Application of Statistical Quality-Control Techniques to Analysis of Highway-Accident Data

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Statistical control techniques, analagous to those employed in industrial quality control, can be applied to the study and control of highway accidents. This paper presents the development of the appropriate statistical techniques, together with the results of a pilot application of these techniques to an actual highway situation. The results show strong promise that the application of this method can contribute substantially to the highway accident problem.

● THE purpose of this study[1] was to explore the possibilities of developing analytical instruments for application to highway accident control. In particular, the aim was to find an effective set of techniques to assist in the identification and correction of factors in the design and operation of highway systems which may contribute to accident hazard.

This study begins with an examination of techniques commonly employed for studying the problem of highway accidents. Some of the advantages as well as possible deficiencies in these methods are reviewed. There follows a description of a proposed technique which the authors believe can contribute effectively to accident control activities. The emphasis in this presentation is on the practical problems of application. The underlying theoretical consideratıcns are not treated in detail here but will be given in a subsequent report. Finally, a pilot application of this technique to a major highway system is described. The procedures by which computations are made and results obtained and interpreted are illustrated.

EXAMINATION OF CURRENT TECHNIQUES FOR THE STUDY OF ACCIDENTS

Before describing the proposed techniques, it would be useful to review in some detail the accident-investigation methods employed in current highway-safety administration. It is possible to classify these methods into a number of basic kinds which more or less complement each other. Some of these are dependent almost entirely on the judgment of the highway engineer or the safety investigator. The others depend on information provided by accident records. In order to demonstrate the prospective role of the techniques to be described in this report, each of the current methods will be described in some detail with illustrations of the practices which one observes.

Application of Personal Judgment and Experience to Accident Situations Without the Use of Summary Data

On-the-Scene Investigations. There can be little question but that direct investigation of accidents immediately after they happen is one of the most-effective techniques for deriving information about accident causation. Such investigations are crucial in that they provide detailed insights into the particular combination of circumstances responsible for certain types of accidents. Such investigations are suggestive in that the cause more often than not suggests the remedy, even though the remedy may be difficult to apply. This procedure is weak only in the evaluation of the less-recognizable causative factors, which may contribute only slightly to any one accident but which may play a

[1] This is a partial report of a study being conducted by Dunlap and Associates, Inc., under the sponsorship of the Commission on Accidental Trauma, Armed Forces Epidemiological Board, which was supported through a contract with the Office of The Surgeon General, Department of the Army.

contributory role in many accidents. It also makes difficult the relative evaluation of a set of causes in the sense that it may be too easy to blame an accident on such factors as drunken driving, high speed, carelessness, sleepiness, etc., while overlooking the contribution of the road surface, design of a slight curve, etc. Effective as this investigative procedure may be in the study of individual accidents, its main omission is that it does not lead to an effective assessment of the overall accident picture.

Intuitive and Logical Evaluation of Accident Hazards. This type of evaluation is one which attempts to anticipate accident causes on the basis of personal experience in driving situations and reasonable or reasoned evaluations of what one thinks will reduce accident rate. It is founded on intuition, feeling, opinions, and other undescribable personal quantities. For example, we have all had the experience of being blinded by the bright lights of an oncoming car and experienced the sensation of recognizing an almost-obvious accident hazard. Another example is the current opinion that highways which are too straight and uninterrupted produce accident hazards by boredom.

There can be no question, again, but that this is a valuable method of anticipating and forestalling accident-producing situations. It, too, is imperfect in the sense that it is responsive mostly to the more-conspicuous factors associated with highway accidents and sometimes misleads us as to the relative importance of these factors. For example, there is some statistical evidence and considerable opinion which would tend to negate the importance of bright headlights as a major causative factor in highway accidents.

Application of Accident Data to Investigation of Highway Accidents

Comparisons between Highways. This is a common method of analysis, which attempts to make judgments by comparing accidents or accident rates between situations (e.g., state versus state, highway versus highway, etc.), usually using yearly data. It has often been suspected that the principal virtue of these comparisons resides in the fact that they result in a continuing pressure on safety engineers and highway officials to keep their accidents down. This is certainly a healthy consequence.

The obvious difficulty with all such comparisons is that the highways being compared differ in innumerable ways in addition to the one being investigated. For example, consider comparing southern versus northern roads, four-lane versus six-lane roads, heavily trafficked versus lightly trafficked roads, rural versus urban roads, etc. Any groups of roads so compared necessarily differ in many obvious equally important ways. Because of this, it is often easy to rationalize away an unfavorable comparison, and more often than not such rationalizations are justified. The result is that, while such comparisons are easily obtained and often published, no one trusts them or uses them.

Another, less-intrinsic difficulty, is that adequate data on exposure (car-miles) are not available for most roads.

A similar difficulty extends to the accident data themselves. The number of accidents reported of any category (except fatalities) depends markedly on definition (both the formal definition and the intuitive definition of the police), on the energy of the police, on the value to the driver of reporting the accident, etc.

These problems are present in all accident comparisons. Adequate data on exposure and uniform reporting of accidents are only obtained by great effort and planning long in advance of the collection of data. Accident-rate comparisons, which have a good chance of reflecting only the causal change being investigated, can only be obtained by extremely thoughtful and careful selection of the units to be studied.

However, the comparison between groups of highways involves these problems to an extreme degree and, probably, to an intractable degree. Hence one goes to other methods which offer some degree of control of the situation.

Application of Internal Accident Data for Reducing Accidents on a Given Highway: Over-All Year-to-Year Evaluations. Historical comparisons represent one method for judging the effects of past safety programs. At best, they provide a real picture of the total effectiveness of the combination of the many changes and actions which may have taken place during the course of the year, e.g., police effort, safety signs, etc. Unfortunately, they cannot separate the effectiveness of individual measures. The greatest dificiency of the procedure lies in the difficulty of assigning meaning to positive or negative changes. The reason for this can be best explained by recalling that there are many other factors over which the highway engineer has no control (often he cannot even measure them) which also change from year to year. For example, the types of factors that can change and, in changing, can affect the accident picture, include variations in the experience and characteristics of the driver population; age, type, or performance of automobiles; traffic density; weather, scenery, or highway surface, and so on. The question of how much of the change in accident rate is a result of safety effort and how much is the result of changes in some of these uncontrollable elements is ignored.

