flexible pavements also. It is further recommended that the possibility of extending the method to more than two layers be investigated.

ACKNOWLEDGMENTS

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Accident-Exposure Index

LEO GROSSMAN, *District Engineer*
Bureau of Public Roads

THE conventional method of portraying traffic movements at highway intersections is by means of traffic vectors. When two highways cross at grade, the vector diagram contains 16 vector crossing points which are defined as collision points. The number of these collision points is reduced to zero under two conditions only; namely, when a grade-separation structure is constructed without interchange ramps and when the grade-separation structure is constructed with a full cloverleaf or direct-connection design.

When traffic densities or economic, topographic or urban-planning considerations indicate that a partial-interchange layout is called for, it is most desirable that that traffic pattern and partial-interchange layout which will offer the greatest traffic efficiency be adopted. Using only the original traffic-vector diagram as a base, the report presents a technique whereby a numerical value or score is established for each layout under consideration. This value is termed the *accident-exposure index*. A comparison of these indices provides a direct evaluation of the traffic efficiency of the interchange. Computations are given in this report to exemplify the technique used in establishing the layout for expressway interchanges.

● COLLISIONS between two moving vehicles can occur only when both vehicles try to occupy the same space at the same time. When referring to highway accidents, such collisions can occur only under four conditions: meeting head on, rear end by overtaking, side-swiping, and crossing each others' travel path. Highway design can minimize or entirely eliminate all of the conditions under which such accidents might occur. The degree of traffic congestion and the degree of hazard are the determinant factors as to the scope of the design, subject to considerations of construction and right-of-way cost, physical topography and man-made development.

This report deals with only one phase of the design—crossing accidents. Crossing accidents at highway intersections can be entirely eliminated by grade separations or grade separations with full interchange. Since it is not always practical to provide complete protection, partial but satisfactory solutions may be provided by means of stop signs, traffic lights or other traffic control devices, or by means of an interchange with an incomplete ramp system.

The purpose of this report is to illustrate all possible interchange layouts involving ramp systems about a single highway grade separation and to offer a technique for measuring the efficiency of the several possible combinations of ramps which make up the interchange. The result of this evaluation is a sensitive numerical score which is called the *accident-exposure index*.

TRAFFIC-VECTOR DIAGRAMS

In studying traffic movements at highway junctions or intersections, the conventional method of portraying the direction and density of traffic is by means of vectors in which an arrow indicates the direction of the flow and a variable band width or a superimposed figure indicates the traffic density. The maximum number of traffic vectors at a junction or intersection is the product of the number of roads entering the intersection times that same number minus one. For example, vehicle movements where a side road enters a main road would be portrayed by six vectors—three roads times two turns for each vector. Two crossroads would be portrayed by 12 vectors—four roads times three turns for each vector. A junction where five roads enter would be portrayed by 20 vectors—five roads times four turns for each entering vector.

Although the technique presented applies to intersections of any number of routes, this report will concern itself only with the crossing of two highways. The traffic-vector diagram for the at-grade crossing of the two highways is the only datum required to make the determination of the most-efficient partial-interchange layout for the particular site in question.

COLLISION POINTS

Traffic diagrams for two at-grade cross roads consist of 12 direction arrows which cross each other at 16 points. It is at any one or more of these 16 intersection points that the crossing type of accident can occur. The purpose of any design which might decrease the frequency of crossing accidents is to reduce the number of these intersection points. These intersection points are termed *collision points*. It is evident that crossing accidents can be entirely eliminated only when the 16 points are reduced to 0, as is the case of traffic circles or complete interchanges involving four-quadrant cloverleaf layouts or directional ramps.

Partial interchanges reduce the number of collision points and thus decrease the hazard. However, the mere reduction in number of collision points does not necessarily mean that the layout affording the fewest number of such points is the most efficient. In many cases, the same number of collision points may apply to two, three, or even four entirely different layouts, so a choice must still be made.

