Interchange Accident Exposure

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Safety is one of the most emphasized features of highway transportation today. Its overall importance is strikingly underlined by the shocking statistics of traffic fatalities and accidents. The economic losses involved are tremendous.

The role of geometric highway design as a contributing cause of accidents has long been recognized. Accident analysis has been extensively used to evaluate design. An accumulation of accidents at a specific point on a highway is evidence of a fault which is related in some way to that location. It is likely that a change in the design could reduce the accident susceptibility.

Evaluation procedures (1) range from a mere accumulation of accident reports on an "Accident Spot Map" to a rather detailed graphic presentation on large-scale sketches of intersections or sections of highway. Further, there are the well-known statistical evaluations, giving the accident or fatality rate per vehicle-mile of travel.

It is the purpose of this paper to show that for intersections, at least, the conventional statistics are rather misleading because the exposure to accident is not proportional to the distance traveled. The exposure rate at interchanges is demonstrated as an example and compared to actual accident experiences at several locations. A qualitative analysis of accidents at these interchanges is also presented.

ACCIDENT EXPOSURE

● A QUANTITATIVE ANALYSIS of accidents at different sites is aimed at finding a basis for the comparison of accident numbers at locations with varying amounts of traffic. The actual number of accidents is compared with a quantity which represents accident exposure. On the open road the basis is "million vehicle-miles." The accident rate is then stated in the number of accidents occurring on a section of road per one million miles of travel thereon. At interchanges involving cross traffic or weaving, such as are considered here, the vehicle-mile basis does not represent a practical basis for accident comparisons.

It is assumed that accidents at a merging or diverging section of roadway are caused by the meeting or separation of the two traffic streams involved. A vehicle in one stream of traffic may collide with a vehicle in the other stream if the movement of the two vehicles converges on the same place at the same time. The possibility of an accident then depends on the presence of a vehicle in each stream of traffic within a given time interval. No matter how abrupt or how gradual the weaving is, there exists one possibility for an accident at each merging or diverging movement. The length of the section in which the maneuver takes place has therefore no influence on the possibility, although it may very well influence the probability.

To express the possibility of accidents in definite figures it must first be remembered that no matter how many vehicles there are in one of the traffic streams, there is no possibility for a weaving accident unless there is another traffic stream. For instance, on an entrance ramp onto a through traffic lane, an entering vehicle may collide with any car of the through traffic stream that passes at the same time interval at which this vehicle attempts to enter. During this critical time interval each entering vehicle has the possibility of colliding with as many through cars as pass on the through road during that time interval, and vice versa. The accident exposure for the entering car is therefore equal to the number of cars passing on the through road during the critical time interval. With several entering cars, each within a small time interval during which chance for a collision exists, the exposure becomes the product of number of cars entering and number of cars passing on the through road within these time intervals.

The time interval during which an accident is possible is very difficult to determine. Its length varies for different layouts. But it is not necessary to know the exact length of the time interval, since the exposure is at any rate only a relative value. Assuming that the traffic flow is of uniform density, the number of cars within a time interval is proportional to the length of the time interval. The longer the time interval is taken, the greater the resulting exposure index. As an extreme, a whole day could be taken as the time interval. In that case, the number of cars would be equal to the daily traffic volume.

Of course, such a long time interval would be far from realistic. An interval of about a second would seem more adequate. Since the exact interval duration is not very significant, it is desirable to take a time interval of such length that the subsequent calculations become as easy as possible.

Taking the critical time interval equal to about one-quarter of a second, a rather simple calculation for the accident exposure index results. The only necessary values to know are the ADT for the two weaving traffic streams. As explained, the accident exposure, E, for each entering car is equal to the traffic flow, V, on the main road during the critical time interval, i.

$$E = V_i \qquad (1)$$

And since the traffic flow is assumed to be uniform during one day, the flow during the interval i is proportional to the flow during the entire day, ADT.

$$E = V_i = \text{ADT}\ \frac{i}{86,400}$$

where 86, 400 is the number of seconds per day.

