Analysis of Traffic Crash Data Using Statistical Quality Control

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Abstract:

Statistical Quality Control has been used in many traffic safety projects to identify locations with excessive numbers of crashes, thus indicating the existence of road hazards. The number of crashes per unit distance is often assumed to follow a Poisson distribution, and then an Upper Control Limit (UCL) is defined. Locations with numbers of crashes above the UCL are identified as hazardous. This paper discusses the formulation of the UCL based on two approaches. First the use of the theoretical Poisson distribution is summarised, and secondly a method is considered wherein there are no distributional assumptions. A comparison of the approaches is also made using Hume Highway data.

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Introduction

A black-spot is a road location where there are clusters of road crashes. The two common types of black-spot are (i) the intersection black-spot, and (ii) the mid-block black-spot (MBBS). The location of the former type is relatively straightforward whereas the identification of the latter type is more difficult, particularly if crash data are unavailable or incomplete. Data with such shortcomings are common in developing countries such as Indonesia. This paper discusses the development of a simple, low-cost method for locating MBBS using a control chart technique similar to that applied in Statistical Quality Control (SQC). SQC is commonly used to investigate unusual behaviour over time but in this context it is used to detect sites with excessive numbers or rates of crashes over a length of road.

The SQC method was first used in connection with traffic crash analysis by Norden et al (1956) and has subsequently been used in many traffic safety projects to identify black-spots (Rudy, 1962; Morin, 1967; Hoque and Andreassen, 1980). The method typically assumes that the number of crashes per unit distance follows a Poisson distribution, and then an Upper Control Limit (UCL) is defined for a certain level of significance (traditionally .01 or .05). Locations with numbers of crashes above the UCL are identified as MBBS. To formulate the UCL, Norden approximated the Poisson by the normal distribution. The resulting formula included a "correction factor". Morin (1967) showed that a more accurate result was obtainable by omitting the correction factor as the size of the samples approached infinity. This corrected formula has been used subsequently by Deacon et al (1975), and also by NAASRA (1988) to compute the critical crash rate. Moreover, the UCL based on the Poisson assumption can also be formulated theoretically from large sample confidence limits (see eg. Kendall and Stuart, 1973).

In an early work on accidents among munition workers by Greenwood and Woods (1919), the workers themselves were treated as "black-spots". A probabilistic analogy was used in which "balls" (the accidents) were thrown into "pigeon-holes" or "cells" (the workers). The known distribution of balls in cells was used to investigate whether the occurrence of accidents was a purely chance phenomenon or whether some workers exhibited an increased liability to accidents, ie. were accident-prone. The Poisson and the negative binomial distributions were used to model the pure chance and the different liability hypotheses respectively. In the data on munition workers examined by Greenwood and Woods, the negative binomial distribution exhibited the best agreement with the data. Greenwood and Woods suggested that the pure chance phenomenon was inappropriate.

A similar method can be applied to road crashes in a mid-block section and provides the first stage in a method for the location of MBBS. A section is divided into a number of consecutive equal subsections and the distribution of crashes therein is considered. The subsections and crashes correspond to cells and balls respectively. Using combinatorics, the probability of a section containing one or more subsections with at least some threshold number of crashes can be derived. Typically, criteria for MBBS are based on this threshold number and the subsection length. The probability of a section containing at least one MBBS can thus be based on very simple information, viz. the length of the section and the total number of crashes along this

length. This approach does not involve any distributional assumptions on, say, the number of crashes per unit distance. Furthermore, as in SQC for the Poisson distribution the UCL for this non-distributional model can be formulated, and control charts can be constructed.

The application of these UCLs for both Poisson and non-distributional models will be demonstrated. The formulae will be applied to crash data for a period of 2.5 years from July 1st, 1987 to December 31st, 1989 for sections of 2-lane 2-way undivided highways on the Hume Highway, New South Wales (NSW). For the Poisson model UCLs are calculated both for crash numbers and crash rates. For the non-distributional model crash numbers only are considered.

