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16. Abstract

The purpose of this study was to examine currently used measures of exposure to risk and to develop new methods for defining these exposure counts. The research was conducted to provide the basis for developing more accurate accident rates in order to produce more sensitivity in countermeasure evaluation and problem identification studies.

The method used in developing the exposure measures involved defining the relevant accident types for a given highway situation based upon the possible interactions between pairs of vehicles or a vehicle and roadside objects. Resultant exposure measures are provided for analysis of intersections, interchanges, roadway segments, fixed object collisions, and research relating to accidents by vehicle class.

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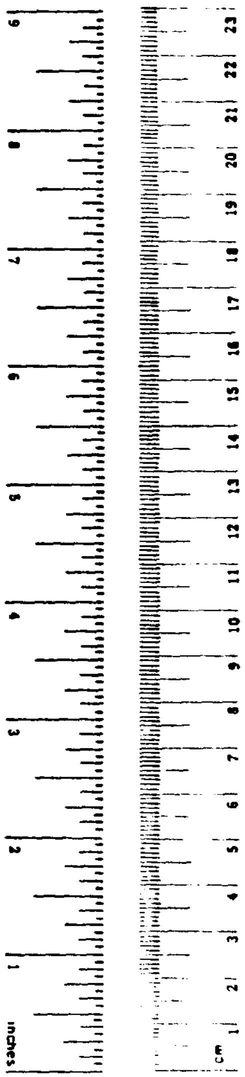
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

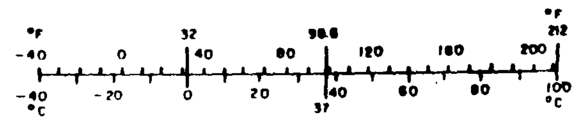
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). [illegible] Units of Weights and Meas[illegible]



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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CHAPTER 1.
INTRODUCTION

I. Statement of the Problem

Highway engineers and planners are currently faced with a situation in which most State and local agencies are rapidly depleting their alloted budgets while anticipating less revenue in the future due to lower gasoline tax revenue. As a result of the shift to smaller, more fuel-efficient vehicles, this lower level of gas tax collections is not necessarily paralleled by fewer miles of travel. Thus, while revenues are decreasing, demands for maintenance and reconstruction (with minor new construction) are remaining constant or increasing. This situation requires that the engineer/administrator continually work to optimize his highway budget process. This optimization process requires, among other factors, accurate specification of hazardous locations which are to be treated, knowledge of the true effectiveness levels of various countermeasures used, and continued efforts to better define safety relationships between various roadway, driver, and vehicle components in order to rationally define problem areas and to design new countermeasures.

As discussed in the Accident Research Manual (Council, et al., 1980), accident-based research is certainly not the only avenue for answering these questions. However, this type of research will probably continue to play a very important role in roadway-related safety decisions since (1) accident-based criteria do possess a great degree of face-validity with respect to safety questions, and (2) accidents are an acceptable measure to decision makers.

The problem with this approach is that accident frequencies alone (or even some accident rates) do not provide all the information needed to answer many of the questions that confront the engineer/administrator, who is faced with the task of identifying safety problems and evaluating countermeasures. Many assumptions are made -- whether explicitly stated or not. For example, in the countermeasure evaluation area, the use of accident frequencies alone assumes equal degrees of potential hazard either before and after the treatment or between treatment and comparison groups.[1] Secondly, in the identification or

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[1] As discussed in the earlier-referenced manual, the use of strong random-assignment designs greatly reduces the importance of this assumption. However, such evaluation designs are very seldom employed.

ranking of problem locations ("high-accident spots or segments"), the comparison of accident frequencies or simple rates assumes that these measures have a strong relationship to the true "degree of hazard" inherent at each location. Third, in the analysis of highway systems, which usually involves comparisons of systems (highway types) or components of these systems, all such comparisons assume an accurate measure of degree of hazard. And finally, in exploratory research (including descriptive studies), one assumes that the available accident statistics (frequencies or rates) represent true degree of hazard for a particular roadway system or geometric component, vehicle type, or driver factor.

While these implied assumptions are sometimes fairly obvious in the countermeasure evaluation area (although certainly not always), they are much less obvious in other areas like problem identification. Problems occur when faulty assumptions lead to incorrect outcomes.

Use of even simple exposure-to-risk measures will often clarify and sometimes even alter the conclusions drawn (Council, et al., 1980). As a simple example, utilizing driving mileage by time of day shows that the risk of a nighttime accident is much higher than for a daytime one even though the daytime accident frequency is much higher.

Thus, the problem that remains is that accident frequencies or simple accident rates are not, by themselves, always the optimal measure of degree of hazard. Not only do we need a measure of "crashes" or "injuries" but also a measure of "crash opportunity" or "injury opportunity" -- in essence, more appropriate "denominator" or "exposure-to-risk" data.

The need for better exposure data is not new. In addition to the previously cited work by Council, et al. (1980), studies by Thorpe (1967), Carroll (1975), and Carroll, Carlson, McDole, and Smith (1971) have all indicated the need for accurate exposure information and have begun to define appropriate measures. Joksch (1973), Haight (1971), and White, Clayton, Bressler, and Stewart (1975) carried these analyses further in attempting to define the components of accurate measures and possible means of collecting such data in innovative ways.

Even with this amount of research effort having been completed, a great deal of information still needs to be specified, particularly as related to the roadway area. Much of the previously cited work has focused on exposure measures related to the driver and vehicle areas. However, the most appropriate measure of exposure is defined in a specific instance primarily by the research question being asked. That is to say, exposure measures should be closely tied to the specific accidents being studied.

II. Research Objectives and Scope

The specific objectives of this project are as follows:

1. Determine the appropriate exposure measures for various highway geometric and/or traffic conditions.
2. Identify data collection techniques for each exposure measure including sampling, cost, and reliability.
3. For those selected exposure measures, identify types and sources of error.
4. Identify methods for minimizing the errors identified above.

This research is intended to determine the relationships that provide the most accurate exposure indices to apply when identifying problems and/or evaluating countermeasures for various highway situations.

Early in this project, the authors and FHWA staff identified approximately 120 areas of current and planned research. It quickly became obvious that developing an exposure measure for each of these areas was beyond the scope of the project. Based on the review of the literature as well as an examination of ongoing research and the known research plans for the near future, the decision was made to cover the following basic areas:

1. Exposure measures for intersection accidents.
2. Exposure measures for interchange accidents.
3. Exposure measures for accidents on non-intersection roadway segments.
4. Exposure measures for fixed object collisions.
5. Exposure measures for accidents involving specific vehicle types.

While five areas is far less than 120, it is noted that (1) many of the measures developed are broad enough to cover many of the original 120 areas, and (2) the measures developed can be modified to cover many of the other research questions of current or future interest.

Primary emphasis in this work was on the first three of these areas. All three are "location-oriented" in that the measures developed concern exposure for a given location or a given set of locations. The fifth group of vehicle-type exposure questions is of an entirely different nature. Here, the issue is not one involving a specific location or set of locations, but instead involves comparisons of accident rates for certain vehicle classes at all locations. An example of this type of question would be the comparison of certain types of heavy trucks with either other types of trucks or with certain classes of passenger cars.

The fourth category above is also somewhat different from the other four in that it includes two distinct types of questions. First, at a given location, how hazardous are the fixed object collisions that occur as compared to, say, other types of collisions such as rear-end, angle, etc., or is this location more dangerous than another location based only on fixed-object crashes? Second, in a given sample, which type of fixed object is the most hazardous?

Thus, this research is designed to cover exposure related to two basic types of research questions:

- Basic research and evaluation involving a relatively small number of locations.
- Problem identification (ranking) or vehicle-oriented studies involving many locations or a statewide jurisdiction.

NOTE: This is not an accident research manual. It is not designed to present the reader with the specifics of how to conduct an evaluation or a piece of basic accident research. In the discussion of how to use the exposure measures and in the discussion of the development of the measures, certain points concerning proper accident research will necessarily be mentioned. However, for the specifics of how to carry out such research, the reader might consult the following references:

- Accident Research Manual. Council, F.M., Reinfurt, D.W., et al. (Final Report FHWA/RD-80/016, January 1980).
- Highway Safety Evaluation: Procedural Guide. Perkins, D.P. (Final Report FHWA-TS-81-219).

This report and accompanying manual are designed to be a companion to these accident research manuals in providing specific inputs concerning how to develop the rates to be used in such accident research.

Traditionally, exposure measures used in accident research have been rather limited. In most cases, vehicle miles or number of entering vehicles have been the measures of choice. Much of the time this choice was made simply because of the lack of a better, well-defined exposure measure. This current study has examined the question of whether or not these simpler measures of exposure are the most appropriate measures. As a result of these examinations, new measures of exposure for use in certain research situations have been developed.

III. Exposure versus Likelihood

This research concerns developing "exposure measures." Unfortunately, since the term "exposure" can and does mean many things to many different people it is necessary to specify the definition used herein -- the "groundrules" under which the authors and FHWA worked. From this point on, exposure will simply be defined as "the opportunity to be involved in a crash," or in similar fashion, "the opportunity for occupants to sustain injuries." The key to this definition is the word "opportunity" -- not likelihood.

The opportunity for a crash depends on the presence of a vehicle in the traffic stream and, in general, the presence of other vehicles or objects which the vehicle of interest might strike. The likelihood or propensity of a crash depends both on having the opportunity and on other factors which could make the crash more probable for a given unit of opportunity. For example, if one is evaluating (comparing) two "no passing zone" signing treatments at two different locations (and thus will be studying primarily head-on and sideswipe accidents), the opportunity for a crash to occur will be affected by the amount of oncoming and/or qame-way traffic. However, if one of the two sites is characterized by more inexperienced drivers than the other site, it may well be that for each pair of meeting vehicles (opportunity = exposure), the likelihood of the pair crashing may be higher at the "inexperienced" site regardless of signing simply because inexperienced drivers cross the centerline more often, judge distances less accurately, read signs less often, or have other characteristics which would cause them to be more involved in passing zone type accidents. Likelihood factors such as these need to be accounted for ("controlled for") in research studies using techniques cited in the accident research and evaluation manuals noted earlier. However, they are not defined as part of exposure and thus will not be included in the formulas developed later in this manual. Thus, for definitional purposes, exposure is herein defined as opportunity to crash or sustain injury.

IV. Philosophy: Exposure Types Parallel Accident Types

Using the definitions cited above, exposure measures were developed for each of the five situations mentioned earlier. While the underlying theory and details of the mathematical development of the individual measures are provided in the following chapters, the basic developmental procedures used will be briefly explained here. This is being done to provide the user with a general understanding of the necessary steps taken. These same steps could then be extended to develop new exposure measures for research questions not covered in this project.

The basic method used in the development of the exposure measures which follow involved (1) defining the accident types relevant to the given specific research question or research location, and (2) developing an exposure measure for each relevant accident type. For example, for a specific location, individual measures are developed for each potential accident type (single vehicle, rear-end, head-on, angle, etc.) within each flow or flows. These individual measures can be used in a study of a given location to determine which accident type is the most troublesome or in a research effort involving only a limited number of accident types (e.g., in a study of a following-too-closely monitor designed to prevent rear-end crashes). If the researcher is interested in studying all types of accidents involving the entire flow, these individual measures then are summed. To study an entire location, the formulas for exposure for each flow are then summed. In most cases, this summing has been done for the user in the material that follows.

V. Review of the Literature

The review of published literature involved an initial screening of a large number of potential studies identified by a computer search of the TRIS network containing the Highway Safety Literature File and Highway Research Information Abstracts. The reports reviewed and summarized for this project fall into several categories including (1) general exposure measure considerations, (2) exposure measures for intersections and interchanges, (3) driver/vehicle oriented exposure measures, and (4) induced exposure. Of these, the series of studies dealing with calculating exposure to accidents at intersections and interchanges has been the most immediately useful, both in terms of their general philosophy and the specific approaches taken to calculating a measure of exposure for these admittedly difficult locations.

Basically, the six principal studies reviewed in this area (Breuning and Bone (1960), Surti (1964), Surti (1969), Hodge and Richardson (1978), Chang (1982), and Chapman (1967)) have all developed methods for calculating exposure to accidents at intersections/interchanges based on quantifying traffic flow conflicts. The work by Hodge and his colleagues is particularly significant since they examine the models proposed by others to determine the causes of their differences. The authors note that observed differences in the past models for the same type location probably arise from the fact that the "propensity function" (the probability of a crash given the opportunity) and the exposure measure (the opportunity for a crash) have been derived simultaneously rather than independently. Their point is that exposure to risk at a given type of site is a function of the products of intersecting volumes, but that the true level of risk also changes with volume. This is true in that, the higher the volume, the more likely a driver will "drive more carefully" and thus the lower the risk per unit volume. Thus, this report views the analysis of exposure to accidents at intersections as a two-step process:

(1) Estimating propensity for a particular type collision, and

(2) Adjusting this propensity based on its known relationship to volume.

A major weakness seen in these studies is that they are restricted to two- (multi-) vehicle accidents only.

A number of the studies reviewed have taken a driver/vehicle orientation to exposure measurement, e.g., Bygren (1974), Carroll (1975), White, et al. (1975), Meyers (1981), and Desrosiers (1982). Taken as a whole, these studies provide some potentially useful information related to the comparison of vehicle types by selected driver variables, and offer general support to the thesis that the usefulness of VMT as a measure of exposure increases as it is cross-classified by other variables of interest.

A key writing here is a "Discussion" by Paul Ross found in the Meyers (1981) report. Ross argues that, except for single vehicle accidents, accident rates for a given vehicle type cannot be accurately determined simply on the basis of a proportion of VMT. Using data on the distribution and relative involvement of various truck sizes in accidents, he proposes a method for adjusting the proportion of total VMT to calculate a better measure of exposure. Ross's commentary is heavily reflected in our own approach to defining appropriate exposure measures.

A third area of exposure measurement addressed in the literature review is that of induced exposure. This approach, as conceived by Thorpe (1967) and extended by Haight (1971), Joksch (1973) and others, infers exposure to accidents for a particular class of vehicles by examining the not-at-fault vehicles and drivers involved in two-vehicle accidents. Although its basis in terms of a cross-classification of accidents and the need for close correlation with accidents is important to our own way of thinking, its lack of applicability to location-oriented problems clearly limits its usefulness to the current project. Induced exposure is, nevertheless, another approach or way of thinking that can be considered as one addresses the issues raised by this project.

A final group of "general" exposure studies offers support for the overall philosophy and approach reflected earlier. In particular, note should be made of the work at the University of Indiana (Squires, et al., 1979) whereby exposure to the risk of an accident is defined in terms of the prevalence of certain precrash conditions, so that exposure and accident measures together yield a probability estimate.

The pole study by Mak and Mason (1980) at Southwest Research Institute is especially relevant to the development of exposure indices for fixed object countermeasures. Similarly, the work by Nilsson (1978) is philosophically akin to our own approach in its view of exposure as a possible combination of a number of factors multiplied together.

In summary, the literature review has been of value to the project efforts in several ways. First, the review has provided the HSRC staff with a clearer philosophy of how to attack the overall issue. Second, specific approaches to exposure measures for certain location and vehicle types have been found. Third, the current literature has provided leads to additional papers as well as ongoing research.

VI. Summary

Exposure issues have been debated for many years, resulting in a wide diversity of opinion about what is appropriate for a given situation. Nonetheless, there exists a considerable amount of tradition, or perhaps inertia, concerned with basic measures like vehicle miles of travel (VMT). Users (researchers, engineers, statisticians, etc.) have become comfortable with this concept of VMT and how it fits into their particular problem or analysis. This report attempts to break from this standard concept by developing non-traditional, but seemingly more appropriate, types of exposure measures.

This may present problems to the reader or user of this report (as indeed it did to a group of workshop participants who critiqued this current research), because the tendency is to think along the following lines:

"That result looks wrong, because the normal rate would show this interchange to be more hazardous."

"You are giving too much weight to this particular exposure component in the overall scheme."

These comments imply that VMT's, entering vehicles, etc. are the standards against which all other exposure measures should be validated. Our philosophy was to start from another vantage point by asking the question,

"What is the most appropriate exposure (= opportunity) measure for this particular problem?"

The results would then be examined to determine if the answer seemed logical, rational, etc. -- but we were not bound by traditional thinking. Our thinking is that, at present, there is no "right" answer to judge other answers against.

One final point should be made. Since we stray from traditional VMT's that yield rates like accidents per million vehicle miles, the reader is forewarned that our denominator terms should be considered as exposure opportunities or exposure involvements. In reality, our exposure measures generally represent an interaction of (1) two vehicles (e.g., head-on exposure within an intersection), (2) a vehicle and a roadside (e.g., single vehicle exposure on a homogeneous section), or (3) a vehicle and a fixed object (e.g., fixed object accident rate).

Those are the caveats. Our hope is that readers will consider what we have proposed and use it in practice. We think the analyst will find that the use of these "denominators" gives more insight into some problems than traditional exposure measures. However, we also realize that our thinking can and should be advanced.

In summary, then, this research covers five main areas for which appropriate exposure measures have been developed, and the following chapters deal with each of these in turn. Chapter 2 covers intersections and includes discussion of the associated concerns of free flow, stop sign, or signal controlled intersections as well as single lane versus multi-lane configurations. Chapter 3 deals with interchanges and the exposure measures related to the various interchange segments (e.g., through lanes, on-ramp merge, off-ramp diverge, weaving areas, etc.). Chapter 4 concerns homogeneous roadway sections -- both single and multi-lane -- that often are examined for problem identification purposes (i.e., questions about which sections of roadway should be improved). Fixed objects are covered in Chapter 5 from two points of view: (1) exposure measures for determining a fixed object accident rate, and (2) exposure measures which enable one to compare the degree of hazard for various types of fixed objects. Finally, Chapter 6 presents exposure measures necessary for use in accident research questions involving specific types of vehicles such as heavy trucks, small cars, motorcycles, etc.

CHAPTER 2.
INTERSECTIONS

I. The Accident Approach to Exposure

The first topic to be covered in-depth was that of intersections. As noted in Chapter 1, exposure measures were developed to parallel accident types. To guide our thinking concerning what type of exposure vehicles are experiencing, an examination of accident data at intersections, both signalized and unsignalized, was conducted. This analysis indicated that the major types of accidents that are occurring (and therefore the major categories of exposure that need to be defined) are (1) angle collisions involving turning traffic from the oncoming direction, (2) cross traffic crashes, (3) rear-end collisions, (4) pedestrian accidents, and (5) (somewhat of a surprise) single vehicle crashes. Thus, our general approach was to develop an exposure measure for each of these major types of accidents.

The initial look at intersection accidents also led us to examine a variety of other intersection-related questions. For example, are single vehicle crashes at intersections basically "almost angle" collisions (i.e., mainly involving turns and perhaps involving a "phantom" vehicle) or are they a distinctly different type of crash? Are sideswipe accidents basically rear-end accidents that "just missed" front-to-rear contact? Are head-on crashes distinct from angle crashes? Obviously the answers to these questions dictate the amount of additional detail necessary to include in our study of intersection accident exposure.

With respect to the question of single vehicle intersection accidents, we looked at the hard copies of 100 single vehicle crashes at signalized intersections and also a sample of 100 single vehicle crashes at non-signalized intersections. In both situations, the accident type was predominantly (74 percent signalized and 91 percent non-signalized) ran-off-road left, right or straight ahead, did not involve a "phantom" vehicle, and also did not appear to be especially intersection related. Thus, it would appear that exposure to single vehicle crashes at intersections is not covered in the considerations of other crash types and must be accounted for separately.

With respect to sideswipe accidents, in nearly every case (approximately 90 percent for both signalized and non-signalized intersections), the two vehicles were traveling in the same direction and were going straight, changing lanes, and/or passing. While some part of sideswipe exposure might be a subset of rear-end exposure, there appears to be a need for a separate measure.

In like manner, it does not appear that exposure to head-on crashes is accounted for by that for angle collisions. For such to be the case, most of the head-on crashes would have to involve turning maneuvers. From the 1981 North Carolina accident data, only 12 percent of the head-on crashes involved left- or right-turning vehicles. Both vehicles were going straight in the vast majority (63 percent) of cases.

From examining intersection accidents it became apparent that exposure measures were needed for:

- single vehicle accidents,
- rear-end accidents,
- head-on accidents,
- sideswipe accidents, and
- angle accidents.

The sections that follow outline the evolution of our thinking on each of these exposure measures and present our final versions of each.

II. Development of Exposure Measures for Uncontrolled Intersections

A. Single Vehicle Exposure

As stated in Chapter 1, our goal for a single vehicle intersection accident exposure measure was that this measure should be an estimate of the total opportunities for single vehicle crashes at the intersection over some interval of time. We were guided in our thinking by the work of Chapman (1967) who states, "There cannot be more (single vehicle) accidents than the number of vehicles." Thus, it seemed that a logical upper bound for the number of opportunities for single vehicle crashes at an intersection during some time interval, T, would simply be the total number of vehicles passing through the intersection during T.

The question then arose, is there some smaller number which represents a more reasonable estimate of the opportunities for single vehicle crashes? For example, one might consider the number of vehicles that "nearly" run off the road; or the number that, in fact, do run off the road; or the number that run off the road in the vicinity of some fixed object, etc. It seems that this progression leads to the lower (illogical) bound of exposure as the number of vehicles that, in fact, have single vehicle accidents. This lower bound was clearly not what we wanted as a measure of opportunity. It also seemed that there was no point between the upper and lower bounds that (1) is a particularly logical measure of crash opportunity, or (2) can be estimated from information readily available to traffic engineers. Thus, the total traffic flow through the intersection seemed to be the most logical choice for a measure of exposure to single vehicle crashes at an intersection.

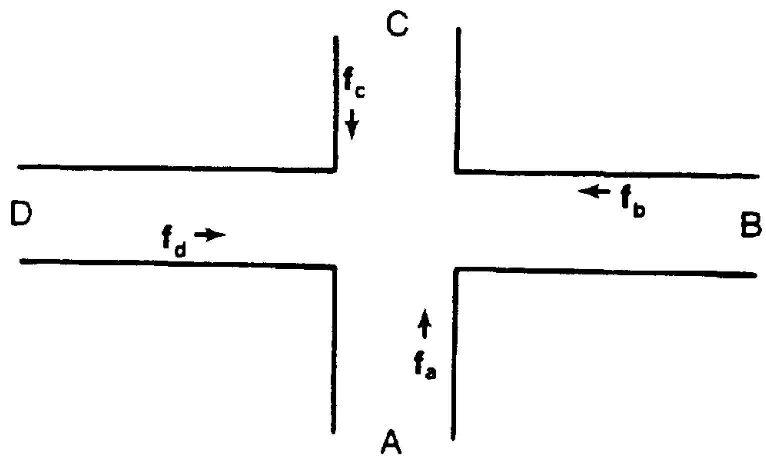


Figure 2.1

Using the notation of Figure 2.1, an expression for this exposure measure is,

$$E_{SV} = T(f_a+f_b+f_c+f_d), \qquad (2.1)$$

where T is the time interval under consideration (e.g., measured in hours) and the f's are flow rates in vehicles per hour. If either T or the f's are given in other units then, of course, the units have to be converted to agree. Also, if the intersection has a different configuration (e.g., three legged or five legged), then the exposure formula must be altered to fit the different configuration.

In a sense the single vehicle exposure measure set the tone for the development of the other exposure measures. In all subsequent cases, we also counted each interaction between a passing vehicle and whatever it might strike (in this case, one "roadside") as a potential single vehicle accident without regard to how likely or unlikely such an accident might be.

B. Rear-End Accident Exposure

Exposure to rear-end collisions was also discussed by Chapman (1967) who pointed out that in a stream of n vehicles there can be at most n-1 rear-end collisions. He also discussed the use of some type of headway distribution to estimate the proportion of headways in a traffic stream that was shorter than some specified limit beyond which a rear-end collision was "unlikely."

Since we were concerned with intersection exposure, one of our first problems was to define the physical limits of the intersection. It was felt that accidents occurring within 100 or 150 feet of the intersection proper are generally considered to be intersection related. Thus, the limits of the intersection were chosen as in Figure 2.2. The distance L might fall within

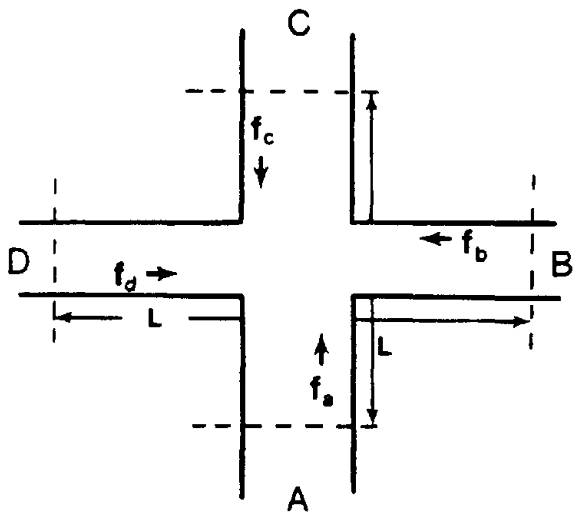


Figure 2.2

the range of 250 to 350 feet (or any distance desired by the researcher), and we want to estimate the number of potential rear-end collisions (i.e., the opportunities for rear-end collisions) that could occur within the intersection extended to these limits.

Continuing the philosphy used for single vehicle exposure, we reasoned that any time both members of a consecutive pair of vehicles in the same traffic stream were simultaneously within the limits of the intersection, an intersection related, rear-end accident could occur. (Again, we are counting the possible interactions between a given vehicle and what it can strike -- in this case the leading vehicle.) Thus, our exposure measure should be taken to be an estimate of the number of such pairs that occur in the given time interval for each traffic stream through the intersection. Knowledge of the traffic flows and average velocity gives an estimate of the average spacing between vehicles. If it is assumed that vehicles are uniformly spaced on the roadway and if the average spacing exceeded the length L of the intersection, both members of a consecutive vehicle pair would never be within the intersection at the same time and rear-end exposure would be zero. On the other hand, if the average spacing was less than L, each entering vehicle would find a leading vehicle still within the intersection, and hence, each entering vehicle would contribute a count of one exposure unit to rear-end exposure.

Assuming uniformly spaced vehicles therefore results in a "step function" for rear-end exposure where the average spacing determines whether the count is zero or the entire flow. This does not reflect reality very well in that all vehicles do not travel exactly the same distance apart.

A more realistic assumption would be that of some underlying distribution of headways or spacings between vehicles which would allow one to calculate the probability of a spacing of any length. Our exposure measure would then be the traffic flow multiplied by the probability of a headway less than L. A particularly simple one parameter distribution which has been found to be fairly realistic in relatively low volume situations is the exponential distribution with density function given by,

$$f(x) = \lambda e^{-\lambda x} \qquad x>0 ,$$

and distribution function given by,

$$F(x) = 1-e^{-\lambda x} .$$

This density function is shown in Figure 2.3 (solid curve) along with what might be considered a more realistic but hypothetical density function (dashed curve). The two curves differ primarily in two regions as follows:

(1) The exponential distribution gives positive probabilities for "very short" ($x < x_1$) headways that can only occur in reality in conjunction with a crash.