INTERCHANGE LAYOUTS

As stated above, a single bridge grade separation with a full cloverleaf interchange layout is the only one which contains no collision points and therefore can have no crossing accidents. However, conditions frequently

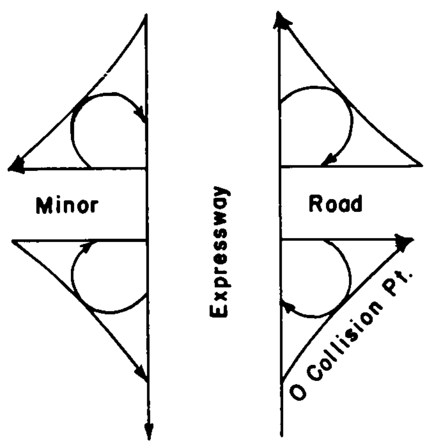


Figure 1.

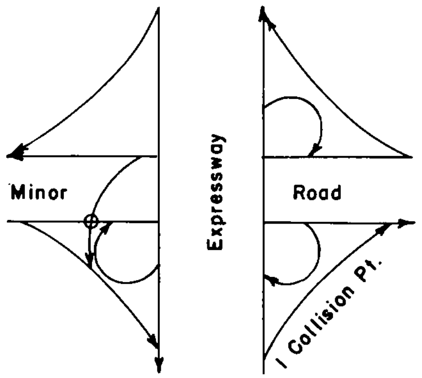


Figure 2.

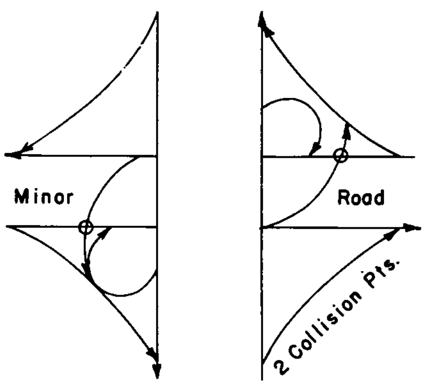
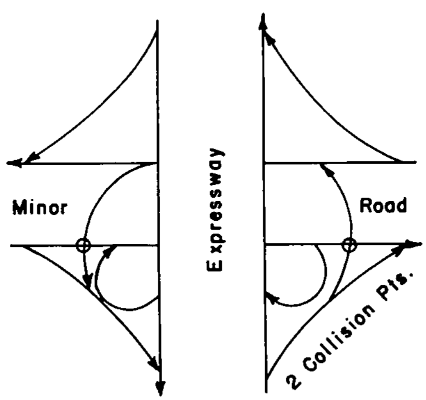


Figure 3.



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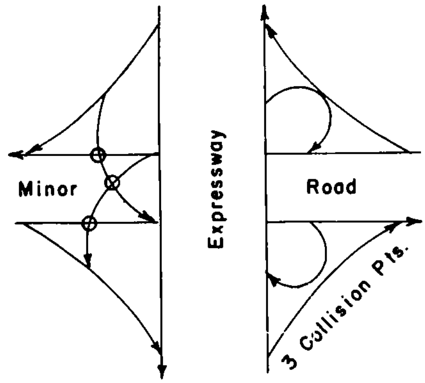


Figure 5.

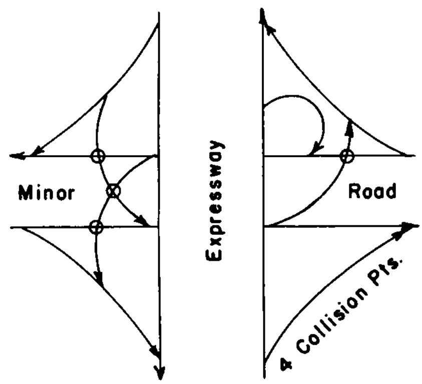


Figure 6.

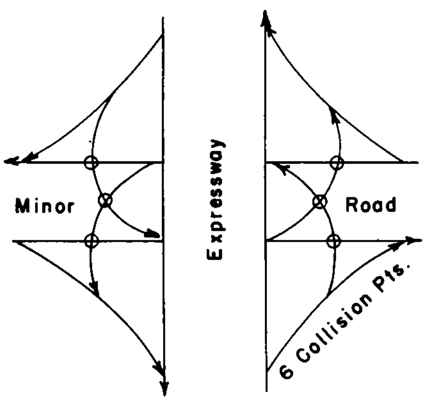


Figure 7.

exist which render it impossible or impractical to design for such a complete facility and partial interchanges must be accepted. In the case of an expressway crossing over or under a minor road, it has been found that there are only 13 possible layouts which can provide for free interchange of traffic in all directions. These are illustrated as Figures 1 to 13.

