Towards a Statistical Approach of Identifying Hazardous Highway Locations

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Abstract

In the presented paper, the writer will try (1) to suggest a scientific approach for identifying hazardous locations of highway systematically and objectively, (2) to develop an analytical procedure designated to facilitate its use by highway and traffic engineers, (3) to show a illustrative example of its application. The overall approach followed in this paper is to apply a statistical test for determination whether or not the accident rate is significantly abnormal as related to a pre-determined average. This approach is just the same as the statistical quality-control concept wihch product quality during the course of manufacture.

1. Introduction

The amazing development of the motor vehicle and adaption of it to move people and goods has made it a very important method of transportation. Thus the national economy and our general way of life has highly become dependent upon motor vehicle transportation. From the opposite viewpoint, there are losses to society from the large-scale use of motor vehicle. Air pollution problems have been noted recently and represent a separate field. But over the years a great deal of loss from traffic accidents both in monetary value and in loss of life and injury have been widely recognized as one of the most urgent social problems in our country. A somewhat similar situations exist in other countries of the world as well.

An increasing losses from the growing magnitude of traffic accident has intensified more pressure on highway and traffic engineers to create safer highway and traffic environments through engineering improvements. Ouite obviously, highway safety imporovement cannot eliminate all accidents because many other factors are involved in the traffic accident causation. But the fact remains that considerable accident reduction can be achieved by correcting accident prone locations of highway.

The philosophy of a highway safety improvement must be the treatment program of locations wherein specific situations are contributing to an accident hazard. More specifically, the highway safety improvement program is based on the theory that the most economical expenditure of fund, which may be measured by accident reduction, can be brought about by identifying locations where meet pre-determined criteria of "hazardous", and then directing efforts of improvement toward these situations. Therefore, identification of hazardous locations is an essential preliminary to the planning of highway safety improvement program.

The basic criteria that utilized to establish a hazardous locations can better be determined by measure of accident experience rather than public complaint or engineering judgement. However, the traditional methods to justify the term "hazardous" with a number of accidents or an accident rate have obvious deficiency. That is to say, the methods lack consideration of chance variation of accident occurrence.

In the presented paper, the writer will try to apply a statistical concept for the purpose of improving such deficiency, to provide a scientific approach for identifying hazardous locations and to present a procedural steps designated to facilitate their use by highway and traffic engineers. The overall approach followed in this study is to apply a statistical test for determination whether or not the accident rate is significantly abnormal as related to a pre-determined average accident rate for location of like characteristics. This is just the same as the statistical quality-control technique which have been employed in maintaining the quality of product during the course of manufacture.

2. Some Problems for Identifying Hazardous Locations

(1) Definition of Hazard

The definition of hazard is implicit in all operational decision toward safety improvement problem. The term "hazard" is abstract and relative, and it may be determined either by intuitional judgement or by measures of accident experience. Using intuitional judgement has demonstrable limitation. Furthermore, without predictions supported by accident data there are no measures of reduction to be obtained from particular improvement.

The use of past accident experience as a predictor of accident expectation, and therefore as an indicator of necessary remedial action, is an accepted approach in highway safety field. Underlying usage of them for operational decision-making is the assumption that these data reflect the accident causation and suggest some necessary remedial countermeasures in some manner.

It is, therefore, concluded that the definition of hazard for identifying hazardous locations should be based on the accident experience.

(2) Method in Use and its Deficiency

Several methods have been developed to identify hazardous location based on accident experience.[1] Among them, the most commonly used methods today are based on the number of accidents (called the Number Method) and accident rate (called the Accident Rate Method). Such methods are based on the assumption that safety improvement will be the most productive in reducing hazard if improvement is directed toward the locations where high-accident frequency will be expected. Thus, locations having more than a defined minimum are classified as hazardous for purpose of detail investigation and improvement program planning.

Although the methods mentioned above are useful, they have obvious disadvantage which limits their effectiveness.[2] The Number Methhod is prone to identify locations as hazardous even though they may not be so in relation to traffic served. Conversely, the Accident Rate Method is apt to be classified as hazardous the locations where have experienced few accident in low volume. These are due to the fact that accident or accident rate by itself do not reflect the chance variation of accident occurrence. The lacking consideration of variability by chance is the prime deficiency of the traditional methods.

