Extent and Some Implications of Incomplete Accident Reporting

E. HAUER AND A. S. HAKKERT

Three questions are addressed: How many reportable accidents are in fact reported? What is the relationship among road safety, accidents occurring, and accidents reported? What are the effects of incomplete reporting on the estimation of road safety? A review of 18 studies made at different times and localities reveals considerable variability in the degree of nonreporting. As a ballpark estimate, fatalities may be known to an accuracy of about 5 percent. Some 20 percent of injuries requiring hospitalization and perhaps 50 percent of all injuries are not found in official statistics. Furthermore, the probability of an accident's being reported depends on the age of the victim; whether the victim is the driver, the passenger, or a nonoccupant; the number of vehicles involved; and several additional factors. Analysis shows that the accuracy with which road safety can be measured depends on the proportion of accidents reported and on the accuracy with which this proportion is known. It appears that the variance of the estimate of safety (or of the safety effect of some measure) is inversely proportional to the square of the average proportion of accidents reported.

Much of what we know and do about road safety is tied to the use of accident information reported to the police. It is therefore natural to think that if the level of accident reporting to and by the police is to be diminished, the ability to manage road safety will also be harmed. Put simply, with fewer accidents reported it will take longer to accumulate the same amount of data; therefore, black spots will take longer to detect, patterns of accidents will be more difficult to discern, the effect of interventions will be even less precisely known, and so on. It is repercussions of this kind that seem to be at the root of the concern about reduced levels of accident reporting.

To retain the proper perspective, it is important to remember that at present not all accidents are reportable and not all reportable accidents are in fact reported. Thus, even in the past we have had to make do with only a part of the accident information. Is the problem that any further decrease in accidents reported is critical? Furthermore, in many countries only injury accidents are reported to the police. Do these countries do a less creditable job of managing safety? Answers to such questions are not easy to provide.

E. Hauer, Safety Studies Group, Department of Civil Engineering, University of Toronto, Toronto, Ontario M5S 1A4, Canada. A. S. Hakkert, Transportation Research Institute, Technion City, Haifa 32000, Israel.

It appears that the discussion about the level of accident reporting might benefit from the resolution of three questions:

1. How many reportable accidents are in fact reported?
2. What is the relationship between road safety, accidents *occurring*, and accidents *reported*?
3. What are the statistical repercussions of incomplete reporting?

These three questions are dealt with in the three sections that follow. We hope that the provision of factual information (next section), conceptual clarification (third section), and analytical tools (fourth section) will bring about more enlightened debate.

KNOWLEDGE ABOUT THE EXTENT OF UNDERREPORTING

Some prefer to call it a motor vehicle accident; others call it a crash. In principle, everybody has in mind the same kind of event. In Ontario, motor vehicle accidents are defined as either a collision of a motor vehicle with a movable or fixed object or an explosion, submersion, or rollover of a motor vehicle. Motor vehicle accidents are reportable if they entail an injury (visible to the police or complained of by the victim) or if the property damage exceeds a certain limit, which is adjusted from time to time. Reportable motor vehicle accidents are events with fuzzy edges. Much of the fuzziness is due to the criteria that make an accident reportable.

In Figure 1 we show a 21-year history of police-reported accidents in Ontario. The intent is to demonstrate how rubbery the yardstick of "reportable motor vehicle accidents" is. Note that the monetary limit for reportable property-damage-only (PDO) accidents was adjusted in 1970, 1978, and again in 1985. As can be expected, some accidents that would have been reportable before the change are not reportable with the higher limit in place. The corresponding precipitous drops in the time series of PDO accidents shown in Figure 1 are evident. If this is how things work, one should also expect that as long as the reporting limit remains constant while the cost of repairs keeps rising, more and more accidents become reportable. Thus, under such conditions, the number of

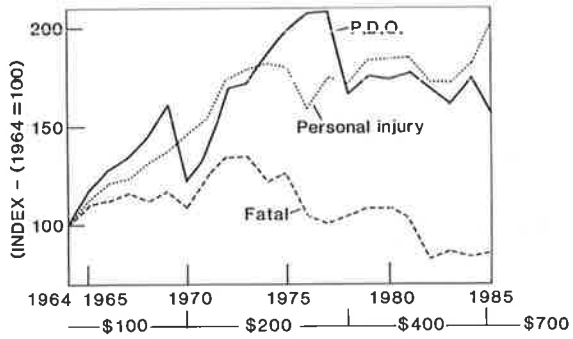

FIGURE 1 Time series of property-damage-only, injury, and fatal accidents in Ontario.

reportable accidents will increase as time passes even if there is no increase in either the number of accidents or their severity. The inflation that eats away at the value of the dollar causes an inflation of reportable accidents. Such accident inflation has nothing to do with changes in road safety. At this time it is unclear how much of the time trend in the PDO accidents in Figure 1 is attributable to "accident inflation."

The second line of defense is the injury accidents, which should be immune to the ravages of monetary inflation. The third line of defense is the fatal accidents, the count of which is generally thought to be the most reliable of all.