(2) In reality (at least in congested traffic), there are many more "median" ($x_1 < x < x_2$) headways than are predicted by the exponential distribution.

While this second point might cause problems in determining the probability of a pair of vehicles being in a very short segment of roadway, the segment length of interest in this project (even for intersections) is long enough so that the

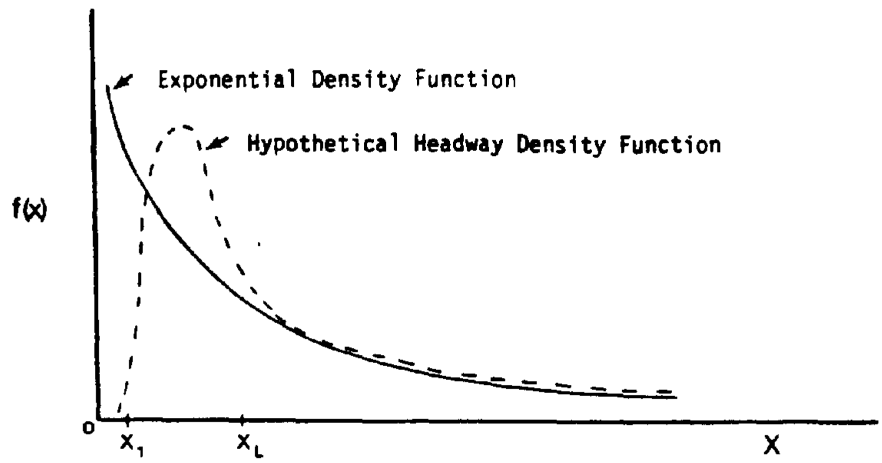


Figure 2.3. Exponential Density Function and Hypothetical Headway Density Function.

headway length of interest falls well out in the tail of the distribution where the hypothetical and exponential differ very little.

To further examine the "accuracy" of the exponential, it was compared to a displaced exponential whose density function is given by,

$$f(x) = \lambda e^{-\lambda(x-x_0)} , \quad x > x_0$$

and distribution function by,

$$F(x) = 1-e^{-\lambda(x-x_0)} .$$

This density function, proposed by Newell (1956), is shown in Figure 2.4. Displacing the function has the effect of defining a minimum headway such that

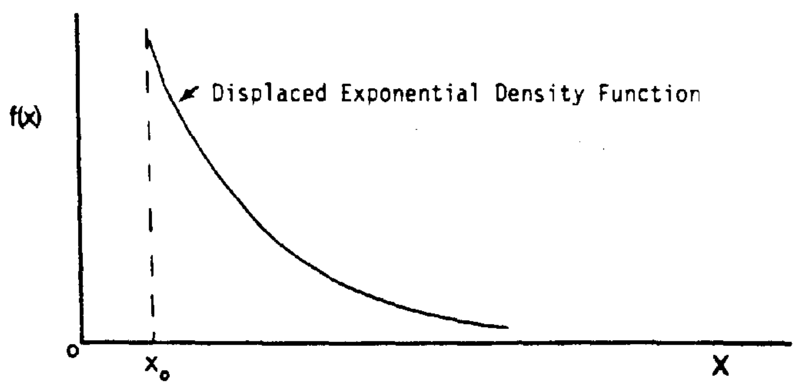


Figure 2.4. Displaced Exponential Density Function.

any headway less than the minimum has a probability of zero. As an example, comparing the exponential distribution $F_1(X)$ with the displaced exponential $F_2(X)$, consider a single flow, f, through an intersection of length L=350 feet = .066 miles, at an average velocity of v=50 mph. Let f take on the values of 200 vph and 500 vph. Let the minimum headway x_0 = 30 feet = .006 miles. Since the mean spacing between vehicles is v/f and the mean of the exponential distribution is $1/\lambda$, we take as an estimate of λ

$$\hat{\lambda} = f/v \ .$$

For the displaced exponential the mean is $x_0 + 1/\lambda$ and equating this to v/f gives

$$\hat{\lambda} = \frac{f}{v - fx_0}$$

as the estimator of λ for the displaced exponential.

Flow	Exponential ($\hat{\lambda} = f/v$)	Displaced Exponential ($\hat{\lambda} = f/(v-fx_0)$)
f = 200 vph	$F_1 (L) = 1-e^{-\lambda L}$	$F_2 (L) = 1-e^{-\lambda (L-x_0)}$
	$= 1-e^{-4(.066)}$	$= 1-e^{-4.1 (.066-.006)}$
	= .23	= .22
f = 500 vph	$F_1 (L) = 1-e^{-\lambda L}$	$F_2 (L) = 1-e^{-\lambda (L-X_0)}$
	$= 1-e^{-10(.066)}$	$= 1-e^{-10.6(.060)}$
	= .48	= .47

Our conclusion was that the use of the exponential distribution rather than some possibly more "realistic" distribution for vehicle headways should not introduce particularly large errors into the estimation of rear-end exposure.

Using the exponential distribution as the headway distribution we get an expression for rear-end exposure at an intersection such as that of Figure 2.2, given by,

$$E_{RE} = T\left[f_a\,(1-e^{-(f_a/v_a)L}) + f_b\,(1-e^{-(f_b/v_b)L}) + f_c\,(1-e^{-(f_c/v_c)L}) + f_d\,(1-e^{-(f_d/v_d)L})\right] \tag{2.2}$$

where $v_a,\ldots,v_d$ are the average velocities of traffic streams A,..,D. As was the case for single vehicle exposure, care must be taken in using the exposure formula that quantities are measured in corresponding units. In particular, if the f's are in vehicles per hour and v's in miles per hour, then L must be in miles. The expression for rear-end exposure, of course, simplifies if some of the flows and velocities are equal on different approaches.

Two concerns we had with respect to rear-end exposure were:

1. Does the variation in traffic flows over the day affect our daily exposure estimates, and

2. For ease in computation, could we completely eliminate the probability factor from the exposure formula, at least for certain ranges of traffic flows and velocities where the probability factor will be nearly equal to unity?

The following example addresses concern number 1.

Example of Exposure for Rear-End Crashes

Single lane of traffic through an intersection of total length L = 350 ft.

ADT = 10,000 vehicles with average velocity v = 25 mph = 36.67 ft/sec.

Case I Traffic uniformly distributed over the day (24 hrs.)

In this case we have 416.7 veh/hr or .12 veh/sec.,

avg. headway = 8.64 sec (center-to-center),

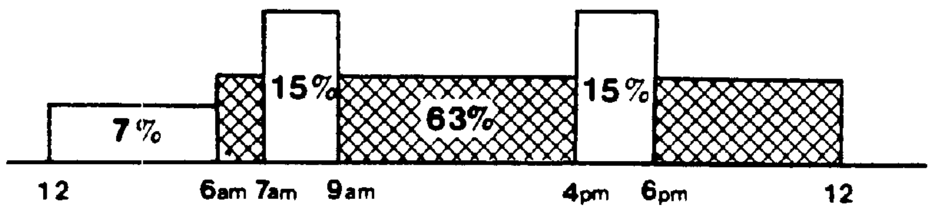
avg. spacing = (8.64)(v) = 316.8 ft.

If spacings have an exponential distribution with mean $1/\lambda$,

then $\hat{\lambda}$ = .0032 and $P_L = Pr$ (spacing < L) = $1-e^{-.0032L} = 1-e^{-1.12} = .67$

Thus, daily exposure E = 10,000 (P_L) = 6,700.

<u>Case II</u> Distribution shown below.



<u>Peak</u> 3,000 vehicles at 750 veh/hr = .208 veh/sec.
avg. headway = 4.8 sec. and avg. spacing = 176 ft.

$\hat{\lambda}$ = .0057, $P_L = 1-e^{-1.989} = .8631$,

Thus, exposure for this period, E_1 = (3,000)(P_L) = 2589

<u>Off-Peaks</u> 6,300 vehicles at 485 veh/hr = .135 veh/sec.,
avg. headway = 7.4 sec. and avg. spacing = 271.4 ft.,

$\hat{\lambda}$ = .0037, $P_L = 1-e^{-1.295} = .7261$,

Thus, exposure for off-peaks, E_2 = 6,300 (P_L) = 4574.

<u>Night</u> 700 vehicles at 116.67 veh/hr = .0324 veh/sec.,
avg. headway = 30.86 sec. and avg. spacing = 1,131.5 ft.

$\hat{\lambda}$ = .0009, $P_L = 1-e^{-.309} = .2661$,

Thus, exposure for night hours, E_3 = 700 (P_L) = 186

Total exposure = $E_{TOT} = E_1 + E_2 + E_3$ = 7,349

The example indicates that simply using average daily traffic flow rates may result in daily rear-end exposure estimates that do not differ greatly from those that would be obtained by using more detailed information concerning peak and off-peak flows, etc.

With respect to the second concern (eliminating the probability factor), the probability term was evaluated for a wide range of values of f and v. These, in turn, yielded a wide range of values of P(L). For this reason it seemed more reasonable to leave the probability function component in the formula for rear-end exposure rather than to specify ways to approximate the function under certain conditions.

A second component of total rear-end exposure would be the opportunities (new "pairs" of vehicles) due to passing maneuvers within L. However, because of the short length of L for intersection, this component was assumed to be zero in this case. It will be discussed in detail in Chapter 3 as related to interchanges.

C. Exposure to Head-On Collisions

Continuing along the lines developed thus far, head-on exposure should represent the potential number of head-on crashes that could occur at an intersection during a given time interval. Each time a vehicle from one traffic stream meets an oncoming vehicle from an opposing traffic stream within the intersection, such a crash could occur. Referring again to Figure 2.2, we develop a method for estimating the number of these occurrences similar to that given by Chapman (1967).

Consider a vehicle from traffic stream A as it enters the intersection. The expected number of opposing vehicles from stream C within the intersection is given by

$$(f_c/v_c)L \quad . \tag{2.3}$$

The average time required for the vehicle from A to pass through the intersection is

$$L/v_a$$

and during that time interval

$$f_c\ (L/v_a) \tag{2.4}$$

more vehicles enter from C. Thus, adding (2.3) and (2.4), the exposure encountered by the vehicle from A is

$$L f_c \left(\frac{1}{v_a} + \frac{1}{v_c}\right) \quad ,$$

and during time interval T, $f_a T$ such vehicles enter from A. As a result the total head-on exposure on the A-C roadway is given by

$$\frac{LTf_a f_c}{5280} \left(\frac{1}{v_a} + \frac{1}{v_c}\right) \tag{2.5}$$

with L_{PD} in feet, T in hours, f in vehicles/hour, and v in miles/hour.

In a similar manner the total head-on exposure for the intersection is given by

$$E_{HO} = \frac{LT}{5280}\left[f_a f_c \left(\frac{1}{v_a} + \frac{1}{v_c}\right) + f_b f_d \left(\frac{1}{v_b} + \frac{1}{v_d}\right)\right] . \tag{2.6}$$

As before, the units must coincide, and if certain flows and/or velocities are equal, simplifications to the basic formula can be made.

D. Angle Exposure at Intersections

Exposure to angle collisions at intersections is discussed in the literature considerably more extensively than is exposure to other accident types. Examples include the work performed by Hodge and Richardson (1978), Hodge (1979), Breuning and Bone (1960), Surti (1964, 1969), and Chapman (1967). The basic solution provided by this series of studies is that exposure to accidents is primarily a function of the intersecting volumes at each of a number of conflict points. Figure 2.5 shows an example of these points for a four-legged intersection. To define the exposure for an entering stream of traffic from a given direction or to measure exposure for the entire intersection, the individual measures for the conflict points would be summed.

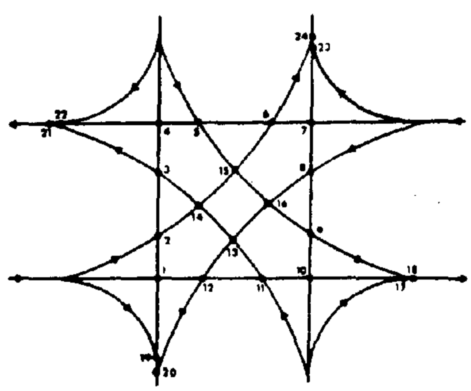


Figure 2.5 Vehicle conflict points at a 4-leg intersection.

While the conflict point approach seemed like a reasonable one, we became aware of certain problems. One major problem was the complexity of the required exposure calculations. For the general four-legged intersection, it is necessary to compute the exposure for 24 conflict points and then sum to get the overall intersection exposure. By making certain assumptions concerning equality of certain flows, simplifications can be made but, in general, the procedure is relatively complicated. Moreover, as the intersection configuration becomes more complicated, the complexity of the approach increases drastically. For example, a five-legged intersection contains 48 conflict points.

A considerable amount of effort was devoted toward attempting to find a relatively simple formula for angle exposure at a four-legged intersection that was a reasonably good approximation to Surti's conflict point method. In particular, a product of the average crossing flows with certain modifications depending on the proportions of turning traffic seemed to give fairly good approximations for this case. It was not clear, however, how such a procedure could be modified for a five-legged intersection, or even a three-legged intersection.

A second problem with the conflict point approach was that it seemed conceptually more restrictive than our other exposure measures. That is, we allow each vehicle to run off the road and have a single vehicle crash or to cross the centerline and strike any on-coming vehicle present. But, with the conflict point approach, each vehicle proceeds through the intersection on its intended path. Perhaps as further evidence of this restrictiveness, numerical calculations of angle exposure using the conflict point method often resulted in angle exposure being orders of magnitude smaller than single vehicle or rear-end exposure. This seemed contrary to intuition (though how much to trust intuition was certainly not clear).

As a result of these problems, an alternative approach to the estimation of angle exposure was developed. This approach was essentially an extension of the method used for head-on exposure with the idea of enumerating the pairs of vehicles in the intersection at a given point in time, where the two members of a pair are from flows at right angles (i.e., crossing flows) to one another. Again referring to the intersection of Figure 2.2, as a vehicle enters from approach A, we estimate the number of vehicles in the intersection from approaches B and D and the additional number entering from these approaches as the vehicle from A proceeds through the intersection. In a similar manner, we get a B-C component and a C-D component. In our original development of this approach, we used the extended intersection of length L on each roadway. This led to considerable discussion concerning the likelihood (or lack thereof) of vehicles at various limits of the intersection actually experiencing an angle collision. Some of the difficulties here seemed even more pronounced with respect to stop controlled and signalized intersections. Finally, after some work had been done on interchanges, it was decided that more appropriate estimates of intersection angle exposure could be obtained by not counting pairs of vehicles in the entire extended intersection, but only those in the intersection proper. The development of this exposure measure follows.

Referring to Figure 2.6, consider a vehicle entering the intersection proper from approach A, and assume that $v_a = v_c$, and $v_b = v_d$. The

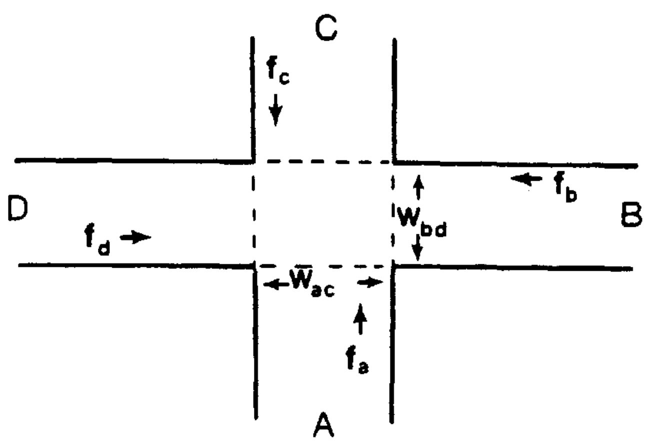


Figure 2.6 Intersection proper

expected number of vehicles within the intersection proper from approaches B and D as the vehicle from A enters is given by,

$$\left(\frac{f_b}{v_b}\right) w_{ac} + \left(\frac{f_d}{v_b}\right) w_{ac} \quad , \tag{2.7}$$

and during the time interval, (w_{bd}/v_a), required for the vehicle from A to cross the intersection,

$$(f_b + f_d) \left(\frac{w_{bd}}{v_a}\right) \tag{2.8}$$

more crossing vehicles enter from B and D.

In time interval T, Tf_a vehicles enter from A, so that, multiplying this quantity by the sum of (2.7) and (2.8), the exposure pairs from AB and AD are given by

$$T\ (f_a f_b + f_a f_d)\ \left(\frac{w_{ac}}{v_b} + \frac{w_{bd}}{v_a}\right) \quad . \tag{2.9}$$

By a similar argument we get the number of pairs from BC given by

$$T\ f_b f_c\ \left(\frac{w_{ac}}{v_b} + \frac{w_{bd}}{v_a}\right) \quad , \tag{2.10}$$

and those from CD given by

$$T\ f_c f_d\ \left(\frac{w_{ac}}{v_b} + \frac{w_{bd}}{v_a}\right) \quad . \tag{2.11}$$

Summing these three components and standardizing units gives our intersection angle exposure measure of

$$E_A = \frac{T}{5280}(f_a f_b + f_a f_d + f_b f_c + f_c f_d)\ \left(\frac{w_{ac}}{v_b} + \frac{w_{bd}}{v_a}\right) \tag{2.12}$$

with T in hours, f in vehicles/hour, w in feet, and v in miles/hour.

It is noted that this concept of angle exposure concerns interactions between pairs of vehicles in crossing flows. Thus, the formulas for angle exposure do not include interactions between a pair including, say, a through vehicle from approach A and a left-turning vehicle from approach C. While a crash between these vehicles might be coded as "angle," we have included their exposure under the "head-on" formulas. This was done for four reasons. First, the exposure for this pair should not be included in both angle and head-on counts since a given pair of vehicles can only be involved in one crash (and thus one type of crash). For this reason, our overall philosophy has been to count a given pair of vehicles in only one type of exposure -- in this case, head-on exposure. Second, not all such crashes will be coded as "angle" making it impossible to guide how to partition this exposure between angle and head-on. Third, including this exposure under head-on requires less input data since turning movement counts are not required. Finally, regardless of which exposure type these counts are included under, the total exposure for the entire interaction will remain the same.

We know that in time interval T, the outer lane is occupied Tf_2 times. Given a vehicle in the outer lane, the probability of a vehicle in the inner lane is approximately equal to the flow rate per unit length multiplied by the length in question

$$= (f_1/v_1)\,\delta\,, \tag{2.13}$$

(assuming independent arrivals for the two lanes). Multiplying (2.13) by Tf_2 then gives the expected count for the number of pairs of vehicles from these two flows that enter the intersection "essentially" side by side. Standardizing units, we write this expression for approach A as,

$$E^A_{SS,sbs} = \frac{\delta T f_1 f_2}{5280\, v_1} = \frac{40\ T f_1 f_2}{5280\, v_1} \tag{2.14}$$

with δ in feet, T in hours, f in vehicles/hour, and v in miles/hour.

Now suppose that $v_1 > v_2$. Let Δ be the additional distance a vehicle in the faster f_1 flow travels while a vehicle in the f_2 flow travels the distance L across the intersection. That is,

$$\Delta = \frac{(v_1 - v_2)\, L}{v_2} \tag{2.15}$$

Referring back to Figure 2.7, <u>each</u> vehicle which is in Δ from flow f_1 at the time a vehicle from f_2 enters the intersection will catch up with or pass this vehicle from f_2 before it clears the intersection. In particular, the vehicle from f_1 in Δ but not in δ will not enter the intersection "paired with" the vehicle from f_2 but will catch or pass it in L. The expected number of times this overtaking happens in approach A can be written as,

$$E^A_{SS,o} = \frac{T f_1 f_2}{5280\, v_1}\,(\Delta - \delta) = \frac{T f_1 f_2}{5280\, v_1}\left[\frac{(v_1 - v_2)\, L}{v_2} - \delta\right] . \tag{2.16}$$

Note that in this development, the assumption was made that $\Delta > \delta$. If $\Delta \le \delta$, (i.e., if the additional distance traveled by a vehicle in the faster lane is less than δ), then this faster vehicle will be beside the vehicle in the slower lane and, thus, no overtaking will occur. In this case we set $E^A_{SS,O} = 0$.

With this convention, we define the total sideswipe exposure from Approach A to be

$$E_{SS}^{A} = E_{SS,o}^{A} + E_{SS,sbs}^{A}$$

$$= \begin{cases} \dfrac{T\ f_1 f_2}{5280 v_1} \left[\dfrac{(v_1 - v_2)\ L}{v_2} \right] , & \text{if} \left(\dfrac{v_1 - v_2}{v_2} \right) L > \delta \quad , \\ \text{or} & \\ \dfrac{T\ f_1 f_2}{5280 v_1}\ \delta \quad , & \text{if} \left(\dfrac{v_1 - v_2}{v_2} \right) L \leq \delta \quad . \end{cases} \tag{2.17}$$

The sideswipe exposure for Approach C would be computed in exactly the same way using flows f_1' and f_2', and velocities v_1' and v_2'. The total intersection sideswipe exposure (assuming the B-D street to be only two lanes) is then given by

$$E_{SS} = E_{SS}^{A} + E_{SS}^{C} \quad .$$

III. Stop Sign Controlled Intersections

A. Introduction

In this section, we develop exposure measures for a four-legged stop sign controlled intersection. We assume that the major street is uncontrolled, while the minor street has a stop sign. Thus, on the major street, only angle exposure will be changed from the preceding formulas. On the minor street, the stop sign does not reduce the overall through flow but it does have the effect of reducing the average velocity through the intersection. Thus, on the minor street, single vehicle exposure will remain unchanged, rear-end exposure should be increased, and head-on exposure and angle exposure will be changed. It should be noted that in the development of many of the exposed formulas that follow we make the assumption that $v_a = v_c$ and $v_b = v_d$.

B. Specific Modifications to Exposure Calculations

Consider the stop sign controlled intersection shown in Figure 2.8 on the following page.

However, it should be noted that analysts working only with angle rates or head-on rates should categorize their accidents in such a way to parallel these exposure definitions to the extent possible.

E. Sideswipe Exposure for Approaches with Two Through Lanes

As noted earlier, no previous research concerning exposure to sideswipe crashes existed. Here the question is one of the number of possible interactions between vehicles in adjacent lanes traveling in the same direction. The total number of such interactions results from two sources -- (1) pairs of vehicles in adjacent lanes who enter L "side-by-side" and who could cross the lane lines and strike each other, and (2) pairs of vehicles resulting from vehicles in the faster lane overtaking vehicles in the slower lane within L.

Consider the situation depicted in Figure 2.7 which represents two adjacent lanes of traffic with flows f_1 and f_2 on approach A, flowing in the same

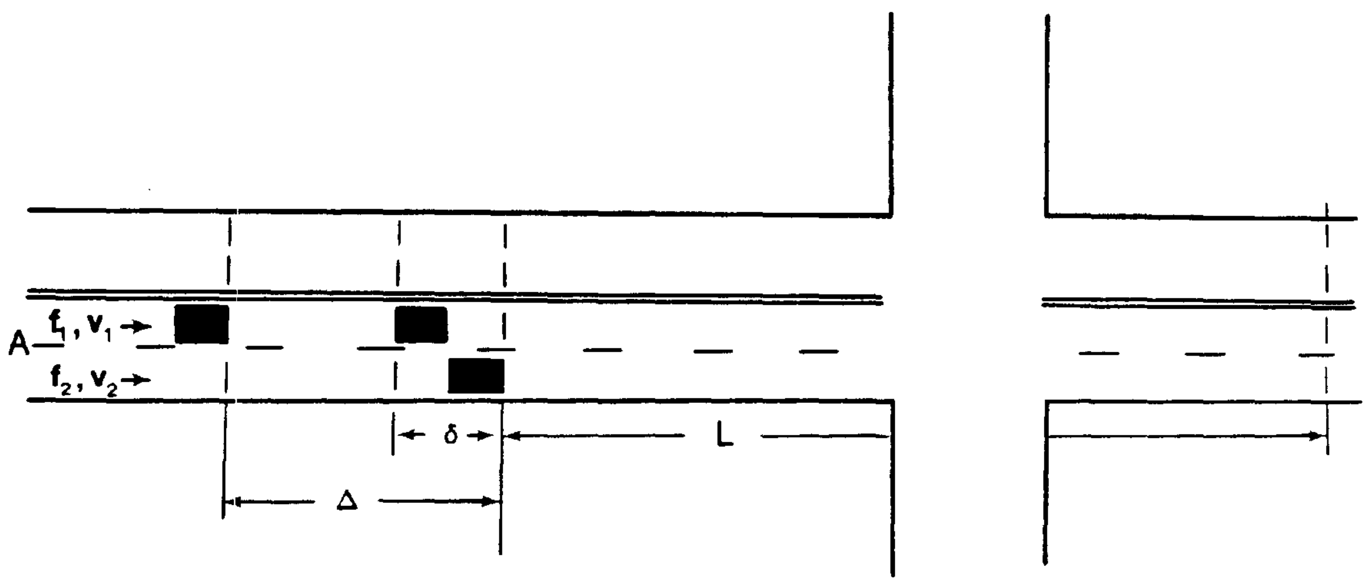


Figure 2.7

direction, and suppose that $v_1 \geq v_2$. Let δ be a distance of approximately two car lengths, (say δ = 40 feet) just prior to the beginning of the extended intersection. (Two vehicles within a 40-foot length are "essentially" side-by-side.) Thus, we first want to estimate the frequency with which both lanes of δ are occupied at the same time.

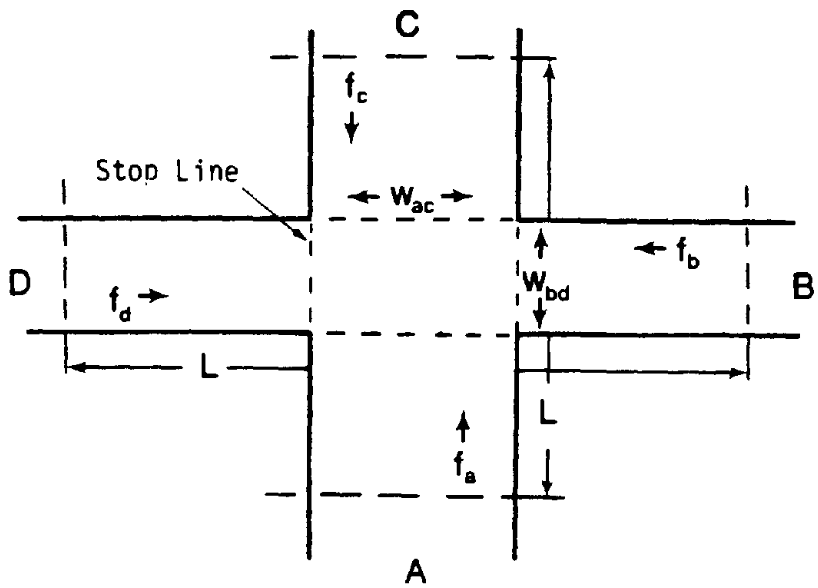


Figure 2.8

1. Single Vehicle Exposure. Just as in (2.1), the single vehicle exposure is given by

$$E_{SV} = T\,(f_a + f_b + f_c + f_d). \tag{2.18}$$

2. Rear-End Exposure. On the major street, A-C, rear-end exposure is unchanged and, if L is in miles, is given by

$$E_{RE,A-C} = T\left[f_a\,(1-e^{-(f_a/v_a)L}) + f_c\,(1-e^{-(f_c/v_c)L})\right]. \qquad 2.19)$$

On the minor street, the vehicle must decelerate from its approach speed to zero at the stop line, wait for some average delay period, d, and then accelerate from zero through the intersection. Using an extended intersection length of 350 ft., a deceleration rate of 6 ft/sec.^{2}, and an acceleration rate of 3 ft/sec.^{2}, the average acceleration and deceleration time works out to be approximately 19 seconds independent of approach speed.[1] The chart below reproduced from Lewis and Michael (1963) gives average delay as a function of the major and minor flows.