(3) Need for Statistical Concept

The important aspect to be recognized in determination of hazardous locations based on accident experience is chance variation of accident occurrence. Even when all factors which conceively could related to accident occurrence remain unchanged, accident experience will nonetheless vary. Therefore, any observed deviation in accident experience from expected one might be reflecting nothing more than the inherent variability of accident by chance. On the other hand, an observed deviation might be suggesting some accident prone situations. Considering these situations, it is very easy to draw errorneous conclusions from accident data.

Another important aspect to be considered is the magnitude of minimum criteria. If defined criteria are too high, many hazardous locations will not be identify for investigation and analysis. Conversely, if criteria are too low, many locations may be identified that are not truely hazardous. In order to prevent such errorneous conclusions it is necessary to give an answer to such questions as, "How much variation in the accident experience should be expected as the result of normal chance variation?" or "How high the minimum criteria that could be concluded it definitively to exceed an established tolerable limit?".[3)4)] To make it possible to give the answer explicitly, it is necessary to express quantitatively the inherent variability of accident occurrence. The proper application of statistical concepts could make it possible and the statistical quality-control concept is one statistical method for doing so.

An attempt is made in the rest of this paper to apply quality-control concept for identification of hazardous location of highway.

3. Probability Distribution of Accident Occurrence

The most commonly recognized basic assumption about accident occurrence today is that they happen at random and independently, and their distribution is according to the probability distribution.[5)] In this paper, such assumption is employed and is assumed the binomial distribution. The binomial distribution is a descrete probability distribution of which outcomes consist of only two mutually exclusive events and its probability remains the same throughout the trials. An accident either occurs or it does not occur, two events being mutually exclusive. Therefore, the binomial distribution is a natural selection for an accident study.[6)]

In addition to the above assumption, it is assumed that an accident is a chance occurrence during vehicular trip to which a certain probability can be assigned, and also is assumed that the probability is same for each vehicular trip and vehicular trip is statistically independent.

Starting with these assumption, then it is well known that

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

where : x=number of accident observed.

m=number of vehicular trip observed.

p=probability of accident in a vehicular trip.

$P(x)$=probability of exactly "x" accidents occurring in m vehicular trips.

Traffic accident is scarce event. Therefore, the probability of accident in a vehicular trip is very small and the number of vehicular trips observed is extremely large. It is also known that, when p is small and m is large so that the prduct pm is in between, a good approximation to $P(x)$ in Eq. (1) is

$$P(x) = \frac{(pm)^x}{x!} e^{-(pm)} \qquad \cdots(2)$$

Note that all that enters in Eq. (2) is the number of accident x and the product pm . Now pm can be interpreted as the expected number of accidents in m vehicular trips. Then assuming that $a=\lambda_0 m$, where λ_0 is average accident rate, Eq. (2) can be rewritten as follows :

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

This is commonly called "Poisson probability distribution", and frequently appears in traffic study. The Eq. (3) means that under preveiling conditions the probability which any given number of accident will occur is described by the Poisson distribution with the expected number of accidents (mean) of a.

4. The Statistical Control Limit on Accident Expectation

To express quantitatively the inherent variability of accident experience, it is necessary to determine the range of frequency that could be expected to result from chance occurrence. In order to make it possible, the procedure requires to set up of an interval that has a defined probability of bracketing the observed numaer of accidents. Defining this probability as P or $(1-\alpha)$, and denoting the bracketing values as N_1, for lower limit and N_2 for upper limit, it can be described as follows :

$$P_r[N_1 < x < N_2] = P = 1 - \alpha \qquad \cdots(4)$$

where : α=probability of false detection.

For the Poisson distribution expressed in Eq. (3), N_1 and N_2 are the solution of the largest and the smallest integers, respectively, which have a probability, $\alpha=1-P$, of being exceeded by chance. That is,

$$\left\{\sum_{x=0}^{N_1} \frac{a^x}{x!} e^{-a} < \frac{\alpha}{2}, \sum_{x=N_2}^{\infty} \frac{a^x}{x!} e^{-a} < \frac{\alpha}{2}\right\} \qquad \cdots(5)$$

or

$$\sum_{x=N_1}^{N_2} \frac{a^x}{x!} e^{-a} \leqq P \qquad \cdots(6).$$

Depending upon P or α, broader or narrower control limits may be specified. A 90% interval will be narrower than a 95% interval for the same expectation ; a 99% interval will be broader. We can compute N_1 and N_2 in number of ways. Among them, an excellent approximation to the resulting limits which is simpler to apply for practical purpose is obtained by approximation of Poisson distribution to the normal distribution as follows[7] :

$$P = \sum_{N_1}^{N_2} \frac{a^x}{x!} e^{-a} \cong \frac{1}{\sqrt{2\pi}} \int_{(N_1+a+1/2)/\sqrt{a}}^{(N_2-a-1/2)/\sqrt{a}} e^{-1/2y^2} dy \quad \cdots(7)$$