Unfortunately, the injury-accident yardstick is also rubbery, though for different reasons. The data in Table 1 were extracted from the Canadian national summary of motor vehicle accident casualties. The corresponding data for Ontario are shown in Table 2. The "Index" column illustrates our point.

Inspection of the "Index" column in both tables reveals that, per injury, only half as many persons die today as did 20 years ago. This trend is quite consistent, even though the number of victims killed and injured goes up and down during these two decades.

The decline in the probability of dying from an injury sustained in a motor vehicle accident (see the killed/injured ratio in Tables 1 and 2) is affected by many factors. Among the main ones that come to mind are less injurious vehicles, use of seatbelts and helmets, forgiving roadsides, and more travel in urban areas. However, the decline may be partly due to an increased inclination to report consequences of an accident as injuries. Indeed, a more detailed examination of the Ontario data revealed that proportionately more and more slight injuries are being reported to the police. Thus, although the number of injuries classified as "major" remained stable over the last decade, the number of "minimal" injuries increased by some 30 percent. Additional reasons for the observed decline in the killed/injured ratio may be that people injured in motor vehicle accidents are more resilient than they were 20 years ago, they get to the hospital in better condition because of improved emergency medical services, and more of them can be saved if they arrive in the hospital alive and are kept alive beyond the 30-day limit, which removes them from the count of motor vehicle accident fatalities.

TABLE 1 MOTOR VEHICLE ACCIDENT CASUALTIES: CANADA

Year	Victims killed	Victims Injured	Killed/Injured	Index
1965	4,902	150,612	0.0325	1.00
1970	5,080	178,501	0.0284	0.87
1975	6,061	220,941	0.0274	0.84
1980	5,461	262,977	0.0208	0.64
1984	4,120	237,455	0.0174	0.53

TABLE 2 MOTOR VEHICLE ACCIDENT CASUALTIES: ONTARIO

Year	Victims killed	Victims Injured	Killed/Injured	Index
1965	1,611	60,917	0.0264	1.00
1970	1,535	75,126	0.0204	0.77
1975	1,800	97,034	0.0186	0.70
1980	1,508	101,367	0.0149	0.56
1983	1,204	91,706	0.0131	0.50

Thus, we have cast some doubt on the reliability of the count of injury accidents reported to the police as a measure of safety. Inasmuch as the count seems to depend on the inclination to complain of injury, it may be the inclination to complain that determines the count. As an aside, we have perhaps raised a question about the count of fatalities (or fatal accidents) as a yardstick of road safety. Suppose that everything remains the same, but doctors keep more victims alive beyond the 30-day limit and therefore the count of fatalities diminishes. Do we equate advances in medicine with improved road safety? Perhaps we should.

In summary, the count of reportable motor vehicle accidents is related to road safety but cannot be considered a good measure of it. The problem of dealing with a rubbery yardstick is further compounded by the fact that not all that is reportable is also reported. A review of what is known about the extent of underreporting is the main object of this section.

Data on accidents recorded by the police are the most widely used source of information in road safety, especially for highway and traffic engineering purposes. The problem of underreporting has received a fair amount of research attention. In Table 3 the results of several studies are summarized (*1–18*). Most estimates of the proportion of accidents reported to the police come from comparisons of police data and hospital files. In some cases the comparison is among several sources (police, hospitals, fire departments, insurance companies, institutes of pathology, self-reporting, employer records, etc.).

TABLE 3 SUMMARY OF STUDIES ON UNDERREPORTING OF ACCIDENTS

Reference & Year of publication	Country	Year	Type of Study	Sample Size	% Reported
(1) 1966	U.S.A California	1963	Police vs. employee records for DOH vehicles	Small 438 cases	Fatal 100% Injury 93% PDO 38% All 49%
(2) 1969	U.S.A Mississippi		Telephone interview vs. police	500 cases	All crashes 42%
(3) 1971	U.S.A	1974	Police vs. self reported accid.		All 35%
(4) 1973	U.K.		Police vs. hospital		Serious Injury 84% Slight Injury 33% Single-vehicle Injury to driver 20%
(5) 1974	U.S.A N.C.		Insurers vs. Dept. of Motor Vehicles		All crashes 89%
(6) 1977	Canada	1974	Police vs. hospital	medium 1008 cases	Fatal 100% In-patient 97% Out-patient 76% All injuries 88%
(7) 1979	U.S.A N.D.		Insurers vs. Dept. of Motor Vehicles (motorcycles)		All crashes 47%
(8) 1981	U.S.A.	1981	Telephone Interview on unreported acc.	large 7624 hshlds.	Injury acc. 79% PDO 54%
(9) 1983	Canada	1981	Police vs. hospital Children less than 15 years old	medium 1767 cases	Injury acc. 59%
(10) 1983	U.K.	1972	Police vs. hospital	large 7630 cases	Injury acc. 50%
(11) 1984	West Germany	1980	Police vs. hospitals, fire dept., patholo-gical inst.	medium	Fatalities 91%
(12) 1984	West Germany	1980	Police vs. medical records of fatalities	medium	2-10% die after 30 days
(13) 1984	several countries	1970s 1980s	Police fatalities vs. health authority death cert.	large	Netherlands 106% New Zealand 97% Norway 80% Sweden 93% USA 96% W. Germany 104%
(14) 1984	Netherlands	1979	Police vs. hospital	large 25,000 cases	In-patients 82-85% All injuries ~45%
(15) 1985	West Germany	1978	Police vs. hospital and insurance data	medium 780 cases	all injuries ~50%
(16) 1985	U.S.A Ohio	1977	hospital vs. Dept. of Motor Vehicles	medium 882 cases	all injuries 55% drivers 74% young (<16 yrs) 28%
(17) 1985	U.S.A. California	1981/ 1982	hospital vs. police non-crash injuries (stops, swerves,..)	small 46 cases	all injuries 38%
(18) 1985	West Germany	1983	Police vs. hospitals insurance, garages	large 2744 cases	fatalities 95% serious injury 78% slight injury 62% major PDO 42%

