Accident liability

J B KUNÉ

From the Instituut voor Actuarial en Econometrie, University of Amsterdam, 1011 NH Amsterdam, The Netherlands

ABSTRACT The idea of accident proneness, which originated in the early 1900s, has proved to be ineffectual as an operational concept. Discrete econometric methods may be useful to find out which factors are at work in the process that leads to accidents and whether there are individuals who are more liable to accidents than others.

The history of the concepts "accident liability" and "accident proneness" goes back to the 1920s when Greenwood and Woods,¹ Greenwood and Yule,² and Newbold³ performed their statistical studies of accident frequency distributions. The term accident proneness was first mentioned by Farmer and Chambers.⁴ Their original definition said, "accident proneness is a narrower term than accident liability and means a personal idiosyncrasy predisposing the individual who possesses it in a marked degree to a relatively high accident rate. Accident liability includes all the factors determining accident rate, accident proneness refers only to those that are personal." Accident proneness thus seems to be a relatively stable and entirely personal characteristic that predisposes some workers to have a higher accident rate than others, although all workers are exposed to equal risk. Apparently it is meant to define some stable personal trait as opposed to some characteristics of the environment. The implied advantage of this reasoning is that after having found out who the accident prone cases are in a group, their removal from it should result in a decrease in the relative frequency of accidents sustained by the remainder. Critical reviews of this line of reasoning are given by, for example, Cobb,⁵ Smeed,⁶ Minz and Blum,⁷ and Arbous and Kerrich⁸; (see also Adelstein's empirical findings⁹). In fairness to the original investigators (Greenwood, Woods, Yule, and Newbold¹⁻³) it must be observed that they themselves made no inferences regarding accident causality based solely on the frequency distribution. This, however, has not prevented others from doing so and frequency distributions are often used as a proof that a relatively small group of individuals is "responsible" for a high proportion of accidents,

which has erroneously led many to formulate the concept of accident proneness as a means of explanation.

My work on the war proneness of nations (see Houweling and Kuné¹⁰) has led me to study published reports of accident proneness. It seems from these that accident proneness is not a useful concept but they have given rise to much important statistical work. The present paper deals with some aspects of the concept of accident proneness and directs attention to the relevance that discrete econometric can have for research on accident liability.

Earlier statistical studies on accident proneness

In 1919 Greenwood and Woods carried out their classic experiment in a British munitions factory and documented the distribution of accidents that occurred in 13 months, as reported by 648 female workers.¹ It was found that 10.5% of workers were concerned in 56% of the accidents. A relatively small proportion of workers thus sustained a relatively high proportion of accidents. The authors, however, were reluctant to draw inferences regarding causality. Newbold continued the statistical investigations begun at the munitions factory and extended them to include other occupational groups.³ Rawson analysed the possible causes of accidents of 1400 truck drivers.¹¹ Cresswell and Frogatt carried out a study of the accident records of bus drivers in Northern Ireland over the years 1952-5¹²; Mellinger *et al.* studied the accident repeatedness among children.¹³ More references are given by Haight.¹⁴ More recently the accident causing propensity of automobile mobile insurees as a regular Markov process was analysed by Hachling von Lanzanauer and Lundberg.¹⁵

In a statistical analysis it is essential to define as precisely as possible what is being analysed. For

Received 11 July 1984
Accepted 30 July 1984

instance, the word "accident" has been used in many senses and this has led to confusion in comparing and analysing statistical data. There seem to be at least three important errors that (can) make the validity and representative nature of an accident frequency distribution doubtful.

Reporting bias The question arises as to which accidents are reported and which not. Often what is being measured is not the occurrence of accidents but the tendency to report accidents. Many accidents are relatively minor and therefore difficult to document accurately. Merely because they are not dramatic many of them are not reported.

Different events The term accident may indicate entirely different events. Injury to oneself, injury to others, and damage to property can be distinguished. In fact one might expect that the tendencies to injure oneself and to injure others may be entirely different aspects of one's personality and the tendency to damage property may be still a third aspect. Furthermore, accidents differ from one another from the point of view of who initiated the chain of events that eventually led to an accidental injury and who was actually injured.