In addition to the difficulty of assigning reasons to any real changes assumed to have taken place in the accident picture, there is another kind of difficulty which is entirely interpretative. This is the problem of determining when the observed differences in accident rates reflect real underlying differences rather than just chance fluctuations. It must be remembered that accident numbers or accident rates are subject to the influence of a large amount of chance random fluctuation. That is, even if accident conditions remained identical, one would obtain noticeable differences in the observed accident rates. To cope with the problem, one needs to compare differences in observed accident rates with some measure of the size of the fluctuation due to chance. This

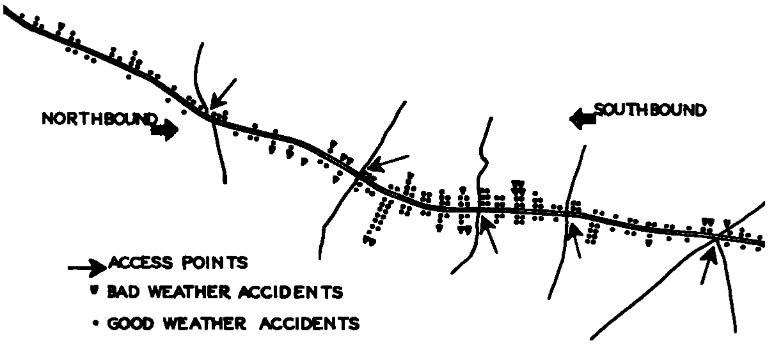

Figure 1. Typical chart showing location of accidents along highway.

must be done whenever we deal with observed data, and it is particularly important in interpreting accident data.

Application of Internal Accident Data for Reducing Accidents on a Given Highway: Analysis of Accidents by Position Along the Highway. This is a potentially valuable approach for supplementing the evaluation provided by the other methods of investigation described above. In one form or another, it is practiced by most highway administrations. It is premised on the understanding that accident risks are greater, perhaps much greater, at particular locations as compared to others and that, by identifying and studying these high-risk accident locations, a general reduction can be brought about. While this is a sound objective, certain problems have been recognized in performing such analyses.

For example, a common technique is to plot individual accidents on a detailed map of the highway. To determine from this map those sections of a highway which have unduly high accident rates, the observer has to perform the following mental functions: (1) He must correct for exposure differences (e.g., car-miles) from section to section. (2) He must summate individual occurrences to obtain totals for the various sections of interest of the highway or the road. (3) He must intuitively see through the fog of the ever-present and large variation in accident occurrences which we call chance.

An example of this approach to the evaluation of accident hazards along a highway is illustrated in Figure 1. Although distorted geographically, this chart represents the plotting of actual accident data drawn from the records of a major highway system. Each point represents a single accident and has been coded by direction. (In actual practice, such charts are also coded by day versus night, weather, etc. Any additional coding makes the mental functions described above harder to perform.) Striking differences in the concentration of accidents are evident in this chart, but the interpretation of these differences still requires knowledge of the accident exposure properties of the highway. Also, because of the large element of chance variation, it appears difficult to make positive interpretation of the differences.

It is probable that a capable safety engineer, with intensive experience on the particular highway, can accomplish the three mental operations described above and obtain valuable information from this chart. However, this will necessarily require a great outlay of time, mental examination, and intuitive contemplation.

In any case, a principal value of such a map presentation would be to refresh the mind of an experienced engineer as to where accidents occurred. There are surely other values, and the map presentation of individual accidents is a method worth retaining.

We propose a precedure by which the above three analytical operations required for the interpretation of accident data can be accomplished in a rational and routine manner and by subordinate personnel under the direction of the safety engineer. This would have the advantage of leaving the engineer free to use his experience and judgment in the evaluation of the results of the proposed procedure and in other directions. In other words, we feel that any reduction in the area requiring the intuition and judgment of the safety engineer will allow him to apply his judgment more effectively to the remaining areas.

Proposed Techniques for Analyzing Accident Data

The techniques described in this report are designed to establish an effective basis for studying the variation in accident risk along a highway. The procedure operates by: (1) cumulating accident data for large enough sections of the highway to be sensitive to reasonable changes in accident rate; (2) using an experienced accident rate based on exposure (e.g., accidents per car-mile) to reflect more properly any real differences in risk; and (3) using a reasonable-allowed random fluctuation as a yardstick for determining when an observed accident rate differs enough from other observed rates to be indicative of a real change in underlying accident probability.

DEVELOPMENT OF PROPOSED PROCEDURE

Background

A methodological study of possible techniques for analyzing highway accidents indicated that the techniques used in what is commonly called "statistical quality control" appeared to form an appropriate basis from which to develop the desired tools. The virtues of these techniques can be summarized as follows: (1) they apply to a wide range of situations; (2) they allow almost all of the experience, intuition, judgment and knowledge concerning a situation to be brought to bear in developing understanding and remedial action; (3) they indicate what is happening and point to places for further investigation in such a way that experience and knowledge can be applied, rather than yielding a mechanical or mathematical solution or explanation; and (4) the effects of the methods of data collection and measurement are made so apparent that it is difficult to avoid their consideration when drawing conclusions.

Statistical quality control was developed as a method of dynamically controlling the quality of industrial production. For that reason most of its growth centered about the development of methods and concepts for finding out what was happening in an industrial process. The methods developed were quite successful in indicating when something went wrong and helped in finding what was wrong. Now highway accidents are not the result of a manufacturing process, and it is almost meaningless to talk about the "quality" of accidents, or of their "control." Hence, as can be expected, it was found that, starting with the techniques currently used in statistical quality control, considerable additional theoretical and practical investigation was necessary to develop methods for the study of highway accidents. It is believed that the methods developed will be as useful in indicating where situations resulting in excessive accident rates occur as the orignial techniques were when applied to industrial processes.

Preliminary Problems

Two important problems arose almost at the start of the investigation, problems that have almost no meaning in manufacturing processes.

