Conceptual Development of Exposure Measures for Evaluating Highway Safety

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An overview of exposure measures such as distance, time, traffic volume, vehicle hours, and vehicle miles used in the past for evaluating accidents on highways and intersections is presented. Their inadequacy and insufficiency are discussed. The conceptual exposure measures for evaluating highway safety are presented for the sections between signalized intersections and at intersections. Exposure measure is suggested to include all highway and traffic elements that affect accidents in the highway-traffic-environment system. Also suggested is that the number of accidents is the square of the exposure measure that operates in the highway-traffic-environment system.

Accident information is required for a variety of safety activities undertaken by states and localities. This information assists in identification of safety problems, establishment of priority locations for safety improvements, and evaluation of specific accident countermeasures. Although this information is essential, some basic problems exist. Accurate accident data are difficult to obtain and, in some cases, totally unavailable. In addition, accident data must be combined with exposure measures in order to place the accident information in perspective so that the effects of various highway and traffic elements on accident risk can be explicitly compared within or between classifications of interest.

For a long time, highway engineers and researchers have realized the necessity of accident-exposure measures. Thorpe (1), in 1967, pointed out that the lack of knowledge on accident-exposure measures severely hampers accident-reduction efforts. Unless the exposure is known, the relative hazards of various situations cannot be compared.

To use accident data without using the appropriate exposure measure can be misleading. Council and others (2) reported that a simple tally of accidents indicates that daytime accidents are more frequent than nighttime accidents. However, when mileage driven during the two periods is considered, the indication is reversed and the risk of a nighttime accident is about twice that of a daytime accident. The use of the appropriate type of exposure measure not only clarifies the relation but sometimes alters the conclusion.

Carroll (3) explained that the primary use of exposure data was the identification of highway safety problems and evaluation of various countermeasures. Exposure data are needed to determine the optimum cost-effectiveness with respect to the classifications of the types of roadways, vehicles, accidents, and the environment.

Carroll and others (4) defined exposure as the frequency of traffic events that create a risk of accidents, measured in vehicle miles of travel (VMT). Vehicle mileage appears to be the prevalent choice to measure the amount of risk for accidents. However, a simple argument shows that this is neither the always acceptable choice nor necessarily the best choice. For example, a car that is driven slower than another car over the same distance, all other things being equal, will meet more on-coming cars than will the other and will therefore have more possibilities of getting into certain types of accidents. This example points out that the time spent on the road appears to be a better measure of the exposure than mileage. However, both are not perfect exposure measures: The same amount of miles or time spent on a road that has fewer intersections is less dangerous than the same exposure on a road that has more intersections, as evidenced by the lower accident rates on limited-access highways. Therefore, Joksch (5) points out that development of a measure of exposure that combines time or mileage with other relevant factors would be desirable.

Haight (6) refines exposure further by relating the size and power of vehicles in the traffic stream, the age and experience of the drivers, weather conditions, time of day, and various classes of accidents. Many factors of the road transportation system could reasonably enter into a definition of exposure. The unanswered problem is in determining what these factors are and what importance should be attached to each.

Exposure measures to evaluate the number of accidents experienced by an individual or group of individuals are not of interest in this study. In other words, the concept of accident proneness (7) (i.e., those situations where some individuals are more likely to have an accident than others due to some characteristic property of theirs) will not be considered.

Highways will be classified into two segments in this paper: sections between signalized intersections and sections at intersections. An overview of exposure measures used in the past for these two segments is presented. Conceptual exposure measures to account for accident risk in the highway-traffic-environment system are suggested.

EXPOSURE MEASURES USED BETWEEN SIGNALIZED INTERSECTIONS

Several exposure measures have been employed for the area between signalized intersections in the past. These exposure measures are mainly in the form of distance, time, traffic volume, and the interaction (or product) of these elements such as vehicle miles and vehicle hours.

Distance

The exposure measure in terms of distance is expressed in miles. Accident rate will be expressed in accidents per mile as follows:

$$R = A/L \qquad (1)$$

where

R = accident rate,
A = number of annual accidents, and
L = section length (miles).