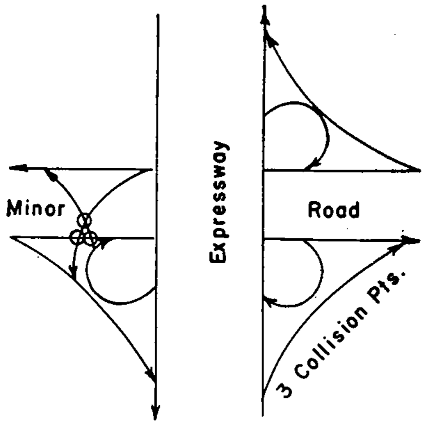


Figure 8.

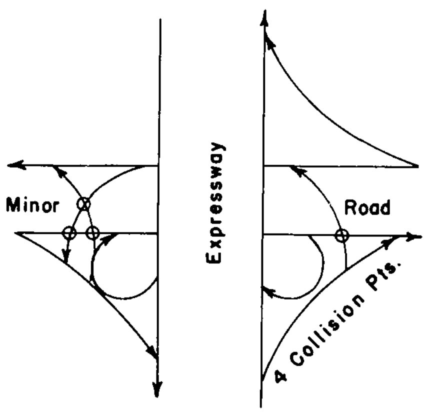


Figure 9.

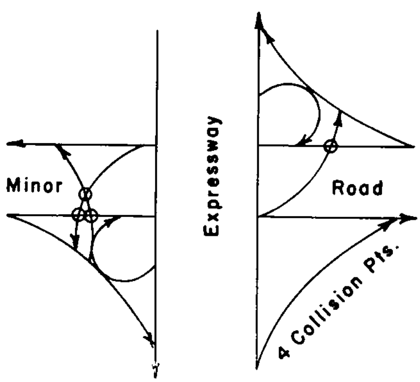


Figure 10.

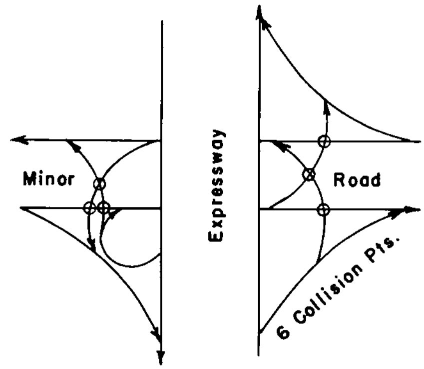


Figure 11.

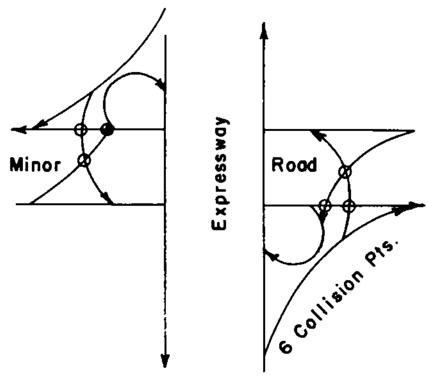


Figure 12.

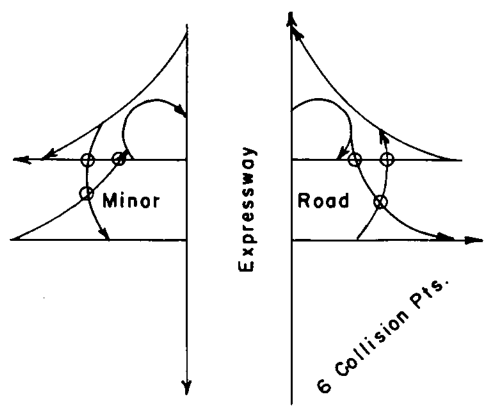


Figure 13.