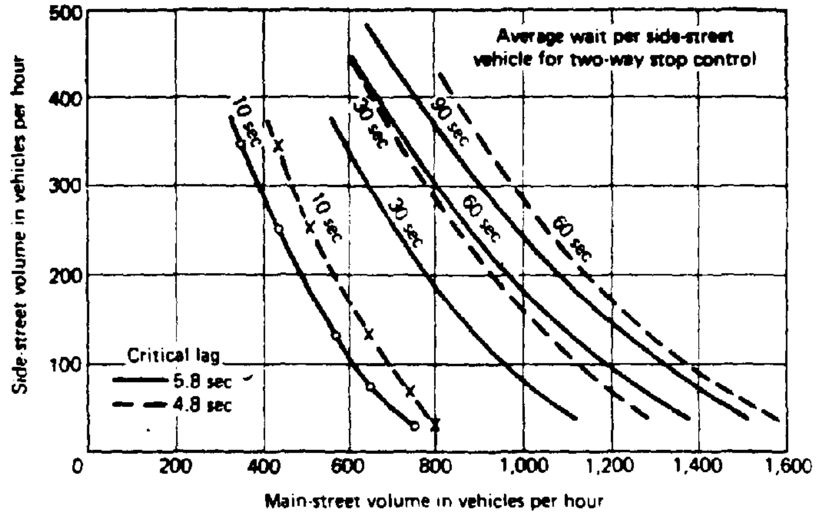


Figure 2.9. Waiting delay to side street vehicles at stop-sign controlled intersections. [Source: Russell M. Lewis and Harold L. Michael, "Simulation of Traffic Flow to Obtain Volume Warrants for Intersection Control," Traffic Flow Theory, Highway Research Record 15 (Washington, D.C.: Highway Research Board, 1963), p. 39.]

Thus, for rear-end exposure on the minor street, approach velocities v_b and v_d in (2.2) are replaced by the velocity

$$v_b^* = \frac{L}{19 + d} \text{ ft./sec.} = \frac{0.68L}{19 + d} \text{ mph} \quad . \tag{2.20}$$

With L again in miles, rear-end exposure on the minor street is

$$E_{RE,B-D} = T \left[f_b \left(1-e^{-(f_b/v_b^*)L}\right) + f_a \left(1-e^{-(f_d/v_b^*)L}\right) \right], \tag{2.21}$$

and total rear-end exposure is

$$E_{RE} = E_{RE,A-C} + E_{RE,B-D} \quad .$$

[1] If the analyst uses an intersection length which differs significantly from 350, this "19-second rule" will not hold, and the average velocity through the length L will have to be based on deceleration and acceleration times within the chosen L plus delay time.

Since v_b^* will, in general, be much less than the approach speeds $v_b = v_d$, the exponent in the exponential term will be of a greater magnitude than in the uncontrolled case. Thus, the exponential term will be smaller, the probability factor larger, and the rear-end exposure estimate on the minor street greater than in the uncontrolled case. Since the rear-end component is unchanged on the major street, the stop sign has the overall effect of increasing rear-end exposure.

3. Head-On Exposure. On the major street head-on exposure is unchanged. Under the assumption that $v_a = v_c$, (2.5) becomes

$$E_{HO,A-C} = \frac{2LTf_a f_c}{5280 v_a} , \qquad (2.22)$$

On the minor street the velocities v_b and v_d are replaced by the v_b^* of (2.20) and head-on exposure on the minor street is given by

$$E_{HO,B-D} = \frac{2LT\ f_b f_d}{5280 v_b^*} \qquad (2.23)$$

Since $v_b^* < v_b$, head-on exposure is increased on the minor street and, hence, for the intersection. Total intersection head-on exposure is given by

$$E_{HO} = E_{HO,A-C} + E_{HO,B-D} \quad .$$

4. Angle Exposure. For angle exposure we are only concerned with the intersection proper. On the minor street, we make the assumption that each vehicle starts with zero velocity at the stop line and accelerates with a constant acceleration through the intersection (a distance of w_{ac} feet). The average velocity through the intersection is then given by

$$\tilde{v}_b = \left[\frac{\alpha w_{ac}}{2}\right]^{1/2} , \qquad (2.24)$$

where α is the rate of acceleration. Taking α to be 3 feet/second^2 gives the velocity

$$\tilde{v}_b = 1.22 \sqrt{w_{ac}} \text{ ft./sec.} = 0.83 \sqrt{w_{ac}} \text{ mph} \qquad (2.25)$$

Using velocity $\tilde{v}_b$ gives the estimate for angle exposure

$$E_A = \frac{T}{5280}(f_a f_b + f_a f_d + f_b f_c + f_c f_d)\left(\frac{w_{ac}}{\tilde{v}_b} + \frac{w_{bd}}{v_a}\right) \quad . \tag{2.26}$$

Since, in general, $\tilde{v}_b < v_b$, angle exposure at a stop controlled intersection is also increased somewhat over angle exposure at an uncontrolled intersection with the same traffic flows.

5. Sideswipe Exposure. For a stop controlled intersection, if there are two-lane streets in both directions, there will be no sideswipe exposure. If there is a four-lane street, it will normally be the major street and will be uncontrolled while the stop sign controlled minor street will have two lanes. In this case, there will be sideswipe exposure only for the major street and it will be the same as for the uncontrolled intersection. For this major street, we label the flows from A by f_1 and f_2 with corresponding velocities v_1 and v_2 assuming $v_1 \geq v_2$. It follows from (2.17) that the sideswipe exposure from direction A is given by

$$E_{SS}^{A} = \begin{cases} \dfrac{Tf_1 f_2}{5280 v_1}\left[\dfrac{v_1 - v_2}{v_2} L\right] \quad , & \text{if } \left(\dfrac{v_1 - v_2}{v_2}\right)L > \delta \\[2ex] \dfrac{Tf_1 f_2}{5280 v_1}\,\delta \, , & \text{if } \left(\dfrac{v_1 - v_2}{v_2}\right)L \leq \delta \end{cases} \tag{2.27}$$

Similarly for E_{SS}^{C} from direction C so that the total intersection sideswipe exposure is given by

$$E_{SS} = E_{SS}^{A} + E_{SS}^{C}$$

If it is assumed that all the lane velocities through the intersection length L are approximately equal, this reduces to

$$E_{SS} = 40T\left(\frac{f_1 f_2 + \tilde{f}_1 \tilde{f}_2}{5280 v}\right) \tag{2.28}$$

where $\delta = 40$ ft.

$\tilde{f}_1$, $\tilde{f}_2$, $\tilde{v}_1$, $\tilde{v}_2$ are flows and velocities from direction C.

IV. Signal Controlled Intersections

A. Introduction

For most of the exposure measures developed in this section we consider an intersection as pictured below in Figure 2.10, where the A-C street is

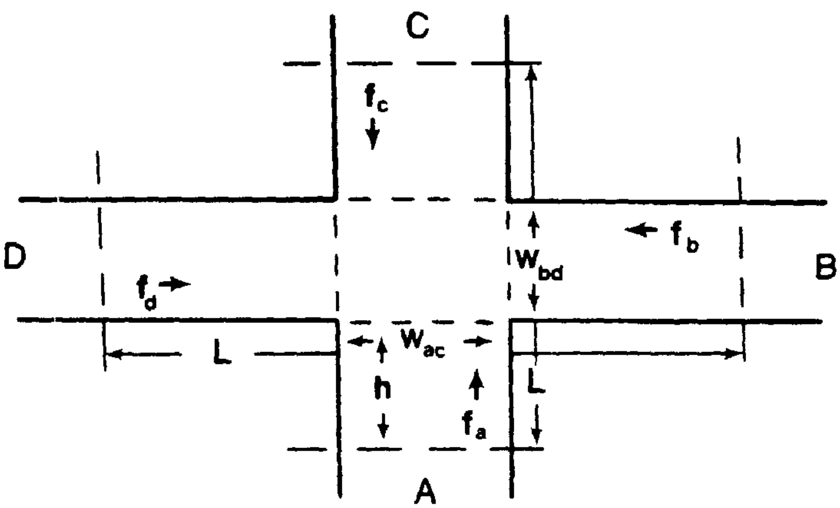


Figure 2.10

considered to be the major street and B-D the minor street. The flow rates f_a, f_b, f_c, f_d, are taken, in general, to be flows for single traffic lanes. The exposure calculations can easily be extended to the case where more traffic lanes are present given their flow rates. It should be noted that there must be at least two lanes in the same direction for this type of exposure to occur.

Like the stop sign, the traffic signal has the effect of reducing the average velocity through the intersection. In addition, the traffic signal restricts certain flows. Thus for angle exposure, vehicles entering the intersection on the green light will only be exposed to crossing flows that enter on red (i.e., right-turn on red or illegally running the signal).

Let the cycle length of the signal be c seconds. Unless c is known, we assume the proportion of red time for the A-C street to be given by

$$r_{ac} = \frac{f_b+f_d}{f_a+f_b+f_c+f_d} = \frac{f_b+f_d}{f_{tot}} , \qquad (2.29)$$

and, similarly,

$$r_{bd} = \frac{f_a + f_c}{f_{tot}} \quad . \tag{2.30}$$

Let $v_a = v_c$ be the approach velocities for the major street and let d_a be the average delay experienced by vehicles on this street due to the signal, and similarly for $v_b = v_d$ and d_b on the main street. (Delay is defined as the additional time required to traverse L due to the signal.) The average velocities through the intersection are then given by

$$\tilde{v}_a = \frac{v_a L}{L + v_a d_a} \text{ ft/sec} = \frac{0.68 v_a L}{L + v_a d_a} \text{ mph} \quad , \tag{2.31}$$

and

$$\tilde{v}_b = \frac{v_b L}{L + v_b d_b} \text{ ft/sec} = \frac{0.68 v_b L}{L + v_b d_b} \text{ mph} \quad . \tag{2.32}$$

Values of the delay d_a can be obtained from the following formula[1] (or from Tables 2.1-2.4 which were calculated using this formula for a range of traffic flows and cycle lengths):

$$d_a = 0.9 \left[\frac{c \left(\dfrac{f_b}{f_a + f_b} \right)^2}{2 \left(1 - \dfrac{f_a}{s_a} \right)} + \frac{\left(\dfrac{f_a + f_b}{s_a} \right)^2}{2 f_a \left(1 - \dfrac{f_a + f_b}{s_a} \right)} \right] .$$

where

c = cycle length (sec.)

s_a = saturation flow on approach A (veh/sec)

(Assume $s_a = 0.5 = s_b$)

Likewise for d_b.

---

[1]Formula derived from Webster's Simplified Formula as noted in Hutchinson, T.P., "Delay at a Fixed Time Traffic Signal--II: Numerical Comparisons of Some Theoretical Expressions." Transportation Science, Vol. 6, No. 3, August 1972, pp. 286-305.

Table 2.1. Delay (d_a) in seconds for the intersection approach of interest for a cycle length (c) of 60 seconds.

Flow (vph) on crossing street												
1200	54.8	44.4	43.2	48.3								
1100	45.6	37.0	34.7	35.5	40.7							
1000	39.2	31.9	29.3	28.7	30.1	35.0						
900	34.4	28.1	25.4	24.2	24.3	25.8	30.4					
800	30.7	25.1	22.3	20.8	20.2	20.6	22.2	26.6				
700	27.7	22.4	19.6	18.0	17.0	16.8	17.4	19.0	23.1			
600	25.0	20.0	17.1	15.3	14.2	13.7	13.8	14.4	16.1	20.1		
500	22.6	17.5	14.6	12.7	11.6	11.0	10.8	11.0	11.8	13.5	17.3	
400	20.0	14.9	11.9	10.1	9.0	8.4	8.1	8.1	8.4	9.4	11.1	14.7
300	17.1	11.8	9.0	7.4	6.4	5.9	5.6	5.6	5.8	6.3	7.2	8.9
200	13.3	8.1	5.8	4.5	3.9	3.5	3.3	3.4	3.5	3.9	4.4	5.3
100	7.4	3.7	2.4	1.8	1.6	1.5	1.5	1.6	1.8	2.1	2.5	3.0
	100	200	300	400	500	600	700	800	900	1000	1100	1200

Flow (vph) on approach of interest

Table 2.2. Delay (d_a) in seconds for the intersection approach of interest for a cycle length (c) of 80 seconds.

Flow (vph) on crossing street												
1200	62.9	51.8	50.1	54.8								
1100	53.6	44.2	41.4	41.8	46.6							
1000	47.1	38.9	35.8	34.6	35.7	40.3						
900	42.1	34.9	31.5	29.8	29.4	30.7	35.1					
800	38.2	31.5	28.0	26.0	25.0	25.0	26.4	30.6				
700	34.9	28.6	24.9	22.6	21.3	20.7	21.0	22.5	26.6			
600	32.0	25.7	21.9	19.5	17.9	17.1	16.9	17.4	19.0	22.9		
500	29.2	22.7	18.8	16.3	14.7	13.7	13.3	13.4	14.1	15.8	19.5	
400	26.1	19.4	15.4	13.0	11.5	10.5	10.0	9.9	10.2	11.0	12.7	16.4
300	22.5	15.4	11.7	9.5	8.2	7.4	6.9	6.8	6.9	7.4	8.3	9.9
200	17.5	10.6	7.5	5.8	4.9	4.3	4.1	4.0	4.1	4.4	5.0	5.9
100	9.8	4.8	3.0	2.3	1.9	1.8	1.7	1.8	2.0	2.2	2.6	3.2
	100	200	300	400	500	600	700	800	900	1000	1100	1200

Flow (vph) on approach of interest

Table 2.3. Delay (d_a) in seconds for the intersection approach of interest for a cycle length (c) of 100 seconds.

Flow (vph) on crossing street												
1200	71.0	59.2	57.1	61.3								
1100	61.6	51.5	48.0	48.0	52.5							
1000	54.9	46.0	42.1	40.5	41.2	45.6						
900	49.8	41.7	37.6	35.3	34.6	35.6	39.8					
800	45.7	38.0	33.7	31.1	29.7	29.4	30.6	34.7				
700	42.2	34.7	30.2	27.3	25.5	24.6	24.7	26.1	30.0			
600	39.0	31.4	26.7	23.6	21.6	20.5	20.0	20.4	21.9	25.8		
500	35.8	27.8	23.0	19.9	17.8	16.5	15.9	15.8	16.4	18.0	21.6	
400	32.2	23.9	19.0	15.9	13.9	12.7	12.0	11.7	11.9	12.7	14.4	18.0
300	27.8	19.1	14.4	11.6	9.9	8.9	8.2	8.0	8.0	8.4	9.3	11.0
200	21.7	13.2	9.2	7.1	5.9	5.2	4.8	4.6	4.7	5.0	5.5	6.4
100	12.1	5.9	3.7	2.7	2.3	2.0	2.0	2.0	2.2	2.4	2.8	3.3
	100	200	300	400	500	600	700	800	900	1000	1100	1200

Flow (vph) on approach of interest

Table 2.4. Delay (d_a) in seconds for the intersection approach of interest for a cycle length (c) of 120 seconds.

Flow (vph) on crossing street												
1200	79.1	66.7	64.0	67.9								
1100	69.6	58.7	54.7	54.2	58.4							
1000	62.8	53.0	48.5	46.4	46.7	50.8						
900	57.6	48.4	43.7	40.9	39.7	40.4	44.4					
800	53.3	44.5	39.5	36.3	34.4	33.8	34.8	38.7				
700	49.5	40.8	35.5	32.0	29.8	28.6	28.4	29.6	33.5			
600	46.0	37.1	31.5	27.8	25.4	23.9	23.2	23.4	24.8	28.6		
500	42.4	33.0	27.2	23.5	20.9	19.3	18.4	18.2	18.7	20.3	24.0	
400	38.3	28.4	22.5	18.8	16.4	14.8	13.9	13.5	13.6	14.3	16.0	19.7
300	33.2	22.7	17.1	13.8	11.7	10.4	9.6	9.2	9.2	9.5	10.4	12.1
200	26.0	15.7	10.9	8.4	6.9	6.0	5.5	5.3	5.3	5.5	6.1	7.0
100	14.5	7.0	4.4	3.2	2.6	2.3	2.2	2.2	2.3	2.6	2.9	3.5
	100	200	300	400	500	600	700	800	900	1000	1100	1200

Flow (vph) on approach of interest

B. Specific Exposure Measures

1. Single vehicle exposure. As previously stated, single vehicle exposure (see (2.1)) is given by

$$E_{SV} = T(f_a+f_b+f_c+f_d).$$

2. Rear-end exposure. Using the "reduced" average velocities given by (2.31) and (2.32), rear-end exposure is calculated from (2.2) as

$$E_{RE} = T\Big[f_a(1-e^{-(f_a/\tilde{v}_a)L}) + f_b(1-e^{-(f_b/\tilde{v}_b)L}) + f_c(1-e^{-(f_c/\tilde{v}_c)L}) + f_d(1-e^{-(f_d/\tilde{v}_d)L})\Big] \tag{2.33}$$

if L is in miles.

3. Head-on exposure. Head-on exposure could be computed using the reduced velocities v_a and v_b as in rear-end exposure together with the formulas given for head-on exposure at an uncontrolled intersection. However, we chose to take a different approach whereby we attempt to estimate the number of oncoming vehicles met by the average vehicle arriving at approach A during the red cycle, and similarly for the average vehicle arriving during the green cycle.

First, in Figure 2.9, consider an Approach A vehicle arriving at a point "h" feet upstream from the intersection proper just as the light changes to red. We assume in this case that vehicles are flowing through the intersection with free flow velocity v_a. Thus, this vehicle is expected to meet

$$(f_c/v_a)\ (h+w_{bd}), \tag{2.34}$$

oncoming vehicles before reaching the stop bar (i.e., the oncoming vehicles in L who pass the signal prior to the red phase). As this vehicle continues on after the signal change, it is expected to meet

$$f_c\ (T_r + \frac{h+w_{bd}}{v_a^*}) \tag{2.35}$$

more vehicles, where T_r is the red time and v_a* is the average velocity of the vehicle after starting from zero at the stop bar. Combining (2.34) and (2.35) the total exposure for this vehicle is, thus,

$$E_1 = f_c \left[T_r + (h+w_{bd}) \left(\frac{1}{v_a} + \frac{1}{v_a^*}\right) \right] \quad . \tag{2.36}$$

Now consider a vehicle arriving at A just as the light changes to green, and continuing on through the intersection at velocity v_a. This vehicle is expected to meet $f_c T_r$ oncoming vehicles that arrived during the red cycle, plus

$$f_c L/v_a = f_c \left(\frac{2h+w_{bd}}{v_a}\right) \tag{2.37}$$

more which enter as the vehicle proceeds through the intersection. Adding $f_c T_r$ to (2.37) gives the total exposure for this vehicle of

$$E_2 = f_c \left[T_r + \frac{2h+w_{bd}}{v_a} \right] \quad . \tag{2.38}$$

Finally, consider the last non-stopping vehicle arriving on green which finds $(f_c/v_a)\ (2h+w_{bd})$ vehicles in the intersection and meets $f_c(2h+w_{bd}/v_a)$ more as it continues on through, for a total exposure of

$$E_3 = f_c \left[\frac{2(2h+w_{bd})}{v_a} \right] \quad . \tag{2.39}$$

[Since $v_a^* < v_a$ it follows that

$$(h+w_{bd}) \left(\frac{1}{v_a} + \frac{1}{v_a^*}\right) > \frac{2h+w_{bd}}{v_a}$$

and, hence, that $E_1 > E_2$. If $T_r > L/v_a$, then also $E_2 > E_3$.]

A reasonable estimate of the exposure for the average vehicle arriving at A during the red cycle might, thus, be given by

$$E_r = \frac{1}{2} (E_1 + E_2) \quad , \tag{2.40}$$

and for a vehicle arriving during the green cycle by

$$E_g = \frac{1}{2} (E_2 + E_3). \tag{2.41}$$

Total head-on exposure would be

$$E_H = \left(\frac{T_r}{c}\right) f_a E_r + \left(\frac{c-T_r}{c}\right) f_a E_g, \tag{2.42}$$

where c is cycle length.

Using (2.29) we have

$$T_r = cr_{ac} = c\left(\frac{f_b + f_d}{f_{tot}}\right) \quad , \tag{2.43}$$

where $f_{tot} = f_a + f_b + f_c + f_d$. If we, moreover, let $f_{ac} = f_a + f_c$, and $f_{bd} = f_b + f_d$, then substituting (2.36), (2.38), and (2.39) into (2.40) and (2.41) and, in turn, substituting (2.40) and (2.41) into (2.42) and standardizing units, we obtain the head-on exposure for the major street, i.e.,

$$\begin{aligned} E_{HO,AC} &= \frac{T}{3600}\Bigg\{ f_a \left(\frac{f_{bd}}{f_{tot}}\right) \frac{f_c}{2} \left[2c\left(\frac{f_{bd}}{f_{tot}}\right) + (h+w_{bd}) \left(\frac{1}{v_a} + \frac{1}{v_a^*}\right) + \frac{2h+w_{bd}}{v_a} \right] \\ &\quad + f_a \left(\frac{f_{ac}}{f_{tot}}\right) \frac{f_c}{2} \left[c\left(\frac{f_{bd}}{f_{tot}}\right) + \frac{3(2h+w_{bd})}{v_a} \right] \Bigg\} \\ &= \frac{T f_a f_c}{7200 f_{tot}} \Bigg\{ f_{bd} \left[2c\left(\frac{f_{bd}}{f_{tot}}\right) + (h+w_{bd}) \left(\frac{1}{v_a} + \frac{1}{v_a^*}\right) + \frac{2h+w_{bd}}{v_a} \right] \\ &\quad + f_{ac} \left[c\left(\frac{f_{bd}}{f_{tot}}\right) + \frac{3(2h+w_{bd})}{v_a} \right] \Bigg\} \end{aligned} \tag{2.44}$$

where velocities are in feet/second, distances in feet, T in hours, and cycle length in seconds.

Similarly, head-on exposure on the other street is given by

$$\begin{aligned} E_{HO,BD} &= \frac{T f_b f_d}{7200 f_{tot}} \Bigg\{ f_{ac} \left[2c\left(\frac{f_{ac}}{f_{tot}}\right) + (h+w_{ac}) \left(\frac{1}{v_b} + \frac{1}{v_b^*}\right) + \frac{2h+w_{ac}}{v_b} \right] \\ &\quad + f_{bd} \left[c\left(\frac{f_{ac}}{f_{tot}}\right) + \frac{3(2h+w_{ac})}{v_b} \right] \Bigg\} \quad , \end{aligned} \tag{2.45}$$

Total head-on exposure is then given by

$$E_{HO} = E_{H,AC} + E_{H,BD}.$$

4. Angle exposure. For purposes of estimating angle exposure we define some different average velocities by

$$v_a^* = \frac{(\text{green + yellow time}_a)}{c} v_a + \frac{(\text{red time}_a)}{c} (0.83) \sqrt{w_{bd}} \qquad (2.46)$$

$$v_b^* = \frac{(\text{green + yellow time}_b)}{c} v_b + \frac{(\text{red time}_b)}{c} (0.83) \sqrt{w_{ac}} \qquad (2.47)$$

These represent weighted average velocities through intersection width w and cycle length c. The first component is the free flow velocity (v_a or v_b) weighted by the proportion of vehicles approaching during the green or yellow signal phase, and the second component is the velocity through w for the proportion who have to stop for the red signal and accelerate at 3 feet/second^2. (For further explanation, refer to page 30, "4. Angle Exposure.") Assuming $f_a = f_c$, $f_b = f_d$, and substituting (2.29) and (2.30) into (2.47) and (2.48) gives

$$v_a^* = \frac{v_a f_a + 0.83 \sqrt{w_{bd}}\; f_b}{f_a + f_b} , \qquad (2.48)$$

$$v_b^* = \frac{v_b f_b + 0.83 \sqrt{w_{ac}}\; f_a}{f_a + f_b} . \qquad (2.49)$$

Now let

P_{g_a} = proportion of vehicles in A passing through green signal

= 1-(proportion right-on-red)-(proportion running red light)

$$= 1 - P_{r_a} , \qquad (2.50)$$

P_{g_b} = proportion of vehicles on B passing through green signal

= 1-(proportion right-on-red)-(proportion running red light)

$$= 1 - P_{r_b} . \qquad (2.51)$$

The effect of the traffic signal is to restrict the conflicting traffic flows so that, for example, the term $f_a f_b$ of equation (2.9) is replaced by the term

$$f_a P_{g_a} f_b P_{r_b} + f_a P_{r_a} f_b P_{g_b} = f_a f_b (P_{g_a} P_{r_b} + P_{r_a} P_{g_b}) \quad . \tag{2.52}$$

Replacing each of the flow products of (2.12) by the appropriate term of the form (2.52) leads to the expression for angle exposure at a signalized intersection, namely

$$E_A = \frac{T}{5280} \left[\left(\frac{w_{ac}}{v_b^*} + \frac{w_{bd}}{v_a^*}\right) (f_a f_b + f_b f_c) (P_{g_a} P_{r_b} + P_{g_b} P_{r_a}) \right] . \tag{2.53}$$

5. Sideswipe exposure. In addition to the type of sideswipe exposure developed in earlier sections, vehicles arriving at a red signal on a multilane roadway will tend to be queued up in side-by-side pairs. In particular, if f_s vehicles are stopped in N lanes, then there are approximately f_s/N "stacks" or rows of vehicles stopped. (The "approximately" results from cases where the number of stopped vehicles is such that equal queues are impossible; e.g., four stopped vehicles in a three-lane situation.) Across the N stacks or rows of stopped vehicles, there are N-1 pairs of adjacent vehicles. (For example, for two lanes there is one pair per stopped vehicle in a given stack or row. For three lanes there are two pairs, etc.). Thus, for N lanes there are

$$\frac{f_s}{N} (N-1) \quad \text{total pairs of adjacent vehicles.}$$

Thus at traffic signals, this type of sideswipe exposure during the red portion of the cycle will be defined as being equal to

$$E_{SS,\, r} = \frac{N-1}{N} \; \frac{(Tf_i R)}{c} \quad , \tag{2.54}$$

where

N = number of thru lanes
T = length of study (hrs.)
f_i = total flow for approach i
R = red time (sec.)
c = cycle length (sec.)

During the green portion of the cycle while vehicles are flowing freely through the intersection, the types of sideswipe exposure developed earlier will come into play.