We assume by using this measure that longer sections have a higher risk of accidents than shorter sections. However, in highway environments, when the traffic volume on intersecting driveways and side streets increases, lengths of the noncontrolled sections become smaller due to the need for traffic control devices such as signals. In other words, the natural evolution of traffic development makes the shorter highway sections more dangerous than the longer highway section. This is easily seen in the dichotomy of urban and rural highways, in which the former has shorter sections and the latter has longer sections. In addition, the meaningfulness of the exposure measure is reduced as the distance over which the rate is computed becomes smaller. This means that, at a single point, the mileage-based accident rates are completely meaningless.

One possible improvement in the expression of an accident rate in terms of section length is one that involves both the length of section and the number of conflicting movements that operate along the sections. This will be accomplished by using measures such as the number of access points, access trips to and from commercial driveways, and the ratio of access trips to through trips (8).

Time

The exposure measure in terms of time is expressed as the number of hours driven, which can be derived mathematically by the division of section length by average speed as follows:

$$R = A/(L/S) \quad (2)$$

where S is the average speed in miles per hour, and others are defined previously.

The use of time as an exposure measure is based on the assumption that an increase in time spent on the road is accompanied by an increase in accident risk. However, higher speeds are, in general, more dangerous than lower speeds. Since estimation of speed on an individual basis is not of interest, estimation on a highway system basis will lead to vehicle hours of operation as follows:

$$R = A/(VM/S) = A/VH \quad (3)$$

where VM is the vehicle miles obtained by traffic volume times section length and VH is the vehicle hours spent on the highway system.

The exposure measure of vehicle hours takes into account the time drivers spend on the highway system. Although vehicle hours of operation is useful to analyze vehicle reliability among different transportation modes, it does not appear to be a good exposure measure for highway systems. Two reasons can be cited for its inappropriateness (9). The first is that not all time spent in travel is of equal accident risk. The second is that it tends to neglect those highway accidents that occur during relatively short time periods.

A possible alternative approach to expressing accident rates in terms of the effect of time spent on the highway would be a technique that adjusts the numerator as opposed to the denominator. In other words, the time spent effect can be appropriately taken into account by the classification of daytime versus nighttime accidents, dry-pavement versus wet-pavement accidents, and accidents caused by different vehicle types due to different speeds. Within this classification, vehicle hours may be analyzed as one of several factors.

Traffic Volume

The exposure measure in terms of traffic volume is usually reported as annual average daily traffic (AADT), peak-hour volume (PHV), and off-peak-hour volume (OPHV). The accident rate is defined as follows:

$$R = A/V \quad (4)$$

where V is the traffic volume in the form of AADT, PHV, or OPHV.

Numerous studies show high correlation among AADT, PHV, and daytime OPHV (8,11); therefore, the use of one of these three volume classes may be satisfactory.

The exposure measure of traffic volume takes into account the interaction effect among vehicles because it is assumed that accident risk increases as volume increases. However, as traffic volume increases toward capacity, accident risk decreases. In addition, as traffic volume increases, single-vehicle accidents, in general, decrease. For example, Chapman (9) reported the empirical relation by using New Zealand data, as follows:

$$p = \exp(-0.000\,865V) \quad (5)$$

where p is the proportion of single-vehicle accidents to all accidents and V is the traffic volume per hour in both directions.

The proper approach to express accident rate in terms of traffic volume is to separate the numerator into single-vehicle versus multiple-vehicle accidents, vehicle types such as trucks and cars, and combinations of these classifications. Within this classification, traffic volume may be analyzed as one of several factors.

Vehicle Miles

The most commonly used exposure measure in accident rates is vehicle miles. The expression for this measure is as follows:

$$R = A/VM \quad (6)$$

Note that the magnitude of the constant, such as 100 million vehicle miles or million vehicle miles, in no way affects the relative comparison of accident rates.

It is assumed in this exposure measure that accident risk increases as more vehicles travel more miles. However, conceptually the assumption itself appears to be incorrect. As is reported by many studies on accident likelihood, the probability or possibility of a driver who has extensive driving experience being involved in an accident is far lower than that of a younger driver who has less driving experience. Although part of the reason is attributable to driver characteristics, Greenberg (12) showed the existance of an accident-experience learning curve. He indicated that the number of accidents per mile decreases as the cumulative mileage increases and compares this with industrial learning curves of occupational injury as it relates to cumulative volume of production. In addition, an exposure measure of vehicle miles does not take into account the different risks associated with highway geometry and their interaction with traffic volume.