Inspection of the entries in Table 3 leads to several observations. It seems that different studies yield widely discrepant estimates of the proportion of reportable accidents found in police records. Part of the discrepancy stems from the diversity in methods of study, another part from genuine differences associated with time and place.

In spite of the discrepant estimates, the factors that affect the inclination to report an accident emerge with clarity. Thus, it seems evident that fatal accidents are reported more fully than serious injuries and that the coverage of the latter is, in turn, better than that for slight injuries. [It deserves noting that even the count of fatalities is not without error (*12*).] As a ballpark average of the entries in Table 3, police records miss some 20 percent of injuries that require hospitalization and perhaps up to half of the injuries that do not. In addition, the probability of reporting an injury sustained in a motor vehicle accident increases with the age of the injured person. For young children it is 20 to 30 percent, and for persons over 60 it is around 70 percent (*15*). Similarly, the probability of reporting such an injury by those involved is largest for the driver, less for the passenger, and even less for nonoccupants. Another factor that affects the inclination to report an accident is the number of vehicles involved. Smith (*1*) reports 57 and 12 percent reporting levels for single-vehicle injury and PDO accidents, respectively; for multivehicle accidents the corresponding percentages are 96 and 41.

The problem of nonreporting is compounded by a variety of inaccuracies and errors that creep into the eventual computerized record of the accident. Shinar et al. (*19*) compared police records of 124 accidents with detailed information collected by multidisciplinary accident investigation (MDAI) teams. Police data were found most reliable for location, date, day of week, and number of drivers, passengers, and vehicles involved and least reliable for information about vertical alignment, road surface, and accident severity. Frequent errors were found in driver age (11.6 percent) and vehicle model year (5.3 percent). Hautzinger et al. (*15*) found inaccuracies in the reporting of accident type and vehicle maneuver in 5 to 16 percent of the cases. Kelman (*20*) finds 2.2 discrepancies between the reported and the coded information per accident. Hakkert and Hocherman (*21*) find 1 such discrepancy per accident in rural areas and 1.5 in urban areas. In particular, there are many errors in the coding of locations (25 to 39 percent). The "unknown" code appears in up to 25 percent of the cases. Keller (*22*) finds small errors (2 to 4 percent) in year of birth, sex, type of road user, number of vehicle users, road condition, and light and weather conditions. Larger errors occurred in accident location (5 to 7 percent) and still larger errors in type and cause of accident (7 to 16 percent).

The main points made in this section are as follows:

- The criteria that make a vehicle accident "reportable" make the count of reportable accidents a questionable measure of road safety. The number of collisions and their objective severity may be constant and still the number of reportable accidents may vary as a function of the limit on property damage, the inclination to complain of injury, and other extraneous factors.
- Only a part of all reportable accidents ends up in the official records. The proportion of reportable accidents in official files depends on many factors. The main determinants of the probability of finding a reportable accident reported are severity, age of victim, role (driver, occupant, etc.), and number of vehicles involved. We know little about how the proportion of accidents reported varies in time or from site to site.

CLEARING THE CONCEPTUAL UNDERBRUSH

Now that we have established that the underreporting of accidents is a sizable problem and before we proceed to explore the statistical implications thereof, we have to get our thoughts straight on matters of definition and principle.

Consider a certain road system for which the 1986 official records show 40 single-vehicle accidents in which the driver was young and impaired. In reality, say, 200 such reportable accidents occurred but only 1 in every 5 gets to be reported, on the average. Few would disagree that it is the 200 accidents that occur (not the 40 accidents that are reported) that should form the basis of statements and inferences about the safety of this road system. Although few would disagree, it is also true that almost all statements now made about road safety (especially in highway and traffic engineering) are about accidents that are reported. The distinction between accidents reported and accidents occurring is just not common in practice.

One reason for accepting this obvious paradox is the hope that as long as the level of accident reporting remains constant, it will still be possible to make comparisons. That is, it will be possible to judge improvement or deterioration and identify high-accident locations or characteristic patterns of accident occurrence even when only a portion of the accidents is reported.