For a given approach A (with N=2 lanes of traffic so that $f_a = f_1+f_2$ with approach velocities v_1 and v_2 with $v_1 \geq v_2$), during the green portion of the cycle, the sideswipe exposure in accordance with (2.17) is given by

$$E^A_{SS,g} = \begin{cases} r_{bd}\left[\dfrac{Tf_1 f_2}{5280v_1} \; \dfrac{(v_1-v_2)L}{v_2}\right] & \text{if } \dfrac{(v_1-v_2)}{v_2} L > \delta \\ r_{bd}\left[\dfrac{Tf_1 f_2}{5280v_1} \; \delta\right] & \text{if } \dfrac{(v_1-v_2)}{v_2} L \leq \delta \end{cases}$$

During the red portion, sideswipe exposure is (from 2.54))

$$E^A_{SS,r} = r_{ac}\left(\frac{Tf_a}{2}\right),$$

where r_{ac} and r_{bd} are as given by (2.29) and (2.30). Thus total sideswipe exposure on A is given by

$$E^A_{SS} = E^A_{SS,g} + E^A_{SS,r} \quad .$$

In a similar manner, sideswipe exposure can be calculated for the other approaches and summed to give total intersection sideswipe exposure.

V. Overall Intersection Accident Rates

Using the specific accident oriented exposure measures developed in this chapter, together with corresponding accident frequencies for the same time interval T, a variety of accident rates can be calculated. In some situations, these individual rates will be very useful to the researcher. For example, in the evaluation of a countermeasure which only affects a given type of accident, this methodology will allow one to form more appropriate rates for that particular accident type by dividing by the specific exposure type in question.

In other situations, however, total accident rates are required. The most obvious of these would be in the problem identification setting where the engineer/analyst is attempting to identify those locations which have a higher accident rate than other similar locations in order to determine which set should be treated in a given time period.

The exposure measures that have been developed in this chapter are in the form of counts of pairs of vehicles. A given vehicle may be a member of several different pairs, but each pair of vehicles appears only once as an exposure count for a particular type of exposure and for no other type. This concept can be extended to single vehicle exposure by thinking, in that case, of each vehicle being paired with some other object (e.g., ditch bank, fixed object, etc.) but not another vehicle. Thus, the different exposure measures represent independent sets of such pairs and the sum of the exposure measures provides an estimate of the overall exposure to accidents of any of the accident types considered.

Another aspect of these distinct counts of pairs which had been noted earlier should also be emphasized. The exposure estimates are made based on the traffic flows entering the intersection. Since some of these incoming vehicles may make turns of one sort or another, a given pair of vehicles could be involved in an accident of one type even though it may be counted as an exposure unit for a different type. The example cited earlier involved two vehicles approaching each other on the same roadway who may be involved in an angle collision if one of them makes a left turn. They would be counted, however, as a head-on exposure unit and not as an angle exposure unit. Similarly, a pair counted as an angle exposure unit may have a rear-end accident resulting from a right turn, etc.

Our assumption is that by using average flows the various turning maneuvers will tend to "even out" in most situations so that reasonable estimates of exposure, both by accident type and in the overall sense, can be obtained and used to form the various accident rates of interest.

Now, let the individual accident rates be given by $r_1, r_2, \ldots, r_k$, where

$$r_i = \frac{a_i}{E_i}$$

Then the problem is to compute some combined or total rate of the form

$$R(w) = \sum_{i=1}^{k} w_i r_i$$

where the w_i's are weights associated with the individual rates. Two possible choices for the w's are:

1. $w_i = \dfrac{E_i}{\sum_{i=1}^{k} E_i}$

where E_i is the exposure measure for the i th accident type, and

2. $w_i = 1$

In Case 1, we obtain

$$R_1 = \frac{\sum_{i=1}^{k} a_i}{\sum_{i=1}^{k} E_i} \qquad \text{(the overall accident rate)},$$

while in Case 2 we get

$$R_2 = \sum_{i=1}^{k} r_i \quad .$$

Other choices for the w_i's might reflect accident severity, likelihood of reducing accidents of given types, costs per accident type, etc.

Determining which of R_1 or R_2 is the most appropriate requires examining both the needs of the accident data analyst and the results of using these two methods. In some situations, the formulas presented may well produce very large exposure counts for certain types of exposure; e.g., head-on exposure on multi-lane roadways. At the same time, smaller counts for other types of exposure will be produced; e.g., sideswipe exposure on multi-lane roadways. If R_1 is used, it will be heavily influenced by the head-on counts (and thus the head-on rates) resulting in a possible loss of sensitivity to small but meaningful changes in sideswipe accidents as reflected by the overall rate.

However, R_2 could be greatly inflated as a result of a very small and probably statistically insignificant change in the number of accidents (one or two accidents) of a given type if this small change were coupled with a low exposure count. For example, a change of one or two sideswipe accidents coupled with low sideswipe exposure as compared to other exposure types could produce a high sideswipe rate and thus a high total rate. Since changes of a few accidents per year at a given location are often the result of the randomness of accidents rather than any real treatable cause, such an inflated total rate, would result in erroneous identification of problem locations which could lead to poor use of funds.

For these reasons, R_1 appears to be preferable to R_2. Thus, in developing total accident rates or injury rates for a given location, it is recommended that one sum all accidents or injuries and divide this total by the sum of all exposure counts to produce a total rate per unit exposure.

CHAPTER 3

INTERCHANGES

I. Introduction

Since interchanges are not totally dissimilar from intersections, it became clear that many of the intersection concepts should be transferable to interchanges. Thus, interchanges became the next focus. Just as with intersections, we started with an examination of the accident types that occur.

II. The "Accident Type" Procedure

As related to interchanges, project staff reviewed collision diagrams obtained from the North Carolina Division of Highways concerning accidents at interchanges. This was done for developmental information to allow us to see what types of accidents occur and thus what components of exposure need to be covered for a given interchange component. A basic issue is related to the varying degrees of complexity that we are working with in trying to calculate exposure for interchanges. One way to handle this complexity is to develop exposure measures for each of a series of basic interchange components (e.g., mainline, ramps, weaving sections, etc.). A second way is to attempt to develop a measure of exposure for the total interchange regardless of its specific components. We considered this question and then called the State of California to obtain information concerning how they currently work with interchanges.

For problem identification (hazardous location) purposes, California breaks interchanges into components and then analyzes each component as a separate possible hazardous location. For example, all accidents occurring on a given ramp are assigned to that ramp (defined for computer purposes as an "address" based on the milepost of the mainline at the exit nose). Thus, this address will contain information on all accidents that occurred on the entire ramp. No information is given on where the accident actually occurred in the length of the ramp. A main through segment in the middle of the interchange might include two or three lanes of through traffic plus the weaving lane and would extend from the nose of the weave entrance to the nose of the weave exit. A rate for each of these "pieces" would then be calculated independently and compared to all other pieces in this and other interchanges as well as other locations such as intersections, hazardous curves, spot locations beside the roadway, etc. Thus a given interchange might possibly produce three or four of the identified the identified high hazardous locations within the list of the top one hundred locations across the State.

Subsequent conversations with North Carolina indicated just the opposite use. Under the procedure now being used (which is soon to be modified slightly), North Carolina analysts define the entire interchange as an intersection, including accidents on all through sections, ramps, Y-lines, etc., as defined by a certain distance from the crossing point of the two roadways. The entire interchange is then included in the list of high accident locations.

Thus, based on a very limited sample of two States, it appeared that we had the problem of having to identify exposure measures for both individual components and for the entire interchange. At this point our thinking was that two measures might have to be developed, and the simplified measure for the entire interchange might or might not necessarily equal the sum of the exposure for the individual components.

For the component by component approach, interchange exposure can be viewed as being related to individual sections and the potential accidents that occur at these sections. The following pages will present measures (formulas) for calculating exposure for the different components which are all common to most interchanges. These components are:

1. Through section prior to the exit ramp.
2. The exit ramp area.
3. The through section between the exit ramp and the weaving section.
4. The weaving section.
5. The through section between the weaving section and the entrance ramp.
6. The entrance ramp area.
7. The through section following the entrance ramp.
8. The ramp proper.
9. Diamond type ramp terminals.

Within each of these components there are numerous types of exposure (based on the types of accidents which occur) which must be accounted for. These types of exposure include:

1. Exposure to rear-end accidents.

2. Exposure to sideswipe accidents.

3. Exposure to "angle" collisions at ramp entrances.

4. Exposure to head-on collisions.

5. Exposure to single vehicle collisions.

As shown in Table 3.1 below, the components differ slightly in terms of which types of exposure are relevant, and thus the final measures of exposure for two adjacent components with the same flows may be different due to the types of accidents that can occur in each.

Table 3.1. Interchange components and accident types where exposure measures are needed

Interchange Component	Accident Type: Rear-End	Side-Swipe	Angle	Head-on[1]	Single Vehicle
1. Through section prior to exit ramp	X	X		X	X
2. Exit ramp/gore area	X	X		X	X
3. Interim thru section, exit to weave	X	X		X	X
4. Weaving section	X	X	X	X	X
5. Interim thru section, weave to entrance	X	X		X	X
6. Entrance ramp/merge area	X	X	X	X	X
7. Through section following entrance ramp end	X	X		X	X
8. Ramp proper	X				X
9. Diamond-type ramp Ends	X	X	X	X	X

[1]Our assumption is that the head-on exposure is zero where either a non-traversable median barrier exists or a median is so wide as to be non-traversable.

The basic exposure measures listed in Table 3.1 were developed in Chapter 2. Certain changes to some of the exposure measures are required for interchanges due to longer section lengths, multiple lanes, and different types of merging traffic flows. In particular, head-on exposure is modified to take into account the multiple lanes; rear-end exposure is extended to include a component due to passing maneuvers by vehicles in the same flow; angle exposure is modified to make it more appropriate for merging traffic; and sideswipe exposure is modified to include an overtaking component. These modifications are developed in the following section.

III. Modification of Basic Exposure Measure for Interchanges

A. Multi-lane Head-on Exposure

Consider the situation depicted in Figure 3.1.

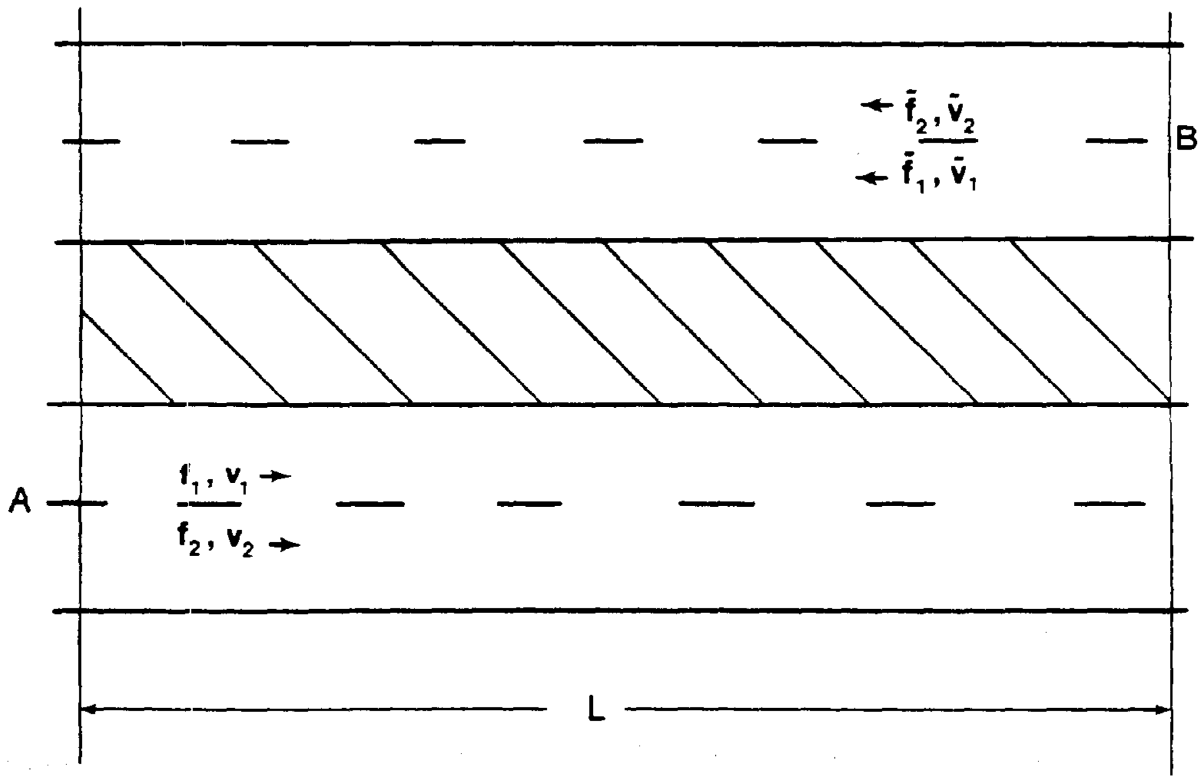


Figure 3.1

A vehicle entering at A from stream f_1 finds $\tilde{f}_1(L/\tilde{v}_1) + \tilde{f}_2(L/\tilde{v}_2)$ opposing vehicles already in L. As this vehicle passes through L, $(\tilde{f}_1+\tilde{f}_2)L/v_1$ more opposing vehicles enter at B. Thus, in time T the total head-on exposure to vehicles in f_1 is given by,

$$E_{H,1} = TLf_1 \left[\frac{\tilde{f}_1}{\bar{v}_1} + \frac{\tilde{f}_2}{\bar{v}_2} + \frac{1}{v_1} (\tilde{f}_1 + \tilde{f}_2) \right]$$

Similarly, from f_2 we get

$$E_{H,2} = TLf_2 \left[\frac{\tilde{f}_1}{\bar{v}_1} + \frac{\tilde{f}_2}{\bar{v}_2} + \frac{1}{v_2} (\tilde{f}_1 + \tilde{f}_2) \right]$$

Combining, simplifying, and standardizing units gives the total head-on exposure

$$E_{HO} = \frac{LT}{5280} \left[f_1 \tilde{f}_2 \left(\frac{1}{v_1} + \frac{1}{\bar{v}_2}\right) + f_1 \tilde{f}_1 \left(\frac{1}{v_1} + \frac{1}{\bar{v}_1}\right) + f_2 \tilde{f}_2 \left(\frac{1}{v_2} + \frac{1}{\bar{v}_2}\right) + f_2 \tilde{f}_1 \left(\frac{1}{v_1} + \frac{1}{\bar{v}_2}\right) \right] \qquad (3.1)$$

Simplification could be made by using total directional flows $f_1 + f_2$ and $\tilde{f}_1 + \tilde{f}_2$, and using some sort of average directional speeds $\bar{v}$ and $\tilde{\bar{v}}$. If, moreover, it could be assumed that $\bar{v} = \tilde{\bar{v}} = v$ (i.e., all lane velocities are equal), then

$$E_{HO} = LT\ (f_1 + f_2)\ (\tilde{f}_1 + \tilde{f}_2)/2640v \qquad (3.2)$$

We also arrive at this simplification by starting out considering only the total flows f_a and f_b in each direction with average velocities v_a and v_b. Then an expression for head-on exposure could be developed as

$$E_{HO} = \frac{LTf_a f_b}{5280} \left(\frac{1}{v_a} + \frac{1}{v_b}\right) . \qquad (3.3)$$

If, moreover, we have a symmetric configuration, then it may be reasonable that $v_a = v_b = v$ and thus

$$E_{HO} = LTf_a f_b/2640v . \qquad (3.4)$$

A final assumption concerns head-on exposure at entrance and exit lanes. While it is logical that entering vehicles are indeed exposed to head-on crashes with opposing flows, the same does not hold for exiting vehicles, who would have to "reverse" their exiting maneuver and cross all same-direction traffic <u>within L</u> to be exposed. Thus, in all equations that follow, exiting vehicles are not included as a component of head-on exposure except in merge sections where they do not exit until the end of the section length.

B. Rear-end Exposure on Two-Lane Roadways

The rear-end exposure measure developed for intersections was based on the assumption of "pipeline flow" through the intersection. For segments of greater lengths, we add to the basic exposure measure a component due to passing maneuvers within the segment. First, consider the two-lane segment shown in Figure 3.2. We assume that for each lane we know the rate of flow (f), the

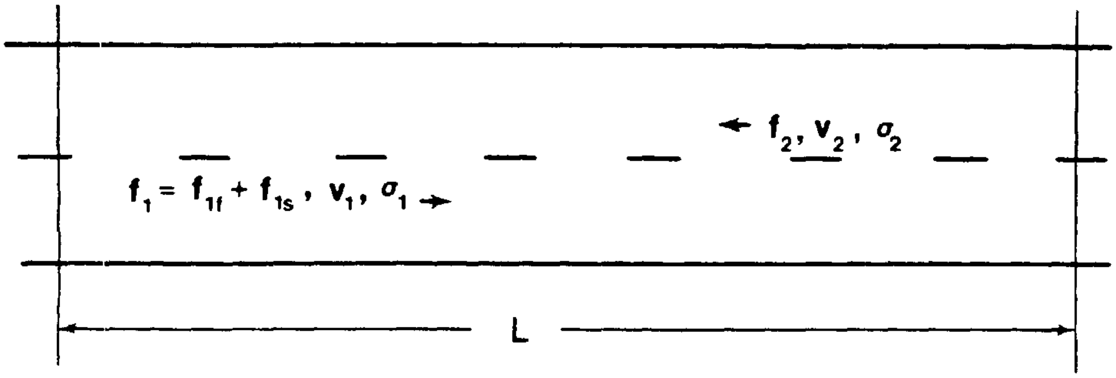


Figure 3.2

average velocity (v), and the standard deviation (σ) of the speed distribution. To estimate the number of passing maneuvers which could occur within L involving vehicles in flow f_1, we essentially split this flow into two components f_{1f} (a fast component) and f_{1s} (a slow component) so that $f_1 = f_{1f} + f_{1s}$. We, moreover, assume that the f_{1f} vehicles are travelling with velocity $v_{1f} = v_1 + \sigma_1$, and the f_{1s} vehicles with velocity $v_{1s} = v_1 - \sigma_1$ It can be shown that passing maneuvers are maximized when $f_{1f} = f_{1s} = 1/2\ f_1$. We then estimate passing maneuvers within f_1 by applying our overtaking formula ((2.16) with $\delta = 0$), to subflows f_{1f} and f_{1s} to give

$$E_{p1} = \frac{LT}{5280} f_{1s} f_{1f} \left| \frac{1}{v_{1s}} - \frac{1}{v_{1f}} \right| . \tag{3.5}$$

With the values of flows and speeds given previously this becomes

$$E_{p1} = \frac{L\ T\ f_1^2}{10560} \left[\frac{1}{(v_1 - \sigma_1)} - \frac{1}{(v_1 + \sigma_1)} \right] = \frac{L\ T\ f_1^2 \sigma_1}{5280(v_1^2 - \sigma_1^2)} . \tag{3.6}$$

Of course, E_{p2} is given by a similar expression and $E_p = E_{p1} + E_{p2}$ is the total passing exposure for the segment. The total rear-end exposure would then be the sum of basic pipeline exposure (Eq. 2.2) and passing exposure (Eq. 3.6).

C. Rear-end Exposure on Multi-lane Roadways

Now consider a four-lane roadway as shown in Figure 3.3.

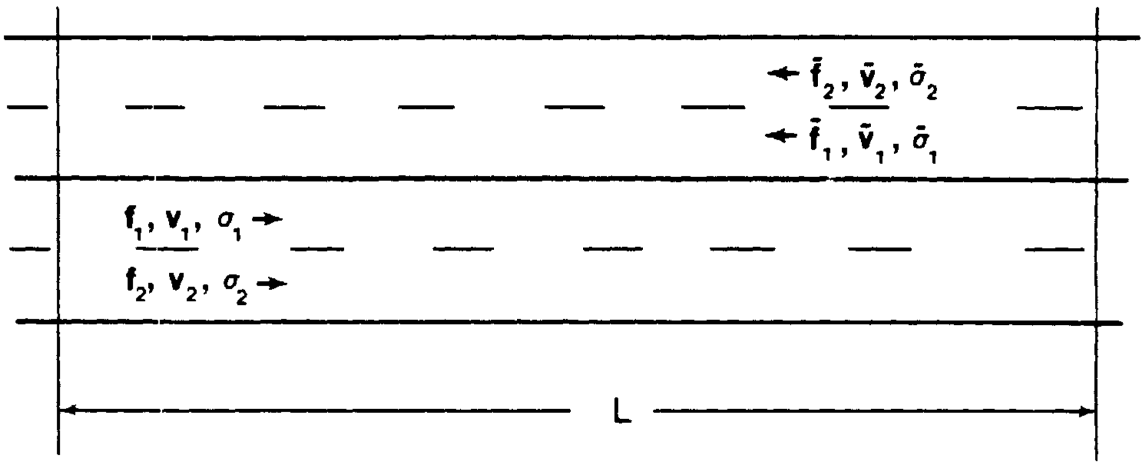


Figure 3.3

To estimate rear-end exposure in the flows f_1 and f_2 we compute,

1) Pipeline flow rear-end exposure within the flows f_1 and f_2, and

2) A component due to passing maneuvers involving faster vehicles in flow f_2 passing slower vehicles in this same flow.

Thus, using (2.2) and (3.6) with L in feet, the rear-end exposure for these flows is given by

$$E_{RE}(f_1, f_2) = T\left[f_1(1-e^{-(f_1/v_1)(L/5280)} + f_2(1-e^{-(f_2/v_2)(L/5280)} + \frac{L \cdot f_2^2 \sigma_2}{5280\,(v_2^2 - \sigma_2^2)}\right]. \tag{3.7}$$

Rear-end exposure for flows $\tilde{f}_1$ and $\tilde{f}_2$ would, of course, be computed in a similar way.

Passing maneuvers were not computed within flow f_1 (nor for entrance, exit, or merge lanes). It seemed likely that for these flows the variation in the speed distribution (σ_1^2) would be relatively small, and the passing component for these flows could be considered negligible.

For certain roadway components where passing maneuvers are impossible (e.g., single lane on ramps), the passing component of rear-end exposure would be omitted.

D. <u>Angle Exposure</u>

Angle exposure is modified for merge areas as shown in Figure 3.4, and discussed below.

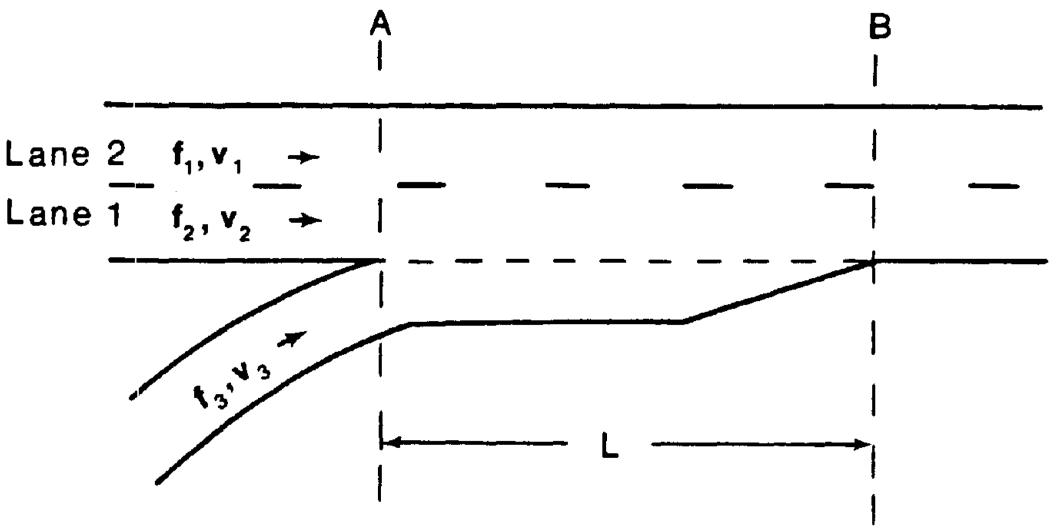


Figure 3.4

Assumptions: v_1, v_2 > v_3; all vehicles from f_3 are merged beyond point B, but are considered as a separate flow until that point.

For angle exposure, a vehicle entering at A from flow f_3 will require L/v_3 time units to reach point B, and $(f_1 + f_2)\ L/v_3$ vehicles enter from f_1+f_2 during this time. A reasonable measure of angle exposure for f_3 might, therefore, be

$$E_A = f_3\ T\ (f_1+f_2)\ L/5280v_3 \quad \text{for any time interval } T. \qquad (3.8)$$

E. <u>Sideswipe Exposure</u>

The basic formulas for sideswipe exposure, including the overtaking component, were developed in Chapter 2. Whereas we assumed for the intersection case that overtaking would not occur since adjacent lane velocities are approximately equal over the short length of the intersection, the overtaking component will come into play in the longer interchange sections. Because the details of the overtaking component were presented in the preceding chapter, they will not be presented here. In summary, for two through lanes, total sideswipe exposure is given as in (2.17) by

$$E_{SS} = E_{SS,o} + E_{SS,sbs}$$

$$= \begin{cases} \dfrac{T f_1 f_2}{5280 v_1} \left[\dfrac{(v_1 - v_2) L}{v_2}\right], & \text{if } \left(\dfrac{v_1 - v_2}{v_2}\right) L > \delta , \\ \text{or} \\ \dfrac{T f_1 f_2}{5280 v_1} \delta , & \text{if } \left(\dfrac{v_1 - v_2}{v_2}\right) L \leq \delta . \end{cases} \qquad (3.9)$$

From here on, all sideswipe formulas will use $\delta = 40$ feet, the approximate length of two passenger cars.

F. Summary

Thus, "X" in Table 3.1 represents a formula (measure of exposure) which has been developed. These measures of exposure are presented on the following pages and can be used in two ways. First, the measures can be utilized separately by the user who desires to examine individual components for ranking purposes, or to conduct a comparative analysis of components within a given interchange, or who wishes to determine which accident types are causing the problem within a given component. Second, for the individual who wishes to develop a rate for the entire interchange, measures can be calculated for each exposure type within each component and then the individual counts can be summed for total exposure. Thus, exposure for a full cloverleaf interchange would be composed of exit, interim, merge, entrance, and ramp components for each direction on each of the two roadways. Exposure for a diamond interchange would only contain exit, interim, entrance and ramp components for the major roadway along with interim diamond ramp terminals and ramp components on the minor roadway. Partial cloverleafs would be some other combination of components.

As the user will see, these individual measures can be computationally complex although most can be programmed on hand-held programmable calculators.

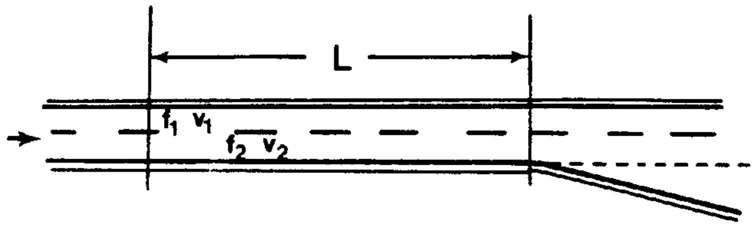
To help ease the computations, simplified formulas have been developed for each measure within each component and for the total exposure for each component. Obviously, the simplified formulas require certain assumptions -- assumptions which are also spelled out in the text -- which may or may not be true for the given interchange being analyzed.

