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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.

This report is the second in a series. The series is comprised of:

FHWA/RD-83/088 - Volume I - Final Report
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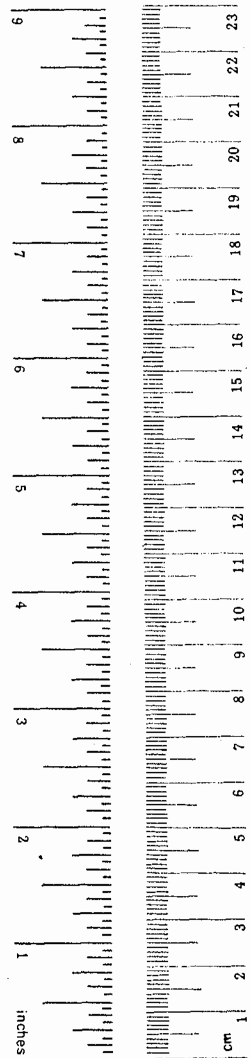
METRIC CONVERSION FACTORS

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). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



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

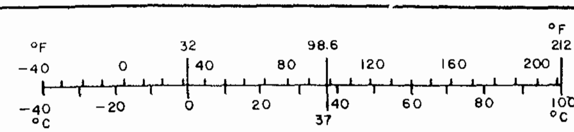


TABLE OF CONTENTS

Table of Contents (Con't)

Table of Contents (Con't)

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1.
INTRODUCTION

The following discussion will concern accident research, and more specifically, how to conduct one part of this research -- the collection of exposure data. Let us examine two research questions.

> Situation 1. The traffic engineer/accident analyst has been asked to evaluate the effects of a signalization treatment at a number of intersections in his locality. More specifically, he has been asked to determine whether the signalization of intersections is reducing angle collisions and, conversely, increasing rear-end and other type collisions. Because of the way the signalization program was implemented, the intersections in the treated group will have different entering vehicles (ADT's) from the intersections not yet treated. Since the research was not planned, there are no randomly assigned control sites and thus the only comparisons that can be made will be between higher volume intersections and those with lower volume which would not yet be treated.

> Situation 2. The highway division is trying to plan how best to spend the hazard elimination dollars in their budget. It is common knowledge within the department that the most hazardous locations on the roadways are intersections, and there is money to treat approximately 50 of these. The specific question remaining is how to use the accident files to choose the 50 most hazardous locations. Here it is important to remember that the engineer will choose 50 locations, treat these locations, evaluate the treatment, and report how well the money was spent to both the administrator and the State legislature. [It is noted here that the easiest solution would simply be to obtain accident frequencies or severities for all intersections and to choose the 50 with the highest frequency weighted by severity. However, this is not necessarily the best way to spend the money. The fact that the biggest problem exists at a single intersection does not mean that the expenditure of funds at that particular intersection would necessarily have the greatest chance for success. The issue here is how to identify those locations where the engineer has the greatest chance of success for the least money.]

In both these situations, the best comparisons which can be made would be between accident rates. There is a need to identify the number of accidents per exposure unit and to use these in comparisons or ranking procedures. The development of these rates requires the specification of some appropriate measure of exposure for the denominator.

Traditionally, exposure measures used in accident research have been rather limited. In most cases, vehicles 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 more simple measures of exposure are the most appropriate measures and, as a result of these examinations, has developed new measures of exposure for use in certain research situations.

I. Purpose of the Manual

The purpose of the manual is to provide appropriate measures of exposure for the many different research problems that are faced by the accident researcher. Obviously, this is a major undertaking in that there is a very large number of research questions which can be asked, each of which might require a unique measure of exposure. Accident researchers and administrators are very inventive. They seldomly run out of ideas of what needs more research (only money). As verification, in an initial task in this study, the authors and FHWA identified approximately 120 areas of current or planned research. To develop exposure measures for 120 different areas is, at first glance, frightening in its scope.