Thus, the two-sided P % control limits on "x" accidents are approximately equal to

$$\left.\begin{array}{l} \text{Upper Control Limit (UCL); } N_2 = a + k\sqrt{a} + 1/2 \\ \text{Lower Control Limit (LCL); } N_1 = a - k\sqrt{a} - 1/2 \end{array}\right\} \quad \cdots(8)$$

where : k=constant and is defined according to the probability P or $\alpha=1-P$

In the Eq. (8), the first two terms are what is obtained by approximating the Poisson distribution to the normal one ; the third term arises because we can only observe integer number of accident. Then, dividing Eq. (8) by m, we get the corresponding control limits on an accident rate as follows :

$$\left.\begin{array}{l} UCL = \frac{a}{m} + k\sqrt{\frac{a}{m}\cdot\frac{1}{m}} + \frac{1}{2m} = \lambda_0 + k\sqrt{\frac{\lambda_o}{m}} + \frac{1}{2m} \\ LCL = \frac{a}{m} - k\sqrt{\frac{a}{m}\cdot\frac{1}{m}} - \frac{1}{2m} = \lambda_o - k\sqrt{\frac{\lambda_o}{m}} - \frac{1}{2m} \end{array}\right\} \quad \cdots(9)$$

where : λ_0=average accident rate (is expressed in accidents per vehicles for spot and accidents per vehicle-kilometer of travel for section).

m=average traffic exposure(is expressed in million vehicle kilometers of travel, MVK).

With reference to above theoretical consideration, the probability of accident occurrence on any given location varies with the traffic exposure, but the limit of the varition are stable. That is, as long as basic factors affecting accident probability incur only minor changes, the accident rate will continue to fluctuate within certain limits defined by Eq. (9). In other words, when the rate fluctuates beyond the upper control limit, it is considered that there would be some significant factors affecting an accident occurrence.[1]

5. Decision Rules for Operational Decision-Making

Bearing in mind that the purpose in constructing control limit is to determine the range of frequency that could be expected to result from chance occurrence of accident, and thereby to distinguish between the chance events required attention, conclusions are drawn according to the following basic set of rules.[8]

Rule I : If actual accident rate at a given location falls out of control regions, it is concluded that the location has experienced abnormal accident rate. When actual accident rate falls outside the *UCL*, the rate is abnormally high and such location is defined as "Hazardous". When actual accident rate falls outside the *LCL*, the rate is abnormally low and such location is defined as "Unhazardous".

Rule II : If actual accident rate falls in control region, it is concluded that the location has experienced normal accident rate and there are no special situations which contribute to realize abnormal rate. Such location is defined as "Normal".

Fig. 1 describes these regions of **"Hazardous"**, **"Normal"**, and **"Unhazardous"** as defihed by decision rules. It is important to note that even though the location which will be in control or out of *LCL*, is defined as "Normal" or "Unhazardous", respectively, this does not necessary imply that there are no assignable situations which contribute to accidents on these locations.

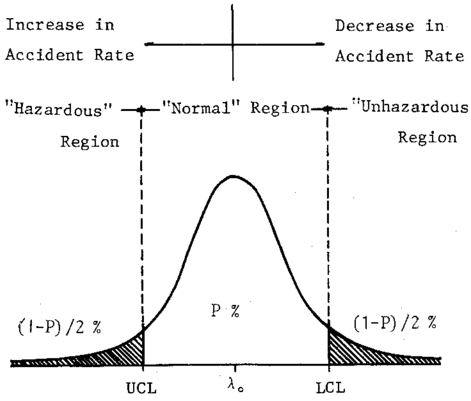

Fig. 1 Normal Probability Distribution for Defining the Regions of "Hazardous", "Normal", and "Unhazardous" by Decision Rules.