Table 1 lists all of the possible interchange layouts in the order of the number of collision points. It would seem logical to assume that the greater the number of quadrants treated, the fewer the number of such collision points. As will be seen from the tabulation, however, this assumption does not hold true, as it is possible for a two- or three-quadrant design

TABLE 1
COLLISION POINTS IN INTERCHANGE LAYOUT

Collision Points	No. of Quadrants	Description of Layout	Figure
0	4	Full clover leaf	1
1	4	4 direct ramps—3 inner loops	2
2	4	4 direct ramps—2 diagonal inner loops	3
2	4	4 direct ramps—2 adjacent inner loops across expressway	4
3	4	4 direct ramps—2 adjacent inner loops on one side of expressway	5
3	3	3 direct ramps—3 inner loops	8
4	4	4 direct ramps—1 inner loop in any quadrant	6
4	3	3 direct ramps—2 diagonal inner loops	10
4	3	3 direct ramps—2 adjacent inner loops across expressway	9
6	4	4 direct ramps—no inner loops	7
6	3	3 direct ramps—1 inner loop on side of expressway having single ramp	11
6	2	2 direct ramps—2 diagonal inner loops	12
6	2	2 direct ramps and 2 inner loops on one side of local road	13

to be equal or superior to a four-quadrant design.

SIGNIFICANCE OF COLLISION POINTS

At first glance, it would appear that the layout having the fewest number of collision points would be the safest design. Because the hazard at the intersection is dependent, not only on the number of possible crossing points, but also on the number of vehicles making the crossing, the number of collision points for a particular layout really has little significance. The interest in the number and location of the collision points is of value in considering how the particular point should be treated. The direction and density of traffic at the point enables a determination to be made as to the type of traffic control which should be established on the minor road—stop signs, warning and stop lights, channelization, etc.

ACCIDENT-EXPOSURE INDEX

The term *traffic-vector diagram* has been defined as a symbolic portrayal of traffic movements about an intersection in which the direction and density are indicated. The term *collision points* has been defined as the point of intersection of two direction lines in the traffic-vector diagram. A traffic-vector diagram for two roads crossing at grade would show 12 vectors which cross at 16 collision points.

The next step in studying the development of the interchange is to sketch a series of traffic vector diagrams for various ramp layouts. These diagrams will be similar to those shown in Figures 1 to 13. On each direction line, a figure representing the traffic density is inserted.

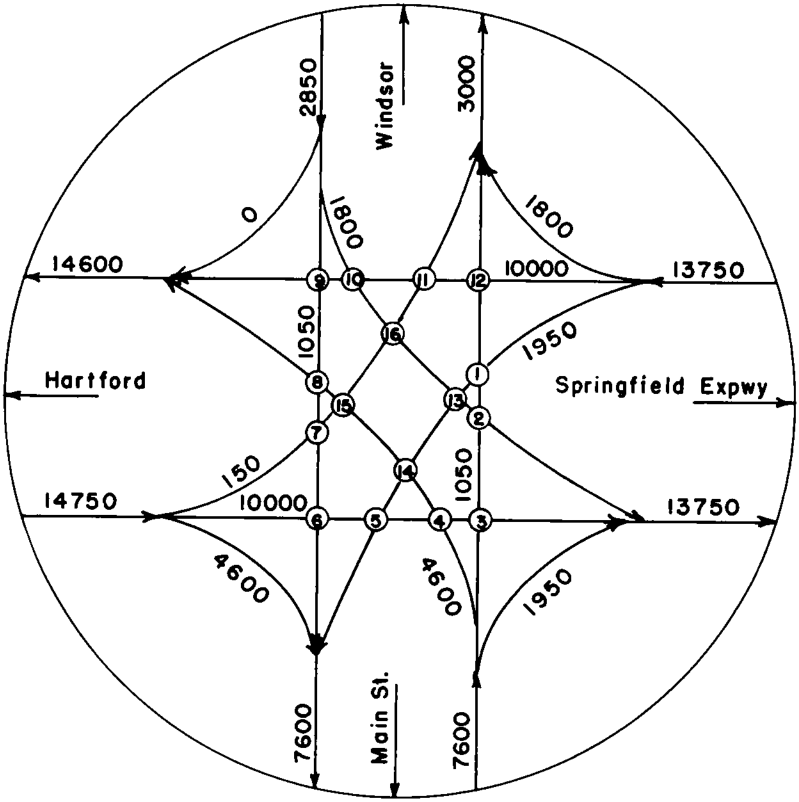
It is now necessary to evaluate the probability of accidents at each of the collision points. There is no proven method of doing this, because of the absence of detailed accident records for use in establishing a method. The most-reasonable assumption to make is that each vehicle passing over a collision point may collide with any vehicle in the conflicting traffic stream. The product of the two traffic vectors will give a reasonable index of collision possibility. However, it has been found that almost-identical results in rating traffic hazard can be obtained by adding the two vector values. The simpler procedure will be used. The next step, therefore, consists of a direct addition of the two traffic densities which occur at each of the collision points. The grand total of all of these additions at all of the collision points results in the accident-exposure index. When two, three or even the entire thirteen layouts are sketched, it will be found that the indices vary widely among each other and a tabulation in ascending order of index figures would indicate the relative efficiencies of the layouts studied.