Poisson model

Approximate methods

When introducing SQC in the identification of black-spots, Norden made the assumption that the each vehicle in the highway system has the same probability of being involved in a crash and is statistically independent of other vehicles. In this case, the number of crashes is very small compared to the number of vehicles. Given the number of vehicles travelling in a unit distance and the number of crashes occurring in a period, the expected number of crashes per vehicle per unit distance, a, will be a very small number, and if the discrete random variable X is the number of crashes per vehicle per unit distance, Norden suggested that X is a Poisson variate with probability distribution

(1) $$P(X=x) = \frac{a^x e^{-a}}{x!} .$$

The upper and lower control limits for the number of crashes (U and L) for a .99 probability level are defined by

(2) $$P(X \le L) = e^{-a} \sum_{x=0}^{x=L} \frac{a^x}{x!} = 0.005 , \quad \text{and}$$

(3) $$P(X \ge L) = 1 - e^{-a} \sum_{x=0}^{x=U-1} \frac{a^x}{x!} = 0.005 .$$

One way of obtaining these limits is to use a table of the Poisson distribution. Norden suggested the use of Molina's (1942) tables which give cumulative Poisson probabilities. The upper and lower control limits (UCL and LCL) for crash rate are obtained by dividing U and L by m, where m is the exposure unit (eg. kilometres or kilometres travelled). To extract U and L from Molina's tables requires double interpolation for a and x. Because the work is very tedious, Norden suggested the use of simpler approximate formulae for control limits in the form

(4) $$\text{UCL, LCL} = \hat{\lambda} \pm \psi\sqrt{\frac{\hat{\lambda}}{m} + \frac{0.829}{m}} \pm \frac{1}{2m},$$

where $\hat{\lambda}$=a/m, is the estimated expected number of crashes, and ψ is a factor associated with the probability level. In these equations, the first two terms result from approximating the Poisson distribution by the normal distribution. The ψ is equivalent to the z of the standard normal distribution, so that eg. $P(L \leq X \leq U)=.01$ implies ψ=2.576. The third term is an empirical one which improves the accuracy of equations (4), and the last term is introduced because crash number is an integer. Morin (1967) suggested omitting the correction factor as the value of $\hat{\lambda}$m approaches infinity.

Control limits for large samples

The UCL and LCL can also be obtained using confidence limits for large Poisson samples in the form

(5) $$\text{UCL, LCL} = \hat{\lambda} + \frac{\psi^2}{2m} \pm \sqrt{\frac{\psi^2\hat{\lambda}}{m} + \frac{\psi^4}{4m^2}},$$

where $\hat{\lambda}$ and m are as defined previously. For the .99 probability level, ie. $P(LCL \leq x \leq UCL)$=.99 or α=.01, ψ=z=2.576 which leads to

(6) $$\text{UCL, LCL} = \hat{\lambda} + \frac{3.318}{m} \pm \sqrt{\frac{6.636\hat{\lambda}}{m} + \frac{11.008}{m^2}}.$$

In MBBS identification generally only the upper control limit is used. U is often called the critical crash number (C_r) and UCL the critical crash rate (C_R).

Control charts

In constructing a control chart for a mid-block section, several data items must be supplied. The estimated expected number of crashes per unit exposure, $\hat{\lambda}$, is calculated from the total number of crashes in the highway system and the measure of exposure. If the exposure is a unit length, then the length of each section must be known. If the common exposure unit "million vehicle kilometres travelled" (MVKT) is used, additional traffic volume data for each section must be supplied.

Once the data are available, $\hat{\lambda}$ can be determined and UCL and LCL can be calculated. The control chart is usually presented as a plot of UCL and LCL on a graph of number of crashes versus distance with sections marked on the horizontal axis. In this paper it is shown as a plot of number of crashes versus section number (see Fig.3). Although a single value of $\hat{\lambda}$ applies to the whole road, traffic volumes and section lengths will vary from section to section so that the values of UCL will also vary from section to section. The sections with number of crashes per unit exposure above the UCL are categorised as MBBS.

The non-distributional model

Probabilistic approach

In the idealised experiment of throwing balls into cells, balls and cells correspond to crashes and subsections respectively. In what follows both have been treated as indistinguishable and the occurrence of "too many" crashes will provide evidence to the contrary, ie. that one or more subsections are different from others in that they may contain MBBS. It is irrelevant to the method whether or not the subsections are identical in any physical sense.