Indeed, it became obvious early in the project that a measure of exposure for each of these areas could not and should not be developed within the scope of this effort. Thus all possible exposure questions will not be covered in the manual. Based on the review of the literature, a review 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 accident rates for certain types of heavy trucks with either those of other types of trucks or these of certain classes of passenger cars. The fourth category above is also somewhat different from the others in that it includes two distinct types of questions. First, at a given location, how hazardous are the fixed object collisions as compared to 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 manual is designed to cover exposure related to two basic types of research questions:

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

NOTE: This manual 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 basic accident research study. In the discussion of how to use the exposure measures developed, 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:

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

This manual is designed to be a companion to these accident research manuals in that it provides specific inputs concerning how to develop the rates to be used in such accident research.

II. Exposure versus Likelihood

This manual concerns the development of 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 in the manual -- 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 same-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, 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.

III. 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 companion technical report entitled Exposure Measures for Evaluating

Highway Safety Issues: Volume 1 - Final Report, 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 here.

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. Thus, 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 then 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 involved in the entire flow, these individual measures are summed. To study an entire location, the formulas for exposure for each flow are summed. In most cases, this summing has been done for the user in the material that follows.

IV. Layout of the Manual

The remaining part of this manual is divided into a series of chapters which cover the five major areas described earlier:

Chapter 2 - Intersection Exposure
Chapter 3 - Interchange Exposure
Chapter 4 - Exposure for Non-Intersection Roadway Segments
Chapter 5 - Exposure for Fixed Object Studies
Chapter 6 - Exposure Measures for Vehicle Type Studies
Chapter 7 - Closure

Each chapter contains introductory and overview material which will provide a brief explanation of the basic measures and the ways they were developed. This material will also include the assumptions which were necessary for this development. Next, sketches of the components of the location being analyzed and the definitions used in the formulas are presented. These are followed by the appropriate formulas for each type of relevant exposure. Where possible, simplifications have been developed and are presented. [NOTE: These simplifications require that certain additional assumptions be made by the researcher. There will be a natural tendency to use the simplification since it requires less complex computations. This may be an acceptable way to proceed if the assumptions hold in that case. However, the reader is admonished to check the necessary assumptions first.]

V. How to Use the Manual

The overall procedure is quite simple. First, decide whether your research question is related to a location or series of locations or to a general issue such as fixed objects or vehicle type studies. Then proceed to the appropriate page of the manual, choose the appropriate measure, and carry out the required calculations. The only complicating factors are deciding whether you are interested in one specific type of accident (and thus one type of exposure measure) or whether you are interested in all accidents in a flow or all accidents at the entire location. Since the first three chapters are developed on a location basis, they will be relatively simple to use. Here exposure for the individual accident types are always presented first, followed by simplifications for each type, followed by the total exposure for the location -- the sum of all the relevant simplified formulas. In the latter two chapters, those concerning fixed objects and vehicle types, the issues are slightly different and will be explained more fully in the introduction section to each of those chapters. In these chapters, more thought is necessary to decide which is the appropriate measure to use.

As a final aid to the manual user, Figure 1.1 presents a guide to help direct the user to the appropriate page(s) in the manual where exposure for the specific accident research question of interest is addressed.

VI. The Rationale for Using These New Measures

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, hopefully, more appropriate types of exposure measures.

This may present problems to the user of this Manual (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 were then 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 others 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 road 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 a more insightful look at some problems than traditional exposure measures. However, we also realize that our thinking can and should be advanced.

In summary, this manual covers five main areas for which appropriate exposure measures have been developed. The following chapters deal with each of these in turn. We ask the potential user to read this material with a "willing" mind, to use it where possible, and to forward comments or suggested revisions to the authors or FHWA.

Figure 1.1 Guide to exposure methods.