The first problem arose because, up to now, all statistical quality control dealt only with variation in time. For example, one sampled the output of the manufacturing process at some fixed interval of time, say every 15 minutes, or every hour, etc., inspected the result and determined whether the result deviated more than should be expected from the inherent variability of the process. One took samples on a rigid time schedule and checked to determine whether the results were any different from what should be expected from a random time pattern. Note that, if they were, the time at which they occurred would already be a help in locating the source of the deviation. Now there were exceptions to this example; sometimes one examined every hundredth item produced, and not all statistical-quality-control systems dealt with manufacturing processes. However, in essence, they all dealt with variation in time.

For our purposes, accident variation in time seems to involve too-many possible causes which can be balanced out. In considering the application of these techniques to the study of the highway, we prefer, at least initially, to avoid study of the variation of accident rate with time. It is known that there are marked yearly, seasonal, weather, and other time-related changes in environment as well as in characteristics of the driver population. These can be balanced out by making comparisons for the same period of time (e.g., yearly rates) omitting bad weather accidents, etc. In any attempt to determine causation it is desirable to limit the possible causes to as small a class as possible.

After considerable thought and discussion, we finally decided that a more-valuable approach would be to study what might be called "variation in space." That is, one could take a highway and study the variation in accident rate along its length. As we saw it, we would break up the length of a highway into a number of stretches or intervals and study the variation in accident rate from stretch to stretch. Accident rates for a whole year would be used to balance out any seasonal characteristics.

The second problem that arose was that of getting a unit of exposure. In manufacturing applications we usually have, or can easily determine, clear-cut items. We can sample 10 pieces, observe the number of defects and compute the average number of defects per piece. But with accidents the unit of risk or exposure is not at all clear. For example, should we consider accidents per car? Accidents per trip? Accidents per mile? Accidents per car-mile? Accidents as a function of the number of miles traveled since entering the highway? Accidents per some weighted function of car-miles and density of cars? For a while, the last possibility was seriously considered, as it was felt that, as density increased, accidents first increased proportionally to the square of the density, then reached a peak, and then dropped off as density was still further increased. This possibility was rejected as being inappropriate for a pilot study and the data seemed to show no need for this assumption.

It was decided that the proper unit of risk was the car-mile, and accidents per car-mile were investigated in the pilot study. This is no hard-and-fast conclusion. The possibility that the wrong unit of risk is being used should always be kept in mind when analyzing the data. If the unit used is inappropriate, our technique will indicate it. We also do not assume that car-miles will always be appropriate. There will always be situations in which a different unit of risk would be more suitable. For example, if we studied the accidents that occur at the toll gates to cars in the toll line, it is clear that accidents per car would probably be more appropriate. In such a case, number of accidents per car-mile is almost meaningless.

Selection of a Highway to Study

The next problem was to apply the ideas of quality control to a real situation. The highway selected was a major eastern throughway. The reasons for this particular choice will be given below.

For each highway interval under consideration, the quantity being studied is the number of accidents per car-mile. To obtain this ratio we need to know, for each highway interval, the number of accidents and the number of car-miles in a year. Both quantities are notoriously difficult to obtain. Perhaps the most-important facotr in selecting the highway to be studied was that exact data on car-miles and excellent, uniform data on accidents were available.

On most highways the car-miles traveled in a year on various segments can only be obtained by some sampling procedure whereby cars are counted at various times. This particular highway had a toll-recording system which made the exact number of car-miles traveled along various segments easy to obtain. (At this point it is well to point out that if the estimate of car-miles is obtained by a sampling procedure, it is subject to sampling fluctuation; then, the techniques to be described here need to be amended to include this additional source of variation.)

Since the techniques proposed in this study were designed to assist in the development of information about the changes in true accident risk along a highway resulting from design, environmental, driver, and similar differences, one other requirement was imposed in the selection of a highway for study. It is important that there be a uniform system of accident reporting in order to avoid differences which are an artifact of reporting as compared with differences of causal significance. The highway selected satisfied this requirement. It was excellently patrolled by a single police organization operating from a control headquarters. Patrol officers were believed to exercise a consistent standard of accident reporting. The safety department vigilantly exercised persistent pressure to keep the difinition of an "accident" (as compared with an "incident") constant. Immobilized automobiles could not escape police attention by being removed through local repair service.

Another reason for selecting this particular highway was the essential uniformity of driving conditions from one end of the road to the other. There are no sharp curves, bottlenecks, congested intersections with other highways or other highway conditions which we would expect to lead to local changes in accident rate. This is extremely desirable for pilot application. If a road has some portions with accident rates markedly different from those of other portions, almost any technique will detect these sections, and we cannot tell much about the sensitivity and properties of a technique by applying it to such a road. In addition, we wished to avoid as many extraneous problems as possible while developing a new technique.