The criteria for MBBS are based on a threshold number of crashes in a given subsection length over a given time period. Such criteria, being based on crash numbers rather than crash rates, may identify as MBBS, subsections of high volume which may in some sense be regarded as "low risk". Ideally, further investigation should include traffic volumes if these data are available. In NSW, the Roads and Traffic Authority (RTA) uses the criterion that a MBBS is a location other than an intersection where there have been at least 5 recorded[1] crashes within a radius of 100m over a period of 2.5 years (Lind et al, 1985). The subsequent analysis uses this criterion but can be easily applied to other criteria.

Suppose that a total of **c** crashes is recorded on a road section of length **L** divided into **k** equal subsections of length ***l*** over a period of **y** years. The RTA criterion has **k**=5**L** subsections (since ***l*** is effectively 200m), y=2.5 years, and c≥5 crashes. The threshold number will be denoted by C_t, so that C_t=5. If c>4k there must be a MBBS because of all possible partitions of the **c** crashes into the **k** subsections there will be at least one subsection containing at least 5 crashes. If c<5 there can be no black-spot. The remaining case is thus 5≤c≤4k for which the theory of combinatorics (see eg. Feller, 1968) can be used to derive a formula for the probability, $\pi_{c,k}$, of a section having at least one black-spot. By definition,

$\pi_{c,k}$ = P(at least one black-spot given c crashes over k subsections),

or, equivalently,

$\pi_{c,k}$ = P(at least 1 partition of the integer c into **k** parts contains an integer 5 or more).

As an example, consider partitions of the integer 6 into at most 5 parts, ie. 6 crashes over 1km. From 10 possible partitions, there are 2 partitions containing at least 5 in a part, so that if C_t=5, $\pi_{6,5}$=2/10.

More generally the $\pi_{c,k}$ can be calculated using the formula

(7) $$\pi_{c,k} = 1 - \frac{P_k(c, C_t)}{P_k(c)},$$

where $P_k(c,C_t)$ = the number of partitions of the integer c into at most **k** parts in which no part is greater than C_t-1, and

[1] A crash is "recorded" by RTA if it is reported to the police, involves fatalities or injuries requiring treatment, necessitates the towing away of at least one vehicle, or results in property damage of at least AU$500.

$P_k(c)$ = the number of partitions of the integer c into at most k parts without restriction.

The $\pi_{c,k}$ may be calculated recursively (Riordan, 1958). The results of some calculations are plotted in Fig.1. A particular feature of these curves is their asymptotic behaviour. For example for k>50 the $\pi_{c,k}$ rapidly approach unity for c>50. Similarly the $\pi_{c,k}$ rapidly approach .90 for c=25 and k>25. This implies, for example, that on a road section of length greater than 10km there is almost certainly a MBBS if there are more than 50 crashes. This provides a simple indication of the MBBS characteristic of a road section.

Although not considered subsequently, care must be taken to ensure that the detection of MBBS is not affected by the choice of origin. For example it is undesirable that the end of a subsection be in the middle of a narrow bridge.

Probability level for MBBS

The foregoing indicates that given only very simple and, therefore, inexpensive data, viz. the total number of crashes, c, and the length of section, L, it is possible to calculate MBBS probabilities.

The choice of a probability level as a criterion for MBBS will have economic and social consequences. If too a high level is chosen (say .99), there is little chance (.01) of a section being incorrectly identified as one containing MBBS. On the other hand a section containing black-spots may not be identified. In the first case less resources may be allocated to road improvements but in the second the failure to identify MBBS may lead to their not being treated promptly and, hence, to further crashes. "Traditional" probability levels of .95 or .99 may be considered.

Once a section is selected for further investigation the next stage in the process involves the precise location of the MBBS. A low-cost sub-division technique (Iskandar and Dunne, 1991) has provided encouraging results.

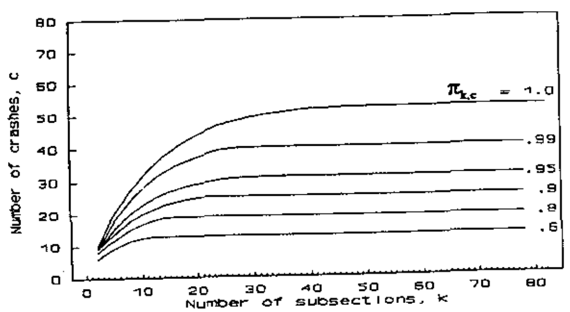

Figure 1. MBBS probabilities of indistinguishable c and k, for C_r=5.