Page

Does your accident research question concern:

Intersections?	See "A" below
Interchanges?	See "B" below
Non-intersection Roadway Segments?	See "C" below
Fixed Objects?	See "D" below
Types of Vehicles?	See "E" below

A. Intersection Exposure

Is the research question related to exposure to all types of crashes within the entire:

Uncontrolled intersection?	16
Stop sign controlled intersection? . . .	18
Signal controlled intersection?	21

OR

Is the research question related to exposure to only the following type of crash:

Rear-end?	(uncontrolled)	16
	(stop controlled) . . .	18
	(signal controlled) . .	21
Head-on?	(uncontrolled)	16
	(stop controlled) . . .	19
	(signal controlled) . .	25
Angle?	(uncontrolled)	16
	(stop controlled . . .	19
	(signal controlled) . .	26
Sideswipe?	(uncontrolled)	17
	(stop controlled) . . .	20
	(signal controlled) . .	27
Single vehicle?	(uncontrolled)	17
	(stop controlled) . . .	20
	(signal controlled) . .	27

B. Interchange Exposure

Is the research question related to exposure to all types of accidents within the entire interchange? 28

OR

Page

Is the research question related to exposure to all types of accidents within only one of the following interchange components:

OR

Is the research question related to exposure to only one type of crash on a specific segment?

Appropriate formulas will be found listed under segment name. See list above for page number.

OR

Is the research question related to only one type of exposure at all components (e.g., total exposure to rear-end crashes)?

Appropriate formulas will be found listed under each segment name. These individual components will then be summed. See list above for page numbers.

C. Exposure for Non-Intersection Roadway Segments

Is the research question related to exposure to all types of crashes within the Segment and is the Segment?

OR

Is the research question related to exposure to only one type of crash within the Segment and is the crash type:

CHAPTER 2.
INTERSECTION EXPOSURE

I. Overview

This chapter is devoted to measures of exposure to accidents at four-leg intersections. Because intersections affect traffic flows and thus accidents at some distance away from the actual crossing point, the boundaries of an intersection (L) will be defined as being 150 ft. upstream and downstream in some of the simplifications developed in this chapter. However, the user may substitute any distance L he desires.

In general, total exposure at the intersection is based on the types of collisions that occur within this area -- rear-end, head-on, angle, sideswipe and single vehicle collisions. An exposure measure (formula) has been developed for each of these accident types in three different types of intersections:

1. Uncontrolled intersections.
2. Stop sign controlled intersections.
3. Signal controlled intersections.

The fact that the individual measures for each of these accident types are presented will allow the user the flexibility of working with a specific accident (and thus exposure) type.

Before addressing the individual formulas, the following narrative presents a brief discussion of the basic theory underlying the development of each of the four major exposure types. This is given to aid the user in understanding the particular formula he is using and to allow him to modify or expand the existing formulas for situations other than four-legged intersections.

II. Basic Concepts

A. Rear-end Exposure

If two vehicles are within the intersection at the same time, they have the opportunity of being involved in a rear-end crash. Thus the question of interest is how many pairs of vehicles will be close enough together in a given lane such that both vehicles in each pair are within the intersection at the same time?

Calculating the number of pairs of vehicles that can be within the intersection at the same time is a two-step process. First, the probability of two vehicles being within a length L (the length of the intersection) is calculated based on an assumed exponential distribution of vehicle headways. The parameters for this distribution include the lane flow rate, the lane velocity, and the length of the intersection. This probability is then multiplied by the lane flow rate to give the number of exposed vehicles within a given lane. The exposure measures for all lanes are then summed to obtain either the total exposure on an approach or the total exposure in the entire intersection.

The differences between uncontrolled, stop sign controlled, and signal controlled intersections are due to the differences in average headways caused by vehicles decelerating, accelerating, and being delayed. In general, however, these differences affect only one parameter -- the average lane velocity.

