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Evaluation of Opportunity-Based Accident Rate Expressions

MARK PLASS AND WILLIAM D. BERG

Recent development of opportunity-based accident rate expressions provides a potentially more sensitive set of indicators for use in safety studies. A comparison and evaluation of conventional versus opportunity-based accident rate expressions was undertaken for a set of 50 case study signalized intersections in Broward County, Florida. The effect of level of aggregation of the exposure data was examined, as well as differences in the rating of intersections by degree of hazard. It was found that hourly traffic volume counts may be necessary for reliable estimation of opportunity-based exposure levels and that the use of opportunity-based accident rate measures will yield significantly different hazard rankings compared with conventional accident rate expressions. Issues relating to exposure-based versus conflict-based opportunity expressions are also discussed.

The use of accident rates is a commonplace but not necessarily unbiased method of analyzing hazardous roadway locations. Typically, an accident rate is defined as either the total number of accidents per million vehicle miles or the total number of accidents per million entering vehicles. The first measure would apply to roadway segments, whereas the second is used at specific locations such as intersections.

Although these rate expressions are easily calculated, because of aggregation effects, it is not clear that they accurately reflect the true degree of hazard. In both formulations, number of accidents is expressed as the sum of all accidents that have occurred at a given location over a specified time period. Locations such as intersections often have predominating types of accidents, the existence of which is not apparent because of this aggregation. In addition, the rate formula for intersections uses total entering vehicles and thus does not account for possible correlation between specific accident types and certain combinations of vehicular movements. Reality is therefore lost by the implied assumption that all entering vehicles have an equal probability of being involved in any type of accident.

Recent work by Council et al. (*1*) has resulted in the specification of a set of opportunity-based accident rate expressions that account for the correlation between accident type and vehicle movement. The opportunity-based accident rate differs from the conventional rate in that the number of opportunities

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for a given type of accident to occur is used as the exposure measure rather than total number of entering vehicles. An opportunity consists of the presence of certain prerequisite conditions related to vehicle speeds and relative positions. Without these conditions, the opportunity and therefore the likelihood of a given type of accident do not exist.

Although the work by Council et al. produced a complete specification of opportunity-based accident rate expressions, no evaluation was made of the impact of their application to hazardous location identification, countermeasure development, or before-and-after studies. The research reported here was undertaken with the objective of performing such an evaluation (2). In addition, a second objective was to assess the impact of the level of aggregation used in the calculation of the traffic flow parameters. This is an important issue in terms of the amount of data that is necessary to reliably estimate the exposure levels. The scope of the study was limited to signalized intersections.

REVIEW OF OPPORTUNITY-BASED ACCIDENT RATE EXPRESSIONS

The opportunity-based accident rate expressions (*1*) are derived using an assumed four-leg intersection (Figure 1). For each of four approaches ($i = A, B, C,$ and D), an entering flow rate (f_i) and an approach speed (v_i) are specified. Also recorded are the respective approach widths, W_{ac} and W_{bd} (opposite approaches are assumed to have equal widths so that $W_a = W_c$ and $W_b = W_d$), and the overall area of influence of the intersection (L).

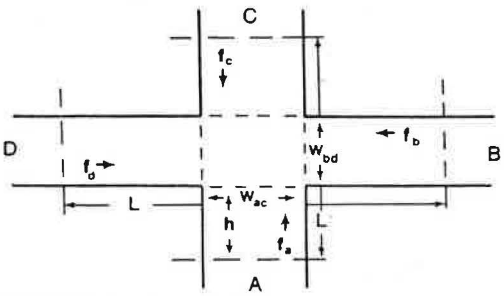

FIGURE 1 Schematic layout of intersection referred to by opportunity equations.

Single-Vehicle Accident Opportunities

A single-vehicle accident is one in which a vehicle runs off the road or strikes a fixed object, or both. The condition that constitutes the opportunity for this type of accident to occur is the presence of a single vehicle within the defined limits (L) of the intersection. The number of opportunities (O_{sv}) at a four-leg intersection during a period of time T is equal to the total number of vehicles entering the intersection. The opportunity equation takes the form

$$O_{sv} = T(f_a + f_b + f_c + f_d) \tag{1}$$

where T is the time period and f_i is the total entering flow rate on approach i.