ILLUSTRATIVE APPLICATIONS

Figures 14 to 18 inclusive serve as an illustration of the application of this technique. The following description of the procedure applies to the development of the series of accident-exposure indices for the basic traffic vector diagram for the intersection shown in Figure 14.

Referring to that figure, the first step consists of noting that there are 16 collision points. The second step consists of recording the sum of the two traffic densities which cross at each of the 16 collision points. The third step is to record the grand total of all of the quantities noted for each of the points. This sum (122,400) is the index for the at-grade crossing.

Rough sketches are then drawn for several possible layouts (four in this illustration) and appropriate traffic density figures are transferred from the basic diagram to the traffic vector diagrams for the four layouts. The num-



Basic Traffic Vector Diagram
Crossing at Grade

Accident Exposure Index - 122,400 Collision Points - 16
Computations -

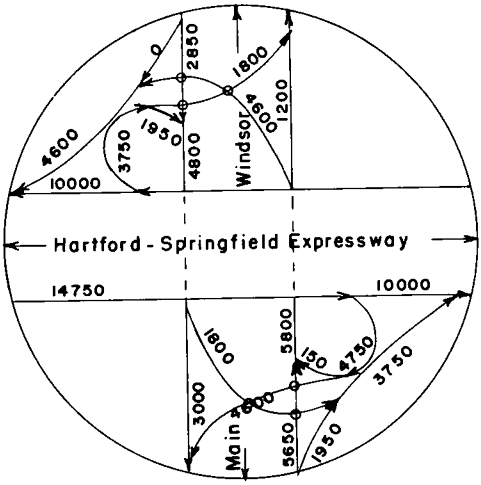
(1) 1950 + 1050 = 3000	(9) 1050 + 10000 = 11050
(2) 1800 + 1050 = 2850	(10) 1800 + 10000 = 11800
(3) 1050 + 10000 = 11050	(11) 150 + 10000 = 10150
(4) 4600 + 10000 = 14600	(12) 1050 + 10000 = 11050
(5) 1950 + 10000= 11950	(13) 1950 + 1800 = 3750
(6) 10000 + 1050 = 11050	(14) 1950 + 4600 = 6550
(7) 150 + 1050 = 1200	(15) 4600 + 150 = 4750
(8) 4600 + 1050 = 5650	(16) 1800 + 150 = 1950

Total - 122,400

Figure 14.

ber of collision points is immediately noted for each layout, and as before, the sum of the two traffic densities at each collision point is then noted. The grand total of all of the quantities recorded for the collision points in each layout is then determined. Each of these grand total figures is the accident-exposure index for the particular layout.