Duration of the observational period Accidents, particularly the minor ones, tend to be distributed more evenly over a long observation period than over a shorter. For example, if on one day one worker had an accident we can say that that worker was in 100% of the accidents. To generalise beyond this and to conclude that this worker is accident prone would be inappropriate. Schulzinger observes, "it appears that when the period of observation is sufficiently long, the small group of persons who are responsible for most of the accidents is essentially a shifting group of individuals with new persons falling in and out of the group."¹⁶

Greenwood *et al* formulated three hypotheses—*pure chance*, *prone*, and *contagion*—to explain the observed frequencies of accidents.¹² With respect to all three hypotheses it was assumed that individuals are working under conditions of equal environmental risk. If accidents are assumed to occur by pure chance in a homogeneous population this hypothesis leads to a Poisson distribution. In this case a decrease in the accident rate might be obtained by ameliorating general working conditions. The hypothesis of *prone* assumes that workers are not equally likely to have accidents. Rather, they may be divided into subgroups, each of which has its own susceptibility to accidents. The overall distribution of accidents is then a compound formed by a number of subdistribution, each of which is a Poisson, with the Poisson parameter showing, for example, a gamma distribution (Pearson type III). The resulting distribution is a negative

binomial. If this hypothesis is true removal of the accident prone cases from a group will result in a decrease in the casualty rate. Note that the same result is obtained when the population is assumed to be homogeneous but when different workplaces with varying conditions of environmental risk may be distinguished. The third model, representing *contagion*, assumes that the individuals all start work with an equal probability of incurring an accident. Nevertheless, if one incurs an accident by chance, his liability of sustaining further accidents is increased or decreased in a certain way. This model may also result in a negative binomial distribution, which, in the univariate case, has the same parametric form as that which results from the model of *prone*.

If a population is homogeneous with respect to personal attitudes or environmental factors then a Poisson distribution will follow. The converse does not necessarily hold. An illustration of this with respect to railway accidents is given by Maritz.¹⁷ If a population is non-homogeneous with respect to personal attitudes or environmental factors or both then a non-Poisson distribution of accidents will follow, which may be the negative binomial distribution (NBD). On the other hand, if the observed distribution is found to be a negative binomial then this may be explained by non-homogeneity of the population with regard to either personal attitudes or environmental factors or both. Note that entirely different hypotheses may also give rise to the NBD (see Boswell and Patil¹⁸). Even if the hypothesis of non-homogeneity can be accepted as the true explanation of the observed NBD, one still does not know whether this is due to non-homogeneity in either personal attitudes or environmental factors or both. This causes much confusion. For occupational health, ergonomics, preventive medicine, and safety authorities have often been too ready to assume—out of many hypotheses—that the observed NBD means non-homogeneity with respect to personal attitudes only, thereby disregarding the role of environmental factors calling people and not workplaces accident prone. It must be concluded, therefore, that there is no easy way to infer from frequency distributions who the accident prone cases are.

Discrete econometrics: a new approach

To find out whether particular personal characteristics and environmental factors exist which influence the accident liability of individuals in a significant way econometric analysis may be useful. The correct specification of the relationship between accident liability and its determining factors appears to be a

Model relating two groups of exogenous variables, denoted by an asterisk, to two groups of endogenous variables and quantity accident liability.

difficult problem. Structural model building is a useful instrument for solving the specification problem. Causal modelling procedures that have been developed in biology,¹⁹ medicine,²⁰ the social sciences,²¹ and on a wide scale in economics provide a means of constructing structural models that depict the causal relationships that are hypothesised as existing among a system of interrelated variables. Once a model has been formulated a set of relationships may be written and the model parameters estimated. This set of equations permits predictions as to how changes in any one variable in the system affect all other variables. The model shown in the figure reflects some tentative hypotheses regarding the causal relationships between a number of selected exogenous variables and a number of endogenous variables in respect of a group of workers exposed to risk of accident. Following Webb,²² an accident may be conceived as a condition of liability, as an event subject to and contingent on the existence of identifiable, at least in a theoretical sense, events. A categorisation of such events is the following.