Rear-End Accident Opportunities

A rear-end accident occurs when a moving vehicle strikes a stopped or slowed vehicle from behind. The opportunity for this type of accident consists of two conditions: two vehicles traveling in the same direction and both vehicles simultaneously within the limits of the intersection. The opportunity equation predicts the number of such pairs of vehicles during a given time period T through the use of a probability distribution function. The distribution function determines the proportion of vehicle headways less than the limits of the intersection L. The number of opportunities during time period T on approach i is equal to

$$O^i_R = Tf\{1 - \exp\,[-(f_i/\tilde{v}_i)L]\} \tag{2}$$

where $\tilde{v}_i = v_iL/(L + v_id_i)$ and d_i is the delay experienced by vehicles on approach i because of the signal.

Head-On Accident Opportunities

A head-on accident is one in which a vehicle strikes a stopped or moving vehicle that is traveling in the opposite direction, including left-turning vehicles. The opportunity for this type of accident consists of two conditions: two vehicles traveling in opposite directions and both vehicles simultaneously within the limits of the intersection. The opportunity equation predicts the number of vehicles traveling in the opposite direction met by an average vehicle on a given approach during both the red and green portions of the cycle for that approach. Opportunity equations are developed for both pairs of approaches (*AC* and *BD* as shown in Figure 1). The equation for the pair of approaches *AC* is

$$\begin{aligned} O_H = {} & (Tf_af_c/7200f_{tot})\,\{f_{bd}\,[(2cf_{bd}/f_{tot})] \\ & + (h + W_{bd})\,[(v^*_a + v_a)/v_av^*_a] + [(2h + W_{bd})/v_a] \\ & + f_{ac}\,[c(f_{bd}/f_{tot})] + 3[(2h + W_{bd})/v]\} \end{aligned} \tag{3}$$

where

$f_{tot} = f_a + d_b + f_c + f_d,$
$f_{ac} = f_a + f_c,$
$f_{bd} = f_b + f_d,$
v^*_a = average velocity of a vehicle that has accelerated from zero at the stop bar,
c = cycle length, and
h = length of intersection approach.

The opportunity equation for the pair of approaches *BD* has the same form as that for approaches *AC*. The total number of opportunities for the intersection is obtained by adding the equations for each pair of approaches.

Angle Accident Opportunities

Angle accidents involve vehicles traveling at right angles to one another that collide within that part of the intersection bounded by the stoplines of each approach. In this case there are two conditions that make up the opportunity: two vehicles traveling at right angles to one another, and both vehicles simultaneously within the area bounded by the stoplines of each approach. Flow products corresponding to perpendicular approaches (f_af_b, f_bf_c, etc.) are used as an estimate of the number of pairs of vehicles that could be involved in an angle collision. The sum of these products, representing an estimate for the entire intersection, is multiplied by an estimate of the percentage of vehicles on each approach that simultaneously pass through the intersection on either a green or red light. This product is then multiplied by an estimate of how long vehicles remain within the area of the intersection. This estimate uses average vehicle speeds to account for those vehicles passing through the intersection on a green or yellow light and those accelerating from a stop. The longer a vehicle takes to pass through the area of angle accident opportunities, the longer it has the opportunity to be involved in an angle accident. The opportunity equation is

$$O_A = T/5280\{[(W_{ac}/v_b^*) + (W_{bd}/v_a^*)](f_af_b + f_bf_c)(P_{g_a}P_{r_b} + P_rP_g)\} \tag{4}$$

where $v_a^* = [v_af_a + 0.83(W_{bd}f_b)^{1/2}]/(f_a + f_b)$ and $v_b^* = [v_bf_b + 0.83(W_{ad}f_a)^{1/2}]/(f_a + f_b)$. P_{g_i} and P_{r_i} are the decimal percentages of vehicles on approach i entering the intersection during the green and red intervals, respectively.