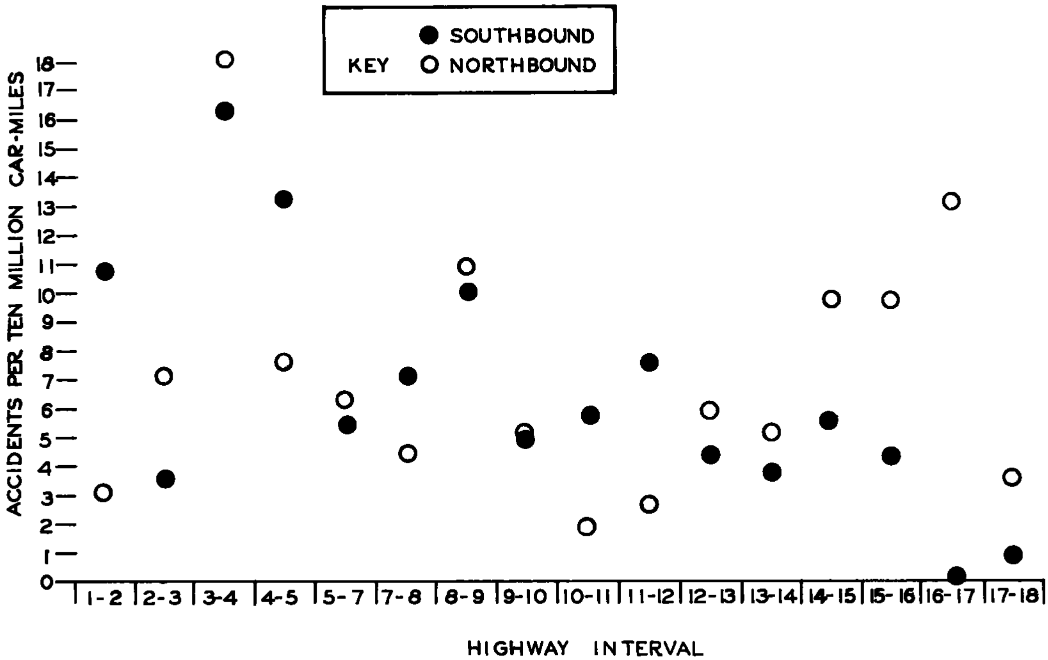

Figure 2. Accident rates plotted by location along highway.

Quality-Control Method Applied to Accidents

At this point, let us summarize our ideas on the application of quality-control concepts to accidents on a road. First we divide the road into a number of intervals. For each highway interval we determine the number of accidents that occurred there and the number of car-miles traveled there during the year. The ratio of the two is the observed accident rate in accidents per car-mile for that interval. These rates are then plotted on a chart.

A chart of this kind is shown in Figure 2. Examination of this chart gives one the feeling of a great deal of variation in observed accident rates with location. One cannot help but feel also that a large portion of this is due to random variation, commonly called "luck."

In order to interpret these data, it is necessary to determine how much fluctuation will occur naturally, i. e., randomly. Accordingly, we also plot, for each highway interval, the expected accident rate and an upper and lower probability limit. A typical such plot is shown in Figure 3 (a slightly different set of road intervals was used).

The limits are such that, by chance alone, the probability of an accident rate falling outside the limits is small. We are using 1-percent limits (0. 5 percent probability of falling above the upper limit and 0. 5 percent probability of falling below the lower limit), but limits for other percentages are possible and may be computed easily.

Accident rates which lie outside these limits are assumed to be the result of significant changes in the underlying accident structure. To determine causes, it is clear that the proper selection of the highway intervals is crucial. Obviously, one prefers intervals as small as possible, yet the smaller the interval, the less sensitive we are to changes in underlying accident rate.

For example, between Points 16 and 17, northbound, a 1-mile stretch, we find an expectation of 2. 1 accidents (based on the overall accident rate for the entire highway and the known number of car-miles traveled between these points). Obviously, if we had observed zero, one, two, three, four, five, or six accidents in the year, this could hardly indicate anything but random deviation from the expectation of 2. 1 accidents. Yet this allowable variation is from zero to three times the expectation, and hence, the allowable variation in observed accident rates would be at least from zero to three times the expectation. Now a 100-percent increase in true accident rate is obviously something any satisfactory technique should detect, and hence, the 1-mile northbound stretch between Points 16 and 17 is much too small for satisfactory sensitivity.

On the other hand, we obtain the greatest sensitivity if we take the largest possible interval, that is, the entire road. But then, obviously, we could not possibly determine local causes. Balancing the two, after considerable thought, we came to the conclusion that the road intervals should be such as to obtain an expectation of between 14 and 25 accidents. This is, of course, quite approximate and, as we shall see, other considerations may be overriding, particularly those dealing with homogeneity of the intervals.

Determination and Selection of Population to be Profitably Studied

Much of the success of any investigation depends on proper selection of the data to be studied, and this is also true of our techniques. An admittedly intuitive, but nevertheless destinct, conceptual picture of what is being studied must be formed. In our pilot study, for example, one of our internal mental pictures was that of the highway proper. Hence, exposure and accidents that occurred in parking areas, access roads, acceleration and deceleration lanes, at the toll gates, etc., were omitted. To avoid studying merely the distribution of snow, ice, and fog along the highway, accidents under these conditions were omitted, whether or not the weather was a contributing factor. Another reason they were omitted was that it was known that many such accidents were not reported. Unfortunately, we could not omit the exposure, as we did not know the car-miles traveled in such weather. However, we felt that these car-miles were a small enough proportion of the total to introduce a negligible error. Notice that we could not conveniently go to the enticing concept of "accidents in good weather" and, hence, omit accidents in rain, as the car-miles traveled in rain were not felt to be negligible, and we had no data on them.

Computation of the "Control Limits" and the Statistical Theory Underlying Such Computation

Underlying Statistical Theory. Let us start with about the simplest, most-naive structure we can imagine. We assume that each car-mile is a sort of discrete entity and that the probability of an accident is the same for each car-mile. We also assume that the car-miles are statistically independent. Starting with this structure we can then let

m = number of car-miles observed.
λ = probability of an accident in a car-mile.
$P(x)$ = probability of exactly "x" accidents occurring in m car-miles.

Then, it is well known that

$$P(x) = \frac{m!}{(m-x)!\,(x)!}\,\lambda^{x}(1-\lambda)^{m-x} \qquad (1)$$

It is also known that, when λ is small and m is large so that λm is in between, a good approximation to $P(x)$ is

$$P(x) = \frac{e^{\lambda m}(\lambda m)^{x}}{x!} \qquad (2)$$

Now for the highway studied, the number of car-miles traveled during the year of study was 766 million, during which 537 accidents of the nature we are considering occurred. This gives an accident rate of 0.701 accidents per million car-miles.

For this value of λ and for the range of m we shall use, the approximation obtained by using Equation 2 for Equation 1 is fantastically good. The error made is of the order of one part in 300,000 or less.

Note that all that enters in Equation 2 is the number of accidents and the product λm. Now λm can be interpreted as the expected number of accidents in m car-miles, and we find it convenient to give this concept the symbol "a." That is, we define

$a = \lambda m$ = expected number of accidents in m car-miles.

In terms of a, we can rewrite Equation 2 as

$$P(x) = \frac{e^{-a}a^{x}}{x!} \qquad (3)$$

This equation describes what is commonly called the "Poisson probability distribution," and constantly appears in traffic studies. Very simply, it describes the probability that any given number of accidents will occur in terms of this number and a quantity which is called the expected number of accidents.