Factors within an individual—for example, intellectual and physical capacities, fatigue, illness, level of education and training.

Factors outside an individual—that is, characteristics of the sociotechnical environment—for example, the company, the firm, the workplace; quality of the maintenance, safety measures, instruction, or communication.

The two groups of variables denoted by an asterisk in the figure are exogenous variables. Variations in these variables are assumed to be caused by variables outside the system. The other variables, characteristics of the workplace and personal attitude towards risk and safety, are endogenous variables and as such are considered to be determined at least in part by some combination of the variables in the system. The interpretation of the model relations is:

(1) The characteristics of the *workplace* are

influenced by the characteristics of the company—for example, its financial and economic conditions, type of production, technology used, management, general labour conditions, or safety measures. Evidently there is interaction of the sociotechnical environment, the personal attitude of workers, and accident liability.

(2) The *personal attitude* of workers towards risk and safety is influenced by underlying personal, physical, and psychological characteristics of the individual such as age, sex, education, income, social status, physiological handicaps, disorders of the nervous system, fatigue, illness, intelligence, work satisfaction, or alertness. Generally, personal attitudes are positively influenced by characteristics of the workplace—for example, good working conditions, safety measures, proper training, and instruction.

(3) Accident liability depends on the two groups of variables referred to, the characteristics of the workplace and the personal attitude of workers towards risk and safety.

The causal model depicted may easily be written as a set of linear structural equations that represent the hypothesised relationships that underlie the model. These structural equations are of a simultaneous character, because the endogenous variables are determined not only by the exogenous variables but by other endogenous variables as well. As is shown in most econometric textbooks the endogenous variables may be expressed as functions of the exogenous variables only. They are called reduced form equations.²³ The resulting equation with respect to accident liability (AL), is given,

$$AL = b_0 + b_1 CC^* + b_2 CI^* + U \quad (1)$$

where AL = 1 for individuals who had at least one accident during the observational period, or

0 for all individuals who were not concerned in any accident,

CC* = a set of variables representing characteristics of the company,

CI* = a set of variables representing characteristics of the individual worker,

b_0 = intercept term, and

U = disturbance term. We assume a normal distribution for the disturbance term with zero expectation.

The reference period must be sufficiently long to ensure that differences in liability observed are

Accident liability

reasonably stable and persistent over time. This type of analysis may help us to find out whether there are individuals with stable personal characteristics which make them more liable to accidents than others or whether there are only sociotechnical environmental factors at work or both.

The presented reduced form equation can be considered as a multiple linear regression equation. The estimation of the unknown α -parameters is usually carried out by means of ordinary least squares. Theoretically, however, multiple linear regression analysis is not quite appropriate for estimating relationships where the dependent variable is binary—that is, takes on only two values, representing occurrence or non-occurrence of some event.

The objects raised against the use of OLS-methods to estimate parameters of the above linear probability model are:

It can yield predicted probabilities outside the acceptable interval $[0, 1]$.

The true probability relationship is more likely to be S-shaped than linear, approaching the limiting probability values of zero and one asymptotically.

The OLS assumptions that the disturbance terms are (a) normally distributed with zero expectation, (b) homoskedastic—that is they all have the same variance—are violated.

The heteroskedasticity that arises causes the OLS estimator of the “ b ”s to be inefficient, though it remains unbiased. Furthermore, the variance of the “ b ”s is biased. Thus we cannot apply the classic tests of significance for the estimated parameters, since the tests depend on the normality of the errors. Also traditional R^2 is no longer meaningful.

The heteroskedasticity problem may be solved by using a weighted least squares procedure. The problem may also be avoided by estimating the model by maximum likelihood methods rather than by a least squares procedure. Maximum likelihood methods, however, are much more difficult computationally than the method of least squares.