Thus, to continue the above example, if 50 single-vehicle accidents by young, impaired drivers were reported on the same road system in 1985 and if there were no change in the inclination to report such accidents, one could legitimately estimate that from 1985 to 1986 the number of such accidents had decreased by $100 \times (50 - 40)/50 = 20$ percent. Note that it is not correct to say that there was a decrease of 10 accidents; for all we know, the reduction is perhaps 50 accidents (because only 1 in 5 is reported, on the average). Only statements about relative magnitude are legitimate. However, should the inclination to report an accident change from 1985 to 1986, even the possibility of making relative comparisons would be destroyed. In that event, the 20 percent reduction in the count of reported accidents could reflect a change in the level of reporting or in the number of accidents occurring, or, most likely, an inseparable mix of the two.

We are now getting close to the heart of the matter. If the inclination to report an accident is constant from time period to time period or site to site, comparisons of safety on the basis of reported accidents are legitimate. In this case, the net effect of a sudden reduction in the level of accident reporting would be that (after some transition period) it will take a proportionately longer time to collect a fixed amount of accident data. No further, complicated analysis is necessary.

However, even if present practice takes no cognizance of the distinction between accidents reported and accidents occurring, the assumption that the average ratio of "reportable accidents reported to reportable accidents occurring" is constant does not seem to be realistic. On the basis of what little we know, the probability of a reportable accident's being reported depends on a host of factors (accident severity, structure of insurance premiums, age and sobriety of driver, age of victims, inclination to seek compensation, number of vehicles involved, proximity to police station, workload of the police force, and so on). Many of these factors change with time and location.

If the inclination to report an accident cannot be realistically taken as constant, one must squarely face the fact that to make an accurate statement about road safety, one has to have some idea of the average proportion of accidents that are reported. At this point we have to state what the phrase "road safety" means.

For the purposes of science and management, "road safety" is a real characteristic; it has a magnitude and is subject to measurement. Thus we may inquire, for example, about the (magnitude of) safety of the Interstate highway system in 1980, the safety of the intersection of High and Main streets in May 1986, or the safety of John Smith next Tuesday. We will use the word "entity" to designate these elements of the real world (highways, intersections, drivers) whose safety is to be determined. The safety of an entity is defined as the number of accidents in several classes *expected* to occur on that entity per unit of time. The term "expected" means "what would be the average in the long term were it possible for all conditions to remain unchanged indefinitely." Thus, a distinction is created between accidents *expected to occur* and accidents *occurring* on an entity. It is the former that we call "safety" and it is the latter that, were it known to us, would allow us to make informed guesses (statistical inferences) about safety. However, as has been stressed, not all reportable accidents that occur are in fact reported. Thus, the link between what is occurring and what is expected to occur is severed, and the customary flow of statistical inference is obstructed.

It should be clear that without some notion about what proportion of accidents makes it into official records, one cannot establish any functional relationship between road safety and reported accidents. Thus, for example, if on a road system there are official reports of 50 single-vehicle accidents in which the driver is young and impaired and we think that 10 to 30 percent of all such accidents get reported, we can estimate that perhaps 500 − 167 such accidents have occurred. But without stating the 10 to 30 percent range, official accident records are apples and the estimates of the expected number of accidents occurring are oranges.

In summary, the link between road safety and the number of (reportable) accidents occurring is through the laws of probability and the methods of statistics. The link between (reportable) accidents occurring and their subset—accidents reported—is through the probability that a reportable accident will get into the official records. A realistic analysis of the repercussions of incomplete accident reporting must take into account the interaction of these three elements and their linkages.

In the next section we make an attempt at analysis. We face the usual dilemma. Some readers who have an interest in the results may find the machinery of analysis obscure. With this difficulty in mind, an attempt will be made, where possible, to translate mathematical statements into their real-world equivalents.

ANALYSIS

In road safety management, official accident reports are used in many ways: to keep tabs on trends, to identify target groups (accidents types, high-risk drivers, dangerous vehicles, hazardous sites, etc.) that for one reason or another demand attention, to examine the relationship between accident occurrence and various causal factors, and to examine changes in road safety as well as the reasons for such changes (as, for example, when the effect of some countermeasure is estimated or when the causal factors of changes in accident occurrence are investigated). All these diverse uses of official accident reports are linked to two generic questions about road safety:

1. What is the magnitude of road safety for some specific "entity" during a certain period of time?
2. What is the change in the relative magnitude of the safety of an entity from one period of time to another or the relative difference in the safety of several entities?

In the interest of clarity, the two cases (estimation of the magnitude of road safety and estimation of change or difference in the relative magnitude of road safety) will be treated separately.

We now introduce the requisite notation. For purposes of analysis, the safety of an entity during a specified period of time is the vector $\langle m \rangle$ of the expected number of accidents $m_1, m_2, \ldots, m_i \ldots, m_n$ in classes 1, 2, ..., $i \ldots, n$. Thus, for example, the entity may be a specific intersection and the classes could be accident types by initial impact (rear end, head on, ...), by accident severity (PDO, injury, or fatal, or perhaps AIS1, AIS2, ...), or by any other category.