And so, given our assumptions, we see that everything has reduced very nicely and we have expressed the probability of x accidents occurring in terms of x and the expected number of accidents, a.

The probability distribution given by Equation 3 is a better approximation to the real situation than our underlying assumptions would imply. For example, it is easy to become uncomfortable about the assumption that the individual car-miles are statistically independent. Could it not be that, if we consider any car-mile in which an accident has just occurred, the probability of an accident's having occurred to this car is higher than usual in the previous mile and lower than usual in the next mile? It could, but it can be shown that the effect is small.

Similarly, we could assume that the basic statistically independent unit is 1,000 car-miles, or the individual trip, or that the basic accident rate varies from point to point along a trip, or from trip to trip. All we really need to assume is that some conglomeration of trips is independent. All such assumptions lead to Equation 3, although the error may be considerably less than one part in 300,000.

Hence, we come back even more strongly to the statement that, under any of the circumstances we shall consider, the probability of x accidents will be given by the Poisson distribution. The correct distribution for any road segment will be described by some number, a, the expected number of accidents which may differ from segment to segment. Of course, a is never known and we shall always have to be satisfied with an estimate of the expectation obtained by making various assumptions. But the point is that all effects and phenomena come into our data only through the unknown expectation and it will be sufficient to describe and study our techniques in terms of the sensitivity to changes in the underlying a. We need not otherwise consider the effect on the distribution of accidents.

Computation of "Control Limits." The basic idea underlying the computation of control limits is as follows: We first determine in some fashion an estimate of a, the expected number of accidents. Assuming that this a is correct, we then want an upper and lower limit, U and L, such that

$$\text{Probability } (X \geq U) = 0.005$$
$$\text{Probability } (X \leq L) = 0.005$$

where X is the observed number of accidents.

We can compute these limits in a number of ways. The basic way, which really underlies all other, is simply to use a table of the Poisson distribution. The most satisfactory such table currently available is: Molina, E. C., "Poisson's Experimental Binomial Limit." New York: D. Van Nostrand and Company, 1942. From this table we can obtain upper and lower limits on number of accidents. Dividing these by the number of car-miles, m, we obtain the upper and lower limits for the observed accident rate. We plot for each road interval considered: (1) the observed accident rate (number of accidents divided by the car-miles), (2) and (3) upper and lower limits on accident rate, and (4) the central value which is the assumed accident rate λ.

To obtain limits in this manner from Molina's Tables, we need to perform a double interpolation (for a and for x) for each road interval, and the work is tedious. An excellent approximation to the resulting limits has been obtained which is simpler to apply. It is

$$\text{Upper limit on accident rate} = \lambda + 2.576\sqrt{\lambda/m} + \frac{0.829}{m} + \frac{1}{2}m \quad (4)$$

$$\text{Lower limit on accident rate} = \lambda - 2.576\sqrt{\lambda/m} + \frac{0.829}{m} - \frac{1}{2}m \quad (5)$$

In these equations, the first two terms are what we obtain by approximating the Poisson distribution by a so-called normal distribution; the third term is a correction to the normal approximation; the last term arises because we can only observe integer numbers of accidents.

Statistical Aspects Underlying Size of Road Interval. The control chart limits are based on assumed values for the accident rate. If the true accident rate is as assumed, the probability of observing a point out of control is one percent. Under these conditions we will find out-of-control observations very infrequently, one in 100 points to be exact, and so, if things are as we assume, we will not look for trouble very often.

However, suppose that the true accident rate is different from what we have assumed. Then we know that the probability of observing a point out of control is larger than one percent. Unfortunately, this does not do us much good unless the probability is considerably larger than 1 percent. Here we see that the size of the road interval or, more exactly, the number of car-miles is important. If the expected number of accidents is small, we just will not be sensitive to changes in accident rate. We must take large enough road intervals so that the sensitivity of the control chart is adequate.

If we take as a sort of minimum condition that we should catch a doubling in accident rate a reasonable amount of time, we can compute the following. If we wish the probability of being out of control to be larger than 50 percent when the true accident rate is more than twice the assumed rate (that is, more than 100 percent larger), then we must take a stretch of road such that the assumed expected number of accidents is larger than 8.21 accidents.

Further such points can also be obtained. For example, it can be shown that if a = 10 accidents, we will detect an increase of 90 percent in accident rate with 50 percent probability. If a = 14 accidents, we will detect an increase of 75 percent with 50 percent probability. If a = 25 accidents, we will detect an increase of 55 percent in accident rate 50 percent of the time. A description of the method of calculating these points will be given in a forthcoming technical report.

Now the selection of the proper highway intervals involves many factors, summarized by the concept of breaking the highway up into rational subgroups. But, crudely, we have the conflicting pressures of, on the one hand, desiring as many road intervals as possible so that we can locate causes of trouble and, on the other hand, wanting each interval to be as large as possible so that we can better detect real changes in accident rate.

From the above discussion it is clear that road intervals which have an expected number of accidents of less than eight are inadequate and that we prefer road intervals with expectations of between 14 and 25 accidents.

PILOT APPLICATION OF TECHNIQUES TO A HIGHWAY SITUATION

Let us now continue to explain the application of the techniques previously described. Full details containing all relevant data together with sample computations and a full description of the underlying theory will be presented in a future technical report.

Selection of Road Intervals

An obvious way of proceeding would be to select the intervals between access points as our road intervals and to plot the accident rate for each interval with appropriate control limits.

However, the intervals between road points differ greatly in the number of car-miles of exposure. Some are so small as to be insensitive to all but large changes in the accident rate. Others are so large both in car-miles and actual length as to make trouble shooting difficult. If these large intervals go out of control, it would be difficult to localize the trouble. A compromise is necessary.

Intervals 10-11, 14-15, 16-17, and 17-18 are too short and so are combined with adjacent intervals. Intervals 7-8 and 8-9 are too large, and so the two halves of each of these intervals are plotted separately for control purposes.