Alternative criteria

Many different MBBS criteria have been used in MBBS identification. Deacon et al (1975) reported that a criterion of 3 crashes or 1 fatality in a 0.1 mile length per year was used to identify MBBS in Kentucky rural highways. Silcock and Smyth (1984) reported various MBBS criteria used by British Highway Authorities. Among them, one authority uses 9 crashes within a radius of 150m of a location in 3 years, another uses 5 personal injury crashes within a 30m radius over a 3 year period. None of these criteria includes traffic volume. One criterion which does include volume is that of Mountain and Fawaz (1991) who proposed 3 crashes for 1 MVKT. Often, analyses of crash data are categorised by crash types (Andreassen, 1980), so that MBBS criteria relate to crash type.

For different MBBS criteria, MBBS probabilities can be calculated by altering either the length of subsection, the time period, or the threshold number of all or certain types of crashes. For this purpose, Fig.2 shows C_r curves for various MBBS criteria. The curves show the number of crashes associated with $\pi_{c,k}$=.99 for values of C_r from 3 to 8.

Control charts

As in SQC for the Poisson model, the control chart is used to distinguish locations with "unusual" (ie. above UCL) crash frequencies from others. For the non-distributional method a similar control chart can be constructed for a given level of probability. To construct a control chart, the MBBS criterion, the length of the sections and the probability level must be given, so that C_r for each section can be defined and UCL can be plotted.

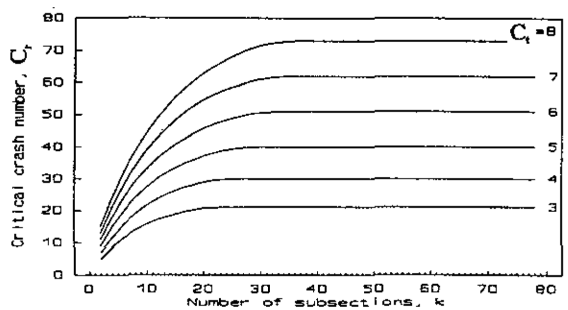

Figure 2. Critical crash number (C_r) for indistinguishable c and k, at 0.99 probability.

Hume Highway example

Crash data

The crash data used for applying and comparing the SQC methods are for a section of the Hume Highway from Goulburn to Yass (about 81.7km) for the 2.5 years period July 1st 1987 to December 31st 1989. The crash data were provided by the RTA. The section consists of two different road types. The first part is a 4-lane 2-way divided highway located at 4km to 20.3km south of Goulburn Post Office (GPO), and the second part is a 2-lane 2-way undivided highway at 20.3km to 85.5km south of GPO. Traffic data are taken from regular reports published by the RTA (1988).

The section is divided into 11 shorter road sections, 2 of 4-lane divided highway and 9 of 2-lane undivided highway. Each section is chosen so as to have cross section as uniform as possible. Data for these 11 sections are presented in Table 1. The expected numbers of crashes for these segments are 22.52 crashes/100MVKT for the divided highway and 62.26 crashes/100MVKT for the undivided highways.

Control charts

The method of SQC for the Poisson and the non-distributional models will be applied to the above data. It is important to note the different process of constructing the

Table 1. Crash numbers, traffic volumes, and length of each of the 9 sections of the Hume Highway.

Section number	Road[1] type	Length [km]	Number of crashes	AADT 1988
1	4LD	8.2	27	15627
2	4LD	9	9	4993
3	2LU	4	16	4993
4	2LU	7.7	27	4993
5	2LU	7.3	53	5762
6	2LU	9	27	5762
7	2LU	10	24	7433
8	2LU	7	34	7433
9	2LU	11	13	7549
10	2LU	5.5	14	7549
11	2LU	3	14	12997

[1] Note: 4LD is 4-lane 2-way divided highway
2LU is 2-lane 2-way undivided highway