Answers to questions about the magnitude of the components of m (as, for example, in the identification of black spots or deviant drivers) or about changes in the

magnitude of $\langle m \rangle$ (as, for example, in research about the safety effect of certain treatments) are provided with the aid of statistics. The mathematical point of departure is a functional relationship among the number of accidents reported in class i (x_i), the probability that an accident in class i will be reported (p_i), and the number of accidents expected to occur (m_i). This functional relationship will, in turn, determine how information about accidents as reported by the police $\langle x \rangle$ is used to make inferences about road safety $\langle m \rangle$. The same functional relationship among x_i, p_i, and m_i has to be used in our attempt to describe in numbers the deterioration in the knowledge of road safety that is caused by a degradation in the level of accident reporting.

If all accidents that occur were also reported, we would be on solid ground. Standard statistical literature gives guidance on how to estimate what is *expected* to occur on the basis of what has been *observed* to occur. In our case, however, only a certain portion of what occurs enters into the data. Important aspects of this problem may be found in the statistical literature under the name "partial ascertainment." It has been shown (*23–25*) that if p_i is the probability for an accident of class i to be reported and that if accident occurrence follows the Poisson (or binomial or negative binomial) probability law with m_i as the expected value, the number of *reported* accidents follows the same probability law but with ($p_i m_i$) as the expected value.

Thus, for example, if the count of accidents per year for some intersection is Poisson distributed with an expected value (mean) of 10 accidents and the probability for such accidents to be reported is 0.7, the count of reported accidents for that intersection is also Poisson distributed with an expected value of 7 accidents.

There is some good and some bad news in this message. The good news is that the loss of data does not alter the shape of the probability distribution and does not increase its variance. The bad news is that from the count of reported accidents, one can only make inferences about the expected number of reported accidents ($p_i m_i$) but not about p_i or m_i separately, a point already stressed by both Rao (*23*) and Kemp (*24*). In other words, the count of reported accidents cannot tell us anything about the number of accidents expected to occur when we have no idea what p_i is. Evident as all this is, the importance of knowing the proportion of accidents reported to the police by accident class does not seem to have been widely recognized or researched.

To make inferences about the magnitude of the components of vector $\langle m \rangle$, one has to have an estimate of p_i for all i. Barring that, it is possible to make inferences about *relative* magnitude of the m's if one is willing to assume that the same vector of values $\langle p \rangle$ applies to all entities among which the comparison is made. In other words, one can still calculate the percentage of change in accidents over two time periods (say, in a before-and-after study) or even compare the relative safety of entities in different parts of the city, state, or country if it is correct to assume that the same vector of probabilities of accidents to be reported applies to all these entities.

Estimation of Magnitude of $\langle m \rangle$

We can use data about x_i—accidents of class i reported to the police—to obtain an estimate of $p_i m_i$—the expected number of accidents in class i reported to the police. To underscore the fact that the two components of the product $p_i m_i$ cannot be told apart, we will use the notation $r_i = p_i m_i$. Thus, r_i is the expected number of *reported* accidents and $\hat{r}_i$ is its estimate. (In what follows we will use a caret to mean "the estimate of.") We are not interested in $\langle r \rangle$ per se; what we wish to estimate is $\langle m \rangle$; $\langle r \rangle$ is only a stepping-stone en route to this goal. To estimate m_i we have to make use of

$$m_i = r_i / p_i \tag{1}$$

replacing r_i by $\hat{r}_i$ and p_i by $\hat{p}_i$. Inasmuch as $\hat{r}_i$ is a function of x_i, Equation 1 is the embodiment of the functional relationship between the x's and the m's of which we spoke earlier. It is now also explicit that $\hat{p}_i$ is an essential part of this relationship; that without some knowledge about the magnitude of $\langle \hat{p} \rangle$, $\langle \hat{m} \rangle$ cannot be related to $\langle \hat{r} \rangle$ and thus no link can be established between safety and the count of accidents reported to the police $\langle x \rangle$.

Note that $\hat{p}_i$ is itself an estimate and is surrounded by uncertainty (which is at present considerable). For didactic reasons we will proceed in two steps. First we will assume that p_i is known with certainty. Next we will explore the consequences of the uncertainty surrounding the actual magnitude of p_i.

Suppose then, first, that p_i is known to us with certainty. We also know that on a particular entity, x_i accidents have been reported. What we are after is the accuracy with which m_i can be estimated from these data. The accuracy of the estimate of m_i is described by $\mathrm{Var}\{\hat{m}_i\}$. In our case,

$$\mathrm{Var}\{\hat{m}_i\} = \mathrm{Var}\{\hat{r}_i\} / p_i^2 \tag{2}$$

A numerical example might help to elucidate the meaning of Equation 2. Suppose that six injury accidents were reported at an intersection during the 3-year period 1982–1984 and it is known that 70 percent of all injury accidents are reported, on the average. In this case, $\hat{m}_{\text{injury}} = 6/0.7 = 8.6$ injury accidents for these 3 years and $\mathrm{Var}\{\hat{m}_{\text{injury}}\}$ is estimated as $6/0.49 = 12.2$ (injury accidents)^2. When the Poisson model is applied to accident occurrence, the variance of the estimate of the mean is the same as the mean. Note that when accident reporting is not complete, the variance of the estimate is always larger than the mean even if p_i is known precisely!