6. Procedural Steps of Application for Identifying Hazardous Locations of Highway

The rationale behind the application of statistical quality-control concept to identify hazardous locations of highway is that by eliminating high accident rate locations which could easily have occurred by chance only, it makes possible to obtain a truely abnomal locations. The accident rate at a given location is compared with the control limit (critical rate). Then, the locations beyond the Upper Control Limit are defined as "Hazardous" according to the decision rules.

The inputs required for identification of hazardous location (location here implies section of highway) by the method suggested in this paper are the followings.

(1) Accident rates.

1) Average accident rate of entire highway system being tested.

2) Accident rates of each section of that highway system.

(2) Time period (presumably increments of one year).

(3) Section length (measured in kilometer).

(4) Annual average daily traffic (ADT) at each section.

(5) Number of accidents occurred on each section during the time period.

(6) Level of statistical significance.

The procedural steps of application in planning of highway safety improvement program is taken in the following sequences.

Step 1 : Determination of highway categories.

Accident rate varies with the nature of highway and its environments. Each section must be assigned a highway category designation defined by highway function and/ or by roadway type. These designations are needed so that average accident rate can be developed for highway of like characteristics. Breaking down the highway must be made to general categories. Otherwise, number of accidents may become too small to calculate the accident rates.

Step 2 : Determination of Accident Rates.

When highway categories are determined, average accident rate of entire highway system to be tested and accident rates of each section are computed by using the following equations.

$$\lambda_o = \frac{\sum A_i \times 10^6}{365 \cdot T \cdot \sum (ADT_i \cdot L_i)} \quad \cdots(10)$$

$$\lambda_i = \frac{A_i \times 10^6}{365 \cdot T \cdot ADT_i \cdot L_i} \quad \cdots(11)$$

where : λ_0 =average accident rate of entrire highway.

λ_i =accident rate of i-th section.

A^i =number of accidents occurred of i-th section during time period T.

L_i =length of i-th section (in kilometer).

ADT_i =ADT for i-th section.

Step 3 : Determination of Criteria.

The criteria used for testing highway sections by the suggested method is the control limits defined by Eq. (9). It is a function of time period, section legth, traffic volume and system average accident rate being tested for accident experience abnormality. The expression of criteria for i-th section is used the following equation instead of Eq. (9)

$$\left.\begin{aligned} UCL_i &= \lambda_o + k\sqrt{\frac{\lambda_o}{m_i}} + \frac{1}{2m_i} \\ LCL_i &= \lambda_o - k\sqrt{\frac{\lambda_o}{m_i}} - \frac{1}{2m_i} \end{aligned}\right\} \quad \cdots(12)$$

where : UCL_i =upper control limit (upper critical rate) for i-th section.

LCL_i =lower control limit (lower critical rate) for i-th section.

m_i =traffic exposure (measured in million vehicle-kilos of travel : MVK) for i-th section.

The magnitude of k determine the level of statistical significance and consequently the final length of the hazardous section list. Therefore, the selection of the value k should be tempered by user's desire regarding the number of sections to be identified as hazardous.

Some sample values of k for various levels of the probability P, with which accident rate out of control is abnormal, are given below :

When P =99.0% (1% false detection), k=2.576

P =95.0% (5% false detection), k=1.960

P =90.0%(10% false detection), k=1.645

P =85.0% (15% false detection), k=1.440

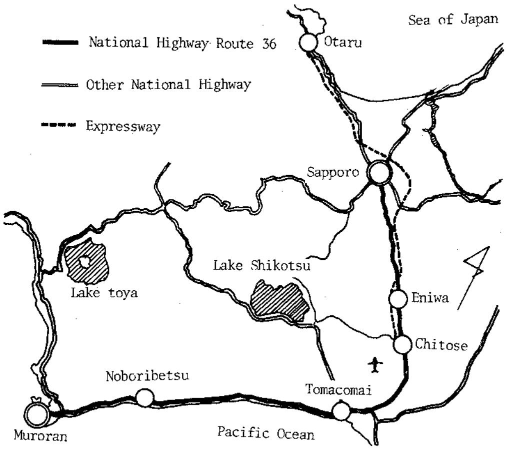

Fig. 3 The Map of National Highway Route-36 and its Surrounding Area.

Step 4 : Determination of hazardous locations.

The procedure for determination of hazardous location is outlined as follows :

(1) Compute the average accident rate for entire highway and the average accident rates for all sections under study by using Eq. (10) and Eq. (11), respectively.