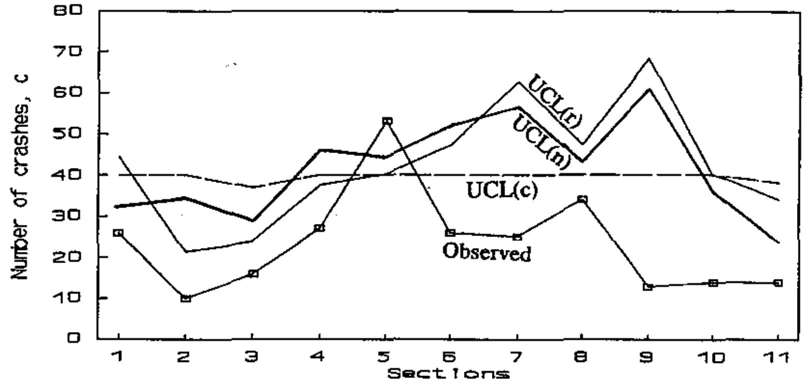

Figure 3. Crash control chart of the SQC method and of the non-distributional method, at 0.99 probability.

control charts for SQC based on these models. SQC for the Poisson model uses confidence limits for a certain probability level to define a critical crash number which depends on $\bar{\lambda}$. Consequently, crash data for all road sections in the system need to be supplied before the control limits can be determined. In the non-distributional method, an absolute number of crashes is used for the MBBS criterion, which is chosen before analysis is carried out. The critical crash number is simply based on this criterion and the section length. This simplifies the MBBS identification procedure by reducing the amount of data required. For example, suppose the only information available is that there were 53 crashes in 2.5 years in a section of length 7.3km. Under the Poisson method it is not possible to determine whether or not the section contains MBBS since $\bar{\lambda}$ is unknown. For the non-distributional method k=37 (≈7.3x5) and with C_r=5 and a probability level of .99 the critical crash number C_r=40 is exceeded by 53, the number of recorded crashes. The section is therefore identified as containing a MBBS at this level of probability.

For the data given in Table 1, the control charts for the Poisson and for the non-distributional models are shown in Fig.3. For the Poisson model, two UCLs are plotted. The first, UCL(n), is based on equation (6) where **m** is length in km. The second, UCL(r), is also based on equation (6) but uses 100MVKT for **m**. The UCL of the non-distributional model is denoted by UCL(c) and uses C_r=5. All three UCL curves in Fig.3 are based on a .99 probability level.

It can be seen from Fig.3 that section 5 has number of crashes greater than all UCLs indicating the existence of MBBS with probability .99. Moreover, sections 2, 3, 4, and 8 appear to be locations which may justify further investigation. They are "almost" MBBS.

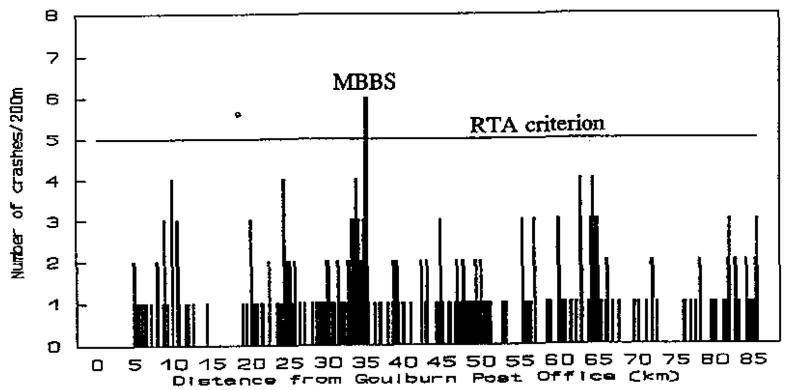

Figure 4. Distribution of number of crashes in 200m consecutive road intervals in which the RTA criterion is applied.

MBBS identification based on RTA criterion

To apply the RTA method, further crash information is needed, viz. the geographical reference of each crash location. This information is used to define positions of previous crash locations from a single geographical reference or a coordinate system (Lind et al, 1985). This enables the production of a chart of number of crashes along the highway in consecutive 200m intervals as shown in Fig.4. The RTA criterion is represented by a straight line at 5 crashes. It is important to note that moving 200m intervals should be considered in order to evaluate changes in the distribution of crashes due to choice of origin.

It can be seen from Fig.4 that at approximately 35km from GPO, in section 5, there are 2 consecutive subsections which have 6 crashes and are therefore MBBS.