Plotting the accident rates for these new and preferable intervals and drawing the corresponding control limits, we obtain Figure 3. This is the type of chart we recommendfor overall practice.

Description of the Computation of the Control Chart

We now plan to describe the computation of this control chart and then to discuss its usage and illustrate the insight it gives into the highway.

The basic data for the preferred road intervals give, for each road interval during the year studied, the number of car-miles traveled northbound and southbound, the number of accidents observed, and the observed accident rates in accidents per 10^7 car-miles. These accident rates are plotted in Figure 3.

The limits on this chart are computed using an overall accident rate of

$$\lambda = \frac{537}{76.64 \times 10^7} = 7.007 \times 10^{-7} \text{ accidents per car-mile.}$$

λ is computed by dividing the total number of accidents (537) by the total number of car-miles (76.64×10^7).

Substituting this value of λ in Equations 4 and 5, described earlier, we obtain (m is in units of 10,000,000 car-miles).

$$\text{Upper limit} = 7.01 + \frac{6.819}{\sqrt{m}} + \frac{0.829}{m} + \frac{1}{2m}$$

$$\text{Lower limit} = 7.01 - \frac{6.819}{\sqrt{m}} + \frac{0.829}{m} - \frac{1}{2m}$$

Note that we have made the simplification of giving only one set of limits for each road interval. Actually, slightly different limits are calculable northbound and southbound. The reason we replace the two limits by their average is simply that, for the

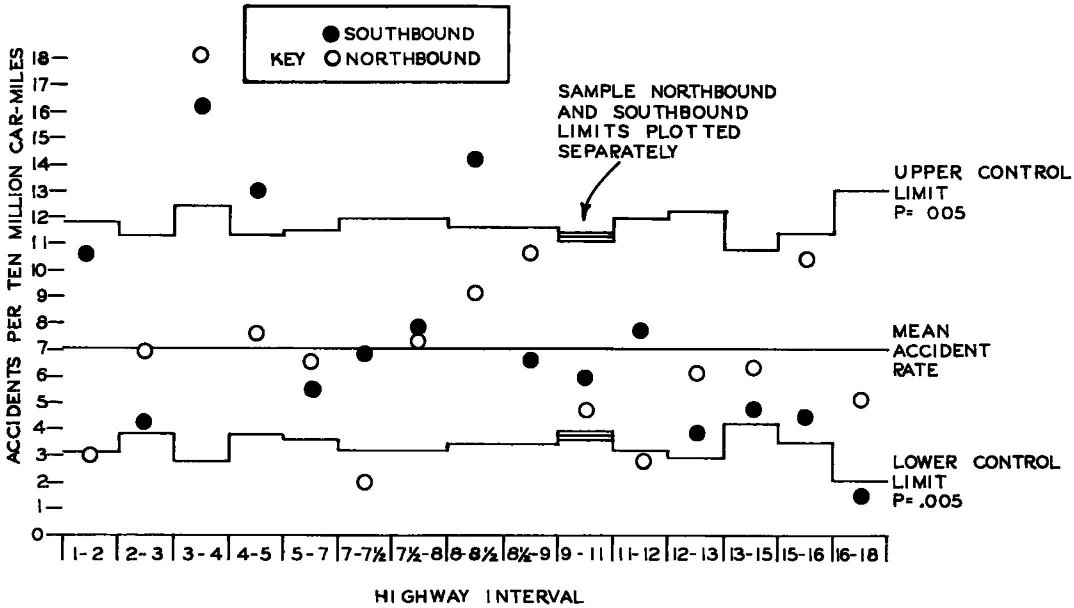

Figure 3. Control chart for accident rates by highway location, with northbound and southbound rates plotted separately.

highway that we studied, the two limits turned out to be very close together for all our road intervals. (If they were not, separate limits should have been calculated.) The largest difference between the northbound and the southbound limits occurs between Points 9 and 11, and separate limits are plotted for this interval on Figure 3 to show the magnitude of the maximum error involved.

Results, Interpretation, and Three Other Control Charts

Now let us examine the control chart for accident rates as drawn in Figure 3. Although we will describe three other charts that illustrate possible alternatives and refinements, all the conclusions obtainable can be gotten from this basic chart.

First Impression. Our first impression was that the results are remarkably well-behaved. After all, the limits are based on one lumped overall accident rate λ, and we really had expected the λ's to differ considerably. If the underlying accident rates do differ appreciably from one road interval to the next, many of the observed accident rates will be out of control.[2]

In fact, in anticipation of such an eventuality, a technique was prepared using mean square successive differences between accident rates to estimate the despersion of the underlying true accident rates λ_i. The λ_1 were then considered to be a random sample from a population of such rates and appropriate control limits drawn which would detect improbable deviations in accident rate. This technique will be described in a later report as it may be desirable for the more usual highway.

It is clear from Figure 3 that such is not the case. Seven out of 30 points are out of control. Some of these will no doubt be the result of known effects that we can do nothing about. The residual, however, gives us heart that the cause of their deviation in

[2] When this happens in industry, shrewd quality control men usually feel that large improvements can be obtained readily at little cost as putting trouble shooting effort almost anywhere will pay off. However, if it happens on a highway, we feel that the ordinary control chart might be of dubious value. Aside from perhaps pointing out the largest deviations, little help would be given to present ongoing efforts by highway personnel to determine accident causation and to reduce accident rates, although it would indicate that reductions in accident rates are possible.

accident rate can be made known by diligent investigation, and we hope that corrective action will be possible in most.

Most Noticeably "Out-of-Control" Accident Rate. We have no mitigating explanations for the extreme out-of-control nature of the accident rates, both northbound and southbound, between Points 3 and 4. We feel that this is a situation which can be most profitably investigated.

Control Chart Comparing Two Portions of the Highway, Six Lanes versus Four Lanes. The highway has one more lane in each direction between Points 11 and 16 than on all other portions of the road. There has always been a feeling that this section has a different accident rate from that of the rest, but it has been difficult to say whether it is higher or lower. The control chart clearly indicates that this section has a significantly lower accident rate than the rest of the highway. This result is also compatible with the assumption that higher car density produces lower accident rates, as the extra-lane sections have densities varying from 13,700 to 14,600 cars per day, while the standard lane sections vary from 5,800 to 10,800 cars per day. Unfortunately, we then also need to assume that, below 10,800 cars per day, the accident rate does not noticeably change with car density. We prefer to assume that the source of the change is the number of lanes, but this cannot be considered as more than a guess without further investigation.