To elaborate on Equation 2, assume that we have n annual counts of reported accidents for some entity. If r_i is now the expected number of reported accidents per annum, $\mathrm{Var}\{\hat{r}_i\} = r_i/n$. Let m_i be the expected number of accidents per annum for this entity. Using Equation 1, it follows that $\mathrm{Var}\{\hat{r}_i\} = m_i p_i / n$. Therefore, Equation 2 takes the form $\mathrm{Var}\{\hat{m}_i\} = m_i/(np_i)$. In this form some of the trade-offs can be made visible.

In Figure 2 we show how the variance-to-mean ratio of the estimate of m changes as a function of the number of

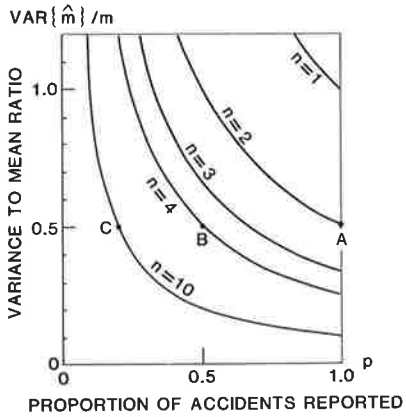

FIGURE 2 Accuracy of estimation when *p* is known exactly.

years of reported accident data used in the estimate and on the level of accident reporting when p is assumed to be known precisely. If accident reporting is complete ($p = 1$) and we wish the variance of the estimate of m to be half of the mean, 2 years' worth of reported accidents is needed (Point A in Figure 2). To keep the same accuracy of estimation when only 50 percent of the accidents are reported, 4 years of data are required (Point B) and with p as low as 0.2, 10 years of data would be required to retain the same accuracy.

The thrust of the argument embodied in Equations 1 and 2 and Figure 2 is as follows: the accuracy with which we can measure (estimate) road safety $\langle m \rangle$ depends not only on the count of reported accidents $\langle x \rangle$ but also on the knowledge of the proportion of accidents that is reported $\langle p \rangle$ (and, as will be shown shortly, on the accuracy with which p is known). We measure the accuracy with which we can estimate $\langle m \rangle$ by $\mathrm{Var}\langle \hat{m} \rangle$. When for an accident class i we manage to express $\mathrm{Var}\{\hat{m}_i\}$ as a function of p_i (and, later also, of the variance of p_i), we can examine quantitatively how the lesser reporting of accidents degrades the accuracy with which we can measure road safety. This is what we set out to do: to tell in numbers how lower levels of accident reporting affect road safety management, which is (or should be) predicated on the measurement of road safety.

Having established the pattern of analysis for the simple but unrealistic case in which p_i is known accurately, we can proceed to the more complex but perhaps more practical case in which we admit that p_i is not known to us with certainty. What we have is an estimate $\hat{p}_i$ of p_i. As with all estimates, $\hat{p}_i$ has a variance $\mathrm{Var}\{\hat{p}_i\}$. Now both the numerator and denominator in Equation 1 are replaced by estimates that have to be regarded as random variables.

One can claim that $\hat{p}_i$ and $\hat{r}_i$ are uncorrelated. If so, it can be shown (*26*, p. 29) that

$$\mathrm{Var}\{\hat{m}_i\} \cong (\mathrm{Var}\{\hat{r}_i\}/p_i^2) + r_i^2\ \mathrm{Var}\{\hat{p}_i\}/p_i^4 \qquad (3)$$

The first term on the right-hand side is as in Equation 2; the second term accounts for the contribution of $\mathrm{Var}\{\hat{p}_i\}$.

To clarify the meaning of Equation 3, we continue the numerical example from above, in which six injury accidents were reported, constituting some 70 percent of such accidents occurring. We now admit that we are unsure about the 70 percent; perhaps the range 50 to 90 percent covers two standard deviations. This translates into $\mathrm{Var}\{\hat{p}_i\} = 0.04$. Now, an estimate of $\mathrm{Var}\{\hat{m}_i\}$ is $6/0.49 + 62 \times 0.04/0.7^4 = 12.2 + 6.0 = 18.2$ accidents^2.