Since accident statistics are commonly added up for one year, it seems advisable to express exposure also for one year's duration.

$$E_A = 365\ V_i = \text{ADT}\ \frac{365i}{86,400} \qquad (2)$$

For i = 0. 237 seconds, the exposure can be expressed as an index:

$$I = \frac{1}{1,000} \times \text{ADT}$$

For each entering car the accident exposure index is equal to one one-thousandth of the average annual daily traffic on the main road. For the merging section as a whole the accident exposure index becomes equal to:

$$I = \frac{1}{1,000}\ \text{ADT}_M \times \text{ADT}_R \qquad (3)$$

$$\text{or } 1,000\ I = \text{ADT}_M \times \text{ADT}_R$$

where:

M = Main roadway (one-way)
R = Entering ramp

Exceptions

The foregoing exposure calculation applies strictly only to those accidents which are caused by the merging of two traffic streams. There are several common occasions that are not well represented by the proposed exposure calculation.

In the derivation uniform distribution of traffic throughout the day was assumed. This, of course, never occurs on our highways. The calculation is correct, however, so long as the fluctuations on main road and entering ramp coincide. This can be proved easily when considering 1-hr intervals instead of one day.

At most highway interchanges one-lane ramps feed into two or more lanes on the highway. It is obvious that chance for collision for traffic entering from the ramp exists mainly with the traffic in the outer lane. But since single-lane roadways do not exist, one can assume that the proposed calculation might hold for a two-lane road, if a consistent distribution of traffic to the two lanes can be expected. For three-lane roadways, the actual exposure would be substantially smaller than the index would imply. It might be necessary in such a case to consider only the traffic in the two outer lanes, or two-thirds of the total traffic flow.

Single-car accidents occur sometimes at interchanges, expecially when cars enter ramps with too much speed. The probability of these accidents would be equal to the number of cars on the ramp and cannot be assumed to be proportional to the product of the two traffic streams.

The exposure data were derived for two merging traffic streams. Of course, they would apply also for diverging traffic streams. One would expect that the accident opportunity for diverging traffic streams should not be as great as for merging streams. This, however, is not verified by the results to be discussed later on.

COMPUTATION OF INTERCHANGE ACCIDENT EXPOSURE INDEX

The accident exposure index for an interchange is equal to the sum of the indices for the individual merging and diverging locations.

In the following paragraphs a calculation is developed which is applicable to all cloverleaf interchanges. First, directions as well as merging and diverging movements are considered separately to provide a basic formula. Equations are developed first for a single acceleration or deceleration lane, then for all acceleration or deceleration lanes combined, and finally for the entire interchange combining all acceleration and deceleration lanes.

Figure 1 shows a hypothetical flow diagram at a cloverleaf interchange. Each of the four legs is designated by a letter. A and B are on the main road to be considered, and X and Y are the two legs of the minor road.

Each flow of traffic is now definitely described by two letters, the first for the origin, the second for the destination of the flow band. Merging and diverging locations are shown in their approximate location on the graph. Some traffic volumes commonly ob-