Work on most of these simplications involved collecting information on possible assumptions which could be made. For example, conversations with traffic engineers in North Carolina (and requests for information from FHWA) were used in the assumptions concerning lane and ramp velocity and lane flow ratios. In addition, other simplifications involved examining the individual components of the basic formulas to determine if any could be deleted or simplified given the existing ranges of possible data. In other cases "numerical" simplifications were developed. For example, the exponential components of the rear-end exposure formulas are difficult to combine and simplify. Here, an overall general formula involving average flows and velocities was developed and the exposure counts calculated with this simplified formula were compared to counts generated by the full basic formula using a wide range of possible through-lane and ramp volumes. This comparison allowed us to develop a correction factor (based on the ratio of ramp to through volumes) to be used in the simplified formula. With this correction factor, the simplified formula generated counts within $\pm$ 6 percent of the counts from the full formula over the range of expected flow rates.

All of the formulas that are presented will cover the basic situation involving four through lanes (two in each direction). These formulas can be modified to cover other cases.

IV. Exposure for Thru Segment Prior to Interchange

A. Assumptions: 2-lanes, each direction
Length = L



B. Definitions:

f_1 = inner (median) lane flow (vph) $= f_{i1A}$

f_2 = outer (curb) lane flow (vph) $= f_{o1A}$

f = total thru flow $= f_1 + f_2$

v_1 = inner lane average velocity (mph)

v_2 = outer lane average velocity (mph)

σ_2 = standard deviation of outer lane speeds (mph)

v = average velocity across all lanes (mph)
s = speed limit (mph)
L = length of component (feet)
T = length of study period (hours)

C. Types of Exposure - Rear-end, sideswipe, single vehicle, head on.

1. Rear-end (from Equation 3.7)

$$E_{RE} = T\left[f_1(1-e^{-f_1L/5280v_1}) + f_2(1-e^{-f_2L/5280v_2}) + \frac{Lf_2^2\,\sigma_2}{5280(v_2^2-\sigma_2^2)}\right]$$

2. Sideswipe (from Equation 3.9)

$$E_{SS} = \begin{cases} \dfrac{TLf_1f_2}{5280}\left(\dfrac{1}{v_2}-\dfrac{1}{v_1}\right), & \text{if } \dfrac{v_1-v_2}{v_2}L > 40, \\ \text{or} & \\ \dfrac{T\,f_1f_2}{132v_1}, & \text{if } \dfrac{v_1-v_2}{v_2}L \le 40. \end{cases}$$

3. Single vehicle (from Equation 2.1)

$$E_{SV} = T(f_1+f_2)$$

4. Head-on (from Equation 3.1)

Note: Head-on exposure involves possible collisions with vehicles in the oncoming lanes. For notation purposes, these oncoming vehicle flows and velocities will be denoted by a "~" above the flow or velocity (e.g. $\tilde{f}_1$, and $\tilde{v}_1$ are the hourly flow and velocity for traffic in the inside oncoming lane.)

$$E_H = \frac{LT}{5280}\left[f_1\tilde{f}_1\left(\frac{1}{v_1}+\frac{1}{\tilde{v}_1}\right) + f_1\tilde{f}_2\left(\frac{1}{v_1}+\frac{1}{\tilde{v}_2}\right) + f_2\tilde{f}_1\left(\frac{1}{v_2}+\frac{1}{\tilde{v}_1}\right) + f_2\tilde{f}_2\left(\frac{1}{v_2}+\frac{1}{\tilde{v}_2}\right)\right]$$

5. Total Exposure = $(E_{RE} + E_{SS} + E_{SV} + E_H)$

D. Simplifications

1. Rear-end

$$E_{RE} = T\left[f\left(1-e^{-fL/10032s}\right) + \frac{Lf^2}{5280(.81s^2 - 16)}\right]$$

Assumptions: (1) $f_1 = f_2 = f/2$
(2) $v_1 = s$, $v_2 = .9s$
(3) $\sigma_2 = 4$ mph

2. Sideswipe

$$E_{SS} = \begin{cases} \dfrac{LTf^2}{190{,}080\ s}, & \text{if } L > 360 \text{ ft.} \\[2ex] \dfrac{Tf^2}{528s}, & \text{if } L \le 360 \text{ ft.} \end{cases}$$

Assumptions: (1) Inner lane velocity = speed limit = s
(2) Outer (curb) lane velocity = 0.9 speed limit
(3) $f_1 = f_2 = .5f$

3. Single vehicle

$$E_{SV} = T(f_1 + f_2) = Tf$$

4. Head-on

$$E_{HO} = \frac{2.05LTf^2}{5280\ s}$$

Assumptions: (1) $f_1 = f_2 = \tilde{f}_1 = \tilde{f}_2 = .5f$

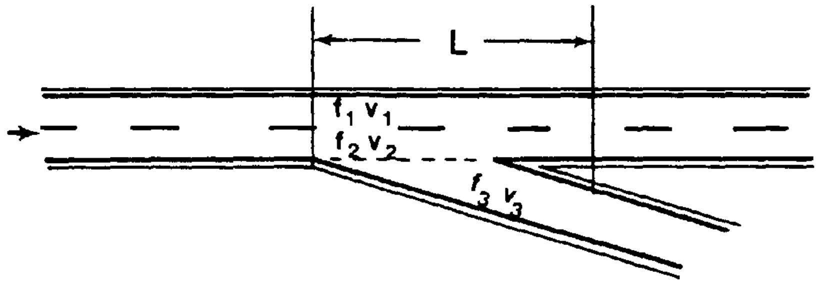
(2) Inner lane velocities = $v_1 = \tilde{v}_1$ = speed limit = s
Outer lane velocities = $v_2 = \tilde{v}_2 = 0.9s$

5. Total exposure (simplified)

$$E_{Total} = (E_{RE} + E_{SS} + E_{SV} + E_{HO})$$

V. Exit Ramp Exposure

A. Assumptions: 2-lanes, each direction plus exit ramp.
Length L extends from point of taper to point 1 ft. beyond nose of gore. This end point (i.e., nose of gore) is the end of pavement or a guardrail nose, attenuator, etc. Thus, any encroachments straight into gore are considered related to this component.



B. Definitions:

f_1 = inner (median) lane flow (vph) = f_{i1A}

f_2 = outer (curb) lane flow (vph) = f_{o1A} - f_{RA}

f_3 = exiting flow (vph) = f_{RA}

f = total thru flow = $f_1 + f_2$

v_1 = inner lane average velocity (mph)

v_2 = outer lane average velocity (mph)

v_3 = exit ramp velocity (mph)

σ_2 = standard deviation of outer lane speeds (mph)

v = average velocity across all lanes in mph

s = speed limit (mph)

L = length of component (feet)

T = length of study period (hours)

C. Types of Exposure - Rear-end, Sideswipe, Single Vehicle, Head-on.

1. Rear-end (by lane; from Equation 3.7)

$$E_{RE} = T\left[f_1(1-e^{-f_1L/5280v_1}) + f_2(1-e^{-f_2L/5280v_2}) + f_3(1-e^{-f_3L/5280v_3}) + \frac{Lf_2^2\ {}_2}{5280(v_2^2-\sigma_2^2)}\right]$$

2. Sideswipe (from Equation 3.9)

If $\frac{v_1 - v_2}{v_2} L > 40$ ft. , then

$$E_{SS} = \frac{TL}{5280} \left[f_1 f_2 \left| \frac{1}{v_2} - \frac{1}{v_1} \right| + f_1 f_3 \left| \frac{1}{v_3} - \frac{1}{v_1} \right| + f_2 f_3 \left| \frac{1}{v_3} - \frac{1}{v_2} \right| \right]$$

If $\frac{v_1 - v_2}{v_2} L \leq 40$ ft. , then

$$E_{SS} = \frac{T}{132} \left[\frac{f_1 f_2}{v_1} + \frac{f_1 f_3}{v_1} + \frac{f_2 f_3}{v_2} \right]$$

3. Single Vehicle (from Equation 2.1)

$$E_{SV} = T(f_1 + f_2 + f_3)$$

4. Head-on (from Equation 3.1)

$$E_{HO} = \frac{LT}{5280} \left[f_1 \tilde{f}_1 \left(\frac{1}{v_1} + \frac{1}{\tilde{v}_1}\right) + f_1 \tilde{f}_2 \left(\frac{1}{v_1} + \frac{1}{\tilde{v}_2}\right) + f_1 \tilde{f}_3 \left(\frac{1}{v_1} + \frac{1}{\tilde{v}_3}\right) + f_2 \tilde{f}_1 \left(\frac{1}{v_2} + \frac{1}{\tilde{v}_1}\right) + f_2 \tilde{f}_2 \left(\frac{1}{v_2} + \frac{1}{\tilde{v}_2}\right) + f_2 \tilde{f}_3 \left(\frac{1}{v_2} + \frac{1}{\tilde{v}_3}\right) \right]$$

Assumption: There is an entrance ramp on the opposite roadway within length L. If not, then the components including $\tilde{f}_3$ would be deleted from the formulae by setting $\tilde{f}_3 = 0$.

D. Simplifications

1. Rear-end

$$E_{RE} = T \left[f(1-e^{-fL/10032s}) + f_3(1-e^{-f_3 L/4224s}) + \frac{Lf^2}{5280\,(.81s^2 - 16)} \right]$$

Assumptions: (1) $f_1 = f_2 = f/2$

(2) $v_1 = s$; $v_2 = 9s$; $v_3 = .8s$

(3) $\sigma_2 = 4$ mph

2. Sideswipe

If $L > 360$ ft., then

$$E_{SS} = \frac{LT(f^2 + 7ff_3)}{190{,}080s}$$

If $L \leq 360$ ft., then

$$E_{SS} = \frac{T(f^2 + 4.22ff_3)}{528s}$$

Assumptions: (1) $f_1 = f_2 = f/2$ (approximately equal lane flow)
(2) $v_1 = s$
$v_2 = .9s$
$v_3 = .8s$
(3) $\sigma_2 = 4$ mph

3. Single Vehicle

$$E_{SV} = T(f_1 + f_2 + f_3) = T\,(f + f_3)$$

4. Head-on

$$E_{HO} = \frac{LT}{5280\ s}\ (2.11f^2 + 2.3f_1 f_3)$$

Assumptions: (1) $f_1 = \tilde{f}_1$; $f_2 = \tilde{f}_2$; $f_3 = \tilde{f}_3$ $\quad f_1 = f_2 = f/2$

(2) $v_1 = \tilde{v}_1 = s$

$v_2 = \tilde{v}_2 = .9s$

$v_3 = \tilde{v}_3 = .8s$

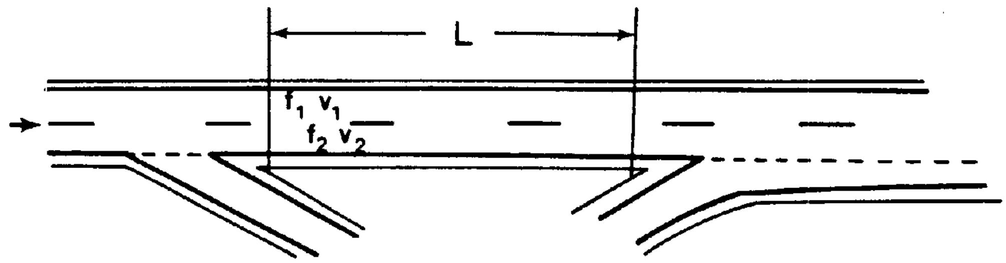
5. Total exposure (simplified)

$$E_{Total} = E_{RE} + E_{SS} + E_{SV} + E_{HO}$$

Assumptions: All mentioned above.

VI. Interior Thru (No Ramp) Section Prior to Weave

A. Assumptions: 2-lanes, each direction
Length = L defined by distance between gore point and next entrance ramp gore point.



B. Definitions:

f_1 = inner (median) lane flow (vph) = f_{i1A}

f_2 = outer (curb) lane flow (vph) = f_{o1A} - f_{RA}

f = total thru flow = $f_1 + f_2$

v_1 = inner lane average velocity (mph)

v_2 = outer lane average velocity (mph)

v = average velocity across all lanes (mph)

s = speed limit (mph)

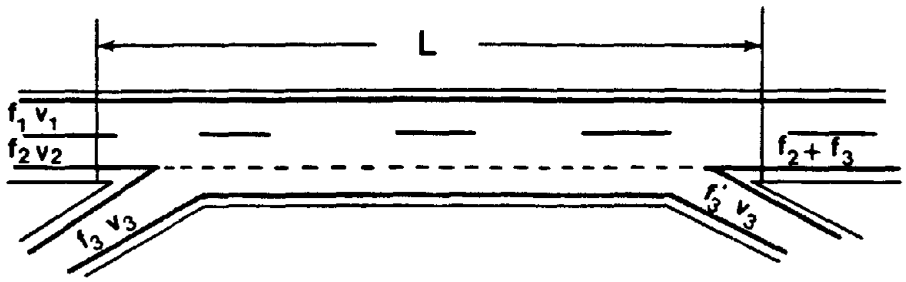
L = length of component (feet)

T = length of study period (hours)

C. Computations: Formulas for this segment are exactly the same as for the "Segment Prior to Interchange." See pages 54-56 for details.

VII. Weave Area

A. Assumptions: 2 through lanes plus 1 weave lane
L= Length, defined by the noses of the pavement gore areas.



Note that f_3 is the entering ramp flow and f_3' is the exiting traffic from the main line.

B. Definitions:

f_1 = inner (median) lane flow (vph) = f_{i1A}

f_2 = outer (curb) lane flow (vph) = $f_{o1A} - f_{RA}$

f_3 = entering flow (vph) = f_{LD}

f_3' = exiting flow (vph) = f_{LA}

f = total entering flow on thru lanes = f_1+f_2

v_1 = inner lane average velocity (mph)

v_2 = outer lane average velocity (mph)

v_3 = exit (entrance) ramp velocity (mph)

σ_2 = standard deviation of outer lane speeds (mph)

v = average velocity across all lanes (mph)
s = speed limit (mph)
L = length of component (feet)
T = length of study period (hours)

C. Types of Exposure

1. Rear-end exposure (from Equation 3.7)

$$E_{RE} = \left[T\ f_1(1-e^{-f_1 L/5280v_1}) + f_2(1-e^{-(f_2)L/5280v_2}) + f_3(1-e^{-f_3 L/5280v_3}) + \frac{L f_2^2\ \sigma_2}{5280(v_2^2 - \sigma_2^2)} \right]$$

2. Single vehicle exposure (from Equation 2.1)

$$E_{SV} = T(f_1 + f_2 + f_3)$$

3. Angle exposure (from Equation 3.8)

$$E_A = \frac{LT}{5280} \frac{f_3}{v_3} (f_1 + f_2)$$

4. Sideswipe exposure (from Equation 3.9)

If $\frac{v_1 - v_2}{v_2} L > 40$ ft. , then

$$E_{SS} = \frac{TL}{5280} \left[f_1 f_2 \left| \frac{1}{v_2} - \frac{1}{v_1} \right| + f_1 f_3 \frac{1}{v_3} - \frac{1}{v_1} + f_2 f_3 \left| \frac{1}{v_3} - \frac{1}{v_2} \right| \right]$$

If $\frac{v_1 - v_2}{v_2} L \leq 40$ ft. , then

$$E_{SS} = \frac{T}{132} \left[\frac{f_1 f_2}{v_1} + \frac{f_1 f_3}{v_1} + \frac{f_2 f_3}{v_2} \right]$$

5. Head-on exposure (from Equation 3.1)

$$E_{HO} = \frac{LT}{5280} \left[f_1 \tilde{f}_1 \left(\frac{1}{v_1} + \frac{1}{\tilde{v}_1} \right) + f_1 \tilde{f}_2 \left(\frac{1}{v_1} + \frac{1}{\tilde{v}_2} \right) + f_1 \tilde{f}_3 \left(\frac{1}{v_1} + \frac{1}{\tilde{v}_3} \right) \right.$$

$$+ f_2 \tilde{f}_1 \left(\frac{1}{v_2} + \frac{1}{\tilde{v}_1} \right) + f_2 \tilde{f}_2 \left(\frac{1}{v_2} + \frac{1}{\tilde{v}_2} \right) + f_2 \tilde{f}_3 \left(\frac{1}{v_2} + \frac{1}{\tilde{v}_3} \right)$$

$$\left. + f_3 \tilde{f}_1 \left(\frac{1}{v_3} + \frac{1}{\tilde{v}_1} \right) + f_3 \tilde{f}_2 \left(\frac{1}{v_3} + \frac{1}{\tilde{v}_2} \right) + f_3 \tilde{f}_3 \left(\frac{1}{v_3} + \frac{1}{\tilde{v}_3} \right) \right]$$

D. Simplifications

1. Rear-end exposure

$$E_{RE} = T\left[f(1-e^{-fL/10032s}) + f_3(1-e^{-f_3L/4224s}) + \frac{Lf^2}{5280\ (.81s^2 - 16)}\right]$$

Assumptions: (1) $f_1 = f_2 = f/2$

(2) $v_1 = s$, $v_2 = .9s$, $v_3 = .8s$

(3) $\sigma_2 = 4$ mph

2. Single vehicle exposure

$$E_{SV} = T(f + f_3) = T(f_1+f_2+f_3+f_3)$$

3. Sideswipe exposure

If $L > 360$ ft., then

$$E_{SS} = \frac{LT(f^2 + 7ff_3)}{190{,}080s}$$

If $L \leq 360$ ft., then

$$E_{SS} = \frac{T(f^2 + 4.22ff_3)}{528s}$$

Assumptions: (1) $f_1 = f_2 = f/2$
(approximately equal lane flow)
(2) $v_1 = s$; $v_2 = .9s$; $v_3 = .8s$
(3) $\sigma_2 = 4$ mph

4. Angle exposure

$$E_A = \frac{LTff_3}{4224(s)}$$

Assumption: $v_3 = .8s$

5. Head-on exposure

$$E_{HO} = \frac{LT}{5280(s)} (2.11f^2 + 4.61ff_3 + 2.50f_3{}^2)$$

Assumptions: (1) $f_1 = \tilde{f}_1$; $f_2 = \tilde{f}_2$; $f_3 = \tilde{f}_3$; $f_1 = f_2 = f/2$

(2) $v_1 = \tilde{v}_1 = s$;

$v_2 = \tilde{v}_2 = .9s$

$v_3 = \tilde{v}_3 = .8s$

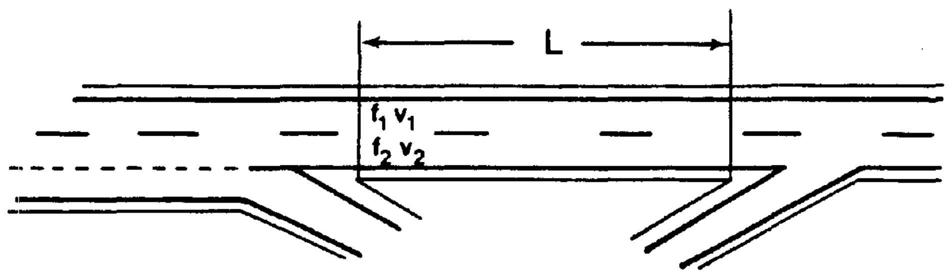
6. Total exposure (simplified)

$$E_{Total} = (E_{RE} + E_A + E_{SS} + E_{SV} + E_{HO})$$

Assumptions: All listed above.

VIII. Interior Thru (No Ramp) Section Following Weave

A. Assumptions: 2 lanes, each direction
Length = L defined by distance between gore point of weave exit ramp and next entrance ramp gore point



B. Definitions:

f_1 = inner (median) lane flow (vph) = f_{i1A}

f_2 = outer (curb) lane flow (vph) = $f_{o1A} + f_{LD} - f_{LA} - f_{RA}$

f = total thru flow = $f_1 + f_2$

v_1 = inner lane average velocity (mph)

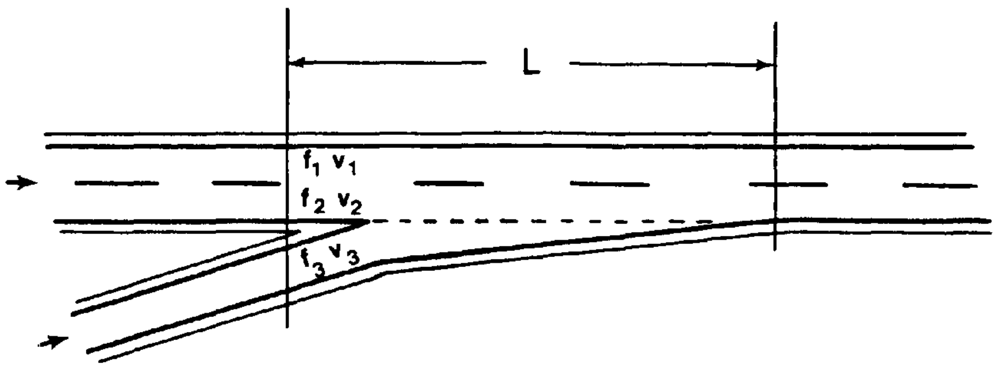
v_2 = outer lane average velocity (mph)

v = average velocity across all lanes (mph)
s = speed limit
L = length of component (feet)
T = length of study period (hours)

C. Computations: Formulas for this segment are exactly the same as the "Segment Prior to Interchange". See pages 54-56 for details.

IX. Entrance Ramp Area

A. Assumptions: (1) 2 through lanes plus 1 entrance ramp
(2) L=length, defined by distance from 1 ft. prior to nose of gore to end of taper.



B. Definitions:

f_1 = inner (median) lane flow (vph) = f_{i1A}

f_2 = outer (curb) lane flow (vph) = $f_{o1A} + f_{LD} - f_{LA} - f_{RA}$

f_3 = entrance ramp flow (vph) = f_{RB}

v_1 = inner lane average velocity (mph)

v_2 = outer lane average velocity (mph)

σ_2 = standard deviation of outer lane speeds (mph)

f = total thru flow = $f_1 + f_2$

v_3 = entrance ramp average velocity (mph)

v = average velocity across all lanes (mph)
s = speed limit (mph)
L = length of component (feet)
T = length of study period (hours)

C. Types of Exposure

1. Rear-end exposure (from Equation 3.7)

$$E_{RE} = T\left[f_1(1-e^{-f_1L/5280v_1}) + f_2(1-e^{-f_2L/5280v_2} + f_3(1-e^{-f_3L/5280v_3}) + \frac{Lf_2^{\,2}\,\sigma_2}{5280(v_2^{\,2}-\sigma_2^{\,2})}\right]$$

2. Single vehicle exposure (from Equation 2.1)

$$E_{SV} = T\ (f_1 + f_2 + f_3)$$

3. Angle exposure (from Equation 3.8)

$$E_A = \frac{LT}{5280} \left[\frac{f_3}{v_3} \ (f_1 + f_2) \right]$$

4. Sideswipe exposure (from Equation 3.9)

If $\frac{v_1 - v_2}{v_2} L > 40$ ft. , then

$$E_{SS} = \frac{TL}{5280} \left[f_1 f_2 \left| \frac{1}{v_2} - \frac{1}{v_1} \right| + f_1 f_3 \left| \frac{1}{v_3} - \frac{1}{v_1} \right| + f_2 f_3 \left| \frac{1}{v_3} - \frac{1}{v_2} \right| \right]$$

If $\frac{v_1 - v_2}{v_2} L \leq 40$ ft. , then

$$E_{SS} = \frac{T}{132} \left[\frac{f_1\ f_2}{v_1} + \frac{f_1\ f_3}{v_1} + \frac{f_2\ f_3}{v_2} \right]$$

5. Head-on exposure (from Equation 3.1)

$$E_{HO} = \frac{LT}{5280} \left[f_1\ \tilde{f}_1\ (\frac{1}{v_1} + \frac{1}{\tilde{v}_1}) + f_1 \tilde{f}_2\ (\frac{1}{v_1} + \frac{1}{\tilde{v}_2}) \right.$$

$$+ f_2\ \tilde{f}_1\ (\frac{1}{v_2} + \frac{1}{\tilde{v}_1}) + f_2 \tilde{f}_2\ (\frac{1}{v_2} + \frac{1}{\tilde{v}_2})$$

$$\left. + f_3\ \tilde{f}_1\ (\frac{1}{v_3} + \frac{1}{\tilde{v}_1}) + f_3 \tilde{f}_2\ (\frac{1}{v_3} + \frac{1}{\tilde{v}_2}) \right]$$

D. Simplifications

1. Rear-end

$$E_{RE} = T\left[f(1-e^{-fL/10032s}) + f_3(1-e^{-f_3L/4224s}) + \frac{Lf^2}{5280\ (.81s^2 - 16)}\right]$$

Assumptions: (1) $f_1 = f_2 = f/2$

(2) $v_1 = s$; $v_2 = .9s$; $v_3 = .8s$

(3) $\sigma_2 = 4$ mph

2. Single vehicle

$$E_{SV} = T(f + f_3) = T(f_1+f_2+f_3)$$

3. Sideswipe

If $L > 360$ ft., then

$$E_{SS} = \frac{LT(f^2 + 7ff_3)}{190{,}080s}$$

If $L \leq 360$ ft., then

$$E_{SS} = \frac{T(f^2 + 4.22ff_3)}{528s}$$

Assumptions: (1) $f_1 = f_2 = f/2$ (approximately equal lane flow
(2) $v_1 = s$; $v_2 = .9s$; $v_3 = .8s$
(3) $\sigma_2 = 4$ mph

4. Angle

$$E_A = \frac{LTff_3}{4224(s)}$$

Assumptions: $f_1 = f_2 = f/2$

$v_3 = .8s$

5. Head-on

$$E_{HO} = \frac{LT}{5280(s)} (2.11f^2 + 2.31ff_3)$$

Assumptions: (1) $f_1 = \tilde{f}_1$; $f_2 = \tilde{f}_2$; $f_3 = \tilde{f}_3$; $f_1 = f_2 = f/2$

(2) $v_1 = \tilde{v}_1 = s$;

$v_2 = \tilde{v}_2 = .9s$

$v_3 = \tilde{v}_3 = .8s$

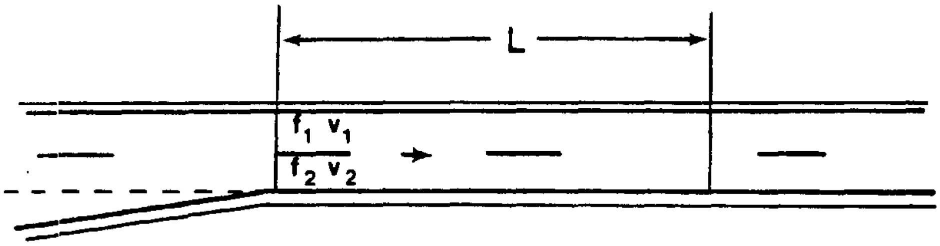
6. Total exposure (simplified)

$$E_{Total} = E_{RE} + E_{SV} + E_{SS} + E_A + E_{HO}$$

Assumptions: All listed above.