It may be useful to rewrite Equation 3 in order to clarify the meaning of its components. Assume, as before, that we have n annual counts of reported accidents and that both r_i and m_i are expected numbers per annum. Again we make use of the relationships $r_i = m_i p_i$ and $\mathrm{Var}\{\hat{r}_i\} = m_i p_i / n$. Substitution into Equation 3 leads to

$$\mathrm{Var}\{\hat{m}_i\} = m_i/(np_i) + m_i^2\ \mathrm{Var}\{\hat{p}_i\}/p_i^2 \qquad (4)$$

It is now clear that the number of years for which accident counts are available (n) affects one component of the variance of $\hat{m}$ but not the other. For no matter how many years we count accidents reported to the police, the uncertainty surrounding $\hat{p}_i$ puts a limit on how accurately m_i can be estimated. We illustrate this point in Figure 3, which was constructed for the case in which 3 years of accident data are available; m is 10 accidents per year and $\mathrm{Var}\{\hat{p}\}$ is 0.04. The ordinate is shown to be constituted of two parts corresponding to the two summands in Equations 3 and 4. The first striking observation is that, in the case shown here, the uncertainty about the proportion of accidents reported ("second term") has a larger effect on the accuracy of estimation than has the randomness in the count of accidents ("first term"). The next feature to note is that when the proportion of reported accidents is small, the second term is so large as to render any attempt at estimation very inaccurate. This is so because the second term is proportional to the reciprocal value of p^2.

Estimation of Relative Changes in $\langle m \rangle$

Often one is not interested in the magnitude of the m_i's or the absolute changes therein. Rather, the goal is to obtain

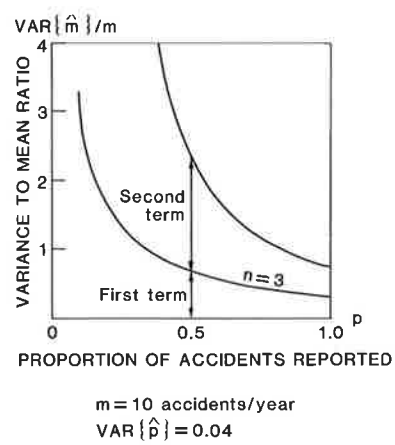

FIGURE 3 Accuracy of estimation when *p* is not known exactly.

estimates of the *ratios* of the m_i's "before" (or "without") treatment to the m_i's "after" (or "with") treatment. For brevity we denote these ratios as θ_i, $i = 1,2,\ldots$. Estimates of the θ_i's are usually obtained by dividing the number of reported accidents of class i before (without) treatment by the number of accidents in the same class reported after (with) treatment. If p_i is the same for the before and after periods (or for the entities with and without treatment that are being compared), the net effect of incomplete accident reporting is merely to reduce the amount of information that can be collected per unit of time. If, say, only 50 percent of the accidents are reported, it will take twice as long to collect the data that would be available with complete reporting. This is the essence of the relationship in Figure 2.

Unfortunately, even if estimates of the relative change in safety are carefully calculated for several accident classes, difficult problems remain. First, official accident reports contain only coarsely graded estimates of severity, which cannot be very reliable. Second, the probability of an accident's being reported increases not only with accident severity but also with the number of vehicles involved and the age of the persons affected. Therefore, classification by severity alone is obviously insufficient to ensure that the p_i's are the same for the entities whose accident histories are being compared. Third, we know of no empirical evidence to support the assumption that the probability of an accident's being reported is the same in different parts of the same city (when entities with and without treatment are being compared) or that it remains constant during different periods of time for a specific set of entities (as in before and after comparisons) or, in the worst case, that it is the same when one compares the reported accident histories of different entities and different time periods.

It is for these reasons that one must admit the possibility that the p_i's for the entities being compared are not identical. The quantitative implications of such an admission are explored below.

We imagine that the two p_i's, the probabilities that an accident of class i will be reported before (with) and after (without), are drawn at random from a distribution of p_i's that has a mean $E\{p_i\}$ and a variance $\mathrm{Var}\{p_i\}$. To keep the algebra manageable, one has also to invoke the assumption that the probability of reporting and the safety effect of a treatment or measure are statistically independent. With this (possibly questionable) assumption, it can be shown that

$$\mathrm{Var}\{\hat{\theta}_i\} \cong \theta_i^2\,[1/(r_i\theta_i) + 1/r_i + 2\,\mathrm{Var}\{p_i\}/p_i^2] \qquad (5)$$

A numerical example may again be of use. Suppose that the number of reported injury accidents changed from 25 before some treatment to 20 after the treatment. It follows that $\theta_{\text{injury}} = 20/25 = 0.8$, indicating a 20 percent reduction in injury accidents. If the probability of reporting an injury accident were constant during the before and after periods, an estimate of $\mathrm{Var}\{\hat{\theta}_{\text{injury}}\} = 0.8^2[(1/20) + (1/25)] = 0.64(0.05 + 0.04) = 0.058$. However, if an estimate of p_{injury} is 0.7 and an estimate of $\mathrm{Var}\{p_{\text{injury}}\}$ is 0.01, we have to add to the sum in square brackets $2 \times 0.01/0.7^2 = 0.04$. Now, $\mathrm{Var}\{\hat{\theta}_{\text{injury}}\} = 0.083$. In this case, the uncertainty in accident reporting contributes to the variance of the estimate of θ_{injury} an amount that is similar to that contributed by the randomness in accident occurrence before or after treatment.

Equation 5 is similar in nature to Equation 4. It shows that even the accuracy of relative comparisons of safety is severely affected by the variability in the probability of accidents' being reported. This variability imposes a limit on estimation accuracy that is not affected by the amount of data collected. Furthermore, the inaccuracy of estimation grows explosively as the proportion of accidents reported diminishes.