The four layouts resulting from the analysis of the possibilities of Figure 14 shows the



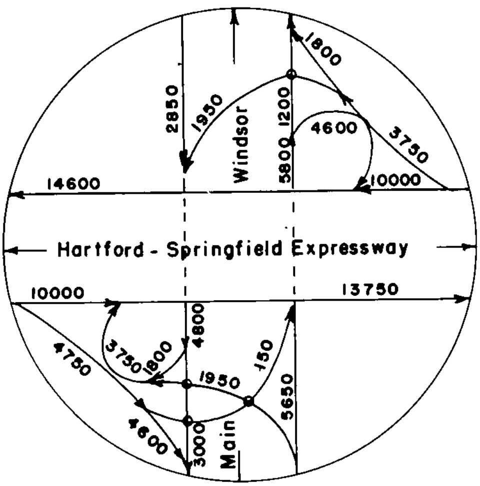
2-Ramp Design NW-SE Inner Loops
Accident Exposure Index - 42,600
Collision Points - 6

Computations -

5650+1800=7450	2850+4600=7450
4600+5650=10250	2850+1800=4650
4600+1800=6400	4600+1800=6400

Total - 42,600

Figure 15.



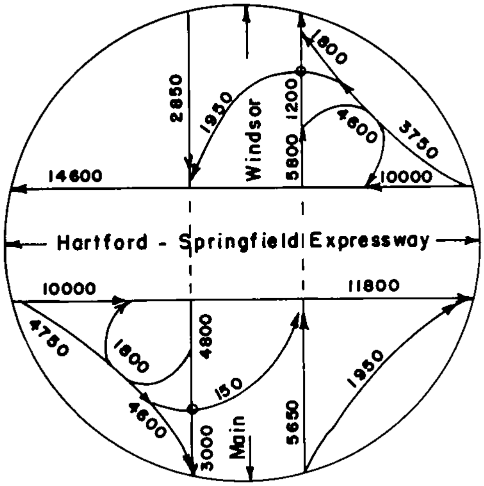
2-Ramp Design NE-SW Inner Loops
Accident Exposure Index - 13,350
Collision Points - 4

Computations -

1950+150=2100	3000+1950=4950
3000+150=3150	1950+1200=3150

Total - 13,350

Figure 16.

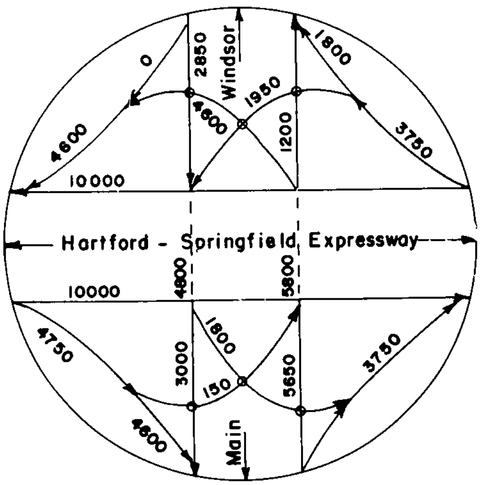


3-Ramp Design NE-SW Inner Loops
Accident Exposure Index - 6300
Collision Points - 2

Computations -

3000+150=3150
1950+1200=3150
Total - 6300

Figure 17.



Four Direct On-Off Ramps
Accident Exposure Index - 29,700
Collision Points - 6

Computations -

5650+1800=7450	1200+1950=3150
1800+150=1950	1950+4600=6550
150+3000=3150	4600+2850=7450

Total - 29,700

Figure 18.

following order of the accident-exposure indices for the four layouts:

Index	Design	Inner Loops	Coll. Pts.
6,300	3-Ramp	2-NE-SW Quadrant	2
13,350	2-Ramp	2-NE-SW Quadrant	4
29,700	4-Ramp	None	6
42,600	2-Ramp	2-NW-SE Quadrant	6

The design having the lowest index figure (6,300) proved to be superior in all respects and is now under construction.

SIGNIFICANCE OF THE INDEX

The series of accident-exposure indices for the various layouts would point to a single solution as being the most effective. However, it must be recognized that there are other factors which have a major influence on the final choice of layout.

It must be recognized that the traffic-density figures are only engineering estimates of conditions 10 to 20 years hence. Because of this, two or more indices which are close together should be regarded as of equal value. (A difference of 5,000 may be assumed as negligible).

All layouts having indices of a total value of under 10,000 should be regarded as of equal merit. Traffic forecasts cannot be made accurately enough to offset adverse economic factors in index ranges of less than 10,000.