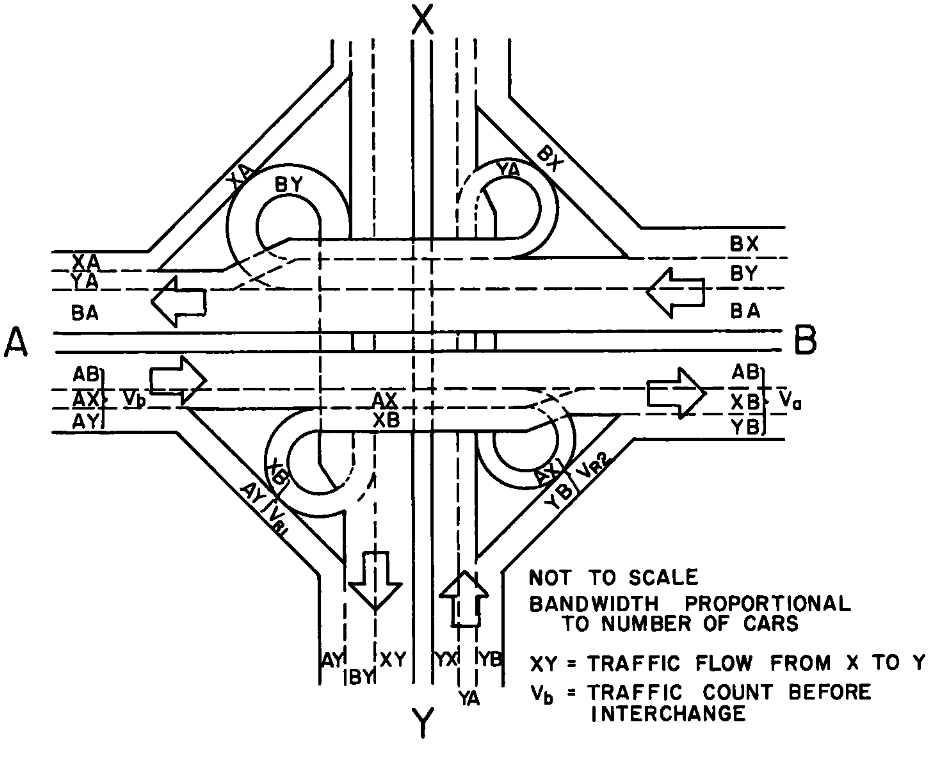

Figure 1. Traffic flow bands at cloverleaf interchange.

tained from available traffic counts are also indicated.

$$\left.\begin{aligned} V_b &= \text{Volume before interchange} = AB + AX + AY \\ V_a &= \text{Volume after interchange} = AB + XB + YB \end{aligned}\right\} = V_M$$

$$\left.\begin{aligned} V_{R1} &= \text{Volume on ramp 1} = AY + XB \\ V_{R2} &= \text{Volume on ramp 2} = AX + YB \end{aligned}\right\} = V_R$$

The indices can now be read from the diagram. The values are then rearranged so that the more common counts listed above can be used to compute the indices.

1. One acceleration (or deceleration) lane $= I_1$

$$1,000\ I_1 = (AB+XB)\ YB = (V_a - V_{XB})\ V_{YB} \tag{4}$$

2. All acceleration (or deceleration) lanes $= I_A$

$$\begin{aligned} 1,000\ I_A &= (AB+XB)YB+(AB+AX)XB+(BA+BY)YA+(BA+YA)XA \qquad (5) \\ &= ABYB+XBYB+ABXB+AXXB+BAYA+BYYA+BAXA+YAXA \\ 1,000\ I_A &= AB(YB+XB)+BA(YA+XA)+XB(YB+AX)+YA(BY+XA) \end{aligned}$$

Assuming that flow in opposite directions is balanced ($AB \equiv BA$, $AX \equiv XA$, etc.):

$$\begin{aligned} 1,000\ I_A &= AB(BX+BY)+AB(AX+AY)+BX(AX+BY)+AY(AX+BY) \\ &= AB(AX+AY+BX+BY) + (AY+BX)\ \ (AX+BY) \end{aligned}$$

which can be expressed in terms of the counts V_b, V_a, V_{R1}, V_{R2}, because
$AB = \frac{1}{2}(V_b + V_a - V_{R1} - V_{R2})$

$$1,000\ I_A = \frac{1}{2}\ (V_b+V_a-V_{R1}-V_{R2})\ (V_{R1} + V_{R2}) + V_{R1}V_{R2}$$

$$1,000\ I_A = \frac{1}{2}\ (V_M - V_R)\ V_R + V_{R1}V_{R2} \tag{6}$$

3. Acceleration and deceleration lanes $= I_T$

In order to consider both acceleration and deceleration hazards together, an equation similar to Eq. 5 can be set up.