The real problem with a linear model for a qualitative dependent variable, as previously argued, is that a linear functional form may be inconsistent with the requirement that a probability be in the interval $[0, 1]$. This can be solved only by using a different functional form that is restricted to $[0, 1]$. The linear model, therefore, has to be abandoned. *Probit analysis*, originated in biology, has been proposed as a preferential technique to correct for the above mentioned technical problems.^{23–25} One can find numerous applications with respect to such things as choice of occupation, job and firm location, union membership, migration, transportation choice, purchase of consumed durables, housing, birth, schooling, crime, and justice. For a survey see

Amemiya.²⁶

Write equation (1) as follows,

$$Y_i = X_i'b + U_i, \quad i = 1, 2, \dots, n \quad (2)$$

where Y_i is the value for individual i of the dependent variable, X_i is the vector of explanatory variables of individual i , b the coefficient vector, U a vector disturbance term, and n the number of observations.

The probit model assumes that the dependent variable is generated by the following mechanism,

- (a) for each observation X_i and disturbance term U_i the underlying process makes $X_i'b - U_i \geq 0$ or $X_i'b - U_i < 0$;
- (b) when $X_i'b - U_i \geq 0$, Y_i is set equal to 1, otherwise Y_i is set equal to 0.

Now we have,

$$\begin{aligned} P_i &= P[Y_i = 1 | X_i'b] = P[U_i \leq X_i'b] \\ &= \int_{-\infty}^{X_i'b} \frac{1}{\sqrt{2\pi}} \cdot \exp(-\frac{1}{2}U_i^2) dU_i \\ &= F(X_i'b), \quad i = 1, 2, \dots, n \end{aligned} \quad (3)$$

The predicted probability P_i resulting from the probit model may be interpreted as the conditional probability that an individual will have one or more accidents during the reference period, given the whole set of individual and environmental characteristics.

The probit model is non-linear and is not as easy to estimate as a linear model. An adequate method of estimation is maximum likelihood. The principle of maximum likelihood necessitates choosing b as estimate of b in such a way that, if they actually were b , the given observations would have the greatest probability of occurrence. The form of the likelihood function is fairly simple. It is the product of n probabilities, one for each observation, where for each observation we use the probability of the observed value of Y . The likelihood function may therefore be written as,

$$L = \prod_{i=1}^n P_i^{Y_i} \cdot (1 - P_i)^{1-Y_i} \quad (4)$$

The estimates are obtained by maximising the logarithm of (4) numerically with respect to b . This necessitates the use of an algorithm, starting from some set of initial guesses for b . For large n , the maximum likelihood estimators of b are unbiased and efficient and are also normally distributed.

Conclusion

There seems to be no agreement in published

reports on what, in fact, constitutes a scientifically operational definition of accident proneness. The area is fraught with contradictions—for example some authors assert that accident proneness is a fixed quality, which imbues individuals with different strength of accident attraction,²⁷ whereas others assert that accident proneness is not a fixed quality, but is likely to be affected by changes of the physical and mental health, which may alter in accordance with one's changes in activity. Analyses of frequency distributions of accidents do not provide an adequate means to find out who are accident prone or more liable to accidents than others due to fixed personal characteristics.

Econometric analyses may show which factors are at work in the process that leads to accidents and whether some individuals are more liable to accidents than others. Because the dependent variable only takes on values 0 and 1 ordinary regression analysis cannot adequately be applied. To avoid the difficulties implied other approaches have become available of which probit analysis is widely used.