X. Thru Segment Downstream from Interchange

A. Assumptions: (1) 2-lanes, each direction
(2) Length = L



B. Definitions:

f_1 = inner (median) lane flow (vph) = f_{i1A}

f_2 = outer (curb) lane flow (vph) = $f_{o1A} + f_{RB} + f_{LD} - f_{LA} - f_{RA}$

f = total thru flow = $f_1 + f_2$

v_1 = inner lane average velocity (mph)

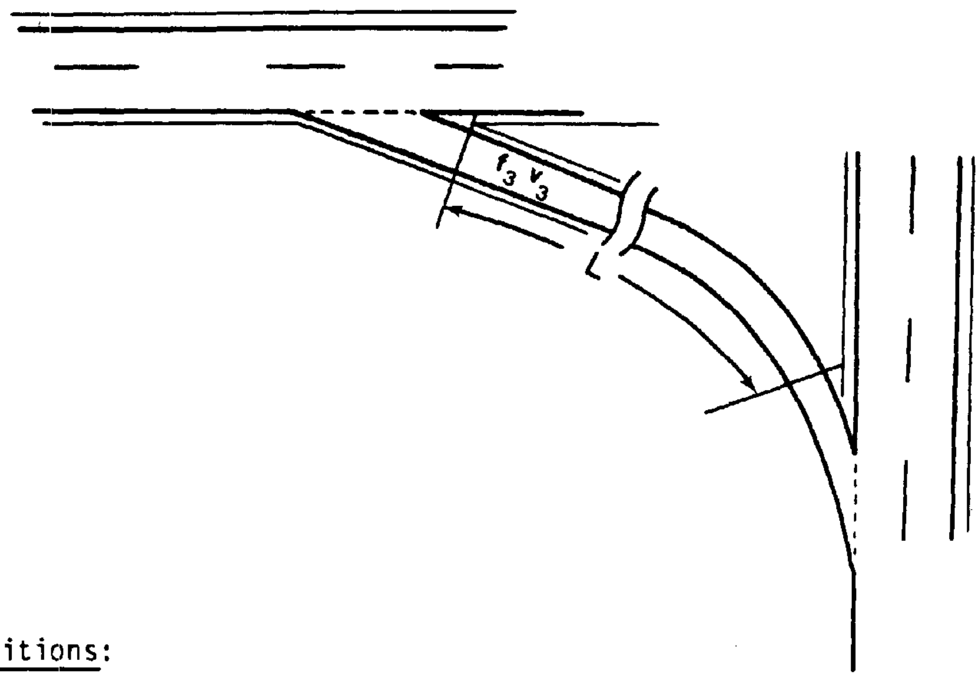
v_2 = outer lane average velocity (mph)

v = average velocity across all lanes (mph)
s = speed limit
L = length of component (feet)
T = length of study period (hours)

C. Computations: Formulas for this segment are exactly the same as for the "Thru Segment Prior to Interchange." See pages 54-56 for details.

XI. Ramp

A. Assumptions: 1 lane, 1 way flow
Length = L, defined by distance from gore point to gore point.



B. Definitions:

f_3 = ramp flow (vph) = f_{RA}

v_3 = ramp average velocity (mph)

s = speed limit (mph)
L = length of component (feet)
T = length of study period (hours)

C. Types of exposure

1. Rear-end (from Equation 3.7)

$$E_{RE} = Tf_3(1 - e^{-f_3L/5280v_3})$$

2. Single vehicle (from Equation 2.1)

$$E_{SV} = Tf_3$$

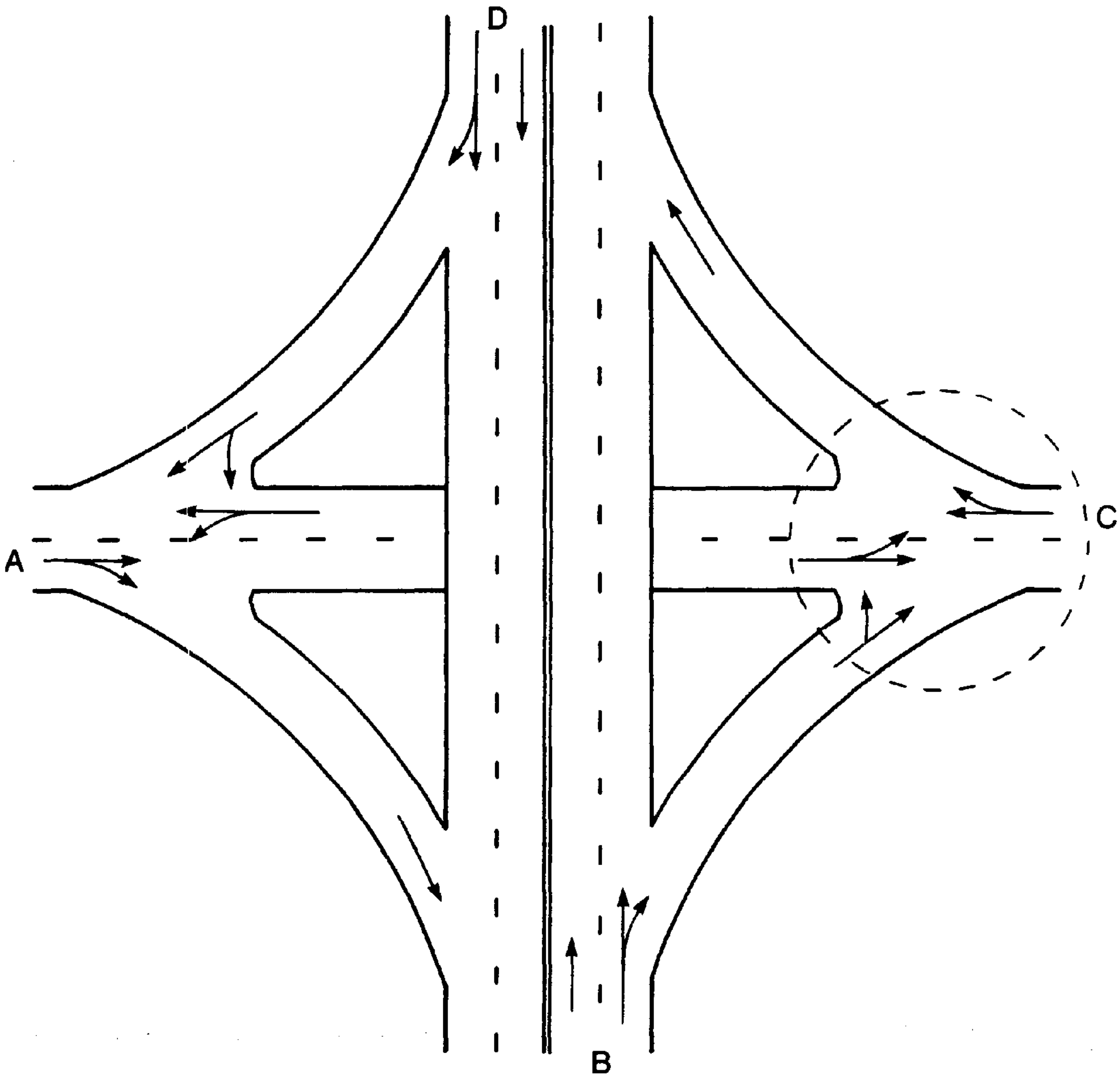
3. Total exposure

$$E_T = Tf_3 \left[2-e^{-f_3 L/5280 v_3}\right]$$

D. Simplifications -- None.

XII. Diamond Ramp Terminals

As noted in the earlier discussion of total interchange exposure, diamond interchanges have certain components which are common with cloverleaf interchanges (e.g., exit ramps, entrance ramps, interim sections, etc.). The only new component is the diamond ramp terminal area (see figure below).

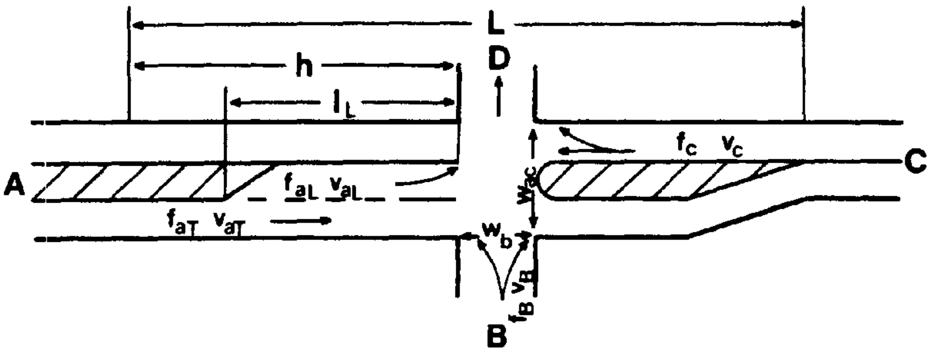


Since formulas for all other sections common to diamond and cloverleaf interchanges were presented in the preceeding pages, only the additional formulas for the ramp terminal areas will be presented here.

A. <u>Assumptions</u>: These diamond ramp terminals will be defined as intersections of widths "w" plus a distance equal to ± 150 ft.

Thus $L = 350'$ if $w_{ac} = 50'$

Two situations may exist. The ramp terminal area may be stop-sign controlled, with the entering ramp B being stopped, or the area may be signal-controlled, with or without a left-turn phase for the minor roadway approach A. The signal-controlled exposure formulas will only be developed for the case involving two thru lanes plus a left turn lane on the minor roadway. The figure below presents the traffic flows, section lengths and widths used in the formulas.



Formulas will be presented for the following situations on the minor roads.

a) one thru lane in each direction with <u>no</u> left turn lane.
b) one thru lane in each direction with a left turn lane from Approach A.
c) two thru lanes in each direction with a left turn lane from Approach A.

The actual exposure measures will be modifications of those developed for intersections and other interchange segments.

B. Definitions:

f_a = total approach flow on approach A (veh/hr)

f_{a_T} = thru flow on approach A (veh/hr)

f_{a_L} = left turning flow on approach A (veh/hr)

f_c = total approach flow on approach C (veh/hr)

f_b = total approach flow on approach B (veh/hr)

v_a = approach A average velocity (mph)

v_{a_T} = approach A thru flow average velocity (mph)

v_{a_L} = approach A left turning flow average velocity (mph)

v_c = approach C average velocity (mph)

v_b = approach B average velocity (mph) -- (this will be the average velocity for the 150' approach distance)

$s_a = s_c$ = speed limit for approach A (minor roadway) (mph)

s_b = speed limit for approach B (ramp speed limit) (mph)

L = total length of segment (ft)

h = length of approach segment (ft)

w_{ac} = total width of through roadway (ft)

w_b = width of ramp approach B (ft)

ℓ_L = length of left turn lane on approach A (ft)

T = length of study period (hours)

C. Exposure for the design including one thru lane only, with the ramp being stop controlled.

1. Rear-end (from Equations 2.19 and 2.21)

$$E_{RE} = T \left[f_a \left(1-e^{-f_a L/5280 v_a}\right) + f_b \left(1-e^{-f_b h/5280 v_b}\right) + f_c \left(1-e^{-f_c L/5280 v_c}\right) \right]$$

2. Sideswipe (from Equation 2.27)

By definition, only allow sideswipe of turning vehicles by through vehicles. Thus, with no left turn lane

$$E_{SS} = 0$$

3. Single vehicle (from Equation 2.18)

$$E_{SV} = T\ (f_a + f_b + f_c)$$

4. Head-on (from Equation 2.22)

$$E_{HO} = \frac{LT}{5280} \left[f_a f_c \left(\frac{1}{v_a} + \frac{1}{v_c}\right) \right]$$

5. Angle (assuming $v_a = v_c$) (from Equation 2.26)

$$E_A = \frac{T}{5280} \left[\left(\frac{w_b}{v_a} + \frac{w_{ac}}{\tilde{v}_b}\right) (f_a\ f_b + f_b\ f_c) \right]$$

$$\text{where } \tilde{v}_b = 0.83 \sqrt{w_{ac}}$$

6. Simplifications

a. Rear-end

$$E_{RE} = T \left[(2f)\ (1-e^{-f_a/13.58 s_a}) + f_b\ (1-e^{-f_b/458}) \right]$$

Assumptions:

$f_a = f_c = f$

$L = 350$ ft.

$h = 150$ ft.

$v_a = v_c = .9 s_a$

v_b = 13 mph regardless of ramp speed limit (based on deceleration time over 150 feet for a deceleration of 6 feet/second^2)

b. Sideswipe

$$E_{SS} = 0$$

c. Single vehicle

$$E_{SV} = T(f_a + f_b + f_c)$$

d. Head-on

$$E_{HO} = \frac{.14\ T\ f_a^{\,2}}{s_a}$$

Assumptions:

$f_a = f_c$

$v_a = v_c = .9s_a$

$L = 350'$

e. Angle

$$E_A = \frac{Tf_a f_b\ (50 + 7.67s_a)}{2376s_a}$$

Assumptions:

$v_a = v_c = .9s_a$

$\tilde{v}_b = 0.83\ \sqrt{w_{ac}}$

$f_a = f_c$

$w_{ac} = w_b = 50'$

f. Total exposure (simplified)

$$E_{TOT} = T \left[(f_a + f_c)\left(1 - e^{-f_a/13.58 s_a}\right) + f_b\left(1 - e^{-f_b/458}\right) + \frac{.14\, f_a^{\,2}}{s_a} + \frac{f_a\, f_b\, (50 + 7.67 s_a)}{2376 s_a} + f_a + f_b + f_c \right]$$

Assumptions: All on previous pages.

D. Exposure for design with one thru lane plus a left turn lane on the minor roadway. The ramp is stop controlled.

1. Rear-end (from Equations 2.19 and 2.21)

$$E_{RE} = T \Bigg[f_{a_T} \left(1-e^{-f_{a_T} L/5280\, v_{a_T}}\right) + f_{a_L} \left(1-e^{-f_{a_L} L/5280 v_{a_L}}\right)$$

$$+ f_{a_L} \left(1-e^{-f_{a_L} h/5280\, v^*_{a_L}}\right)$$

$$+ f_c \left(1-e^{-f_c L/5280\, v_c}\right) + f_b \left(1-e^{-f_b h/5280\, v_b}\right) \Bigg]$$

Here $v^*_{a_L}$ = velocity of vehicle after turning left

2. Sideswipe (from Equation 2.27)

$$E_{SS} = \frac{T\ L f_{a_T}\ f_{a_L}}{5280} \left| \frac{1}{v_{a_T}} - \frac{1}{v_{a_L}} \right|$$

3. Single vehicle (from Equation 2.18)

$$E_{SV} = T\ (f_a + f_b + f_c)$$

4. Head-on (from Equation 2.22)

$$E_{HO} = \frac{LT}{5280} \left[f_a f_c \ \left(\frac{1}{v_a} + \frac{1}{v_c}\right) \right]$$

5. Angle (assuming $v_a = v_c$) (from Equation 2.26)

$$E_A = \frac{T}{5280} \left(\frac{w_b}{v_a} + \frac{w_{ac}}{\tilde{v}_b}\right) (f_a f_b + f_b f_c)$$

where $\tilde{v}_b = 0.83 \sqrt{w_{ac}}$ mph.

6. Simplifications

a. Rear-end

$$E_{RE} = T\left[(2f)\ (1-e^{-f_{a_T}/13.58s_a}) + 2\ f_{a_L}\ (1-e^{-f_{a_L}/422.4}) + f_b\ (1-e^{-f_b/457.6})\right]$$

Assumptions:

v_{a_L} = 12 mph (based on assumption that each left turning vehicle decelerates to a stop over the ℓ_L = 150' before turning)

$v_{a_L}^*$ = 12 mph (based on acceleration at 3 ft/sec over the h + w = 200' after stopping)

$v_{a_T} = v_c = .9s_a$

v_b = 13 mph (based on deceleration rate of 6 ft/sec over h = 150' distance)

$f_{a_T} = f_c = f$

L = 350'

$w_{ac} = w_b$ = 50'

h = 150'

ℓ_L = 150'

If left-turning volume is not known, then use the rear-end exposure formula found under the previous situation "C".

b. Sideswipe exposure

$$E_{SS} = \frac{T\ f_{a_T}\ f_{a_L}\ \left|0.9s_a - 12\right|}{380.2s_a}$$

Assumptions:

$v_{a_T} = .9s_a$

$v_{a_L} = 12$ mph

$\ell_L = 150'$

c. Single vehicle

$$E_{SV} = T\ (f_a + f_b + f_c)$$

d. Head-on

$$E_{HO} = \frac{Tf_a f_c}{13.58s_a}$$

Assumptions:

$v_a = v_c = .9s_a$

$L = 350'$

e. Angle

$$E_A = \frac{T\ f_a\ f_b\ (50 + 7.67s_a)}{2376s_a}$$

Assumptions:

$v_a = v_c = .9s_a$

$\tilde{v}_b = 0.83\ \sqrt{w_{ac}}$

$f_a = f_c$

$w_{ac} = w_b = 50'$

f. Total exposure (simplified)

$$E_{TOT} = E_{RE} + E_{SS} + E_{SV} + E_{HO} + E_{A}$$

Assumptions: All on previous pages.

E. <u>Exposure for design with two thru lanes in each direction, plus a left turn lane. The ramp is stop controlled.</u>

1. Rear-end (from Equations 2.19 and 2.21)

Assume thru lane flows in a given direction are approximately equal and that the average approaching and departing velocities for the left turning vehicles are equal.

$$E_{RE} = T \left[f_{a_T} \left(1-e^{-f_{a_T} L/10560\, v_{a_T}}\right) + f_c \left(1-e^{-f_c L/10560\, v_c}\right) + 2 f_{a_L} \left(1-e^{-f_{a_L} (h+w_b)/5280\, v_{a_L}}\right) + f_b \left(1-e^{-f_b h/5280 v_b}\right) \right]$$

2. Sideswipe--(under the assumption of an overtaking component between each thru lane and the vehicle in the left turn lane and a side-by-side component between vehicles in the thru lanes.)

$$E_{SS} = \frac{T\ell_L f_{a_T} f_{a_L}}{5280} \left| \frac{1}{v_{a_L}} - \frac{1}{v_{a_T}} \right| + \frac{T f_{a_T}^2}{528 v_{a_T}} + \frac{T f_c^2}{528 v_c}$$

3. Single vehicle (from Equation 2.18)

$$E_{SV} = T\,(f_a + f_b + f_c)$$

4. Head-on (from Equation 2.22)

As for all intersections, assume thru lane volumes and velocities in a given direction are approximately equal.

$$E_{HO} = \frac{LT}{5280} \left[\left(\frac{1}{v_{a_T}} + \frac{1}{v_c}\right) (f_{a_T} f_c) + \left(\frac{1}{v_{a_L}} + \frac{1}{v_c}\right) (f_{a_L} f_c) \right]$$

5. Angle (assuming $v_{a_T} = v_c$) (from Equation 2.26)

$$E_A = \frac{T}{5280} \left[\left(\frac{w_b}{v_a} + \frac{w_{ac}}{\tilde{v}_b}\right) (f_a f_b + f_b f_c) \right]$$

where $\tilde{v}_b = 0.83 \sqrt{w_{ac}}$ mph.

6. Simplifications

a. Rear-end

$$E_{RE} = T \left[(2f)\left(1-e^{-f_{a_T}/27.15s_a}\right) + 2f_{a_L}\left(1-e^{-f_{a_L}/316.8}\right) + f_b\left(1-e^{-f_b/458}\right) \right]$$

Assumptions:

$f_{a_T} = f_{c_T} = f_c = f$

$v_{a_T} = v_c = .9s_a$

$v_{a_L} = 12$ mph

$v_b = 13$ mph

$L = 350'$

$h = 150'$

$h+w = 200'$

b. Sideswipe

$$E_{SS} = \frac{T}{475.2s_a} \left[f_{a_T}^2 + f_c^2 + 1.25\, f_{a_T} f_{a_L} \left| .9s_a - 12 \right| \right]$$

Assumptions:

$v_{a_T} = v_c = .9s_a$

$v_{a_L} = 12$ mph

$\ell_L = 150'$

c. Single vehicle

$$E_{SV} = T\,(f_a + f_b + f_c)$$

d. Head-on

$$E_{HO} = \frac{Tf_c}{13.58s_a}(2f_{a_T} + f_{a_L} + .07s_a f_{a_L})$$

Assumptions:

$$v_{a_T} = v_c = .9s_a$$

$$v_{a_L} = 13 \text{ mph}$$

$$L = 350'$$

e. Angle

$$E_A = \frac{T\ f_a\ f_b\ (50 + 7.67s_a)}{2376s_a}$$

Assumptions:

$$v_a = v_c = .9s_a$$

$$\tilde{v}_b = 0.83\ \sqrt{w_{ac}}\ \text{mph.}$$

$$f_a = f_c$$

$$w_{ac} = w_b = 50'$$

f. Total exposure

$$E_{TOT} = (E_{RE} + E_{SS} + E_{SV} + E_{HO} + E_A)$$

Assumptions: All stated above.

F. Exposure for signal-controlled ramp terminals.

Assume the only signal control situation would be situation "E" above - the situation with two thru lanes and a left turn lane on the minor road.

1. Rear-end (from Equation 2.33)

$$E_{RE} = T \Big[f_{a_T} (1-e^{-f_{a_T} L/10560\, v^*_a}) + f_c (1-e^{-f_c L/10560\, v^*_c})$$

$$+ 2 f_{a_L} (1-e^{-f_{a_L} (h+w_b)/5280\, v^*_{a_L}})$$

$$+ f_b (1-e^{-f_b h/5280\, v^*_b}) \Big]$$

Here the "v*'s" are based on free flow travel time plus estimated delay.

$$v^*_c = v^*_a = \frac{(L)(s)}{1.47(s)(d) + L}$$

$$v^*_{a_L} = \frac{12\ (h+w_b)}{h + w_b + 17.6d}$$

$$v^*_b = \frac{13\ (h+w_{ac})}{h + w_{ac} + 19.1d}$$

In each formula, d = delay (sec.) is extracted from one of the tables found in Chapter 2, p .

2. Sideswipe (from Equations 2.17 and 2.54)

Sideswipe exposure is calculated assuming adjacent thru lane flows and velocities in the roadway are approximately equal, and the opposing velocities (i.e., v_a and v_c) are approximately equal. Under these assumptions, sideswipe exposure is composed of three components, one resulting from the flows stopping in signal queues, the second from vehicles in the thru lanes side-by-side, and the third resulting from thru vehicles (i.e., f_{a_T}) overtaking left turning vehicles on Approach A (i.e., f_{a_L}) during the green phase of the cycle.

a. Calculate

$P_{g_{ac}}$ = proportion of total cycle length that is green for approach A or C, the minor roadway

P_{g_b} = proportion of total cycle length that is green for ramp Approach B

If these are known, use in the formulas below. If not, assume

$$P_{g_{ac}} = \frac{f_a + f_c}{f_a + f_b + f_c}$$

$$P_{g_b} = \frac{f_b}{f_a + f_b + f_c}$$

b. Calculate sideswipe exposure

$$E_{SS} = T \left[p_{g_{ac}} \frac{(f_a^2 + f_c^2)}{528 v_a} + p_{g_h} \frac{(f_a + f_c)}{2} + p_{g_{ac}} \frac{f_{a_T} f_{a_L} L}{5280} \left(\frac{1}{v_{a_L}} - \frac{1}{v_a} \right) \right]$$

3. Single vehicle (from Equation 2.1)

$$E_{SV} = T\,(f_a + f_b + f_c)$$

4. Head-on (Assume $v_a = v_c$) (from Equation 2.44)

$$E_{HO} = \frac{T\, f_a f_c}{7200} \left\{ f_b \left[\frac{2c f_b}{f_a + f_b} + \frac{(h+w_b)}{1.47} \left(\frac{1}{v_a} + \frac{1}{v_a^*} \right) + \frac{2h+w_b}{1.47 v_a} \right] + (f_a + f_c) \left[\frac{c f_b}{f_a + f_b} + \frac{3(2h+w_b)}{1.47 v} \right] \right\}$$

where c = cycle length in seconds
v_a^* = average velocity (mph) of vehicle on A or C after starting from zero mph at the stop bar.

5. Angle (from Equation 2.53)

$$E_A = \frac{T}{5280} \left(\frac{w_b}{v_a^*} + \frac{w_{ac}}{v_b^*}\right) (f_a\ f_b + f_b\ f_c) (P_{g_a} P_{r_b} + P_{g_b}\ P_{r_a})$$

where

$$v_a^* = \frac{(\text{green + yellow time}_a)}{c}\ v_a + \frac{(\text{red time}_a)}{c}\ (0.83\ \sqrt{w_b})$$

$$v_b^* = \frac{(\text{green + yellow time}_b)}{c}\ v_b + \frac{(\text{red time}_b)}{c}\ (0.83\ \sqrt{w_{ac}})$$

P_{g_a} = proportion of vehicles in A passing through green signal

= 1 - (proportion right-on-red) - (proportion running red light)

P_{g_b} = proportion of vehicles on B passing through green signal

= 1 - (proportion right-on-red) - (proportion running red light)

Assuming the signal timing is weighted by vehicle flows and

$$f_a = f_c\ ,\ f_b = f_d$$

then

$$v_a^* = \frac{v_a f_a + 0.83\ \sqrt{w_b}\ \ f_b}{f_a + f_b}$$

$$v_b^* = \frac{v_b f_b + 0.83\ \sqrt{w_{ac}}\ \ f_a}{f_a + f_b}$$

6. Simplifications

None possible -- see preceding formulas

CHAPTER 4

EXPOSURE ON HOMOGENEOUS HIGHWAY SECTIONS

I. Exposure for Sections of Two Lane Roadways

Consider a section of highway such as shown in Figure 4.1.

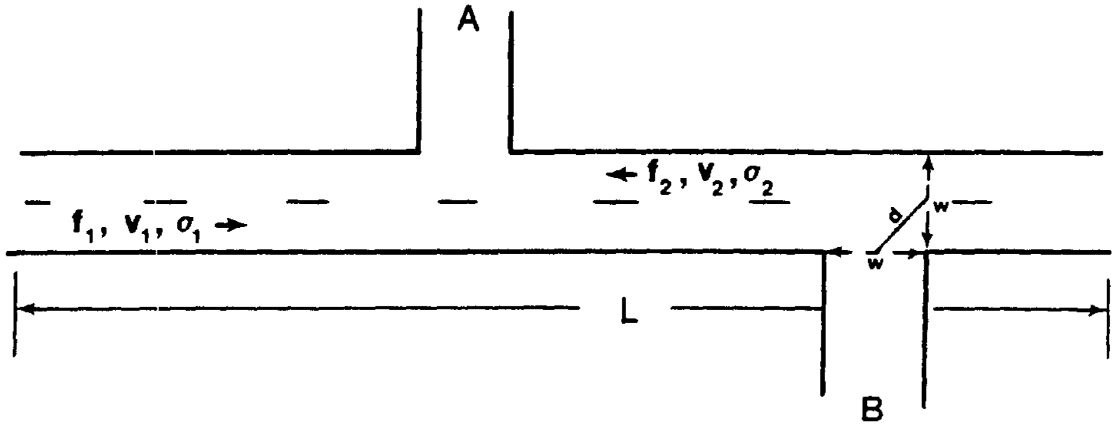


Figure 4.1

In the figure, the flows f_1 and f_2 represent average flows (over L) for some time unit. The accident and exposure types relevant for this type of highway section are:

- o single vehicle
- o head-on
- o rear-end
- o angle involving vehicles entering or exiting from private driveways (A and B in Figure 4.1)

The first three of the exposure types are essentially the same as those presented earlier in Chapters 1, 2, and 3.