B. Angle Exposure

Based on approach volumes, average velocities through the intersection, and the width of the intersection, how many pairs of vehicles in the crossing flows are in the intersection proper at the same time (and thus have the opportunity to strike each other) during time T? Note that exposure to angle collisions is only allowed in the intersection proper (within the curb lines) and thus, unlike other types of exposure, is not allowed upstream or downstream.

The calculation of the number of pairs of exposed vehicles involves starting with one approach, calculating the number of vehicles on all other legs that are in the intersection boundaries when a vehicle arrives plus all that enter while that vehicle is traversing the intersection, and multiplying by the number of vehicles entering from this first approach during time T. Next, this same procedure is used for vehicles entering the second approach to calculate the additional crossing flows that each vehicle can be paired with. One then proceeds to the third, fourth, fifth, etc. approach to calculate all additional pairs. All of these calculations involve the flow rates, the velocities of each flow, the intersection length and the time period T.

The differences between the angle exposures for the three types of intersections again result from differential crossing velocities, which are themselves affected by deceleration and acceleration times and delay.

It is noted that while a vehicle approaching an uncontrolled or stop controlled intersection is assumed to have the opportunity to strike any crossing vehicle that is there at the same time, the vehicle approaching a green signal can only be exposed to a crossing vehicle that either runs a red signal or turns right-on-red.

C. Head-On Exposure

Based on opposing flow rates and opposing velocities, how many pairs of vehicles meet each other within the bounds of the intersection within time T? This calculation involves determining how many opposing vehicles a given vehicle will meet, and then multiplying this average exposure by the total number of vehicles that enter the intersection from that direction within the time period T.

Again, for stop-controlled and signal-controlled intersections, the number met will be a function of acceleration, deceleration, and delay times, as well as the number of vehicles queued at the signal.

D. Sideswipe Exposure

Exposure to sideswipe accidents affects pairs of vehicles traveling in the same direction in adjacent lanes. It can be considered to be composed of two components: (1) the pairs of vehicles which either enter the expanded intersection side-by-side or which become side-by-side in queues at traffic signals, or (2) the pairs of vehicles which become side-by-side due to one overtaking the other. This second overtaking component may often be equal to zero since adjacent lane velocities are approximately equal over the short length of the intersection. Thus, the calculation will involve determining the number of pairs of vehicles which enter the length L side-by-side in the uncontrolled case and in the major uncontrolled flows at stop-controlled intersections, and the number of vehicles which are side-by-side in queues at traffic signals. This calculation is based on the average headways (and velocities) of vehicles as they enter.

E. Single Vehicle Exposure

Any and every vehicle that enters the expanded intersection (L) has the opportunity to run off the road, overturn, hit a fixed object, etc. Thus, exposure to single vehicle crashes is simply a function of the number of entering vehicles within the time period of interest (T). This can be calculated either for individual approaches or for the total intersection.

NOTE:

Single vehicle exposure depends on the presence of one vehicle, while rear-end, head-on, angle and sideswipe exposure requires the presence of at least two vehicles. Thus, it would first appear that summing single and multiple vehicle exposure to obtain total intersection exposure should not be done since single and multiple vehicle exposure differ philosophically. However, single vehicle exposure requires the presence of something for the single vehicle to strike, just as multi-vehicle exposure does. In the multi-vehicle case, the "something" is another vehicle. In the single vehicle case, the "something" is the extended roadside. Even though the "pairs" are composed of different things to strike, the pair still exists, and the exposure units can be summed.

In summary, for each intersection type (i.e., uncontrolled, stop sign-controlled, signal-controlled), the formulas for each of the five types of exposure (rear-end, head-on, angle, sideswipe, single vehicle) are presented. Following the individual exposure type formulas, instructions are provided for obtaining total exposure for each intersection type. All formulas are based on distances, flows, and velocities shown in Figure 2.1 and defined in the following section.