CONCEPTUAL DEVELOPMENT OF EXPOSURE MEASURES

From an overview, it appears that conventional exposure measures of accidents are either inappropriate or insufficient. Conventionally, an exposure measure is treated exclusively of highway geometrics and the roadway environment. The variables typically used for exposure measures were time, distance, traffic volume, and the product of these elements. However, as pointed out, many aspects of the highway-traffic-environment system enter into the exposure measure. The question is, What highway and traffic elements should be included in exposure measures and of what importance and relation are these variables to accident risk?

Previously, an induced exposure measure first suggested by Thorpe (1) and modified by Haight (6) had received attention due to the difficulty in estimating accurate exposure measures by driver and vehicle types. However, the induced exposure measure suggested can only indicate what importance each of the variables of interest has relative to other variables on accident risk. Aside from the validity of the assumption and limitations on the applicability of accident causative factors, it cannot determine the functional relation of the variables to explain accident risk. As pointed out by Carr (11), "The best measure of exposure is clearly some form of site-matching in a rigorously controlled, expert investigation." Accident rates are expressed as follows:

$$A/E(x) = f(x) \tag{7}$$

where

A = annual number of accidents,
E(x) = exposure measure as a function of x,
f(x) = accident rate as a function of x, and
x = highway and traffic elements that affect accidents.

As mentioned, typical variables used for the exposure measure function [E(x)] were time, distance, traffic volume, and the product of these elements. However, many factors in the highway-traffic-environment system enter into exposure measures that represent potential accident risk.

Let E(x) in Equation 7 be a linear combination of variables related to the accident risk. Then,

$$E(x) = a + b_1x_1 + b_2x_2 + \ldots + b_nx_n \tag{8}$$

where a, b_i are constant $(i = 1,\ldots,n)$ and x_i is the exposure variable $(i = 1,\ldots,n)$.

Then, each b_i will represent the different weights associated with accident risk that correspond to each exposure variable x_i. Furthermore, the function f(x) in Equation 7 is also composed of variables to indicate the different contribution of accident rate for each exposure variable that exists in the highway-traffic-environment system. Therefore, the two functions E(x) and f(x) should be equal because a variable could not possess different weights associated with accident risk. That is,

$$E(x) = f(x) \tag{9}$$

Substitution of Equation 9 into Equation 7 yields

$$A = f^2(x) = E^2(x) \text{ or } \sqrt{A} = E(x) = f(x) \tag{10}$$

Equation 10 shows that the annual number of accidents is the function of the square of the exposure measure that is the combination of variables. Note that the concept is equally applicable to both linear and nonlinear combinations of variables.

Empirical Evaluation of Exposure Measure Used Between Signalized Intersections

The concept is empirically supported from the study by Heimbach and others (8) by using the North Carolina accident data. The objective of the study was to investigate the effect of lane width on traffic operations and accidents on urban four-lane arterials. Sites were limited between signalized intersections that are not influenced by traffic signals. Accident data were classified into four groups based on the initial classification of 17 accident types. They were (a) all accidents, (b) flow-interruption accidents including rear-end accidents and accidents due to vehicles attempts to enter or leave side streets or adjacent land use activities, (c) lane-width accidents due to roadway geometry and maneuvering skills, and (d) lane-maneuver accidents as a subset of lane-width accidents to cover lane-encroachment and lane-changing accidents. It becomes apparent in grouping accident data that accidents that involve flow interruptions are not related to lane width.

The study analyzed four types of accident exposure measures. These are vehicle accidents per year, annual vehicle accidents per mile, annual vehicle accidents per 100 million vehicle miles, and the square root of the annual vehicle accidents.