The principal results of this analysis can be summarized as follows. The level of accident reporting plays a central role in the estimation of road safety. Were it realistic to assume that the proportion of accidents reported is constant during a fairly long period of time, a lesser level of reporting would merely correspondingly prolong the time required to collect a fixed amount of accident data. However, it appears unrealistic to so assume. If we admit that the probability of reporting an accident is not known with precision, our ability to estimate road safety is seriously affected. There is now an added term in the variance of $\hat{m}_i$ or $\hat{\theta}_i$. This "second term" increases in direct proportion to the variance of p_i (or its estimate) and with the square of $1/p_i$.

DISCUSSION AND SUMMARY

We set out to describe the extent of accident underreporting and some of its quantitative implications.

It appears that accident underreporting is rather substantial. Estimates of underreporting culled from the literature differ widely. It is therefore difficult to know by how much accidents are underreported in some specific region during a certain period of time. As a ballpark figure, fatalities seem to be known to an accuracy of ±5 percent; perhaps 20 percent of injuries that require hospitalization do not show up in police records; of all injuries sustained in motor vehicle accidents, perhaps half are not reported to the police and the reporting of PDO accidents is likely to be even lower. The probability of an accident's being reported depends on the severity of the outcome, the age of the victim, his or her role in the accident, the number of vehicles involved, and other factors.

The importance of incomplete accident reporting derives from the uses to which the information is put. The use considered here is that of measuring road safety. In this respect there appears to be a curious inconsistency in that road safety must be measured in terms of accidents that *occur*, yet most statements about road safety rely solely on accidents that are *reported*.

The analysis leads to several observations. First, it should be self-evident that one cannot make statements about the size of a road safety problem (the magnitude m for accidents of kind i) without using an estimate of the proportion

of accidents in that class that get reported. Equation 1 only reaffirms the obvious. Still, it is rare to encounter statements about the magnitude of a safety problem in which the obvious and the self-evident are given consideration. Most of what is said about safety is confined to statements based on accidents that have been reported and not on estimates of what has occurred. Not only do such statements make the safety problem appear to be smaller than it really is, they also mix and confuse changes and trends in safety with changes and trends in the inclination to report or record accidents.

Second, statistical statements about the accuracy with which the magnitude of m_i's is estimated have to recognize the effect of p_i and $\mathrm{Var}\{\hat{p}_i\}$. If this is not done, estimates appear to be more accurate than they really are. The implication is that virtually all that has been said (in safety) about the statistical significance of the differences between means, about the significance of a deviation from an expected value, or about the size of confidence intervals requires reexamination.

Third, accuracy of estimation improves sharply as p_i increases and as $\mathrm{Var}\{\hat{p}_i\}$ decreases. This serves to emphasize the importance of completeness in accident reporting by police and supports the investment of effort in the merging of police, hospital, and insurance records. It also supports the need for better information about the magnitude of p_i by accident type.

Fourth, if one is interested only in the ratio of m_i's, that is, in the relative change of safety, the requirement of paramount importance is that the entities for which reported accident histories are being compared ("before" versus "after" or "without" versus "with") have the same probability of an accident's being reported. If that requirement is satisfied, the effect of incomplete reporting is merely that of prolonging the time required to collect a fixed amount of accident data.

Inasmuch as the probability of an accident's being reported is known to increase with its severity and because all real treatments affect both the frequency and the severity of accidents, it seems never correct to estimate the safety effect of some treatment using the ratio of all accidents without to all accidents with treatment. Doing so violates the aforementioned requirement. When estimating the safety effect of some treatment, accidents should be divided into classes in such a manner that, within each class, average severity "without" is likely to be the same as the average severity "with." However, accident severity is not the only factor that influences p. Because p increases with the number of vehicles in the collision, single-vehicle, two-vehicle, and multivehicle accidents should also form separate classes. It is easy to see that the aforementioned requirement is not easy to satisfy in practice.

Fifth, although convenient and tempting, there is no reason to assume that the probability of an accident's being reported is the same for the two sets of entities whose accident histories are being compared. The real question is not whether the two probabilities are equal but how large the difference is between them. The implications of this are captured by Equation 5. Once again, the effect of uncertainty about the difference in the two probabilities is to decrease the accuracy with which the safety effect of the treatment can be known. As the amount of accident data increases, the uncertainty about the differences in the probability of reporting begins to dominate the accuracy of estimation. In fact, it determines a limit on the accuracy with which the safety effect of a treatment can be known irrespective of the amount of available accident data.

In summary, the ability to make quantitative statements about the number of accidents occurring requires that we know what proportion of these accidents gets into police records. Thus, research is needed to find out what the p_i's are by type of accident, by region, by time, and so on. Furthermore, the accuracy of our statements deteriorates rapidly as the proportion of accidents reported diminishes and the uncertainty about the prevailing level of accident reporting increases. Thus, for credible statements about road safety and its changes, the proportion of accidents reported to the police needs to be high, stable over time and location, and accurately known.

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