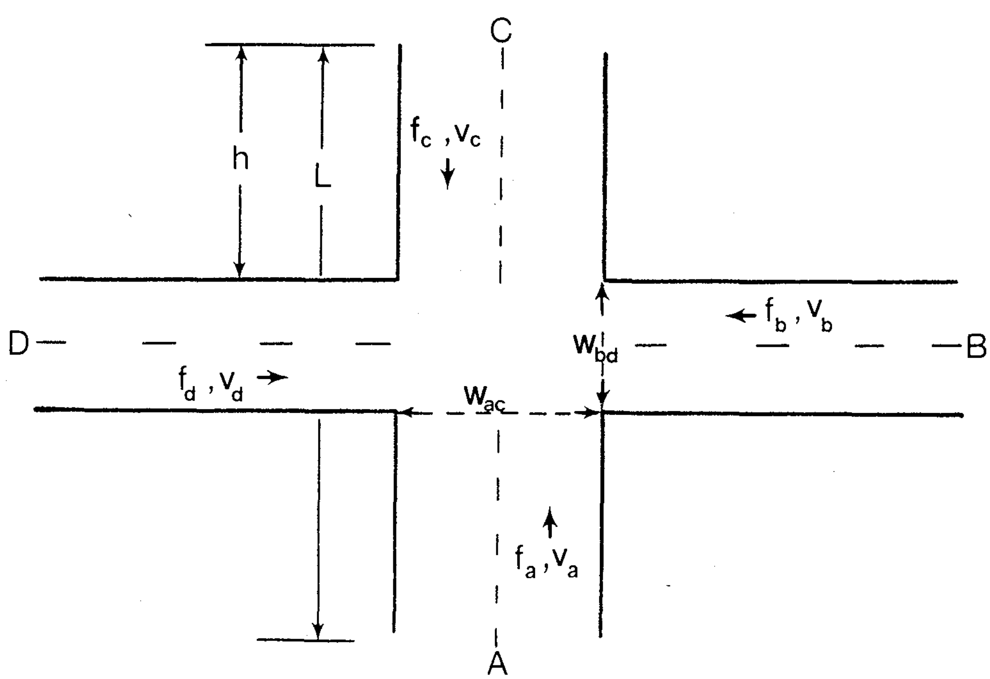


Figure 2.1

III. Definitions

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

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

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

f_d = total approach flow on approach D (veh/hr)

f_{tot} = total approach flow = $f_a + f_b + f_c + f_d$

v_a = approach A average velocity (mph)

v_b = approach B average velocity (mph)

v_c = approach C average velocity (mph)

v_d = approach D average velocity (mph)

$s_a = s_c$ = speed limit for approach A and approach C (mph)

$s_b = s_d$ = speed limit for approach B and approach D (mph)

L = total length of segment (ft)

h = length of approach segment (ft.)

w_{ac} = width of AC roadway (ft)

w_{bd} = width of BD roadway (ft.)

T = length of study period (hours)

N_a = number of lanes on approach A

N_b = number of lanes on approach B

N_c = number of lanes on approach C

N_d = number of lanes on approach D

c = traffic signal cycle length (sec.)

IV. Exposure Measures for Uncontrolled Intersections

A. Rear-end exposure

Note: Rear-end exposure is calculated in a lane-by-lane manner. However, under the assumption that lane flows are approximately equal, rear-end exposure for a given approach and for the total intersection can be calculated as follows.

1. Define approach velocities:

   For uncontrolled, free flow conditions,

   $v_a = v_c$ = average velocity on AC

   $v_b = v_d$ = average velocity on BD

2. Using these velocities along with the appropriate distances and flows, calculate exposure:

   For approach A:

$$E_{RE,A} = T \quad f_a(1-e^{-f_a L/5280(N_a)(v_a)})$$

   For the total intersection:

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

B. Head-on exposure

$$E_{HO} = \frac{LT}{2640}\left[\frac{f_a f_c}{v_a} + \frac{f_b f_d}{v_b}\right]$$

C. Angle exposure

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

D. Single vehicle exposure

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

E. Sideswipe exposure

Sideswipe exposure only applies to intersections with two or more through lanes on a given approach. Since most uncontrolled intersections have only one through lane from each approach, no sideswipe exposure exists. If two through lanes exist on a given approach, use the sideswipe exposure formula found in Section V.E as related to stop sign controlled intersections.