$$\begin{aligned} 1,000\ I_T = &\ (AB+AX)AY+(AB+AX)XB+(AB+XB)AX+(AB+XB)YB \\ &+(BA+BY)BX+(BA+BY)YA+(BA+YA)BY+(BA+YA)XA \end{aligned} \tag{7}$$

This complicated expression can be greatly simplified if balanced traffic is assumed again ($AB \equiv BA$, etc.). The equation then reduces to two series of identical terms. The basic series is the same as in Eq. 5.

$$1,000\ I_T = 2(ABAX+ABAY+ABBX+ABBY+AXAY+AXBX+AYBY+BXBY)$$

It can be expressed again by traffic counts:

$$1,000\ I_T = (V_M - V_R)V_R + V_{R1}V_{R2} \tag{8}$$

It should be noted that a combination of all accidents and all exposure indices at one interchange into one expression may obscure a difference in accident frequency between acceleration and deceleration accidents.

Accident Rates

The Accident Exposure Index should be a representative measure for the likelihood of accidents to cumulate at the interchange considered. The actual number of accidents compared to the index gives an indication of the safety, or lack thereof, of the interchange under consideration. The following example will demonstrate the importance of a proper exposure determination for a representative accident evaluation at different interchanges.

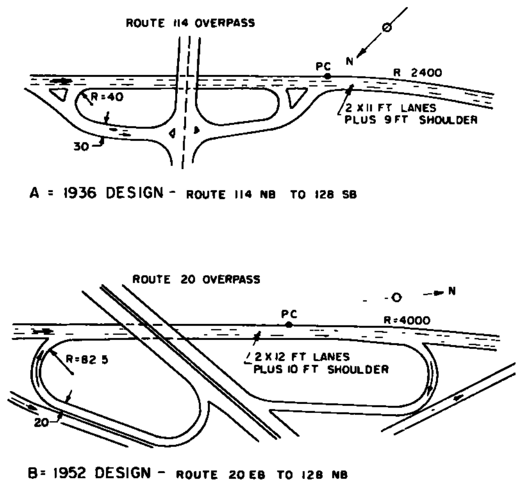

Figure 2. Typical 1936 and 1952 interchange designs on Route 128.

APPLICATION TO SAMPLE INTERCHANGES

The theory developed above is tested at several interchanges for which traffic counts and accident statistics are available. The interchanges are located on Massachusetts Route 128, the circumferential expressway around Boston. Of five interchanges considered, the first two were designed about 1936 and the remaining three about 1952. The variation of the design standards used can be seen readily on Figure 2.

Exposure Index

The traffic counts which were needed for the actual computation of the indices at several sample interchange sites were obtained from the Traffic Division of the Massachusetts Department of Public Work Works. The counts, one of which is shown in Figure 3, represent the average daily traffic in 1955. Figures are given separately for each traffic stream. These separate figures are combined to give the required volumes V_b, V_a, V_{R1}, and V_{R2} and also the totals V_M and V_R. The procedure is demonstrated in Figure 3. Since counts are given separately for each direction, averages for the required volumes are obtained by adding the counts for the opposing directions and dividing by two. For the ramps this can be done simply by adding all four volumes diagonally across the interchange, a procedure which is indicated by the dashed line in Figure 3.

From the volumes obtained, the accident exposure index is now computed by Eq. 6. This is carried out in Table 1 for all sample interchanges.

Accident Data

The accident information for the sample interchanges was obtained from the files of the Massachusetts Department of Public Works. Only accidents on the expressway or at ramp entrances or exits of the expressway were considered. In order to test accidents at acceleration and deceleration lanes, the accidents were taken separately for the four acceleration lanes, and for the four deceleration lanes.

The small number of accidents which occurred at the test sites makes it difficult to discuss the results of the table with confidence. A thorough study of the accident files indicated, however, that the quality of accident reporting for all sample sites may be expected to be uniform.