By using multiple linear regression, the analysis obtained statistically significant independent variables and a coefficient of multiple determination (R^2) for various accident models. The dependent variables used are as follows:

RVAPY = square root transform of total vehicle accidents per year,
VAPY = total vehicle accidents per year,
VAPM = total vehicle accidents per year per mile,
VART = total vehicle accidents per year per 100 million vehicle miles,
RFIAPY = square root transform of flow-interruption accidents per year,
FIAPY = flow-interruption accidents per year,
FIAPM = flow-interruption accidents per year per mile,
FIART = flow-interruption accidents per year per 100 million vehicle miles,
RLWAPY = square root transform of lane-width accidents per year,
LWAPY = lane-width accidents per year,
LWAPM = lane-width accidents per year per mile,
LWART = lane-width accidents per year per 100 million vehicle miles,
RLMAPY = square root transform of lane-maneuver accidents per year,
LMAPY = lane-maneuver accidents per year,
LMAPM = lane-maneuver accidents per year per mile, and
LMART = lane-maneuver accidents per year per 100 million vehicle miles.

The independent variables used are as follows:

NNINT = number of side street intersections per mile,
ATCDW = number of access trips to and from commercial driveways,
ADT = average daily traffic,
HR = square root of the sum of the changes in horizontal direction,
VR = square root of the sum of the changes in vertical elevation,
LW = total traffic lane widths,
NINT = number of side street intersections,
TACR = total access trip conflict ratio (sum of access trips divided by ADT), and
NATCDW = number of access trips to and from commercial driveways per mile.

Table 1 shows that the models that involve the square root of the annual number of accidents (RVAPY, RFIAPY, RLWAPY, RLMAPY) not only had the greatest explained variation (see R^2) but also demonstrated the variables attributable to different accident types. For example, the flow-interruption accidents (about three-quarters of all accidents) that involved rear-end accidents and accidents due to vehicles entering or leaving side streets and driveways are not associated with highway geometric

Table 1. Comparison of accident rate models.

Grouping	Dependent Variables	Independent Variables Significant at $\alpha = 0.10$	R^2 (%)	Detransformed[a] R^2 (%)
All accidents	RVAPY	NNINT, ATCDW, ADT, HR, LW, VR	72	76
	VAPY	NINT, ATCDW, ADT	69	NA
	VAPM	NNINT, ATCDW, ADT	58	NA
	VART	TACR, NNINT, NATCDW	37	NA
Flow-interruption accidents	RFIPAY	NINT, ATCDW, ADT, TACR	69	76
	FIAPY	NINT, ATCDW, ADT	70	NA
	FIAPM	NNINT, NATCDW, ADT	56	NA
	FIART	TACR	23	NA
Lane-width accidents	RLWAPY	NINT, ATCDW, ADT, LW, VR, HR	73	65
	LWAPY	NINT, NCDW, ATCDW, ADT HR	63	NA
	LWAPM	NNINT, ATCDW, ADT LW	57	NA
	LWART	NNINT, NNCDW, LW, HR, VR	49	NA
Lane-maneuver accidents	RLMAPY	NNINT, ATCDW, ADT, LW, HR, VR	70	66
	LMAPY	NINT, ATCDW, ADT	61	NA
	LMAPM	NNINT, ADT, ATCDW	53	NA
	LMART	NNINT, ATCDW, LW	38	NA

[a]Detransformed is the process of converting RVAPY to VAPY by using significant figure.

elements. A rather significant association with those factors that interrupt steady flow such as (a) the number of intersections, (b) the number of conflicting movements due to commercial driveways, (c) the average daily traffic, and (d) the ratio of conflicting movements to ADT is indicated. However, lane-width accidents and lane-maneuver accidents, which are assumed to be due to not only traffic volume but also highway geometry, revealed exact relations by such variables as lane width, horizontal alignments, and vertical alignments. However, other accident-exposure measures, such as section length and vehicle miles of travel, failed not only to explain more variation but also to relate these relations accurately. The study revealed that accident rate per vehicle mile is the poorest model, in terms of both the least association with the variation for all four accident groupings and the misleading relation with classified accident characteristics contrary to the general tendency to take it as granted. If others would analyze the data by using only accident rates per vehicle mile, their conclusion would be erroneous and misleading.

The most important thing to note in Table 1 is that the different types of dependent variables are associated with different independent variables. Therefore, for different accident-exposure measures the countermeasure will be different. Thus, different exposures will adversely affect the efforts to improve safety.