(2) Compute the critical rates, UCL_i and LCL_i, by using Eq. (12), and evaluate the actual accident rates for each section against them. If the section's actual accident rate is greater than UCL_i, the section is defined as "Hazardous" and should be selected for detail investigations and analysis.

(3) The hazardous sections are listed.

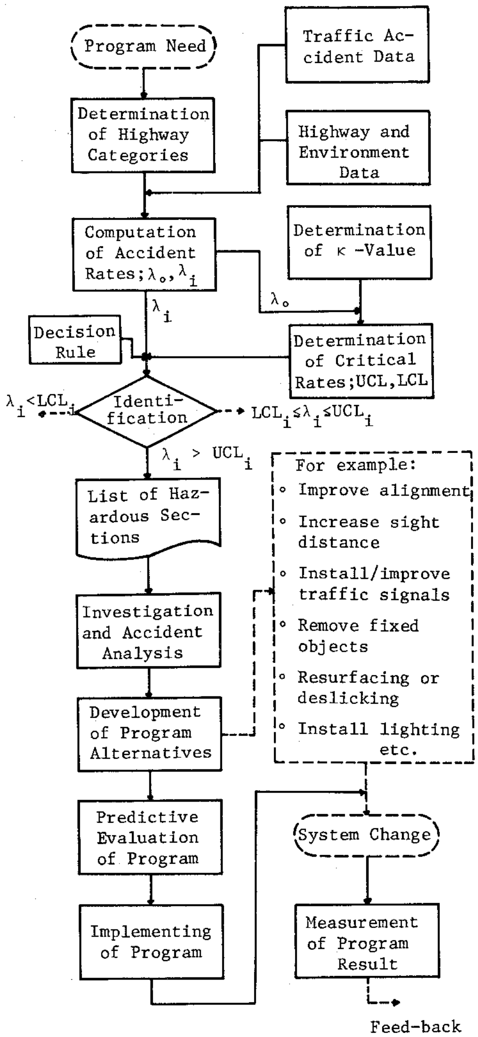

Fig. 2 The Flow-Diagram of Implementation of Highway Safety Improvement Program.

(4) The section having actual accident rate lower than LCL_i should be selected to investigate the causes of its abnormally low accident rate.

Step 5 : Determination of program and action.

To insure full utilization of hazardous location identification, highway agency should establish the policy which sets objectives, assigns responsibility, and provides procedures to be developed for

(1) accident analysis and field investigation of identified locations,

(2) selection of possible hazard-reducing alternatives,

(3) cost-effectiveness analysis for developing priorities of these alternatives in implementation, and
(4) measurement of system changes at some time after the program in operation.

The flow-diagram of these analytical procedures is shown in **Fig. 2.**

7. Illustrative Example-Trial Application to National Highway Route 36 in Hokkaido.

The highway system selected for trial application of the approach suggested in this paper was the National Highway Route 36 in Hokkaido. This highway is an important artery running from the center of Sapporo City to the center of Muroran City, and passes through the urban areas of Eniwa, Chitoshe, Tomakomai and Noboribetsu (see **Fig. 3**). The highway section used in this study was the control sections of "National Highway Traffic Census of 1971". This route was comprised of twenty-six sections of varying lengths which were divided according to geometrical and enviromental conditions, and handled from about 9,000 to about 60,000 vehicles per day. The input data required were assembled for the period of the year of 1971. The method was applied in the following sequences.

(1) Determination of accident rates.

The input data required and result of compution of accident rates for each section are shown in **Table 1.** The average accident rate is computed by dividing the total number of accidents of this route by the total amount of exposure, that is

$$\lambda_0 = 1.541/888.870 = 1.788 \text{ accidents/MVK}$$

(2) Determination of criteria.

To facilitate computation of critical rate, the family of curves was obtained by

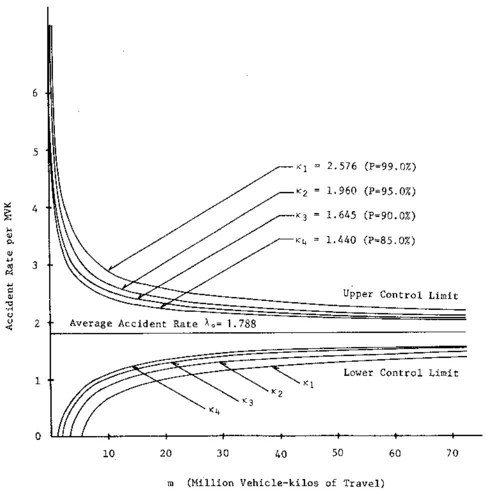

Fig. 4 Trial Control Limit Curves vs Traffic Exposure for the Average Rate of $\lambda_0 =$ 1.788, and for Various Levels of Significance.