TABLE 1

COMPUTATION OF ACCIDENT EXPOSURE INDICES [a]

Year of Design	Rt. 128 Interchange w. Rt.:	One-Way Volume: Before Interchange, V_b	One-Way Volume: After Interchange, V_a	One-Way Volume: Total, $V_M = V_a+V_b$	Two-Way Volume: Ramp 1, V_{R1}	Two-Way Volume: Ramp 2, V_{R2}	Two-Way Volume: Total, $V_R = V_{R1}+V_{R2}$	Through Volume, $V_T = \frac{V_M+V_R}{2}$	Exposure (x10³): $V_T V_R$	Exposure (x10³): $V_{R1} V_{R2}$	Exposure (x10³): Index,[b] I
1936	114	6,000	5,660	11,660	1,184	2,089	3,273	4,194	13.72	2.48	16.20
	1	9,595	9,301	18,896	1,212	5,035	6,247	6,325	39.51	6.10	45.61
1952	20	13,818	14,832	28,650	3,467	2,580	6,046	11,303	68.33	8.94	77.27
	2	16,431	15,340	31,771	2,976	4,759	7,735	12,018	92.96	14.16	107.12
	9	12,047	17,514	29,561	3,877	4,830	8,707	10,427	90.79	18.72	109.51

[a] Based on ADT data for 1955, furnished by Mass. Dept. of Public Works.

[b] Acceleration exposure index for cloverleaf interchange computed from

$$1{,}000\ I = \tfrac{1}{2}\left[V_a + V_b - (V_{R1} + V_{R2})\right](V_{R1} + V_{R2}) + V_{R1}V_{R2}.$$

