety measures (including legislation), the age distribution of road users, and construction and the availability and price of fuel. Mathematical models fitted to long-term time-series data will be described in the next section, while this section concentrates on more elementary treatments of the data.

Kroj\textsuperscript{67} analyses monthly accident statistics in West Germany between 1960 and 1965 and compares the monthly totals with monthly petrol consumption figures, which can be regarded as being roughly proportional to the volume of traffic. It is found that the moving averages (over a year) of the numbers of accidents and the fuel consumption figures are negatively correlated, but that the residual quantities (subtracting the moving averages to give measures of seasonal variation) are highly correlated positively. The implication is that, while the seasonal pattern of accidents closely mirrors that of traffic volumes, this is not the case with regard to long-term patterns, which may reflect the effect of quite different factors such as those associated with the general level of motorisation in society.

Baldwin\textsuperscript{68} tabulates annual numbers of road deaths in the United States from 1906 to 1951. Estimates of vehicle mileage prior to 1925 are not available, but between then and 1951 there was a steady decrease in the mileage-based rate to less than half its former value.

More recently, a useful, if not profound, set of papers is provided by Theme IV of the Ninth International Study Week in Traffic and Safety Engineering\textsuperscript{69}. These 16 papers, most of them giving basic accident statistics and trends for a single country, are ably summed up by Smeed\textsuperscript{70}. The papers show that while the numbers and mileages travelled by vehicles has been increasing rapidly, there has been no strong universal trend in accident numbers and a general drop in mileage-based accident rates where these were available.

Munden\textsuperscript{71} tabulates estimates of casualty rates, for different kinds of road user, by year, from 1953 to 1966 in Britain. Whilst during this period the overall casualty rate per vehicle mile travelled fell by over 30 per cent, for each particular vehicle type there was a tendency for the rate to rise. This apparent paradox arises, firstly, because of the changing traffic composition during this period, with the relatively dangerous two-
wheeled vehicles being replaced by safer and larger vehicles, and, secondly, because pedal cycle and pedestrian travel are not allowed for in the denominator of the accident rate. Similar points are made by Johnson and Garwood\textsuperscript{14}, whose more recent data suggest that casualty rates for individual vehicle types were by 1969 no longer rising.

Chapman\textsuperscript{4} gives curves showing the long-term variation up to 1966 in death rates per vehicle in Great Britain, Australia, New Zealand and the USA. All show a rate decreasing, perhaps to an asymptotic value, and the New Zealand and American data suggest that the asymptote has been reached in the case of these two countries. However, subsequent experience shows that, in the United States, between 1966 and 1975, the mileage-based traffic death rate fell by a further 38 per cent (US Department of Transportation\textsuperscript{72}). In New Zealand, on the other hand, the death rates per vehicle and per estimated vehicle mileage, do not exhibit a downward trend between 1966 and 1973 (Toomath\textsuperscript{73}), suggesting that Chapman's speculation may have been correct in the case of New Zealand. But the contrasting experiences of these two countries illustrate the difficulty in making generalisations about long-term trends in accident rates without performing detailed analyses.

The rather erratic year-to-year variation in accident frequencies contrasts sharply with the smooth upward progression of the numbers of motor vehicles and of the traffic volumes. Clearly there are important factors tending to create this irregularity, and various authors give examples of such factors. Garwood\textsuperscript{74} gives annual numbers of road deaths and injuries in Britain between 1909 and 1960. Years when the numbers failed to rise can be readily identified as years affected by war, fuel shortages or changes in legislation. A paper from the Road Safety Research Foundation\textsuperscript{75} in the Netherlands similarly points out that three years with anomalously small numbers of road deaths or casualties coincided with the imposition of a speed limit, an unusually severe winter and a change in the procedure for reporting accidents. Foldvary\textsuperscript{76} examines statistics from Australia and New Zealand and relates the fluctuations in accident frequency to economic conditions and to demographic variations in the numbers of young people reaching the driving age (resulting from such things as the slump in birth rate during wartime). Smeed\textsuperscript{60} suggests that periods of social tension may produce more accidents because people are prepared to have lower standards of safety at such times; however, the evidence regarding this is inconclusive.
It is remarkable that the number of road accidents and deaths has not, generally, risen greatly over the past few years. Miller and the US Department of Transportation both list factors which might be expected to lead to a steep rise in the frequency of accidents in the United States. These include, of course, the increase in the amount of traffic, and also increasing speeds, an increase in the number of young drivers and the widespread use of alcohol. These factors are, of course, not confined to the USA. Evidently important and effective accident counter-measures have been applied - to improve driver behaviour and road and vehicle design. Smeed catalogues the measures which could be taken and estimates the probable effects of their implementation. Since that paper was written, many of these measures have been carried out in Great Britain.

Lest the impression be given that accident rates must automatically decrease with time, the study by Sabey of a 36 km section of heavily-trafficked motorway in Britain, showing an opposite result over two years, should be mentioned. Between 1966 and 1967 the flow increased by between 8 and 14 per cent and the number of injury accidents increased by 30 per cent. However, few roads carry volumes of traffic so close to their capacity at such high speeds, and such roads can have only a very small effect on the national statistics.