Recomputing, we find an overall accident rate of 7.58 accidents per 10^7 car-miles for the standard lane section, and a rate of 5.57 accidents per 10^7 car-miles for the extra-lane section. The difference is statistically significant at the one percent level.

Separate control limits for the two sections based on the two accident rates of 7.58 and 5.57, respectively, were computed and the results plotted in Figure 4. The difference between the two sections is now clearer.

Figure 4 is also an excellent illustration of the technique of adjustment when we wish to include imformation on known differences in accident rates.

End Effects on the Highway and the Control Chart for Observed Differences in Accident Rates. Looking at Figure 4, we see points that are out of control at Intervals 1-2, 15-16, and 16-18. From the point of view of the highway, these are the road intervals from or to which large-scale entering and leaving occurs. Looking at the chart, we note that these intervals are also characterized by having large differences between

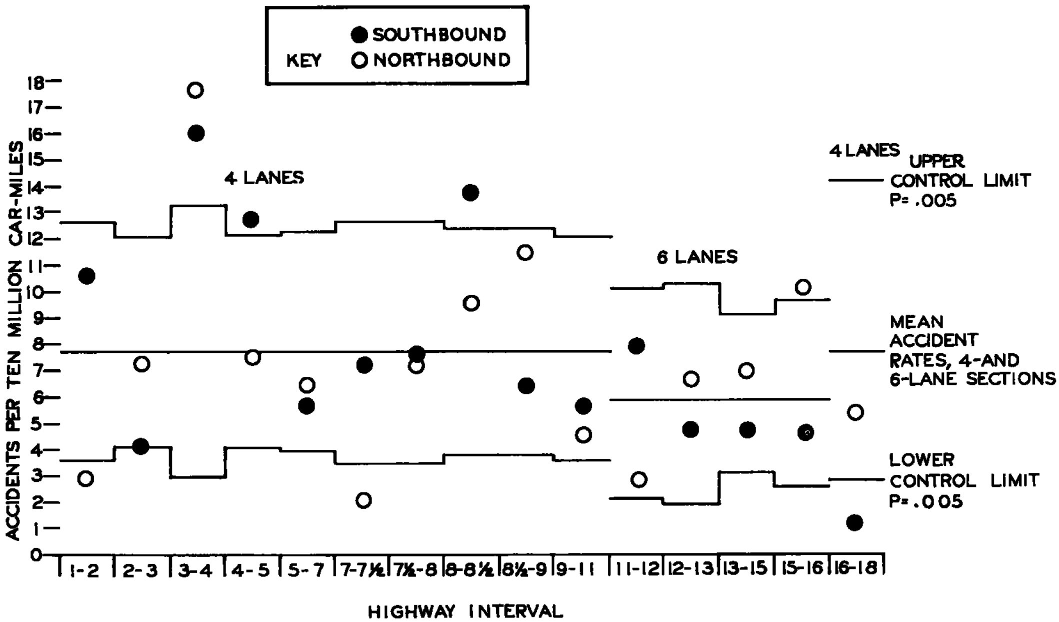

Figure 4. Control chart for accident rates by highway location, with rates for four- and six-lane highway sections plotted separately.

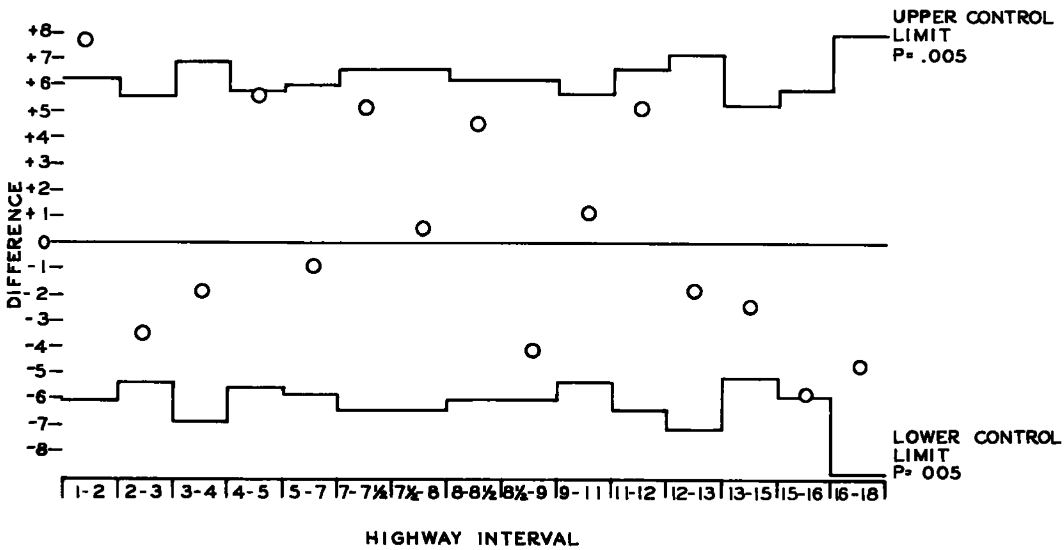

Figure 5. Control chart for differences between northbound and southbound accident rates. The differences plotted are for southbound minus northbound.

their northbound and southbound accident rates. To verify this, Figure 5, a control chart for the difference, southbound minus northbound accident rates, was prepared.[3] The differences for Intervals 1-2 and 15-16 are out of control, although admittedly the latter is barely out. All other differences lie within the control limits. Hence, we assume the difference is real at the two ends. (The accompanying assumption that the northbound and southbound rates are the same elsewhere and its implications are discussed in a later paragraph.) This conclusion would not be changed if we computed limits separately for the standard and extra lane portions of the highway.