A. Single Vehicle Exposure

Single vehicle exposure is given by

$$E_{SV} = T(f_1 + f_2) \quad . \tag{4.1}$$

It should be noticed that this formulation does not depend upon the length of the section. The reasoning here is that each vehicle passing through the section has one chance for a single vehicle crash with one long "roadside." Thus, the interaction opportunity is between a "pair" which includes the given vehicle and the roadside, paralleling the multi-vehicle opportunity between a pair involving the given vehicle with another vehicle.

In comparing intersections or interchanges where section lengths are essentially equal, accident rates computed as total single vehicle accidents divided by single vehicle exposure can be compared directly. To compare homogeneous sections where section lengths may differ substantially, the section length must be taken into account in the accident rate computation. In particular, suppose we want to compare two sections of lengths L_1 and L_2 with $L_1 > L_2$, and suppose, moreover, that the traffic flows are equal on the two sections. They both have exposure $E = Tf$ (total), but on L_1, everything else being equal, the probability of each vehicle having a single vehicle crash is higher since L_1 is greater. If a_1 and a_2 are the single vehicle accidents occurring on L_1 and L_2, respectively, then it would be expected that $a_1 > a_2$. If we compute accident rates as $R_1 = a_1/E$ and $R_2 = a_2/E$, then $R_1 > R_2$. But we really don't want the rates to simply indicate which section is longer. This problem is avoided if we compute rates per mile rather than the raw rates. Thus, we could compute rates such as

$$R_1^* = \frac{a_1/L_1}{E} \quad \text{and} \quad R_2^* = \frac{a_2/L_2}{E} \,. \tag{4.2}$$

Note that in the expressions for the R*'s, the section lengths are used to adjust accidents rather than included as part of the exposure measure. The reason for this would be to have the exposure measure, E, retain its interpretation as the potential number of single vehicle accidents that could occur. This interpretation might appear to be lost if E is replaced by LE, especially since L can be measured in miles, kilometers, etc. On the other hand, if single vehicle exposure is to be combined with other exposure measures for use in computing an overall accident rate, then the single vehicle exposure should reflect the length of the segment since many of the other exposure measures inherently have this property.

Thus, the most reasonable characterization of single vehicle exposure for homogeneous segments (which may vary considerably in length from segment to segment) seems to be to think of

$$E_1 = Tf \tag{4.3}$$

as single vehicle exposure per mile of roadway, and to express the total single exposure for the entire section as

$$E^* = TLf. \tag{4.4}$$

Accident rates of the form

$$R = \frac{a}{E^*} = \frac{a}{LE_1} \tag{4.5}$$

yield the same values as those of (4.2) above.

B. Head-on Exposure

As in (2.6), head-on exposure is given by

$$E_{HO} = \frac{LT}{2640} f_1 f_2/v \quad , \tag{4.6}$$

where it is assumed that flows f_1 and f_2 both have average velocity v.

C. Rear-End Exposure

When L is relatively long (e.g., several miles), a problem also arises with the pipeline flow component of rear-end exposure. The problem is that for most flows the large value of L causes the probability factor to be nearly equal to one, both for the entire segment of length L and even for half the segment length. Thus, this component of rear-end exposure, like single vehicle exposure, does not adequately reflect the segment length.

A reasonable remedy for this problem would seem to be to compute the pipeline flow rear-end exposure component for a one mile segment length and multiply by the section length L in miles (when $L \geq 1$ mile). The pipeline flow rear-end exposure component would, thus, be given by

$$E_{RE}^{(1)} = \frac{LT}{L^*} \left[f_1(1-e^{-(f_1/v)L^*}) + f_2(1-e^{-(f_2/v)L^*}) \right]$$

where $L^* = \begin{cases} L \text{ if } L < 1 \text{ mile} \\ 1 \text{ if } L > 1 \text{ mile.} \end{cases}$ (4.7)

Total rear-end exposure is given by the pipeline flow component plus the passing component. From (3.6) and (4.7) rear-end exposure is

$$E_{RE} = \frac{LT}{L^*} \left[f_1(1-e^{-(f_1/v)L^*}) + f_2(1-e^{-(f_2/v)L^*}) \right]$$

$$+ LT \left[\frac{f_1^2 \sigma_1}{v_1^2 - \sigma_1^2} + \frac{f_2^2 \sigma_2}{v_2^2 - \sigma_2^2} \right] \quad . \tag{4.8}$$

D. Driveway Exposure

With respect to angle exposure, there is sufficient evidence that between 3 and 12 percent of all accidents in rural and urban areas involve vehicles entering from driveways. Thus, exposure to these accidents should be accounted for. Suppose that within the section of interest there are J private drives such as those labeled A and B in Figure 4.2, and let f_j be the (entering and exiting) average traffic flow on the j-th such drive. Let d be the average distance an entering or exiting vehicle travels at an angle to f_1 or f_2, when

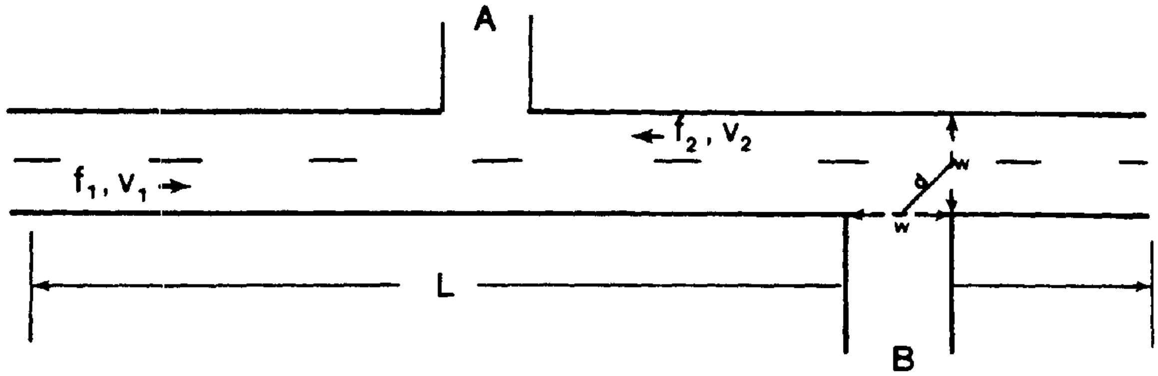


Figure 4.2

turning in either direction, and let v* be the average velocity of such vehicles. Then the average entering or exiting vehicle is exposed to flows f_1 and f_2 for d/v* time units to give the exposure component for the j-th driveway of $Tf_j(f_1 + f_2)\, d/v^*$.

Thus, the entire section has angle exposure of

$$E_A = T \sum_{j=1}^{J} f_j(f_1 + f_2)\, d/v^* \quad . \tag{4.9}$$

If, on average, there are N driveways per unit length ℓ of highway, and if we can assume an average flow $\bar{f}$ for this collection of driveways, then (4.9) becomes,

$$E_A = \frac{TN\, L\bar{f}(f_1 + f_2)\, d}{5280 v^*} \quad . \tag{4.10}$$

where

T = time period of interest (hours)

N = average number of driveways per unit length ℓ

L = section length (in same units as ℓ, e.g., miles)

$\bar{f}$ = average flow per driveway (vph)

$f_1 + f_2$ = total two-way flow on roadway (vph)

d = average distance traveled by entering vehicle before becoming part of main flow (ft.)

v^* = average velocity of entering vehicles over length d (mph)

Further, d can be assumed to be approximately equal to $w/\sqrt{2} = .71w$, where w = width of roadway, and v^* could be defined as $1.03\sqrt{w}$ (ft/sec) under the assumption that each entering vehicle stops and then accelerates at 3 ft/sec^2. Under these assumptions:

$$E_A = \frac{TN\,L\,\bar{f}\,(f_1 + f_2)\ .69\sqrt{w}}{5280} \tag{4.11}$$

Unfortunately, while there is a significant body of research indicating the size of the problem, there is no information providing ranges for the driveway flows or frequency (N or $\bar{f}$) for use in this formula. Thus the researcher must input his own values.

If local data are not available, estimates must be made. If one is willing to estimate the total driveway entering flow as a proportion (p_d) of the total flow such that

$$f_{driveway} = NL\bar{f} = p_d\ (f_1 + f_2)$$

then, (4.11) reduces to

$$E_A = \frac{T\,p_d(f_1 + f_2)^2\ .69\sqrt{w}}{5280} \tag{4.12}$$

II. <u>Exposure for Section of Four-Lane Roadways</u>

The four-lane case is similar to the two-lane case except that two additional flows and velocities are to be included in some of the formulas. Other differences are:

1. An overtaking exposure component is included, and
2. The distance travelled by vehicles entering or exiting from driveways is slightly increased.

Based on the sketch shown in Figure 4.3, the required flows and velocities are defined by:

f_1 = total flow in inner lane, one direction (vph)

f_2 = total flow in outer lane, one direction (vph)

$\tilde{f}_1$, $\tilde{f}_2$, $\tilde{v}_1$, and $\tilde{v}_2$ are flows and velocities in opposite direction

$f = f_1 + f_2 + \tilde{f}_1 + \tilde{f}_2$ = total two-way flow (vph)

$\bar{f}$ = average flow per driveway (vph)

v_1 = average velocity for vehicles in inner lane (mph)

v_2 = average velocity for vehicles in outer lane (mph)

v = average velocity of all vehicles (mph)

L = total length of segment (ft)

T = length of study period (hours)

N = average number of driveways per foot of section length

$= \dfrac{\text{number of driveways in } L}{L}$

w = width of roadway (feet)

p_d = proportion of total flow (f) entering from driveways

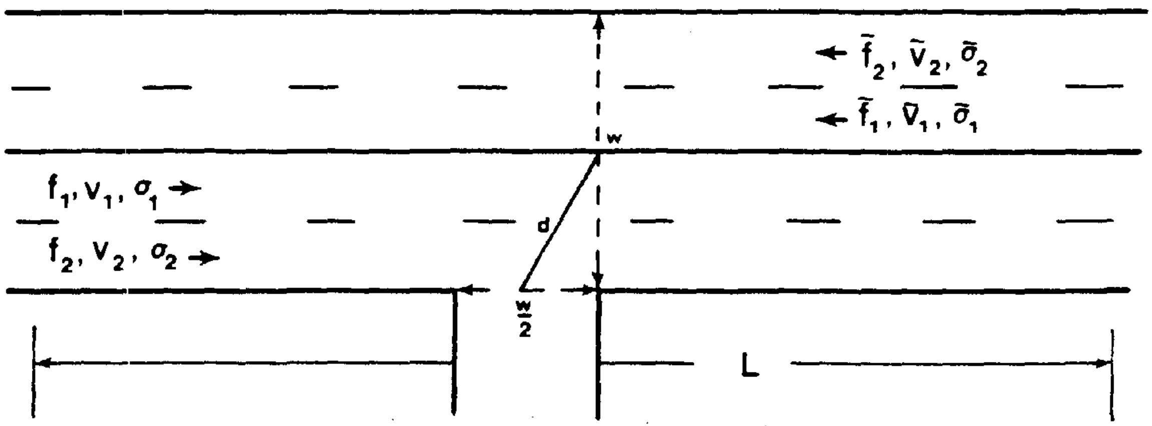


Figure 4.3

The four lane exposure indices are given by the following formulas:

1. Rear-end exposure (using (3.7) and (4.8))

$$E_{RE}^{A} = \frac{LT}{L^*}\Big[f_1(1-e^{-(f_1/v_1)(L^*/5280)}) + f_2(1-e^{-(f_2/v_2)(L^*/5280)})$$

$$+ \tilde{f}_1(1-e^{-(\tilde{f}_1/\tilde{v}_1)(L^*/5280)}) + \tilde{f}_2(1-e^{-(\tilde{f}_2/\tilde{v}_2)(L^*/5280)})\Big]$$

$$+ \frac{LT}{5280}\left[\frac{f_2^2\,\sigma_2}{v_2^2 - \sigma_2^2} + \frac{\tilde{f}_2^2\,\tilde{\sigma}_2}{\tilde{v}_2^2 - \tilde{\sigma}_2^2}\right] , \tag{4.13}$$

where $L^* = \begin{cases} L \text{ if } L < 5280 \text{ feet} \\ 5280 \text{ if } L > 5280 \text{ feet} \end{cases}$

2. Sideswipe exposure (following (3.9))

$$E_{SS}^{A} = \begin{cases} \dfrac{Tf_1 f_2}{5280 v_1}\left[\dfrac{(v_1-v_2)L}{v_2}\right] & \text{if } \left(\dfrac{v_1-v_2}{2}\right) L > \delta , \\[2ex] \dfrac{Tf_1 f_2}{5280 v_1}\,\delta & \text{if } \left(\dfrac{v_1-v_2}{v_2}\right) L \le \delta \end{cases} \tag{4.14}$$

where δ = 40 ft. Similarly for E_{SS}^{B} so that the two-way sideswipe exposure is given by

$$E_{SS} = E_{SS}^{A} + E_{SS}^{B} . \tag{4.15}$$

3. Head-on exposure (as in (3.1))

$$E_{HO} = \frac{LT}{5280}\Big[f_1\tilde{f}_1(\frac{1}{v_1}+\frac{1}{\tilde{v}_1}) + f_1\tilde{f}_2(\frac{1}{v_1}+\frac{1}{\tilde{v}_2}) + f_2\tilde{f}_1(\frac{1}{v_2}+\frac{1}{\tilde{v}_1}) + f_2\tilde{f}_2(\frac{1}{v_2}+\frac{1}{\tilde{v}_2})\Big] \tag{4.16}$$

4. Driveway exposure (modifying (4.11))

$$E_D = \frac{TNL\bar{f}f(.61)\sqrt{w}}{5280} = \frac{TNL\bar{f}\,f\sqrt{w}}{8656} \tag{4.17}$$

If the driveway flow is expressed as a proportion of the total flow = p_d

$$E_D = \frac{Tp_d f^2 \sqrt{w}}{8656} \tag{4.18}$$

5. Single vehicle exposure

$$E_{SV} = LTf \tag{4.19}$$

6. Total exposure

$$E_{TOT} = E_{RE} + E_{SS} + E_{HO} + E_D + E_{SV} \tag{4.20}$$

CHAPTER 5.
FIXED OBJECTS

I. Fixed Object Exposure from Two Points of View

The exposure indices developed up to this point in the project all had a roadway orientation. That is, they provided estimates of the potential number of accidents that could occur on various highway components (e.g., segments, intersections, etc.), and when combined with accident counts provided a mechanism for estimating the degree of hazard of these components.

A fixed object exposure index was also developed from this point of view. Since this index was not useful for comparing types of fixed objects, a second type of fixed object exposure index was developed specifically for this purpose.

A. Roadway Oriented Fixed Object Exposure

A vehicle striking a fixed object along the roadway is a special case of a single vehicle accident. As with single vehicle accidents in general, the potential number of these accidents occurring over a given section of highway in a given time interval cannot exceed the total number of vehicles flowing through the section in the time interval. On the other hand, if at least one fixed object is present along the roadway, then any vehicle passing by could potentially strike a fixed object, and, hence, represents a potential fixed object accident or an exposure unit. This reasoning leads to the same definition of exposure for fixed objects as that for single vehicle accidents. Thus, the fixed object exposure for a roadway section and a given time interval T would be given by,

$$E_F = T^*(\text{total vehicular flow through the section}). \qquad (5.1)$$

It may be noted that this definition of exposure does not include any measure of the number of fixed objects present along any highway section nor any indication of their proximity to the highway. The idea here is that these factors should influence the accident probabilities or propensities rather than exposure. For example, suppose two roadway sections have equal traffic flows but section A has only a few fixed objects while section B has many. Under the above definition, the sections would have equal exposures. If section B has more fixed object accidents (as might be expected), then it would have the higher accident rate and, thus, be judged more hazardous. As another example, suppose A and B are two sections of roadway having equal traffic flows and equal numbers of fixed objects, but suppose the fixed objects of section B are, on average, nearer the roadway than those of section A. As before, section B would be expected to have more fixed object accidents, and, if so, would have a higher accident rate since both sections would have the same exposure. In both cases, the higher accident rate indicates a more hazardous condition with respect to fixed objects, but, in general, it may require further analyses to determine why a given section has a high accident rate.

Now suppose two roadway segments of different lengths are to be compared. Assuming equal densities of fixed objects per mile, the longer segment should have more fixed objects and, hence, a higher accident rate. Since it is not of interest to have a higher accident rate provide only information on segment length, it seems reasonable in this case to examine accident rates per mile in the form

$$R = \frac{a/L}{E_F} \tag{5.2}$$

where a is the total number of fixed object accidents, L the length of the segment in miles, and E_F the exposure measure given above.

B. Exposure Indices for Comparing Types of Fixed Objects

The general question of interest here is that of determining whether one type of roadside fixed object is more hazardous than some other type. It seemed that, in order to answer this kind of question, it was necessary to consider classes of fixed objects. Two candidate classes are:

- point objects (trees, poles, etc.), and
- extended objects (guardrails, bridges, etc.).

While it was not possible to enumerate all of the potential specific questions which fall under each of these general areas, the following are examples:

1. Is one design of a given "point" fixed object (e.g., a breakaway utility pole) less hazardous than a second design (a non-breakaway pole)?

2. For a given type of point object (e.g., utility poles), how much more hazardous is a pole closer to the roadway than one further away from the edge of pavement (EOP)?

3. Is a given type of extended object (e.g., a guardrail) more hazardous than an alternative design?

4. Is a given type of extended object (a guardrail), more or less hazardous than the object it protects (a culvert wall or a point object such as a tree)?

5. For problem identification purposes, are utility poles in general more hazardous than trees, guardrails, or other objects?

In attempting to define appropriate exposure measures and thus appropriate rates to answer these questions, two additional considerations are important. First, in answering many fixed object questions, it appears that there is a need to use severity-related rates rather than accident-related rates. Many countermeasures are designed to reduce the severity of the crash rather than the number of crashes. Thus, it is proposed that the rates used be some frequency of injury divided by the potential number of injuries that could occur.

Because questions of differential occupancy between vehicles which strike different fixed objects at different locations can affect the total number of injuries (minor, serious, fatal) per crash, it is suggested that one appropriate severity measure would be driver injury. Since there is one driver per vehicle that strikes a fixed object and since most of these collisions are single vehicle collisions, it would appear that number of driver injuries of a certain severity could be divided by the appropriate exposure measure (to be developed below) to provide an appropriate rate.

A second consideration in this development of rates for fixed object collisions concerns the question of whether to "control" for other potential causes of the observed differences such as the type of location (curve or tangent), the distance of the fixed object from the edge of pavement, the speed of traffic, etc. The following rules are proposed for use here.

Rule 1. In general, if the sets of fixed objects being compared (e.g. breakaway versus non-breakaway poles) differ on any (or each) of these factors (i.e., other potential "causes") <u>in nature</u> (e.g., if one type of pole always is placed at a certain distance from the EOP while a comparison type of pole is always placed closer to the EOP), then the differences should <u>not</u> be controlled for. This means that differences which exist due to the placement of objects in nature will continue to exist and thus appropriate predictions can be made concerning hazardousness.

Rule 2. If the question of interest is the difference in a given set of objects <u>due to</u> one of these other factors (see Question #2 above related to the distance from EOP), the factor should <u>not</u> be controlled for.

Rule 3. If the difference between sets of fixed objects to be compared is (or could be) caused by the sample of locations used (i.e., the locations are not all homogenous locations), the factors <u>should</u> be controlled for.

How are these factors "controlled for"? Three possible approaches include:

1. Classify the objects by the levels of these extraneous factors and compare rates within these different levels. (An example of this method will be presented below.)

2. Adjust the accident counts (or rates) using known research results concerning the likelihood of a vehicle striking a fixed object as a function of its distance from the roadway, speed of encroachment, type of location, etc., and compare these adjusted rates.

3. Include these necessary adjustments within the exposure measures developed.

We strongly propose that Approach 1 above is the appropriate approach. Approach 2 requires information that does not exist from current research or at least is not readily available. Approach 3 is not recommended since we feel that these factors affect "likelihood" of a crash rather than "exposure to" a crash (or injury). Thus they should not be included in the exposure measure but should be accounted for in the construction of rates. If the rates are constructed within various levels of these extraneous factors as in Approach 1, then the differences are accounted for.

<u>Question 1.</u> Is one design of a given "point" fixed object (e.g., a breakaway utility pole) less hazardous than a second design (a non-breakaway pole)?

For example, suppose we want to compare two types of poles that are used in similar settings. In particular, suppose that both types are placed the same distance from the edge of the roadway. To address this question we can examine injury counts for hits involving both types of poles gathered from some collection of roadway sections. A high injury count for a given pole type could mean that that type of pole was inherently more hazardous. The high injury count could also, however, result from there simply being more poles of the one type than of the other, or higher traffic flows past the one type, or, in general, more pole-vehicle interactions for that type of pole. In this case it would seem that an accident rate of the form

$$R = \frac{\text{Pole accidents}}{\text{Vehicle-pole exposure}} \tag{5.3}$$

would be required in order to determine which type of pole was more hazardous.

Now suppose we have S roadway segments over which we gather our accident data for some time interval T.

Let

a_{ij} be the number of accidents on the i-th segment involving a pole of type j, where $i = 1,2,\ldots S$; $j = 1,2$

n_{ij} be the number of poles of type j on the i-th segment,

f_i be the traffic flow per unit time on the i-th segment.

Each vehicle on the i-th segment is exposed to n_{ij} poles of type j so that in the time interval T the number of vehicle-pole interactions on segment i is

$$E_{ij} = T\, f_i\, n_{ij}. \tag{5.4}$$

The overall accident rate per unit of exposure for pole type j would, thus, be given by

$$R_j = \frac{\sum_i a_{ij}}{T \sum_i f_i n_{ij}} \quad , j = 1, 2 . \tag{5.5}$$

It should be mentioned that, if the assumption of equal placements with respect to the roadway was not satisfied, then differing accident rates might simply be reflecting this differential placement. As indicated above, proximity to, or distance from, the roadway does not seem to be a factor which should logically be included as part of the exposure index itself, but it should be accounted for. Following Rule 3 above, the proposed method would be to classify the objects by their distance from the roadway, and then to make the comparisons within fairly narrow ranges of this distance (i.e., only compare objects that are "nearly" the same distance from the roadway). The distributions of distances for each object type to be studied would have to overlap to some extent for this approach to be feasible (i.e., if in the sample drawn all of one type were at 30 feet and all of the other type at 10 feet from EOP, no comparison should be made using this approach since the sample does not reflect reality).

Question 2. For a given type of point object (e.g., utility poles), how much more hazardous is a pole closer to the roadway than one further away from the edge of pavement (EOP)?

The question here concerns differences between sets of similar objects due to one of these "extraneous" factors (e.g., distance from EOP). Here, following Rule 2, the appropriate procedure would be to calculate rates within the subclassifications of other important extraneous variables such as speed limit, type of location, etc., and to compare the rates within these classifications. For example, compare the rate for utility poles closer to the pavement versus the rate calculated for poles further away where all poles in both groups are at locations which have a speed limit of 55 miles per hour. The actual exposure measure used in the calculation of these rates would be exactly the same as shown above (i.e., it would be a function of the number of objects and the amount of traffic passing each object).

Question 3. Is a given type of extended object (e.g., a guardrail) more hazardous than an alternative design?

In this case it would seem that the most appropriate exposure index would involve interactions between the number of vehicles and the number of some length units (e.g., feet, meters, etc.) making up the extended object. Thus, in comparing guardrail types we could examine the rates

$$R_j = \frac{\sum_i a_{ij}}{T \sum_i f_i \ell_{ij}} \quad , j = 1,2 \quad , \tag{5.6}$$

where ℓ_{ij} is the number of length units of guardrail type j located along segment i, and the other symbols are as before. The same remarks as before would apply with respect to comparing similar extended objects that are not placed equidistant from the roadway or for controlling other extraneous factors.

Question 4. Is a given type of extended object (a guardrail), more or less hazardous than the object it protects (a culvert wall or a point object such as a tree)?

In particular, consider the problem of whether guardrails placed to prevent vehicles from striking culverts are more or less hazardous than the culverts themselves. Since the guardrails would have to be placed nearer the roadway than the culverts, it might well be expected that the placement of guardrails would result in more accidents but perhaps less severe ones. Thus, the basic comparison here is between injury rates for these guardrails versus unprotected culverts. It is also obvious that the distance from edge of pavement between the guardrails and culverts should not be controlled for since the guardrails must be placed in front of the culverts to have the desired effect.

The basic comparison is between two extended objects of different lengths. This comparison could be made by collecting data in two different ways. The most obvious procedure would be to collect data at sites with unprotected culverts and sites where the culvert is protected by a section of guardrail. Note that these two types of locations must be similar for this comparison to be meaningful (i.e., culvert size, distance from pavement, etc. should "match".)

The most appropriate injury rates (within a given classification of injury) for culverts and guardrails, respectively, would be calculated as follows:

$$R_c = \frac{\sum_{i=1}^{S} di_i}{T \sum_{i=1}^{S} f_i N_{c_i}} \quad \text{(with } N_{c_i} = \text{number of culverts at location i)} \qquad (5.7)$$

$$R_g = \frac{\sum_{i=1}^{S} di_i}{T \sum_{i=1}^{S} f_i N_{g_i}} \quad \text{(with } N_{g_i} = \text{number of guardrail sections at location i)} \qquad (5.8)$$

where di_i = number of driver injuries of a given severity level at location i.

While in the past the exposure to extended objects included the factor of length of the object, in this case length should not be part of the exposure measure. This is justified on the basis that the rate for the culvert (of whatever length) should be compared to the rate for the amount of guardrail that is required to protect it. Thus, even though the guardrail will be longer than the culvert, its length is defined by the need to protect the culvert and thus this length should not be included in the denominator. Doing so would produce a lower than correct injury rate for guardrail accidents. For example, if a 10-foot culvert required 50 feet of guardrail to protect it, it would be inappropriate to divide the guardrail injury frequency by an additional factor of 5 simply because the guardrail is 5 times longer than the culvert. This five-fold increase in length is required as part of the treatment and thus should not be "controlled out."