Sensitivity of models

As shown in Fig.3, SQC for the Poisson and for the non-distributional models identified section 5 as containing MBBS. This result is verified in Fig.4 which shows that section 5 contains two subsections with more than 5 crashes. SQC for the Poisson model identified sections 2, 3, 4, and 8 as "almost" being MBBS. These are at distances of about 10km, 20km, 25km and 65km from GPO. The site approximately 20km from the GPO has 3 crashes in 200m whereas all other sites have 4 crashes in 200m. The non-distributional method does not identify these "near" MBBS, except for the site in section 8. Given the limited amount of data used it is not surprising that this method is less capable of identifying "near" MBBS. An example of the sensitivity in identifying MBBS can be seen by comparing UCL(n) and UCL(c) in section 6 and 7 (see Fig.3). UCL(c) is almost constant over the entire

section but UCL(n) varies with the length and exposure unit for each section. Using these additional data and the Poisson assumption UCL(n), as expected, more accurately reflects subsection variation. Further sensitivity may be achieved by using additional data such as traffic flow data (see UCL(r) in Fig.3). Nevertheless the non-distributional method has a more sensitive control limit for subsections 6,7,8, and 9.

The lesser sensitivity of the non-distributional method is related to the asymptotic behaviour of the $\pi_{c,k}$ which, in turn, is a consequence of the assumption that subsections and crashes are indistinguishable. However, other assumptions, for example that crashes are indistinguishable and subsections are distinguishable do not lead to greater sensitivity.

There are other ways of increasing sensitivity of the non-distributional method to reflect site variations. One way is to ensure that the number, **k**, of subsections is less than the number, $\mathbf{k_a}$, of subsections at which the **c** versus **k** curves appear to attain their asymptotic values. For example for $\pi_{c,k}$=.99 and C_l=5 the value of $\mathbf{k_a}$ is 30 so it is suggested that $\mathbf{k<30}$. A second way involves altering the values of C_l and l. For instance C_l=6 and l=300 gives a plot of **c** versus section number of similar nature to that obtained with the Poisson assumption.

Discussion

The method of SQC has been used in the identification of black-spots usually with the assumption that crash numbers follow a Poisson distribution. It has been shown in this paper that the method can produce control limits for a model which contains no distributional assumptions. Both models successfully identified MBBS on the Hume Highway.

The Hume Highway example demonstrated that the Poisson assumption generally leads to more sensitive control limits than the non-distributional model. The greater simplicity of the non-distributional model must be weighed against the greater sensitivity of the Poisson model.

MBBS identification depends on the nature of the available data. If complete crash data are available and each crash location can be specified using a standard geographical reference, the spatial distribution of crashes can be produced and MBBS located precisely. Such data are not always available and are expensive.

The non-distributional method uses only very simple data, ie. total number of crashes and the length of the section, and it has been shown that this method can be applied to data which are insufficient for the application of the Poisson method. Thus SQC for the non-distributional assumption provides a simple and low-cost method for the preliminary identification of MBBS and is particularly applicable for developing countries such as Indonesia.

Further research is being continued on cost-efficient probability levels, on a sub-division technique for the precise location of MBBS, and in investigating the distribution of crash numbers over roads containing known MBBS.

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Some Aspects of the Australian Road Research Board's Accident Costs Study

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Abstract:

The Australian Road Research Board (ARRB) project *Accident Costs for Project Planning and Evaluation* has been completed and the reports are progressively being published. This paper outlines the project from inception to completion, touches on the methodology and the rationale and discusses some of the findings and results. The costs that have been derived are costs per accident for a range of 19 accident-type groups and represent the costs of accidents reported to the police. Reported accident data forms the basis of the information used by practitioners for a range of applications. There were four areas in which costs had to be determined. The first was the costs per person related to the five casualty classes that appear on the report form (killed through to not injured). The costs per person were based on lost productivity, medical costs, hospital costs, ambulance, time lost at the scene, and pain and suffering. The second was to determine the casualty outcomes of the 19 accident type groups in urban and rural area and hence the person costs for each of them. The third was the vehicle repairs costs, again for each of the 19 accident-types. These were determined by an extensive surey of individual motor insurance claim forms. The fourth was the costs associated with the accident per se such as delay to other traffic, accident recording by police, attendance of emergency services, legal cost, and value of alternative transport. These cost items are combined to generate the standardised cost for each of the accident-type groups. The costs for the five casualty classes had not previously been estimated in Australia and their absence inhibited the application of previous road accident cost data. The detailed look at the insurance claims is also believed to be the first published report that tackles the topic in such detail.

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