Sideswipe Accident Opportunities

In a sideswipe accident one of two vehicles traveling in the same direction in adjacent lanes encroaches on the other vehicle's lane, which leads to a collision. The conditions of opportunity for a sideswipe accident are two vehicles in adjacent lanes simultaneously within the intersection as defined by L and portions of the vehicles being side by side. An estimate for each approach of such pairs moving through the intersection during the green phase is made, and the number of pairs that form during the red phase at each approach is then added to it.

TABLE 1 INTERSECTION CHARACTERISTICS

Characteristic	No. of Intersections	Characteristic	No. of Intersections
Geometry		Average daily traffic	
Four legs	45		
Three legs	5	Major street	
Signal control		0–10,000	0
Two phase	6	10,000–20,000	3
Three phase	11	20,000–30,000	8
Four phase	8	30,000–40,000	17
Five phase	1	40,000–50,000	12
Six phase	5	>50,000	10
Seven phase	1	Minor street	
Eight phase	18	0–5,000	13
		5,000–10,000	12
		10,000–15,000	7
		15,000–20,000	5
		20,000–25,000	4
		>25,000	9

The opportunity equation for a given approach is the sum of the opportunities occurring during the green and red phases:

$$O^i_{ss} = O^i_{ss,g} + O^i_{ss,r} \tag{5}$$

where

$$O^i_{ss,g} = r_{bd}[Tf_1f_2(v_1 - v_2)L/5280v_1v_2] \qquad \text{if } L(v_1 - v_2)/v_2 > 40 \text{ ft}$$

$$O^i_{ss,g} = r_{bd}[40Tf_1f_2/5280v_1] \qquad \text{if } L(v_1 - v_2)/v_2 \leq 40 \text{ ft}$$

$$O^i_{ss,r} = r_{ac}(Tf_i/2)$$

$$r_{ac} = (f_b + f_c)/f_{tot}$$

$$r_{bd} = (f_a + f_c)/f_{tot}$$

The total number of opportunities for the intersection is obtained by adding the opportunities for the individual approaches.

Accident Rate Equations

Using the opportunity equations just described, two types of accident rates may be calculated. The first is the rate for a specific type of accident and has the form

$$r_i = a_i/O_i \tag{6}$$

where a_i is the number of accidents of type i, and O_i is the number of opportunities for accident type i.

The second type of rate is the total, or aggregate, rate for a given intersection. The total rate may be expressed in two ways:

$$R_1 = \sum_{i=1}^{k} a_i / \sum_{i=1}^{k} O_i \tag{7}$$

$$R_2 = \sum_{i=1}^{k} r_i \tag{8}$$

The R_2 measure only includes the opportunities for the accident types that have actually occurred. Before the accident rates are calculated, a decision must be made regarding an appropriate time period (T) during which flow rates and signal timing will be assumed to remain constant.

DATA BASE

The evaluation of the opportunity-based accident rate expressions was limited to 50 signalized intersections in Broward County, Florida. The basic characteristics of these intersections are summarized in Table 1. Accident data were obtained for each intersection from the Florida Department of Transportation for the year 1982. From these data the total number of vehicle-related accidents at each intersection was determined as well as the number of accidents by type. Conventional accident rates were also calculated for each of the intersections.

The number of opportunities per day at each intersection for

TABLE 2 RESULTS OF *F*-RATIO TEST FOR SIGNIFICANCE OF LEVEL OF AGGREGATION ($\alpha = 0.05$)

Accident Rate	No. of Intersections	Average Day Versus Hourly			Peak/Off-Peak Versus Hourly		
		F[a]	F_c[b]	Significant	F[a]	F_c[b]	Significant
R_1	50	28.91	4.08	Yes	16.89	4.08	Yes
R_2	50	1.04	4.08	No	1.02	4.08	No
Angle	39	3.36	4.17	No	4.59	4.17	Yes
Single-vehicle	29	Rate Values Identical Over Level of Aggregation					
Head-on	7	0.30	5.99	No	0.008	5.99	No
Rear-end	41	119.58	4.08	Yes	119.31	4.08	Yes
Sideswipe	37	36.12	4.17	Yes	50.48	4.17	Yes