References

- ¹ Greenwood M, Woods HM. *A report on the incidence of industrial accidents upon individuals with special reference to multiple accident*. London: HMSO, 1919. (Industrial Fatigue Research Board, report No 4.)
- ² Greenwood M, Yule GU. An inquiry into the nature of frequency distributions representative of multiple happenings, with special reference to the occurrence of multiple attacks of disease or repeated accidents. *Journal of the Royal Statistical Society* 1920;**93**:255–79.
- ³ Newbold EM. Practical application of the statistics of repeated events, particularly to industrial accidents. *Journal of the Royal Statistical Society* 1927;**90**:487–535.
- ⁴ Farmer E, Chambers EG. *A psychological study of individual differences in accident rates*. London: HMSO, 1926. (Industrial Fatigue Research Board, report No 38.)
- ⁵ Cobb PW. The limit of usefulness of accident rate as a measure of accident proneness. *J Appl Psychol* 1940;**24**:154–9.
- ⁶ Smeed RJ. Some statistical aspects of road safety research. *Journal of the Royal Statistical Society*. 1949;**112**:33–47.
- ⁷ Mintz A, Blum ML. A re-examination of the accident proneness concept. *J Appl Psychol* 1949;**33**:195–211.
- ⁸ Arbous AG, Kerrich JE. Accident statistics and the concept of accident-proneness. *Biometrics* 1951;**4**:340–432.
- ⁹ Adelstein AM. Accident-proneness: a criticism of the concept based upon an analysis of shunter's accidents. *Journal of the Royal Statistical Society* 1952;**115**:354–400.
- ¹⁰ Houweling H, Kuné JB. A note on the statistics of war. *Development and Peace* 1981;**2**:37–40.
- ¹¹ Rawson A. Accident proneness. *Psychosom Med* 1944;**6**:88–94.
- ¹² Creswell WL, Froggart P. *The causation of bus driver accidents—an epidemiological study*. London: Oxford University Press, 1963.
- ¹³ Mellinger GD, Sylwester DL, Gaffey WR, Manheimer DI. A mathematical model with applications to a study of accident repeatedness among children. *Journal of the American Statistical Association* 1965;**60**:1046–59.
- ¹⁴ Haight FA. *Handbook of the Poisson distribution*. London: Wiley, 1967.
- ¹⁵ Hachling von Lanzanauer C, Lundberg WN. The propensity to cause accidents. *Astin Bulletin* 1973;**7**:154–64.
- ¹⁶ Schulzinger MS. *The accident syndrome*. Springfield, Ill: Charles C Thomas, 1956.
- ¹⁷ Maritz JS. On the validity of inferences drawn from the fitting of Poisson and negative binomial distributions to observed accident data. *Psychological Bulletin* 1950;**47**:434–43.
- ¹⁸ Boswell MT, Patil GP. Chance mechanism generating the negative binomial distributions. In: Patil GP, ed. *Random counts in scientific work*. Vol 1. London: Pennsylvania State University Press, 1970.
- ¹⁹ Wright S. The interpretation of multivariate systems. In: Kempthorne O, ed. *Statistics and mathematics in biology*. Amer: Iowa State University Press, 1954.
- ²⁰ Feldstein MS. *Resource allocation model for public health planning*. Geneva: World Health Organisation, 1973. (Supplement bulletin WHO 49.)
- ²¹ Goldberger AS, Duncan OD. *Structural equation models in the social sciences*. New York: Seminar Press, 1973.
- ²² Webb WB. The illusive phenomena in accident proneness. *Public Health Reports* 1955;**70**:951–6.
- ²³ Goldberger AS. *Econometric theory*. New York: Wiley, 1964.
- ²⁴ Nerlove M, Press SJ. *Univariate and multivariate log-linear and logistic models*. Santa Monica: Rand Corporation, 1973. (Report R-1306-EDA/NIH.)
- ²⁵ Manski CF, McFadden D. Alternative estimates and sample designs for discrete choice analysis. In: Manski CF, McFadden D, eds. *Structural analysis of discrete data with econometric applications*. Cambridge, Mass: MIT Press, 1981.
- ²⁶ Amemiya T. Qualitative response models: a survey. *Journal of Economic Literature* 1981;**19**:1483–1536.
- ²⁷ Farmer E, Chambers EG. *A study of accident proneness among motor drivers*. London: HMSO, 1939. (Industrial Health Research Board report No 84.)