Exposure Measures for Intersections

Each year about half of all accidents that occur in urban areas take place at intersections, and in rural areas about a quarter of all accidents are intersection related (13). Unsignalized intersections and signalized intersections have different risks of different accident types. Universally accepted is that, in general, proportionately more angle collisions take place at unsignalized intersections and more rear-end collisions take place at signalized intersections. The accident-exposure measure for intersections should reflect these characteristics, among others.

Exposure measures used in the past for intersections were based on the concept of conflict points, defined as the points or sections where two-directional traffic meets together. These will be points and sections where crossing, merging, and diverging maneuvers occur. Difference was found in the definition of conflicting maneuvers and the combined forms of traffic volume. Some treated all crossing, merging, and diverging movements as conflict traffic, and others considered one or more of them as conflict traffic. Also, some treated conflict traffic volume separately and others considered them as the sum of one or more approach-leg traffic volumes.

Note that these exposure measures, based on collision points, are only applicable to multivehicle accidents and not to single-vehicle accidents. Of course, single-vehicle accidents should be looked on as a function of a traffic volume not of a pair of conflicting volumes. In both cases, other elements that operate at the intersection, such as traffic control devices, speed, and geometry, should be examined.

Unsignalized Intersections

Grossman (14) defined collision points as conflict points in crossing maneuvers only. The exposure index at an intersection is defined as the total summation of the pairs of traffic volumes (ADT) at these collision points. Surti (15) used the same collision-points concept but added the merging maneuver. He used the product of the pair of traffic volumes at collision points by using peak-hour volume. However, he did not differentiate the different likelihood of accidents for different maneuvers.

Peleg (16) proposed collision points as the conflict points for crossing, merging, and diverging maneuvers. He considered an exposure measure as the product of the total number of vehicles per hour and the total number of collision points. However, this approach neglects that not all of the traffic at the intersection is in conflict at every collision point.

Some researchers approached intersection accident exposure as two intersecting conflict zones instead of conflicting points. From this concept, Chapman (17) proposed an exposure measure at a single conflict zone as follows:

$$E = [1 - \exp(-q_1 t)]\ [1 - \exp(-q_2 t)]\,T/t \tag{11}$$

where

E = accident exposure over time T,
q_1, q_2 = flows per unit time, and
t = time taken for a vehicle from direction 1 to pass in front of a vehicle from direction 2 plus the time for a vehicle from direction 2 to pass in front of a vehicle from direction 1.

Holland (18), who independently used a similar approach, added overall conflict zones within a four-leg intersection and derived the basic equation below for a range of volumes and turning flows.

$$E = KV_1{}^aV_2{}^b \tag{12}$$

where

E = accident exposure per time unit,
V_1, V_2 = hourly aggregate major and minor traffic volume, and
K, a, b = constants.

Richardson (19) generalized the Chapman (17) and Holland (18) approaches by allowing that either a direction A vehicle could conceptually hit a direction B vehicle or vice versa and the directional speeds could both be different. Richardson's theoretical exposure formulation is as follows:

$$E = T\Big[\{[1 - \exp(-q_At_B)]\,[1 - \exp(-q_Bt_B)]/t_B\} + \{[1 - \exp(-q_At_A)]\,[1 - \exp(-q_Bt_A)]/t_A\}\Big] \tag{13}$$

where

E = accident exposure over time T,
q_A, q_B = direction A and B flows per unit time, and
t_A, t_B = time for an A vehicle to clear the conflict zone and the time for a B vehicle to clear the conflict zone, respectively.

Hodge and Richardson (20) attempted to evaluate Richardson's (19) theoretical exposure formulation by using a simulation model. Their simulation results suggest that the exposure level between two crossing movements is simply proportional to the product of the intersecting volume. That is,

$$E = V_1 \cdot V_2 \tag{14}$$

The generalization of this equation would be

$$E = K(V_1 \cdot V_2)^c \tag{15}$$

where c is a constant.