The research described in this section does not tell one very much about underlying relationships between accident rates and traffic volumes, but it illustrates the multiplicity of factors other than traffic volumes which may influence long-term trends in accident frequency.

9. MATHEMATICAL MODELS OF ACCIDENT TRENDS

Researchers in several countries have fitted models to accident and traffic data, often with a view to the prediction of accident numbers in the future or to evaluating the effect of a road safety measure or another change. Generally, in order to form a prediction of future accident frequencies, it is desirable to study accident numbers over a considerable period of time and the resulting models suffer from the difficulty that a wide range of factors are at work, as mentioned at the beginning of Section 8, and many of the variables are closely correlated with time, which may make the predictions unstable. Such models do not necessarily imply causal
relationships between the numbers of accidents and the independent variables. Nevertheless, analyses of this type have been used in attempts to investigate relationships between numbers of accidents and traffic volumes.

Several of Smeed's papers provide an insight into the mechanism underlying long-term traffic accident trends. The first of these tabulates road deaths, numbers of motor vehicles and populations over a wide range of countries by year, from 1930 to 1946. Despite great differences with regard to motorisation levels and other factors between countries and between years, some general tendencies are picked out from the data, and it is found that a fair approximation to most of the data is given by the formula, derived from the 1938 statistics,

\[ D = 0.0003(Np^2)^{1/3} \]  

where \( D \) is the number of deaths in a particular country in a given year, \( N \) is the number of motor vehicles and \( P \) the population. Many years later, Smeed still finds reasonable agreement between his formula and data from the years 1957-1966, and for years up to 1972.

If one makes the reasonable assumptions that the population and the average mileage per vehicle remain fairly constant from year to year (or, at least, vary much more slowly than the number of motor vehicles), then the formula implies that in one country over a period of years the number of traffic deaths increases roughly in proportion to the cube root of the traffic volume. The formula is, however, a great simplification of a complicated set of interactions, and the data for any particular country and period of years shows considerable variation about the relationship. Some of this variation is random, but substantial systematic changes in trends may be associated, for example, with the introduction of far reaching safety legislation.

Srour starts with Smeed's formula and derives some further relationships, with particular reference to the French accident experience and the traffic composition in France.

Couvreur points out that, in Belgium, while the traffic volume trends between 1951 and 1966 can be expressed as an exponential curve, the annual
numbers of accidents $Y$ vary more in accordance with the formula

$$Y = \frac{k}{1 + 10^{a+b n}} \quad \cdots \cdots (31)$$

where $n$ is the number of the year and $a$, $b$, $k$ are constants. However, this equation does not seem to have any universal validity.

Smeed's fundamental hypotheses that single-vehicle accidents and two-vehicle accidents should be proportional respectively to the volume of traffic and to the square of the volume are to some extent in conflict with his formula (30), which predicts accident numbers rising much more slowly over time. To resolve the contradiction, Smeed replaces 'traffic volume' in his hypotheses by 'effective exposure', which is assumed to be a power of the vehicle mileage. The appropriate powers are assumed to be different for different vehicle types, and, using the British data for eight years between 1951 and 1963, he finds that the best-fitting powers are 0.67 (cars), 0.77 (goods vehicles), 0.58 (pedal cycles) and 1.02 (motor cycles). An example of the formulae thus obtained is the one giving the number of collisions $Y$ between cars and goods vehicles,

$$Y = 55.9X_c^{0.67} X_g^{0.77} \quad \cdots \cdots (32)$$

where $X_c$, $X_g$ are the mileages travelled per year, measured in thousands of vehicle-kilometres. Using these equations, Smeed estimates the number of accidents which would occur assuming various hypothetical traffic compositions.

At a more detailed level is the regression model developed to analyse the effect of the 70 mile/h speed limit imposed on all roads in Britain from December 1965 (Road Research Laboratory). The regression equations are derived using weekly accident data from 1960 to 1965, the dependent variable being the estimated accident rate per million vehicle miles. Separate regressions are calculated for major/minor roads inside/outside built-up areas and the independent variables used are the following, together with several squares and products of the basic variables:

(i) Time
(ii) Estimated vehicle mileage
(iii) Proportion of accidents on wet roads
(iv) Proportion of accidents on icy roads
(v) Proportion of accidents involving two-wheeled vehicles
(vi) Estimated proportion of travel in hours of darkness.

Apparently this gives a satisfactory fit to the 1960-65 data, and the numbers of accidents which would have occurred in each week of 1966 in the absence of the speed limit are estimated. Allsop gives further details of the regression procedure and discusses the variances of the estimates obtained from the equations.

Much less convincing is the model of Sweet who attempts to predict the number of accidents which will occur in Britain as far as the year 1990. The model fitted to the data is so detailed that far too many assumptions are needed, many of them implausible. The estimates of future vehicle mileage have, in any case, been overtaken by events.