[a] Calculated *F*-ratio.
[b] Critical *F*-ratio.

each accident type was computed for three levels of aggregation:

1. Average day: Accident opportunities are calculated by using average hourly flow rates for the 16-hr period from 6:00 a.m. to 10:00 p.m.
2. Peak/off-peak: Accident opportunities are calculated by using average hourly flow rates for the peak (7:00–9:00 a.m. and 4:00–6:00 p.m.) and off-peak (6:00–7:00 a.m., 9:00 a.m.–4:00 p.m., 6:00–10:00 p.m.) periods, and then the results for the two periods are weighted and summed.
3. Hourly: Accident opportunities are calculated for each of the 16 hr from 6:00 a.m. to 10:00 p.m., and then the results for the 16 periods are summed.

Opportunity-based accident rates were then calculated for each level of aggregation at each intersection. Each rate was calculated as the total number of accidents occurring during the study year divided by the annual number of opportunities (365 times the number of opportunities during the average day).

FINDINGS

Effect of Level of Aggregation

The level of aggregation used in calculating the number of opportunities for a given type of accident has the potential to significantly influence the value of the resulting accident rates. This can subsequently introduce uncertainty into the ranking of intersections on the basis of relative hazard, as well as into the evaluation of countermeasure effectiveness.

An evaluation of these impacts was made by comparing the R_1, R_2, and individual opportunity-based accident rates calculated at each of the levels of aggregation identified earlier. For each accident rate type (R_1, R_2, angle, single-vehicle, head-on, rear-end, and sideswipe), an $m \times 3$ matrix of accident rates was prepared. The number of rows (m) corresponded to the number of intersections that experienced that accident type, each row representing a specific intersection. Each of the three columns corresponded to one of the three levels of aggregation. Using the hourly level as the base, a set of *F*-ratio tests (*3*, pp. 383–384) was performed to determine whether accident rates calculated using a higher level of aggregation are significantly different at the 95 percent level of confidence. As summarized in Table 2, there were statistically significant differences between accident rate values calculated at a low level of aggregation (hourly) and those calculated at higher levels (average day, peak/off-peak) for the R_1 total rate and the rear-end and sideswipe individual rates. This implies that level of aggregation does have an important effect and that the opportunity expressions may need to be calculated at the hourly level to assure the most reasonable and reliable safety evaluations.

Sensitivity of Hazard Rankings to Exposure Measures

Rankings of the 10 most hazardous study intersections on the basis of accident rate were made by using both conventional (accidents per million vehicles) and opportunity-based (accidents per million opportunities) rate measures as summarized in Tables 3 and 4. The opportunity-based measures were calculated at the hourly level of aggregation. This level was selected on the basis that it would provide the most accurate estimate of the opportunities for the occurrence of accidents and, as revealed by the *F*-ratio tests, some accident rates calculated at this level are significantly different from those calculated at a higher level of aggregation.

As shown in Table 3, the R_1 and R_2 rankings differ from the

TABLE 3 HAZARD RANKING OF CASE STUDY INTERSECTIONS BY OVERALL ACCIDENT RATE

Conventional		R_1		R_2	
Intersection	Rate[a]	Intersection	Rate[b]	Intersection	Rate[b]
49	3.64	15	0.171	36	5.847
15	2.79	49	0.118	47	0.679
5	2.72	42	0.082	31	0.196
42	2.64	7	0.079	15	0.171
40	2.61	29	0.078	49	0.122
24	2.52	40	0.064	12	0.089
34	2.40	39	0.056	42	0.086
22	2.19	5	0.054	27	0.085
7	2.09	34	0.051	29	0.082
21	2.02	1	0.049	7	0.079

[a] Accidents per million vehicles.
[b] Accidents per million opportunities.