No matter how favorable the index, certain layouts must be discarded because of conditions which render the layout impractical. As examples, a river or ravine may make certain quadrants impossible of construction; adverse topography or right-of-way developments may make certain quadrants unavailable; the cost of construction of ramps in certain locations may render certain quadrants inadvisable; and urban planning may indicate that the desired direction of future traffic dispersal may be controlled by the layout.

CONCLUSIONS

Given any at-grade traffic-vector diagram for a location where a partial interchange is proposed, the technique described in this report furnishes a sensitive tool for scoring the traffic efficiency of various possible layouts. This score is termed the accident-exposure index.

The technique places the choice of layout treatment for a particular location on a statistical basis and resolves itself into an orderly evaluation of 1 of 13 possibilities.

The 13 accident-exposure indices, when placed in numerical order, provide the foundation against which locational, economic, and political factors must be pitted in order to establish the degree of traffic efficiency which the layout justifies.

A byproduct of the study is the focusing of attention on and the control of the location and number of collision points on the minor road where the crossing type of accidents must occur. When evaluated with the traffic density, a determination can be made as to the degree of protection required, such as stop signs, traffic lights, traffic-light cycles, or channelization.

DISCUSSION

O. K. Normann, *Chief, Traffic and Operations Section, Highway Transport Research Branch, Bureau of Public Roads*—The idea behind the accident-exposure index as presented by Grossman is appealingly simple and appears to have considerable value for the intended purpose. There are many modifications of the procedure that could be applied, but the more of these that are added, the more-complicated the analysis becomes; therefore, it may lose some of the effectiveness which, as he has stated, is gained largely by its simplicity.

Grossman's proposed index, for example, ignores weaving maneuvers that might necessarily take place in much-greater numbers in one layout than in another. In a full cloverleaf, which receives a perfect score by Grossman's method, weaving maneuvers that must take place between traffic entering an expressway from an inner loop and traffic leaving the expressway on another inner loop might be of sufficient magnitude, under certain conditions, to render even a full cloverleaf design inoperative. It therefore seems that even though there might be some sacrifice of simplicity, the index should include the number of vehicles that cross the paths of other vehicles by performing weaving maneuvers. It would probably be desirable, however, to apply some factor of less than 1, depending on the length of the weaving area to the vehicles involved in the weaving maneuvers.

One of the interesting features of Grossman's index is that it employs the sums of the crossing movements rather than the products obtained by multiplying each pair of crossing movements. The products would seem to be a more-reasonable index, since products are generally employed where chance probabilities are involved, as for example in the hazard index for railroad grade crossings.

Table A shows a comparison of the results obtained by adding the vehicles involved in the intersecting traffic movements with the results obtained by multiplying each pair of intersecting movements for the four different layouts used by Grossman in his illustration. When products rather than sums are used, there is a wider spread between the indexes for the four different designs, but the designs rank in the same order, regardless of whether sums or products are used.

Another feature of Grossman's index is that it employs the 24-hour traffic counts. This might seem to be a serious flaw of the index, since the computations for certain layouts would include values for probable conflicts which actually do not exist. With one layout, for example, heavy movements which cross each other may occur during approximately the same period of the day, whereas in another layout two heavy movements whose paths cross each other may occur at different times of the day, one principally during the morning rush hour and the other during the evening rush hour. The second layout would be preferable if both resulted in the same accident-exposure index as calculated by Grossman's method.

Also, the geometrics of a highway are generally based principally on peak or near-peak traffic volume conditions. It therefore seems desirable to compare the accident exposure indexes for various design layouts as obtained by using the total 24-hour traffic counts with those obtained by using traffic counts during individual hours of the day and to compare the results when products rather than sums are used.

For this purpose, a traffic-flow diagram obtained at a local interchange with a high reversal of traffic by directions during the morning and afternoon peak periods was used. Table B shows the results of this analysis.