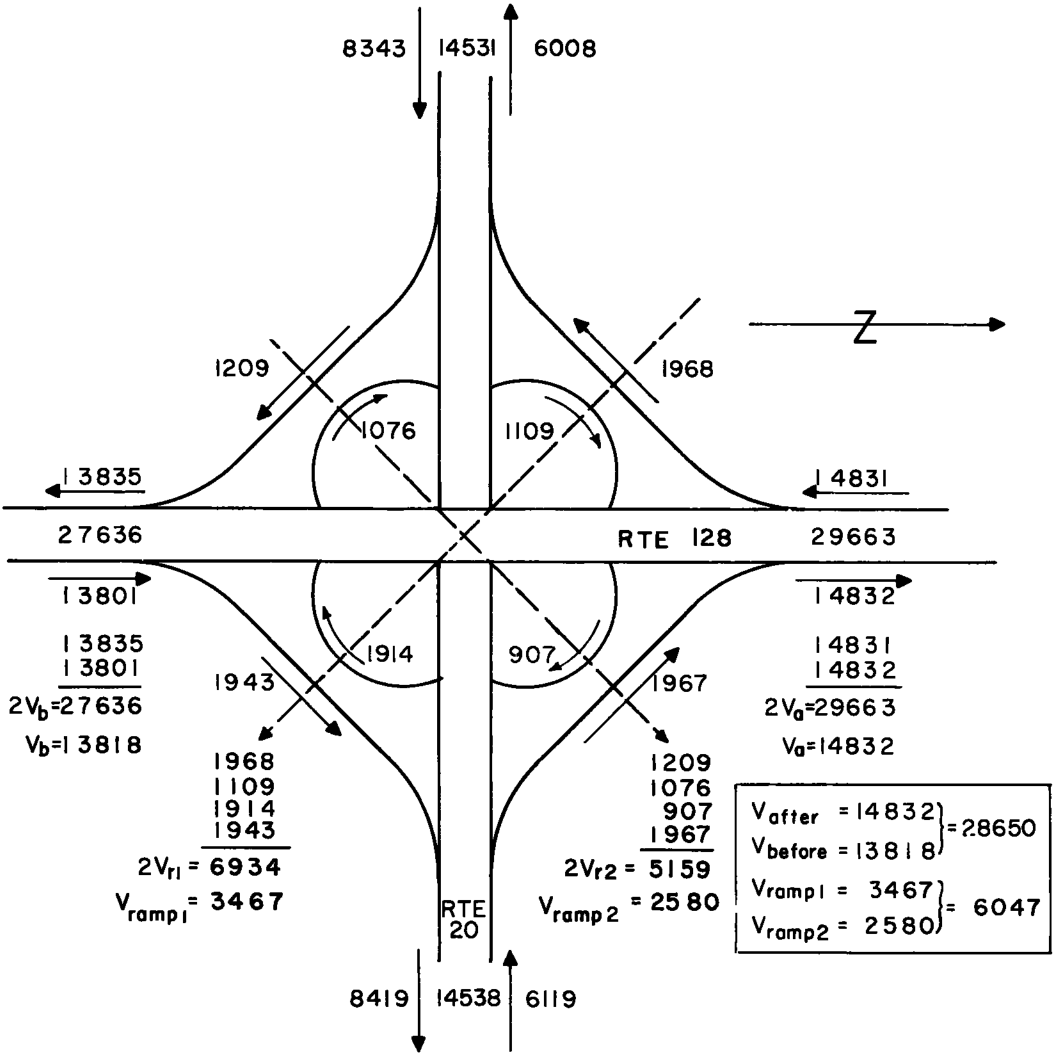

Figure 3. ADT volumes at interchange of Routes 128 and 20 in 1955.

Evaluation

With exposure index and accident figures Table 2 was prepared. In this table the interchanges are grouped by design period. The accidents were subdivided into acceleration and deceleration accidents and for each of these two groups the accident rate (Number of accidents/Accident Exposure Index) was computed.

The accident rates show an improvement of the newer design over the older one of 2. 5 to 3 times. Without the exposure index or with consideration only for the volume variations one would have concluded that no appreciable increase in safety was accomplished by the more modern design. The substantial improvement indicated by the calculations in the table is borne out also by traffic observations, as discussed hereafter.

The classification of acceleration and deceleration accidents brings out the most striking fact that there are just about twice as many deceleration accidents as acceleration accidents. This is not an expected result, but one that can be explained readily considering that rear-end collisions account for more than half of all accidents.

A through car traveling fast on a through way, such as Route 128, will have little difficulty in watching out for cars entering at the few entrances present on the road.

TABLE 2

SUMMARY OF ACCIDENTS AND ACCIDENT RATES[a]

Year of Design	Rt. 128 Inter-change w. Rt	Accidents		Accident Rates				Ratio Decel. to Accel. Accidents	
		No.	Exposure Index[b] (000's)	Accel.		Decel.			
				No.	Rate[c]	No.	Rate[c]	Indiv.	Avg.
1936	1A	4	—	1	—	2	—		2.0
	114	4	16.2	2	0.12	3	0.19	1.6	
	1	13	45.6	5	0.11	12	0.26	2.4	
1952	4, 25	13	—	6	—	8	—		2.2
	20	12	77.3	3	0.04	6	0.08	2.0	
	2	15	107.1	4	0.04	11	0.10	2.5	
	9	10	109.5	4	0.04	7	0.06	1.5	1.5
Ratio of Accident Rates: 1936 Designs / 1952 Designs =					2.9		2.5		

[a] Based on 1955 accident and exposure data.
[b] See Table 1.
[c] Per 1,000 exposures.

Even if an entering car cuts in daringly close to the through car the latter can be alert and apply the brakes immediately or swerve into the other lane. And while the through car decelerates the entering car accelerates, thereby reducing steadily the probability of a crash.

A deceleration accident is caused differently. The through car travels along behind another car at constant speed for quite a distance. If the car in front decelerates suddenly the following driver will have to apply the brakes very quickly if a collision is to be avoided. And because both vehicles decelerate, the chance of a collision is not reduced as deceleration goes on. Thus it is quite logical that there should be more deceleration than acceleration accidents.

The foregoing is supported in a way by the ratios presented in Table 2. It is shown there that deceleration accident rates do not decrease as much with an improvement in the design. Consequently the ratio of deceleration to acceleration accidents increases for more modern design.