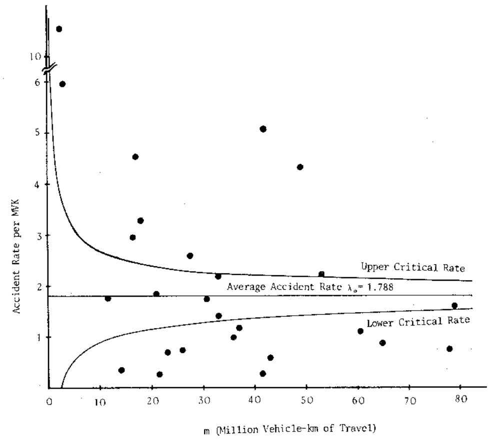

Fig. 5 Comparision of Actual Accident Rate to the Critical Accident Rate for Each Section of National Highway Route-36.

Table 1 Input Data and Accident Rate for Each Section of National Highway Route 36

No. of control section	Frequency of all accidents	Section length (km)	A D T (vehicles per day)	Traffic exposure (MVK)	Accident rate per MVK
i	A_i	L_i	ADT_i	m_i	λ_i
1	54	0.7	19 814	5.122	10.543
2	213	2.2	59 884	49.173	4.332
3	213	3.3	34 450	42.004	5.071
4	53	2.4	34 565	30.673	1.728
5	56	6.4	27 595	65.139	0.860
6	58	12.0	17 745	78.216	0.742
7	124	10.0	21 469	78.945	1.571
8	59	2.2	22 135	18.011	3.276
9	5	2.1	18 459	14.225	0.352
10	16	4.8	13 200	23.236	0.689
11	26	10.4	11 357	43.360	0.600
12	6	3.3	17 744	21.535	0.279
13	20	3.9	18 459	26.707	0.749
14	78	2.3	31 755	27.471	2.839
15	77	2.1	21 651	17.002	4.529
16	43	7.2	13 694	36.710	1.171
17	11	11.6	9 710	41.530	0.265
18	20	2.5	12 416	11.485	1.741
19	66	17.4	9 420	60.382	1.093
20	46	7.7	11 571	32.971	1.395
21	35	5.8	16 596	35.978	0.973
22	39	2.5	22 124	20.738	1.881
23	48	2.1	20 814	16.379	2.931
24	72	2.2	39 641	33.031	2.180
25	118	4.6	30 572	53.321	2.213
26	33	1.1	13 179	5.536	5.961
Total	1 589	132.8	-	888.870	$\lambda_o = 1.788$

Table 2 Computed Critical Rate for Each Section of National Highway Route-36

No. of section	Upper critical rate	Actual accident rate	Lower critical rate
i	UCL_i	λ_i	LCL_i
1	3.043	10.543$^{\uparrow}$	0.532
2	2.172	4.332$^{\uparrow}$	1.404
3	2.204	5.071$^{\uparrow}$	1.371
4	2.277	1.728^{+}	1.298
5	2.120	0.860$^{\downarrow}$	1.455
6	2.090	0.742$^{\downarrow}$	1.485
7	2.089	1.571^{+}	1.486
8	2.433	3.278$^{\uparrow}$	1.142
9	2.518	0.352$^{\downarrow}$	1.058
10	2.353	0.689$^{\downarrow}$	1.223
11	2.197	0.600$^{\downarrow}$	1.378
12	2.376	0.279$^{\downarrow}$	1.200
13	2.314	0.749$^{\downarrow}$	1.262
14	2.306	2.839$^{\uparrow}$	1.270
15	2.453	4.529$^{\uparrow}$	1.123
16	2.234	1.171$^{\downarrow}$	1.342
17	2.206	0.265$^{\downarrow}$	1.369
18	2.605	1.741^{+}	0.971
19	2.133	1.093$^{\downarrow}$	1.442
20	2.259	1.395^{+}	1.316
21	2.239	0.973$^{\downarrow}$	1.337
22	2.387	1.881^{+}	1.188
23	2.466	2.931$^{\uparrow}$	1.110
24	2.259	2.180^{+}	1.317
25	2.156	2.213$^{\uparrow}$	1.419
26	2.992	5.961$^{\uparrow}$	0.584