Unfortunately, while the above described method is the most appropriate, the procedure which must often be used (since not enough protected or unprotected culvert sites exist) is to calculate an injury rate for unprotected culverts and to compare it to the injury rate for all guardrail accidents, regardless of what the guardrail is protecting. The rate for culverts would be calculated as above and the guardrail rate would be based on the exposure for a guardrail of length g_a -- the average length of guardrail section required to protect a culvert. Specifically,

$$R_g = \frac{\sum_{i=1}^{S} di_i}{T \sum_{i=1}^{S} f_i L_{0_i} / g_a} , \tag{5.9}$$

where

L_{0_i} = total length of guardrail at location i

g_a = average length of guardrail section required to protect a culvert

For example, if one could obtain data on roadway sections with 10,000 feet of guardrail and if the average length of guardrail required to protect a culvert is 50 feet, one would calculate the injury rate per 50 feet of guardrail. Unfortunately, there is some error in this calculation due to the fact that a guardrail section 50 feet long should be hit slightly more often than a 50 foot section in the middle of an extended guardrail. This is due to the fact that the one foot at the end of a guardrail can be struck in more ways than one foot in the middle of the rail. More specifically, for a given collision angle, some parts of a given vehicle can strike an end section but not a center section.

Unfortunately, there is no research which indicates the specific degree of increased opportunity for the end section. (Such a study could be done, however, using this exposure measure.) In its absence, an interim solution would be to calculate guardrail rates for the first g_a feet in every section and to use this rate as a comparison for the unprotected culvert rate. Obviously, this would be very difficult to do given the less than perfect way that accidents are located by the investigating officer. It would be virtually impossible to obtain adequate data on only the first 50 feet of a given section of guardrail.

Perhaps a more feasible alternative would be to design the study so that only sections of guardrail approximately g_a feet long would be included. If g_a = 50, then the study might only include guardrails in the range from 30 to 75 feet long. Obviously, this would require a detailed roadside characteristics file and a computer search for sections of the proper length.

Question 5. For problem identification purposes, are utility poles in general more hazardous than trees, guardrails, or other objects?

Finally consider the problem of comparing various types of fixed objects beside the roadway--some point objects and some extended objects. This usually arises in a problem identification setting, and the question really is which type of object should receive higher priority for cleanup funding. Here the most appropriate rates in these comparisons would appear to be injury rates calculated using the method cited above under Question 1 (for point objects) and Question 3 (for extended objects). It does not appear in this case that corrections need to or should be made for the extraneous factors since the objects being compared differ on these factors in nature (see Rule #1 above). The point here is to define which set of fixed objects are more hazardous as they exist in the given population. (Note that the comparison of rates using the number of point objects and the feet or meters of extended objects implies an assumption that a point object on the average is equal to one foot or meter in width.)

CHAPTER 6.

EXPOSURE MEASURES FOR RESEARCH QUESTIONS CONCERNING VEHICLE TYPES

I. The Need for Two Kinds of Vehicle Specific Exposure Measures

Unlike the previous chapters which dealt with location specific exposure measures, this chapter concerns an entirely different issue -- the exposure measures necessary for use in accident research questions involving specific types of vehicles (e.g., heavy trucks, tractor trailer rigs with twin trailers, small cars, motorcycles, etc.). There is obviously a long list of accident research questions that fall within this area. Two types of research questions will be covered in this chapter.

1. Exposure measures for use in the evaluation of countermeasures which are designed for a specific vehicle class.
2. Exposure measures for use in studies involving comparisons of the accident rates of vehicle classes over an entire jurisdiction.

II. Exposure Measures for the Evaluation of Vehicle Specific Countermeasures

The first of the questions that often arises relative to exposure measures for specific classes of vehicles is related to the evaluation of countermeasures which are designed for a certain vehicle class. A recent example is the development and evaluation of the Grade Severity Rating System, a signing system designed to provide information to heavy truck drivers concerning the maximum safe speed on a given downgrade for a specific truck weight. This system is designed to help prevent run-away truck accidents.

The accident rates, and thus exposure measures, to be used in these evaluations are similar to the measures developed in the first three chapters in that they are location specific; i.e., the evaluations will be conducted at a given location or set of locations and the exposure to be used is specific to these locations.

In these cases, it would appear that appropriate exposure measures are very similar to the measures already developed in the earlier chapters with slight modifications. These modifications would involve limiting the previously calculated exposure to the amount experienced by the vehicle class in question. For example, in the study cited above, while the treatment might be assumed to affect rear-end, overtaking, head-on, and single vehicle accidents, the exposure should be limited to that amount directly involving the heavy truck population.

It is noted, however, that in making these modifications, one must be careful not to limit exposure only to the flows for the specific class. In the above example, while the heavy trucks are the class of interest, their exposure is a function of the total flows including all other vehicles.

If P_v represents the proportion of the flows corresponding to vehicles of class v of interest, then $f_v = P_v f$ is the flow rate for vehicles of this class. The location specific exposure indices are all functions of flows to the first power or products of flows. More specifically, single vehicle exposure and pipeline (non-passing) rear-end exposure both involve only single traffic flows and, hence, are functions of flows to the first power, while all of the other exposure indices involve products of two flows. Single vehicle and pipeline rear-end exposure indices for the specific vehicle class can, thus, be obtained by computing exposure for the entire traffic flow and multiplying by the factor P_v. That is

$$E_{SV,v} = P_v\ E_{SV} \quad \text{and} \tag{6.1}$$

$$E_{RE,NP,v} = P_v\ E_{RE} \quad \text{(for non-passing component only)} \tag{6.2}$$

where $E_{SV,v}$ and $E_{RE,NP,v}$ represent single vehicle and non-passing rear-end exposure indices respectively, for class v vehicles.

Now suppose that N represents the total number of vehicles under study in some situation, and that $N = n_v + n_o$ where n_v is the number of these vehicles that belong to class v and n_o is the total number of other kinds of vehicles in the fleet. If each vehicle can potentially collide with each other vehicle, then the total number of potential two vehicle crashes is N(N-1). Substituting $n_v + n_o$ for N gives

$$N(N-1) = n_v\ (n_v-1) + 2n_v n_o + n_o(n_o-1). \tag{6.3}$$

But, since $N = n_v + n_o$, multiplying out and simplifying, we have

$$N^2 = n_v^2 + 2n_v n_o + n_o^2 \tag{6.4}$$

Dividing both sides of (6.4) by N^2 gives

$$1 = P_v^2 + 2P_v P_o + P_o^2 \quad , \tag{6.5}$$

which shows that the distribution of two-vehicle crashes over the class v - class v, class v - class o, and class o - class o types is given by P_v, $2P_vP_o$, and P_o, respectively. Since $P_o = 1-P_v$, the proportion of expected two- vehicle crashes involving one vehicle from class v and one from class o becomes

$$2P_vP_o = 2P_v(1-P_v) = 2P_v - 2P_v^2 . \tag{6.6}$$

Adding P_v^2 (the proportion involving two class v vehicles) to (6.6) gives

$$P_v^2 + 2P_vP_o = P_v(2-P_v) \tag{6.7}$$

as the expected proportion of two vehicle crashes involving <u>at least one</u> vehicle of class v.

Exposure indices involving two flows (i.e. angle, head-on, sideswipe) for the class v vehicles are, thus, obtained by multiplying the corresponding overall exposure indices by the factor P(2-P). Specifically,

$$E_{A,v} = P_v(2-P_v)\ E_A, \tag{6.8}$$

$$E_{HO,v} = P_v(2-P_v)\ E_{HO}, \tag{6.9}$$

$$E_{SS,v} = P_v(2-P_v)\ E_{SS}. \tag{6.10}$$

In similar fashion, the passing component of rear-end exposure which also involves pairs of vehicles is modified by multiplying by this same factor:

$$E_{RE,P,v} = P_v(2-P_v)E_{RE,P} \quad \text{(for passing component only).}$$

Total rear-end exposure for class v vehicles is the sum of the modified pipeline (non-passing) component and the modified passing component:

$$E_{RE,v} = P_vE_{RE,NP} + P_v(2-P_v)E_{RE,P} \quad .$$

III. <u>Exposure Measures for Comparisons of Vehicles Types</u>

A. <u>The Use of Vehicle-Mile Data</u>

Consideration was next given to the problem of assigning an exposure index to a fleet of vehicles operating in an extended area (e.g., a State or the entire country, as opposed to some specific section of roadway). As with other exposure indices, this exposure index should be a measure of the opportunities for crashes involving these vehicles to occur -- not a measure of the likelihood of crashes occurring.

Anytime a vehicle is operated on the road for some unit of time or over some unit of distance it has the opportunity for a single vehicle crash. It seemed, then, that an exposure index for single vehicle crashes could be obtained by summing these time or distance units for each vehicle and over the vehicles in the fleet. The index might, thus, be expressed in terms of vehicle hours or vehicle miles for this particular vehicle class.

It should be noted that this type of exposure index differs from the location specific indices developed in earlier chapters in that vehicle miles or vehicle hours cannot be interpreted as a count of potential accidents that might occur. Rather, the potential number of single vehicle accidents may logically be thought of as being proportional to fleet vehicle miles or vehicle hours with some unknown constant of proportionality. This type of index should be quite useful for comparing accident rates among vehicle classes. A vehicle class accident rate should not, however, be directly compared to location specific accident rates since their respective exposure indices have quite different interpretations.

To be involved in a two-vehicle crash not only does a particular vehicle need to be driven on the road for some unit of time or distance, but other vehicles need to be present during the same intervals. An exposure index for two vehicle crashes, then, might most appropriately be expressed as a function of products of these time or distance units for different vehicles or classes of vehicles. There are potentially other factors which may act to modify the accident opportunities per unit of time or distance which could be incorporated into the exposure indices. These will be discussed later.

It should be noted that, as in the single vehicle case, the interpretation would be that the potential number of two-vehicle accidents should be proportional to products of vehicle miles or vehicle hours for different vehicles or vehicle classes. The proportionality constants, in general, might be expected to be quite different for single vehicle and two vehicle exposure.

As an illustration of the main ideas, consider the situation of three vehicle classes -- small car, large car, and truck -- and suppose that total vehicle mileage figures are available for each vehicle category, at this point not cross-classified by any other factors. Suppose we have, also, accident data broken out by type (single vehicle, two-vehicle). Thus, we have the three arrays as shown below. Following the ideas of Ross (1981),

	Mileage	Single Vehicle Accident		Two Vehicle Accident	
S.Car	M_S	S.Car	a_S	S.Car x S.Car	a_{SS}
L.Car	M_L	L.Car	a_L	S.Car x L.Car	a_{SL}
Truck	M_T	Truck	a_T	S.Car x Truck	a_{ST}
				L.Car x Truck	a_{LT}
				L.Car x L.Car	a_{LL}
				Truck x Truck	a_{TT}

exposure indices for single vehicle crashes are logically given by the class mileages themselves, and single vehicle accident rates would be given by

$$R_{1S} = \frac{a_S}{M_S}, \quad R_{1L} = \frac{a_L}{M_L}, \quad \text{and} \quad R_{1T} = \frac{a_T}{M_T} \tag{6.11}$$

For a particular class of two-vehicle crashes, the exposure index should be a function of the mileages of both of the vehicle classes involved. In particular then, the exposure index for small car-large car crashes should be $2M_SM_L$, that for truck-truck crashes is given by M_T^2. It seems reasonable that both accidents and exposure could then be summed over the various vehicle class pairs to give the overall two vehicle crash rates

$$R_{2S} = \frac{a_{SS} + a_{SL} + a_{ST}}{M_S^2 + 2M_SM_L + 2M_SM_T} = \text{two-vehicle crash rate involving at least one small car}$$

$$R_{2L} = \frac{a_{SL} + a_{LT} + a_{LL}}{M_L^2 + 2M_SM_L + 2M_LM_T}, \quad \text{and}$$

$$R_{2T} = \frac{a_{ST} + a_{LT} + a_{TT}}{M_T^2 + 2M_SM_T + 2M_LM_T}. \tag{6.12}$$

A numerical example may help to further clarify these ideas. The following table contains the basic data on fleet mileage, single vehicle accidents, and two-vehicle accidents for the three-vehicle types.

Vehicle Type	Mileage	Single Vehicle Accidents	Two Vehicle Accidents
			$a_{SS} = 400$
Small Car	$M_S = 2{,}000{,}000$	$a_S = 250$	$a_{SL} = 500$
			$a_{ST} = 300$
			$a_{SL} = 500$
Large Car	$M_L = 3{,}000{,}000$	$a_L = 300$	$a_{LL} = 500$
			$a_{LT} = 300$
			$a_{ST} = 300$
Truck	$M_T = 1{,}000{,}000$	$a_T = 125$	$a_{LT} = 300$
			$a_{TT} = 100$

It should be noted that some of the entries for two-vehicle accidents are listed more than once (e.g., a_{SL} is shown both for small cars and for large cars). Using the data from the table we can compute exposure estimates and accident rates (according to (6.11) and (6.12)) as follows:

$$E_S = M_S = 2{,}000{,}000$$

$$E_L = M_L = 3{,}000{,}000$$

$$E_T = M_T = 1{,}000{,}000$$

$$R_{1S} = a_S/M_S = 250/2{,}000{,}000 = 12.5/100{,}000$$

$$R_{1L} = a_L/M_L = 300/3{,}000{,}000 = 10/100{,}000$$

$$R_{1T} = a_T/M_T = 125/1{,}000{,}000 = 12.5/100{,}000.$$

$$E_{SS} = \text{small car/small car exposure} = M_S^2 = 4 \times 10^{12}$$

$$E_{SL} = 2M_SM_L = 12 \times 10^{12}$$

$$E_{ST} = 2M_SM_T = 4 \times 10^{12}$$

$$E_{LL} = M_L^2 = 9 \times 10^{12}$$

$$E_{LT} = 2M_L\,M_T = 6 \times 10^{12}$$

$$E_{TT} = M_T^2 = 1 \times 10^{12}$$

Total two-vehicle exposure for small cars is given by

$$E_{2S} = E_{SS} + E_{SL} + E_{ST} = 20 \times 10^{12} \tag{6.13}$$

and similarly,

$$E_{2L} = E_{LL} + E_{SL} + E_{LT} = 27 \times 10^{12} \tag{6.14}$$

$$E_{2T} = E_{TT} + E_{LT} + E_{ST} = 11 \times 10^{12} \tag{6.15}$$

The expressions (6.13) - (6.15) are then used as the denominators of the rate equations (6.12) to give,

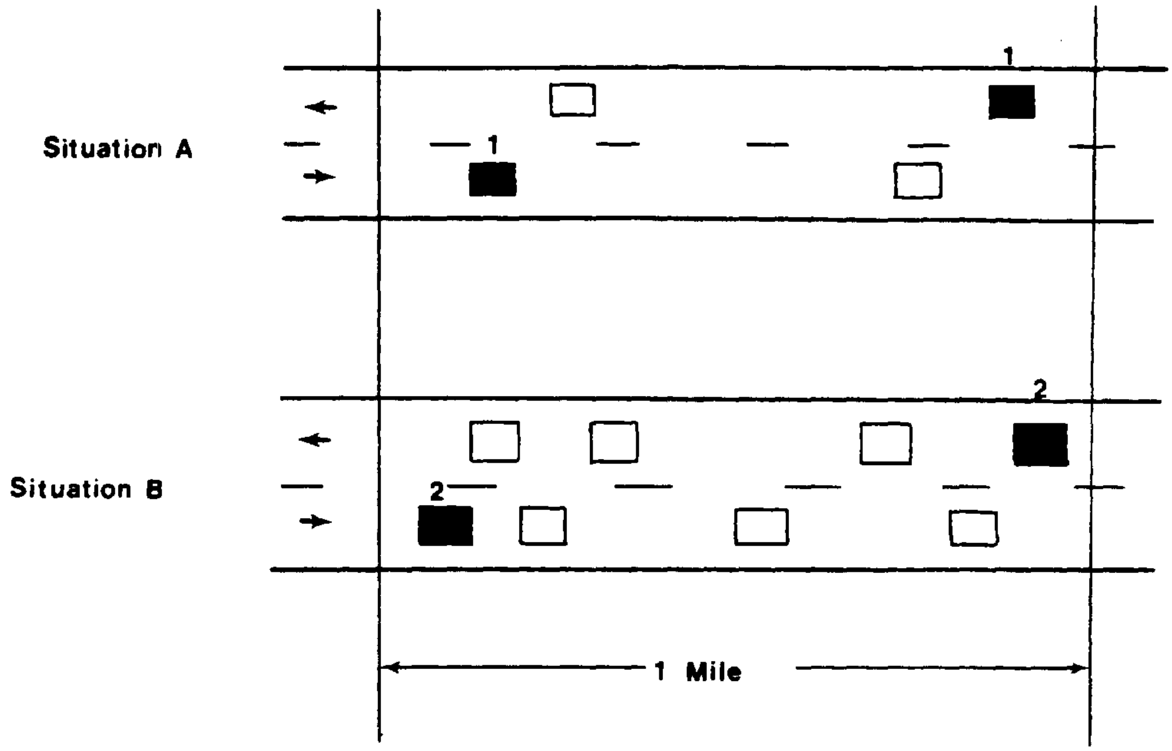
$$R_{2S} = \frac{1200}{20 \times 10^{12}} = 6/100 \text{ billion}$$

$$R_{2L} = \frac{1300}{27 \times 10^{12}} = 4.81/100 \text{ billion}$$

$$R_{2T} = \frac{700}{11 \times 10^{12}} = 6.36/100 \text{ billion} \quad .$$

There are a variety of factors which may affect either the opportunity to crash or the propensity to crash (or perhaps both) per unit of vehicle time or vehicle distance. A factor which only affects crash propensity should not be included in the exposure indices. For example, light and weather conditions may affect the propensity for single vehicle crashes. To the extent, however, that such factors do not affect the number of opportunities for such crashes, they should not be included in the exposure index. Factors related to traffic density, on the other hand, have an effect on the number of opportunities for two-vehicle crashes per vehicle mile (or hour), and should, therefore, be taken into account in the exposure index. That is to say, for a given class of vehicle, vehicle-miles accumulated in traffic of higher density will result in higher opportunity for crashes per vehicle mile.

For example, consider situation A and B below with reference to one type of two-vehicle exposure -- exposure to head-on crashes. In situation A, class 1 vehicles are accumulating 2 vehicle miles and 4 opportunities for head-on



crashes, a ratio of two-to-one. However in situation B, class 2 vehicles, in higher density traffic, are again accumulating 2 vehicle-miles, but this time these vehicles are experiencing 8 opportunities for head-on crashes, a ratio of four-to-one. Thus, it appears that differential densities must be accounted for.

As an illustration of a method which can be used, consider the case where we have not only total vehicle miles of travel, but vehicle miles cross-classified by some other factor associated with greater or lesser exposure per vehicle mile. One such factor might be a variable indicating either an urban or a rural setting, where an urban setting would usually indicate higher traffic densities and, hence, more chances for a two-vehicle accident per mile than a rural setting. In this case, suppose we have mileage and accident data as shown below.

	Mileage			Accidents	
Vehicle Type	Urban	Rural	Vehicle Pair	Urban	Rural
S	$M_{S,u}$	$M_{S,r}$	SS	$a_{SS,u}$	$a_{SS,r}$
L	$M_{L,u}$	$M_{L,r}$	SL	$a_{SL,u}$	$a_{SL,r}$
T	$M_{T,u}$	$M_{T,r}$	ST	$a_{ST,u}$	$a_{ST,r}$
Total	M_u	M_r	LL	$a_{LL,u}$	$a_{LL,r}$
		$M = M_u + M_r$	LT	$a_{LT,u}$	$a_{LT,r}$
			TT	$a_{TT,u}$	$a_{TT,r}$

Urban and rural accident rates for, say, trucks are given by the expressions,

$$R_{Tu} = \frac{a_{ST,u} + a_{LT,u} + a_{TT,u}}{M^2_{T,u} + 2M_{S,u}M_{T,u} + 2M_{L,u}M_{T,u}} \text{ , and}$$

$$R_{Tr} = \frac{a_{ST,r} + a_{LT,r} + a_{TT,r}}{M^2_{T,r} + 2M_{S,r}M_{T,r} + 2M_{L,r}M_{T,r}} \text{ .} \qquad (6.16)$$

Similar rates can, of course, be computed for the other vehicle types. Finally, the urban and rural rates can be combined to give overall two vehicle crash rates, by vehicle type, as follows:

$$R_v = R_{uv}\left(\frac{M_u}{M}\right) + R_{rv}\left(\frac{M_r}{M}\right) \quad , \qquad (6.17)$$

where the subscript v indicates vehicle type S,L, or T. The resulting overall rates have been adjusted to reflect the rates that would have occurred if all vehicle types had had equal proportions of rural and urban mileage.

When more than one factor is included or factors with more than two levels are used in the analysis (e.g., urban/rural <u>and</u> four levels of time of day), the same sort of procedure can be used. But now instead of two rates per vehicle class we have to compute K rates where K is the product of the number of levels in all the factors. The overall rates are then weighted sums with K terms in each. Thus, the general formula for the two-vehicle crash rates analogous to that given above would be given by

$$R_v = \sum_{k=1}^{K} \left(\frac{M_k}{M}\right) R_{kv} \quad , \tag{6.18}$$

where M_k is the total vehicle mileage for vehicles in the k-th combination of factor levels, and R_{kv} is the two-vehicle crash rate for vehicle type v in this k-th category. Similar formulas would apply in the single vehicle crash case, but, in general, the relevant factors would likely be different in the single vehicle and the two-vehicle cases.

As an illustration, suppose that time-of-week with three levels -- weekday rush hour (wr), weekday non-rush (wn), and weekend (e) -- was to be included as a density related factor along with the urban/rural factor. The two factors together define K = 2 x 3 = 6 levels or cells as shown in the following table.

		Time-of-Week		
		wr	wn	e
Urbanicity	Urban	M_v a_{1v} $a_{2v_1v_2}$		
	Rural			

In each cell of the table, it is required that we have fleet mileage for each vehicle class, single vehicle accidents for each vehicle class, and/or two vehicle accidents for each combination (pair) of vehicle classes. With these ingredients, accident rates such as given by (6.16) can be computed within each cell, and overall rates by vehicle class computed according to (6.18).

It does not seem clear at this point that there is a very logical way of combining single vehicle and two-vehicle rates into one overall rate. Thus, until such a method is developed, it appears that the most appropriate comparison would be a two-stage process -- first a comparison between single vehicle rates and then a comparison of two vehicle rates in, say, treatment and comparison groups or class by class comparison. If, for example, a given vehicle class has a higher single vehicle and a higher two-vehicle rate than a comparison class, the answer to the question of level of safety is obvious. If, however, one class has a higher single vehicle rate but a lower two vehicle rate, the final decision must be based on the accident type which is most important in the specific question. If the question involves which of two classes of trucks is most dangerous to other vehicles, the two-vehicle rate would be more important. In cases where neither of the accident types is clearly most important, the final decision could be an economic one, with the single vehicle rate weighted by the cost of single vehicle accidents and the two-vehicle rate weighted by the cost of two-vehicle accidents.

B. The Issue of Cargo-Miles versus Vehicle-Miles in the Calculation of Truck Exposure

Certain researchers and others interested in truck safety questions have argued for the use of rates based on ton-miles or cubic foot miles for truck safety questions. The rationale is that the use of a vehicle-mile figure does not adequately reflect the increased benefits to society of carrying additional weight or volume. Thus, they argue that the "measure of exposure" used should reflect these factors.

However, there is a basic argument against the use of such figures in exposure calculations -- particularly if one agrees with the defining of exposure as a measure of the "opportunity to crash" (or "opportunity to sustain injuries"). Obviously the presence of a vehicle in the traffic stream (vehicle-miles) does affect the opportunity to crash and to sustain injuries. But if a vehicle is present in the stream, its cargo carrying capabilities have nothing to do with this opportunity. Accident or injury frequency has very little to do with the "cargo" part of cargo-miles.

Thus we would argue that the "cargo-mile" question is one of economics rather than exposure, and that as such, cargo-mile data should not be combined with simple accidents or injury frequencies but instead should be combined with other costs and benefits. Increased cargo miles are important but only as compared to increased levels of injury (accidents), road maintenance, and other costs. Therefore, a study conducted using ton miles as a basis of comparison should include the dollars of cost in the numerator (fatalities, injury, and PDO costs along with road maintenance and other costs) and the dollar value of increased benefit (from increased cargo miles) in the denominator.

While agreeing with the basic argument of this being an economic question, the cargo mile advocates might continue to argue that, in comparisons of vehicle classes, it would be valid to use such cargo-mile based rates since (1) it is very difficult to determine injury cost and (2) conceptually accidents and injuries are a "cost" and cargo mile is a "benefit", meaning that "costs" and "benefits" are actually being included. Thus they might argue that it would be valid to carry out comparisons between cargo-mile based rates for specific classes of vehicles since the differential in cost for similar classes would "average out". Unfortunately, this begs the essential question that must be answered. How many injuries or accidents is an added cargo mile worth?

Perhaps an example will make this point somewhat clearer. The fictitious injury rates in the table below might indicate to the observer that vehicles in Class 2 are safer than vehicles in Class 1 on a cargo mile basis.

	Vehicle Class	
	Class 1	Class 2
Injury Rate (per 1 million cargo miles)	25	20

However, these rates could be produced in two very different ways as shown in the table below:

		Vehicle Class	
		Class 1	Class 2
Case 1	Injuries Cargo Miles	25 1,000,000	25 1,250,000
Case 2	Injuries Cargo Miles	25 1,000,000	50 2,500,000

In Case 1, the vehicles in Class 2 would indeed appear to be "safer" than those in Class 1 in that while cargo miles have been increased, the number of injuries remained the same. Thus, in this case, it appears that cargo miles might well be an acceptable substitute for vehicle miles in producing valid rates. However, the figures in Case 2 above would also produce the same rates but for very different reasons. Here the lower rate for the Class 2 vehicles is produced by a 100 percent increase in injury frequency and a 150 percent increase in the number of ton miles. Even though the rate is again lower for Class 2 than Class 1, a very important question remains. We are seeing an increase of 25 injuries for an additional 1,500,000 ton miles. Question: Is the benefit to society of the additional 1.5 million ton miles greater than the cost of the additional 25 injuries that were experienced in carrying this tonnage?

In summary, it appears to HSRC staff that the issue of the use of cargo-miles as an exposure measure is fairly clearcut. Since cargo miles have little to do with the opportunity to crash, they are not a valid measure of exposure. Instead, if cargo-mile based rates are to be used, the comparisons made must be between the cost of the injuries relative to the benefits of the increased cargo miles.

CHAPTER 7

CLOSURE

The preceding six chapters have provided the theoretical basis and specific methods for calculating measures of exposure in five major research areas:

1. Intersections
2. Interchanges
3. Homogeneous (non-intersection) sections
4. Fixed object collisions
5. Vehicle type studies.

The exposure measures developed were based on a slightly nontraditional concept--that of exposure paralleling applicable accident types. For this reason, the developed measures, which count numbers of possible interactions between pairs of vehicles or vehicles and other objects are more complex than traditional measures such as million-vehicle-miles or entering vehicles. However, the authors feel strongly that this increase in complexity is also accompanied by an increase in precision which can lead to more accurate determination of countermeasure effectiveness and better identification of hazardous locations.

In this regard, we ask the potential user for one favor. Don't reject these methods simply because the exposure numbers produced don't "look right" as compared to traditional mileage-based rates. As with all innovative research, the methods proposed need to be used by the practitioner to test their applicability. These methods represented what we hope is an expansion of current knowledge rather than a final answer. Only through use and user inputs can they be further refined.

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