COMPARISON WITH TRAFFIC PERFORMANCE

In addition to the accident analysis evaluations of traffic performance at the different interchanges were carried out. Detailed traffic performance data were collected for acceleration lanes by various methods (2). For each entering car, speed and position in relation to the distance from the entrance point of the ramp to the expressway were determined. For decelerating cars, only general observations were made.

From this traffic observation it was possible to determine the average path and acceleration behavior of the stream of entering cars. In addition, the range of performance was determined for acceleration as well as for the traveled path. From this information, taken at all sample locations, it was possible to judge the amount of interference that could be expected between each entering car and the through traffic.

At the older interchanges (designed in 1936) the entering cars had to come to virtually a complete stop before entering the through roadway. Consequently all acceleration had to be performed on the through roadway. The exposure to a rear-end collision in that case is about the maximum possible. Further, the radii of the entering ramps were so small that it was almost impossible to follow the ramp closely to enter onto the proper acceleration lane. Therefore, many entering cars swung right into the first through traffic lane and some even entered the inner lane directly. At the interchanges of 1952 design, larger radii had been used for the ramp connections and a taper of the shoulder had been introduced to serve as an acceleration lane. At these locations, cars entered with a speed of about 15 mph and most of them remained on the acceleration lane for a length of about 400 ft. However, there were wide variations in travel pattern at these locations, also.

For cars leaving the expressway, deceleration travel patterns were observed only very generally. They seemed to exhibit behavior similar to the acceleration patterns. At the older interchanges, the sharp curves at the exits forced leaving cars to rapid deceleration. The use of the deceleration lane was not advantageous because then an even sharper turn would have had to be executed at the proper exit turn. The 1952 design allowed higher exit speeds and the taper in the deceleration lane invited a gradual turnoff from the through traffic lane.

The analysis of traffic performance observations pointed out strongly that substantially greater hazards seem to exist at the older interchanges. Therefore it was expected that the accident rate at those interchanges should be higher than at the newer interchanges. The accident rates presented in this paper prove this point.

It should be noted, however, that the same accident rates would not have been obtained if only a linear correlation to accident volume had been considered. The traffic volume at the older interchanges is about ⅔ of the volume at the newer interchanges, but the accident frequency is about the same or less. For that reason, it had been seriously suggested that the interchanges of 1936 design might be safer than the newer ones at which higher entering speeds and high-speed merging maneuvers were necessary.

In the development of the exposure index, it was felt that the index would have to be representative of the actual "possibility" of an accident. A mere summation of traffic volumes, as suggested by Grossman (3), would not have been adequate for this analysis. Further, the computation as derived in this study is reduced to a very simple formula.

SUMMARY AND CONCLUSION

The chief causes of accidents at modern high-speed expressways are the interchanges where cars merge with or diverge from the through traffic stream.

In order to assess the accident danger at these locations and to find ways to reduce the hazard, a significant analysis of the accident potential is necessary.

The exposure to accidents is proportional to the product of the numbers of cars in the two merging or diverging traffic streams.

The calculation of an exposure index for an interchange on this basis can be reduced to a relatively simple formula using generally available traffic counts.

Based upon this exposure index, accident rates for interchanges become easily comparable and allow a direct and significant analysis of the safety of each intersection design.

A demonstration of this theory on several sample interchanges shows a very reasonable correlation. An evaluation of the traffic performance at the test interchanges confirms the results.

The accident analysis for the test sites showed that deceleration accidents are twice as frequent as acceleration accidents. There is further indication that design improvements result in greater reduction in acceleration accidents than in deceleration accidents.

It can be concluded that the accident exposure index calculation as developed in this paper is a good basis for a quantitative analysis of accidents at expressway interchanges.

Accident rates based on improper exposure values are misleading and can delay the proper correction of accident hazards. There is also a danger that highways of modern design with large traffic volume will be termed unsafe merely because accident rates are not based upon the proper exposure data.

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