Remarks ↑ : outof upper critical rate
+ : in critical rates
↓ : out of lower critical rate

computing the values of UCL and LCL vs m for the average accident rate of $\lambda_0=1.788$, and for various levels of significance by using Eq. (9). The results are shown in **Fig. 4.** In this figure, some difference is noted between k_1-curve and k_2-curve, but the difference between k_2-curve and k_3-curve is small. Therefore, the value of $k=1.960$ ($P=95\%$ or $\alpha=5\%$) is employed in this case.

Substituting these values of λ_0 and k in Eq. (12), the following equation is obtained

$$\left.\begin{aligned} UCL_i &= 1.788 + 1.960\sqrt{\frac{1.788}{m_i}} + \frac{1}{2\,m_i} \\ LCL_i &= 1.788 - 1.960\sqrt{\frac{1.788}{m_i}} - \frac{1}{2\,m_i} \end{aligned}\right\} \quad \cdots(13)$$

by which the critical rates for each section can be established. The computed critical rates for each section by Eq. (13) are shown in **Table 2**.

(3) Identification of hazardous sections.

A comparison of actual accident rates of each section to critical rates can be made from the **Table 2**, or **Fig. 5** which is plotted the actual accident rates against the traffic exposure of each section. Looking at this table or figure, it is clear that twenty of 26 sections are out of control. Also, it can be seen that nine sections are experienced abnormally high accident rate in excess of upper critical rate, and these sections are defied as "hazardous" sections and should be selected for detailed investigations and for safety improvement program planning. **Fig. 6** shows these result in a control-chart style for a series of sections along the studied route.

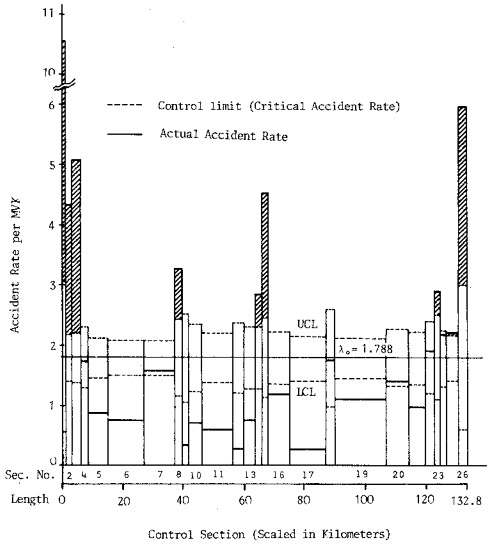

Fig. 6 Control Chart-Actual Accident Rate vs Critical Accident Rate for Each Section along the National Highway Route-36.

8. Concluding Remarks

Implementation of highway safety improvement program is based on four elements. Firstly, highway and traffic engineer must identify abnormal high-accident rate locations. Secondly, he must determine what enineering changes can be made to reduce these accidents. Thirdly, he must develop priorities for these expenditures. Fourthly, he must evaluate their actual effectiveness after implementation for further program planning.

Recognizing the importance of the first element which is an essential preliminary to the planning of hazard-reducing improvement program, the writer has devoted a great deal of attention to the establishment of scientific approach which might overcome the deficiency in traditional methods for identifying hazardous locations of highway, and development of an analytical procedures for using it by highway and traffic engineer.

The approach suggested in this paper is an application of statistical quality-control concept which applies a statistical test to determine whether or not the accident rate is significantly abnormal as related to an average accident rate. The statistical test applied is based on the commonly accepted assumption that accident event happens at random and independently, and that their distribution fits the Poisson distribution.

The use of this approach for operational decision-making would enable an engineer to determine the amount of variation inherent in accident rate and thereby minimize the possibility of errorneous conclusions in determination of "hazardous" locations. For maximum use of this method, it is essential to establish an accident record systems which provide complete data on the accident and the exact location where accident occurred togather with associated data on traffic and enviroment.

Finally, it should be noted that even though many locations will in control, this does not necessarily imply that there are not present on these locations assignable situations which contribute to an accident.

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