TABLE 4 HAZARD RANKING OF CASE STUDY INTERSECTIONS BY INDIVIDUAL ACCIDENT TYPES

R_1		Angle		Single-Vehicle		Head-On		Rear-End		Sideswipe	
Intersection	Rate	Intersection	Rate	Intersection	Rate	Intersection	Rate	Intersection	Rate	Intersection	Rate
15	0.171	15	4598.2	49	0.552	15	0.375	34	1.13	15	0.0400
49	0.118	49	111.3	42	0.329	7	0.327	42	1.11	49	0.0205
42	0.082	29	64.2	34	0.286	29	0.169	6	1.08	42	0.0220
7	0.079	37	39.7	22	0.233	9	0.119	11	1.06	7	0.0150
29	0.078	48	37.0	32	0.195	1	0.115	5	0.96	39	0.0140
40	0.064	31	21.7	29	0.180	5	0.106	24	0.96	28	0.0130
39	0.056	30	17.0	8	0.164	18	0.079	15	0.92	8	0.0116
5	0.054	40	16.5	43	0.154	8	0.079	8	0.85	5	0.0114
34	0.051	46	10.7	44	0.137	10	0.065	23	0.83	22	0.0112
1	0.049	39	10.0	23	0.094	19	0.050	22	0.82	23	0.0108

conventional at each position within the ranking. In addition, of the 10 most hazardous intersections according to the conventional accident rate, only 7 appear in the R_1 list and 4 in the R_2 list. This is significant only from the standpoint that it reflects the difference in what is being measured (i.e., accidents per entering vehicles as opposed to accidents per opportunities). Because different things are being measured, it would be expected that the rankings would also differ. If the rankings obtained through the opportunity-based R_1 and R_2 measures did not significantly differ from the conventional ranking, the higher level of sensitivity to hazard implied by the opportunity-based measure would be in doubt.

The differences between the R_1 and R_2 rankings is a reflection of the varying sensitivity to hazard found within the opportunity-based measures. This sensitivity is related to the level of aggregation used in establishing the total accident opportunities. In the case of the R_1 measure, the level of aggregation is high, because all possible opportunities are used in the denominator of the rate expression. In effect, the R_1 rate measure provides an indication of the overall "level of service" offered by an intersection. The inclusion of opportunities for occurring accident types gives an indication of relative hazard, whereas the additional use of opportunities for nonoccurring types allows for a reflection of the relative safety at the intersection.

The R_2 measure, on the other hand, uses only opportunities for accident types that actually occurred. In instances where only one type of accident has occurred, the R_2 measure becomes, in essence, an individual rate measure and is therefore more sensitive to the specific hazard than the R_1 measure. In cases where more than one accident type has occurred, the R_2 measure tends to mask specific hazards, as does the R_1 measure because of the increased aggregation of opportunities. However, the R_2 measure also fails to completely account for the level of safety implied by the lack of certain types of accidents. In addition, it has the potential to be biased in cases where the occurrence of a given accident type at an intersection is reduced to zero from a given year to the next. Because the R_2 rate expression uses only opportunities corresponding to occurring accident types in its denominator, a reduction to zero for a given accident type can result in a significant change in the value of the denominator, and therefore in the rate value (and implied hazard) assigned to the intersection. In the following hypothetical example, the total number of accidents at one of the study intersections has been reduced by 33 percent, resulting in an increase of approximately 11,000 percent in the R_2 rate measure (expressed as accidents per million opportunities):

	1982		*1983 (hypothetical)*	
	No. of Accidents	*R_2 Rate*	*No. of Accidents*	*R_2 Rate*
Angle	4		4	
Sideswipe	2		0	
Total	6	0.196	4	21.713

The data in Table 4 can also be used to examine the relationship between overall accident rate and individual accident types. Using the ranking of the 10 most hazardous intersections based on the R_1 rate, only 3 of these appear on the lists of the 10 intersections with the highest angle and head-on accidents, only 4 appear on the single-vehicle list, and only 6 appear on the rear-end and sideswipe lists. This demonstrates that overall accident rates are not necessarily good indicators of the existence of special types of hazardous conditions that may merit additional attention. This should not be unexpected given that collision diagrams generally reveal an accident pattern in which some, but not all, accident types dominate. This furthermore suggests that some treatable intersection problems may escape notice if overall accident rates are the only indicators used to identify hazardous locations. Upon implementation of a countermeasure to address a specific problem, a before-and-after comparison using the associated rate for that accident type and adjusted for regression to the mean would clearly be the most sensitive indicator of countermeasure effectiveness.