Tanner (21) found that c equals 0.5, Leong (22) suggested c equals 0.42, and Hodge and Richardson (20) found c to be equal to 1. In summary, exposure measures suggested for unsignalized intersections in the past were as follows. For simplicity, these are shown in mathematical form.

$\Sigma(V_i + V_j)\ \delta_{ij}$ Grossman (14),
$\Sigma(V_i \cdot V_j)\ \delta_{ij}$ Surti (15),
$N\ \Sigma\ V_{ij}$ Peleg (16),
$(V_1 \cdot V_2)^a$ Tanner (21) and others, and
$V_1{}^b \cdot V_2{}^c$ Holland (18).

where

V = traffic volume,
i, j = traffic direction,
N = total number of conflicting points,
V_1 = major traffic volume,
V_2 = minor traffic volume,
a, b, c = constants, and
δ_{ij} = 1 if i and j are in conflicting points, 0 if i and j are not in conflicting points.

Note in the above summary that exposure measures suggested in the past were exclusive of intersection geometry and other traffic elements except traffic volume. Also note that the conventional approach treated crossing, merging, and diverging maneuvers as having the same accident risk.

Extension of Exposure Measures for Intersections

A logical assumption may be that different conflicting maneuvers have different accident risk. Two approaches may be possible to reflect this assumption. One is to differentiate the different traffic conflicts and the other is to differentiate the functional form of interactions between different traffic conflicts. For example, crossing maneuvers at intersections may have greater accident risk than other conflicting maneuvers and can be reflected by the product form while others are reflected as the summation form. Also necessary is that the intersection geometric features and other traffic elements, including traffic control devices, be included for measurement of intersection exposure. Therefore, the suggested measure of intersection exposure will be oriented as follows:

$f\{(V_i \cdot V_j)^p\ \delta_{ijk},\ (V_i + V_j)^q\ \delta_{ijk},$ and other intersection geometric and traffic elements$\}$

where

p, q = constant (probably, $0 < p < 1$),
k = type of conflict maneuver (crossing, merging, and diverging), and
δ_{ijk} = 1 if i and j having maneuver type k are in conflicting directions, 0 if i and j having maneuver type k are not in conflicting directions.

Signalized Intersections

At signalized intersections, the magnitude of accident risk depends not only on conflicting traffic volumes but also on site parameters such as signal phases, cycle length, splits, lens size, signal mountings, and the types of signal actuation. These components of traffic signals are found to be significantly related to traffic accidents at signalized intersections (23,24).

An accident exposure measure is desirable that can incorporate as many factors as is reasonable to distinguish varying accident experiences at signalized intersections. Thus, the suggested exposure measure at signalized intersections will be oriented as follows:

$f\{(V_i \cdot V_j)^p\ \delta_{ijk},\ (V_i + V_j)^q\ \delta_{ijk},$ other intersection geometric and traffic elements, and components of traffic signals and their operation$\}$

Note, again, that the exposure measures for both unsignalized and signalized intersections should be developed from the relation of $A = f^2(x)$ presented in Equation 10. A word of caution is added to the boundary of intersection accidents that is different from study to study. Some studies did not even mention what distance from the intersection was defined as the point where accidents become intersection related. The definition of intersection accidents with respect to distance to the boundary should be explicitly established for both the major and minor streets.

CONCLUSIONS

An overview of exposure measures such as distance, time, traffic volume, vehicle hours, and vehicle miles used in the past for evaluating accidents on highways and intersections revealed that they are inadequate and insufficient primarily for the following two reasons:

1. Conventional exposure measures were used exclusive of highway geometric and other traffic elements that affect accident risk and
2. Conventional exposure measures failed to recognize that accident rate is an equivalent expression of accident-risk exposure, which operates in the highway-traffic-environment system.

For sections between signalized intersections, the conventional exposure measure of using a single variable is to be replaced as an exposure measure that can encompass all highway and traffic elements that affect accidents. For intersections, the conventional exposure measure that treats the different traffic conflicts as the same accident risk is to be replaced as an exposure measure that can distinguish the propensity of accident risk of different traffic conflicts.

For both highways and intersections, exposure measure should contain all highway geometric and traffic elements that affect accidents. The number of accidents is the square of the exposure measure operating in the highway-traffic-environment system.

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