More recently, models based on historical time-series data enable an estimate to be made of the decrease in accidents at the end of 1973 and in 1974 owing to the fuel supply shortage, the price increases, speed limits and other associated factors.

A report from the Netherlands (Central Bureau of Statistics) gives a model, based on yearly totals of accidents from 1948 to 1956, which is used to predict how many accidents would have occurred in later years had a speed limit not been introduced in urban areas in November 1957. A later report (Road Safety Research Foundation) shows that in 1960 and 1961 the actual numbers of accidents are still appreciably below the expected numbers.

An especially thorough investigation is described by Erlander, Gustavsson and Larusson, who examine the influence of traffic volumes on daily road accident numbers in rural areas of Sweden. Different forms of mathematical model are discussed and fitted to accident and traffic data between May and September, 1962, and an appreciable degree of mathematical rigour is shown, not normally associated with road safety work. However, it is a pity that no account is taken of weather in the models, which have traffic volume as the only independent variable.

Finally, mention should be made of Peltzman's model, examining long-
term trends in accident rates in the USA. The emphasis is on social and economic variables, and traffic volume as such does not appear in the model, which is criticised by Joksch 87.

10. DISCUSSION AND CONCLUSIONS

The two basic ways of relating accident rates to traffic volumes - by looking at a range of roads and looking at a range of times - should lead to the same fundamental relationships if all other relevant factors are controlled fully. It is more difficult to obtain such a relationship by studying long-term trends in traffic and accident data, because traffic composition, and levels of road and vehicle safety and driver behaviour change with time and are often strongly inter-correlated with variations in traffic volumes.

The most successful of the analyses described in this report are, generally, those using data which are extensive or very carefully selected or both and restricting their attention fairly narrowly. Although the range of applicability of results of such studies has to be considered carefully, the results have the advantage of being sufficiently specific for their reliability to be assessed.

The more ambitious studies have met with less success; for example, regression analyses applied to accident and traffic data show a bewildering variety of dependent and independent variables. These analyses, particularly the most complicated ones, have not proved very useful in general, and, although the authors rarely recognise this, many of the coefficients of individual variables are inherently implausible. The simpler regressions of Belmont 38,39 and Nilsson 21,22 are more convincing.

Knowledge about the relationship between accidents and traffic volumes at junctions is particularly limited. Results have not been very consistent, and it would seem that more research is desirable in this direction.

A clearer pattern emerges from studies relating accidents to traffic volumes on sections of road. The weight of evidence suggests that single-vehicle and collision rates depend in a fundamentally different way on traffic volumes. The single-vehicle rate per vehicle mile has almost always been found to be highest at low volumes. On the other hand, the collision
rate appears to increase with increasing traffic, with some evidence of
decrease in rate after a certain volume, perhaps corresponding to the onset
of congestion; however, evidence on the latter point is conflicting. The
implication of these relationships is that the total accident rate varies in
a U-shaped fashion with the traffic volume, but the form of this relationship
is likely to vary substantially, depending upon the relative numbers of single-
vehicle accidents and collisions. It is therefore probably preferable to
consider these two types of accidents separately when seeking relationships
with traffic volume.

The data requirements for studies of the type described in this report
are considerable, and it is important that in future better use is made of the
data by more careful choice of methods of analysis than has often been the
case. Many questions remain, and if these are to be answered, the researcher
must be aware of the many factors which are likely to influence accident
statistics and allow for them in some way.

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Fig. 1 Form of relationship between single-vehicle accident rates and traffic

Fig. 2 Form of relationship between collision rates and traffic
Rate per vehicle mile

Average daily traffic

Fig. 3 Total accident rates and traffic (form given by Yu)

Fig. 4 Flows at T junction
ABSTRACT

A SURVEY OF RESEARCH INTO RELATIONSHIPS BETWEEN TRAFFIC ACCIDENTS AND TRAFFIC VOLUMES: S P Satterthwaite (University College London): Department of the Environment Department of Transport, TRRL Supplementary Report 692: Crowthorne, 1981 (Transport and Road Research Laboratory). Previous research into relationships between road accident frequencies and traffic volumes is reviewed. Methods used are assessed and the main conclusions of the soundest studies drawn together. Some researchers have deduced theoretical relationships between accident numbers and traffic volumes and checked these against data, while others have derived relationships more empirically.

In order to deduce an empirical relationship, it is necessary either to study different roads carrying different volumes of traffic, or to examine time-series data. Research of the former type has often shown that the number of single-vehicle accidents per unit of vehicle distance travelled tends to decrease with increasing traffic, while the number of collisions between two or more vehicles tends to increase. Knowledge about relationships between accidents and traffic volumes at intersections is less extensive but includes useful results. Time-series studies have usually shown that accident numbers have grown more slowly in the long term than have volumes of traffic, but, because of the many other time-dependent factors which affect the incidence of accidents, care must be taken in drawing conclusions from such studies about the underlying relationship between accidents and traffic volumes.

Comments are made concerning the data and methods likely to be useful in further research.

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