CONCLUSIONS

The level of aggregation used in calculating the opportunity expressions has a significant impact on the value of the R_1 total rate and the rear-end and sideswipe individual rates. This suggests that the use of hourly traffic count data for the calculation of the opportunity expressions will reduce the likelihood of creating bias in hazard rankings or error in before-and-after comparisons.

On the basis of the case study comparisons, it is clear that the conventional accident rate does not provide the same indication of hazard as the opportunity-based measures. The conventional measure is considered to be a less sensitive indicator because it assumes that all vehicles entering an intersection are equally likely to be involved in any type of accident. In addition, the predominance of certain accident types cannot be made apparent by the rate values because of the aggregation of all occurring accidents in the rate expression.

In comparing the R_1 and R_2 opportunity-based measures, the criteria for using a total accident rate measure and the degree to which each measure meets the criteria must be considered. The reason for using a total rate is simply to provide a basis for comparison of relative overall intersection hazard. The R_1 measure achieves this in its use of both opportunities corresponding to occurring accidents, which denotes relative hazard, and opportunities corresponding to accident types that did not occur, which denotes relative level of safety. The R_2 measure is sensitive to specific hazard in instances where only one type of accident has occurred, in which case it effectively becomes an individual rate. Whenever more than one type of accident occurs, the R_2 measure becomes similar to the R_1 from the standpoint that specific problems are masked. However, because opportunities for accident types that did not occur are not included in the R_2 rate expression, the relative safety of an intersection is not reflected in the rate value. Because neither measure is strictly able to identify specific hazards, the R_1 measure, which offers the most balanced appraisal of overall relative hazard, is considered the most appropriate for use as a means of overall comparison.

In considering the applicability of the various accident rate measures to the identification of hazardous locations, the development of countermeasures, and the performance of before-and-after studies, several recommendations are offered. First, the identification of hazardous locations is obviously critical and is achieved to some degree by the conventional and the R_1 and R_2 measures. Although each of these is capable of illustrating relative hazard among a group of intersections by the assignment of aggregate rate values, none is able to address the specific hazards. As discussed previously, the aggregation present in each of their measurements causes the "true" hazard at a given location either to be masked or, in the case of the R_2 measure, to be represented in a biased manner.

The use of individual opportunity-based accident rates would be the most effective means of identifying specific hazards. Rather than a single ranking of hazardous intersections whose true hazards would not be apparent if total accident rates were used, individual rankings by accident type would be more appropriate. The use of individual rate measures would not only provide an efficient and effective means of hazard identification, but would also facilitate the development of countermeasures because the hazards they are designed to alleviate would be made apparent.

For before-and-after studies, both conventional and total opportunity-based measures lack sensitivity because of the aggregation of accident types present in their rate expressions. The effect of a countermeasure will not always be apparent from these measures because it is not possible to determine whether the accident type related to the countermeasure has been reduced. Individual rates, on the other hand, address specific accident types and therefore offer the best appraisal of the effect a countermeasure has had.

FUTURE RESEARCH

The opportunity-based accident rate expressions examined in this research are now undergoing further refinement by Council and his colleagues at the University of North Carolina. Nevertheless, the general observations noted regarding the effect of the level of aggregation used in calculating opportunities and the sensitivity of various accident rate formulations to specific types of hazard are likely to remain relevant. One issue that merits additional research is the relationship between the specification of the opportunity-based accident rates and their sensitivity to changes in intersection geometry and signal timing. At the heart of this matter is the fundamental question of whether these opportunity expressions are measuring exposure to accidents or traffic conflicts that may result in an accident. An excellent discussion of this definitional problem can be found in a paper by Hauer (*4*).