TABLE A
ACCIDENT EXPOSURE INDEXES FOR GROSSMAN'S LAYOUTS AND VOLUMES

Design			24-Hour index		
Figure	Ramps	Inner loops	Sums	Multiples	Rank
No.	*Quadrant*	*Quadrant*	*Number*	*1,000's*	
17	NE, SE & SW	NE & SW	6,300	2,790	1
16	NE & SW	NE & SW	13,350	8,932	2
18	All 4	None	29,700	35,310	3
15	NW & SE	NW & SE	42,600	70,960	4

TABLE B
ACCIDENT EXPOSURE INDEXES FOR SELECTED LOCATIONS

Design			Rank of accident exposure index					
			Peak hours		24-Hour by hours		24-Hour totals	
Figure	Ramps	Inner loops	Sums	Products	Sums	Products	Sums	Products
No.	*Quadrant*	*Quadrant*						
17[b]	All	NE & SW	1	2	1	2[c]	1	2[c]
15	NW & SE	NW & SE	2	1	2	1	2	1
[a]	NW & SW	NW & SW	3	3	3[c]	3[c]	3[c]	3[c]
18	All 4	None	4	5[c]	4[c]	4[c]	4[c]	4[c]
[a]	NE & SE	NE & SE	5	4[c]	5	5	5	5
16	NE & SW	NE & SW	6	6	6[c]	6[c]	6[c]	6[c]

[a] Designs not included by Mr. Grossman.
[b] Modified by addition of one ramp.
[c] Less than 25 percent difference between indexes represented by this rank and next lower numerical rank.

For Table B, a total of six different interchange layouts were used—the four employed by Grossman in his illustration and two others with ramps and inner loops in different quadrants.

It may be noted that when the sums are used, the various designs rank in exactly the same order of preference regardless of whether total 24-hour volumes, 24-hour volumes by hours, or peak-hour volumes are used. Also, there are only slight differences between the results obtained by the use of products and those obtained by the use of sums. The principal difference is that the sums show a high preference for the one design, whereas the products indicate that at least the first two designs should receive consideration with a slight preference for the second design, especially during peak conditions.

The fact that there are only minor differences in the results obtained by the use of products rather than sums, or by the use of the total 24-hour traffic counts, peak-hour traffic counts, or individual traffic counts for each of the 24 hours, makes Grossman's index a much-more-reliable index than if the method of calculation resulted in large differences in the order of preference.

The idea behind the accident-exposure index is appealingly simple and appears to have considerable value for the intended purpose. Grossman realizes that an analysis of this type has its limitations and is useful only when applied in combination with many other criteria for the adequacy of an interchange layout.

There is, of course, the possibility that even though two layouts result in the same index, the crossings made in one layout may be far-more dangerous than those made in the other layout. It is believed, therefore, that the method can be applied most beneficially in the preliminary stages of design to select two or three layouts for a thorough and detailed investigation of such items as ramp and roadway capacity, safety features, and cost. As a final criterion for selecting the most satisfactory of several possible layouts, its use would be limited to those layouts in which the many other factors involved in a proper design have been found to be equally satisfactory.

Deformation Mechanism and Bearing Strength of Bituminous Pavements

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The mechanical behavior of bituminous pavements and their substructures is of importance in relation to the stresses acting on them. This paper deals with the deformation mechanism of such structures and the measurement of the bearing strength, defined as the maximum load per unit area which a bituminous pavement can carry without causing initial failure.

The deformation of bituminous pavements consists of an instantaneous and retarded elastic deformation followed by a plastic deformation. The mechanical behavior is primarily determined by the plastic deformation which is accompanied by hardening. As a result of the hardening process, the coefficient of plastic traction, which is stress over strain rate and is related to the viscosity, increases with increasing compressive stress and time to a maximum within a certain region of stress. At this point the shearing stress and shear are zero, and the maximum coefficient of plastic traction is an isotropic or volume viscosity, i.e., the material behaves like a solid. The principal stress corresponding to this maximum coefficient is the bearing strength. At greater stresses the coefficient of plastic traction decreases rapidly and the material is in the region of failure.

A bituminous pavement at rest is conceived as containing simultaneously particles in the disordered state and in the ordered state. The latter state refers to positions of minimum potential energy. Under stress the particles in the ordered state rarely escape their positions, while the remaining particles move from positions of disorder to those of order. At the maximum value of the coefficient of plastic traction the number of particles in the disordered state approaches zero. The change in free energy of activation in going from a disordered to an ordered state and the mass of a particle are also