The explanations of this phenomenon are fairly obvious to anyone who has driven long distances on this particular highway. Coming in at the upper or lower end from adjacent feeder roads, one tends at first to drive carefully and perhaps more slowly. Hence, the out-of-control accident rates on the low side of cars just entering at Points 1, 17, and 18.

As one drives to the other end, one is definitely lulled into a false sense of security concerning the nature of the effort required to control one's car. Hence the out-of-control accident rate for cars about to leave at Point 16 in Figure 4 and the high (but in control) accident rate for cars about to leave at Point 1.

This conclusion is also borne out by the known data concerning accidents at the toll booths and the entry and exit areas which were omitted from the control chart as not having occurred on the highway. During the year studied, there were 74 such accidents. Of these, 50 occurred to cars on line at the exit toll booths, three occurred to cars on line at the entrance toll booths, 14 occurred in the exit area while leaving and seven occurred while entering.

Of the 50 accidents that occurred to cars on line at the exit toll booths, 44 accidents or 88 percent occurred at Points 1, 16, and 18. Yet only 39.7 percent of the cars left at these points. At the 26 other possible points of exit, only six accidents or 12 percent of such accidents occurred, yet 60.3 percent of the cars used such exits. This clearly indicates the effect of long trips, and strongly suggests the desirability of some study or control chart analysis of the accident rate as a function of the distance traveled since entering the highway.

[3]A description of the underlying theory together with the resulting computation procedure for preparing control charts of differences between observed accident rates will be given in a subsequent technical report.

One conclusion is that the effect, indicated by the plethora of toll-gate accidents in which exiting cars just do not stop, extends back quite a way. For example, the out-of-control northbound accidents between Points 15-16 are uniformly scattered throughout the interval. This would appear to mean that sleepiness, overconfidence, oversecurity or whatever is producing the toll gate accidents, is also acting for quite a way back on the highway and does raise the accident rate.

Interpretation of Other Points Out of Control. There are four other points out of control in Figure 3. These are in Intervals 4-5, 7-7½, 8-8½, and 11-12. The last disappears when we separate the four-lane from six-lane sections on Figure 4 and, hence, can be taken to indicate that the accident rate for the six-lane portion is lower. The 8-8½ point seems real and must surely be investigated. The other two also warrant investigation.

Control Chart for Combined Northbound Plus Southbound Accident Rates. Since Figure 5 indicates that accident rates southbound do not differ from the northbound rates, except at the ends of the highway, it is reasonable to combine the two observed accident rates for each interval, so doubling the expected number of accidents in each interval and greatly increasing the sensitivity. This was done and Figure 6 is the result. Note that the limits are narrower by a factor of about $\sqrt{2}$. The computational techniques for obtaining the limits are the same as those for Figures 3 and 4 and for any control chart of accident rates.

Looking at this chart we see how far out of control the data for Interval 3-4 are, with 8-8½ also being out of control. Interval 4-5 is now only slightly out and 7-7½ has come in. If, as we should, we compute limits for the four- and six-lane sections separately, 4-5 will come into control and 7-7½ will go out. The accident situation at 3-4, 8-8½, 4-5, and 7-7½ will all profitably bear looking into.

Note that this chart is considerably more sensitive than the control charts for individual rates given as Figures 3 and 4. This is indicated by the narrower limits. We can use this increased sensitivity as it stands or, if we are satisfied with the sensitivity of Figures 3 and 4, we could use shorter intervals on the highway. The shorter intervals will improve our ability to localize the causes of differences in accident rates. However, the combined chart does mask the effects of causes which affect northbound and wouthbound accident rates differently.

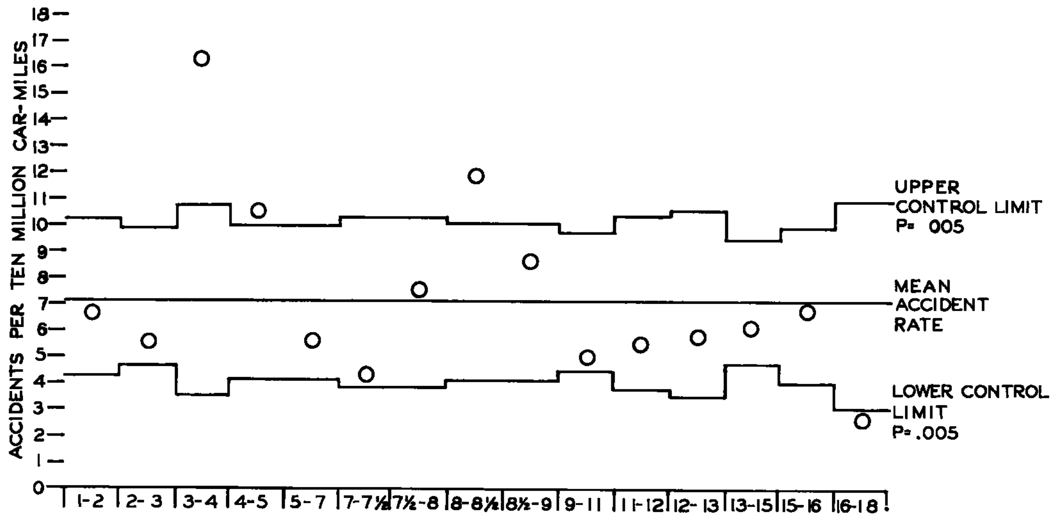

Figure 6. Control chart for combined northbound and southbound accident rates.

SUMMARY

In this paper, we have reported on the development of a technique for studying highway accidents with the aim of obtaining information about the variation in accident risk along a highway. The method which was employed was a modification of the statistical quality control technique which has gained wide acceptance and application in industry.

We have endeavored to present some of the problems which were found to exist in selecting a highway for study and in interpreting the accident data which highway situations usually produce. The underlying theory was reviewed briefly, and the computational procedures inherent in statistical control chart analysis were described.

Results were presented on the application of this proposed technique to a specific highway situation. These results, which consisted essentially of a set of accident control charts, suggested some interesting locations along the road which are desiring of some detailed investigation. It is felt that investigations which are motivated by careful analysis of this kind can contribute substantially to accident reduction.

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