If the opportunity expressions are specified to measure exposure to various accident types, then their numerical value for any given intersection should be independent of geometrics and signal timing (except where certain movements become prohibited) and should only be a function of the exposed traffic flows. The safety effectiveness of common geometric and signal timing improvements will then be measurable by using accident rates formulated with exposure-based opportunities. This is an important capability because safety is fundamentally achieved by separating traffic flows either spatially or temporally. Accordingly, safety measures of effectiveness should be sensitive to these types of countermeasures.

On the other hand, if opportunity expressions are specified to measure expected number of vehicle conflicts of various types, then their numerical value will be dependent on the geometrics and signal timing at the intersection. This means that accident rates calculated by using conflict-based opportunities will be relatively insensitive to the geometric and signal timing characteristics of the site because the effect of these elements will have already been accounted for in the denominator of the accident rate expression. However, such accident rates would presumably remain sensitive to the effects of human factors, environmental conditions, and information system design at the intersection.

The implication of these comments is that if one can predict conflicts, a certain fraction of which result in accidents, then the expected number of conflicts becomes a surrogate measure for the expected accident rate. This is analogous to the premise underlying the traffic conflicts technique (*5*). Expressions for estimating the expected number of conflicts as a function of traffic flows, intersection geometry, and signal timing would become useful planning and design tools for the engineer. They would effectively complement the delay-based evaluation techniques found in the *Highway Capacity Manual* (*6*).

Where accident data rather than conflict data are to be used in evaluating relative safety, the denominator of the accident rate expression should reflect exposure to accidents. With a reasonable formulation of exposure, it should be possible to have an indicator that can be used to evaluate the safety effectiveness of a variety of countermeasures aimed at achieving higher levels of flow separation. These would include various forms of channelization and signal timing (especially left-turn phasing alternatives).

The opportunity expressions examined in this research include several that fall in the category of a conflict measure rather than an exposure measure. It is recommended that future research closely examine the exposure versus conflict issue as well as the sensitivity of the resulting accident rate expressions to typical countermeasures.

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Demonstration of Regression Analysis with Error in the Independent Variable

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Regression analysis is frequently used in the engineering field to develop mathematical models for a wide variety of applications. Of the several assumptions upon which regression theory is based, one of the most fundamental is that the *X*-values are known exactly and that any error is associated only with the *Y*-measurements. Because this is not the case for many engineering applications, a study was conducted (*a*) to determine the magnitude of this problem and (*b*) to develop and test a software package that incorporates a theoretical solution found in the literature. Computer simulation is used to demonstrate both the seriousness of the problem and the effectiveness of the solution. An example based on early-strength tests of concrete is presented.

Many engineering applications require the development of a mathematical model (equation) to characterize some physical relationship. Examples include those shown in Table 1.

In the first example, the objective is a reliable early predictor of the 28-day strength of concrete, a measure upon which many acceptance procedures are based. The objective of the second example is to replace a costly and time-consuming subjective rating procedure with a simple mechanical device. In the third example, a relationship is sought that will become an integral part of a pavement management system.

The variable to be predicted or estimated is placed on the Y-axis and an equation of the form $y = f(x)$ is desired. The equation may be linear, quadratic, exponential, or any other appropriate form. The analyst, from his understanding of the physical process, will often know the correct form in advance. In other cases, it may be necessary to let the data dictate the form.

The desired relationship is often derived empirically from a set of X,Y-data values by using the technique of least squares (*1*) as shown in Figure 1. The procedure, invisible to the analyst when executed by a computer program, consists of solving for

TABLE 1 PHYSICAL RELATIONSHIPS CHARACTERIZED BY MATHEMATICAL MODELS

Characteristic of Interest	*X*-Data (Independent Variable)	*Y*-Data (Dependent Variable)
Compressive strength of concrete	Seven-day test results	Twenty-eight-day test results
Rating of highway pavement serviceability	Output of mechanical roughness-measuring device	Average rating of a team of panelists
Rating of highway pavement serviceability	Cumulative axle loads	Current rating of serviceability

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