F. Total exposure at uncontrolled intersections (sum steps A-D)

$$E_{TOT} = T\Bigg[f_a(1-e^{-f_a L/5280(N_a)(v_a)}) + f_b(1-e^{-f_b L/5280(N_b)(v_b)})$$
$$+ f_c(1-e^{-f_c L/5280(N_c)(v_c)}) + f_d(1-e^{-f_d L/5280(N_d)(v_d)})$$
$$+ \frac{L}{2640}\left(\frac{f_a f_c}{v_a} + \frac{f_b f_d}{v_b}\right)$$
$$+ \frac{1}{5280}\left(\frac{w_{ac}}{v_b} + \frac{w_{bd}}{v_a}\right)(f_a f_b + f_a f_d + f_b f_c + f_c f_d)$$
$$+ (f_a + f_b + f_c + f_d)\Bigg]$$

V. Exposure Measures for Stop Sign Controlled Intersections

(Define approaches B and D as stopped flows, with A and C being uncontrolled free flows.)

A. Rear-end exposure

Note: Rear-end exposure is calculated in a lane-by-lane manner. However, under the assumption that lane flows are approximately equal, rear-end exposure for a given approach and for the total intersection can be calculated as follows.

1. Define approach velocities:

The velocity on the non-stopped roadway (AC) is the free flow velocity.

The velocity on the stopped roadway (BD) is calculated using the following formula:

$$v_b^* = v_d^* = \frac{0.68L}{19 + d}$$

where d (delay) is obtained from the following chart:

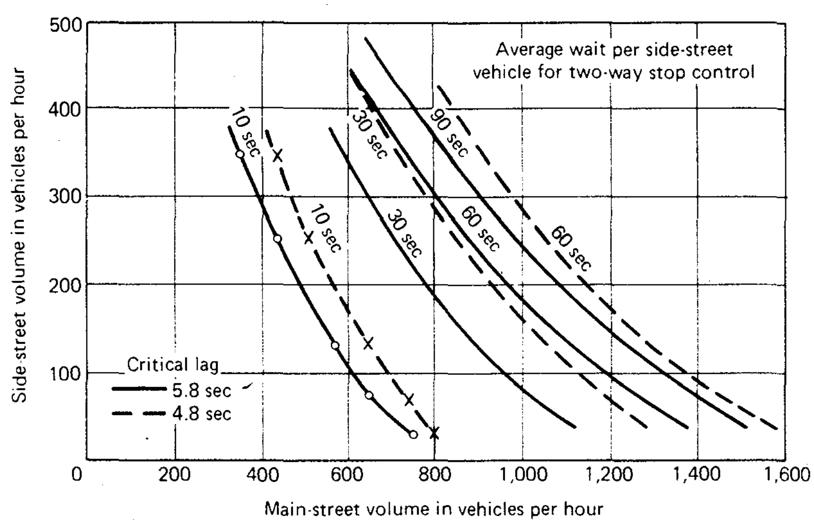


Figure 2.2 Waiting delay to side street vehicles at stop sign controlled intersections. [Source: Russell M. Lewis and Harold L. Michael, "Simulation of Traffic Flow to Obtain Volume Warrants for Intersection Control," Traffic Flow Theory, Highway Research Record 15 (Washington, D.C.: Highway Research Board, 1963), p. 39.]

2. Using these velocities along with the appropriate distances and flows, calculate rear-end exposure:

For approach A:

$$E_{RE,A} = T \quad f_a(1-e^{-f_a L/5280(N_a)(v_a)})$$

For the total intersection:

$$E_{RE} = T \left[f_a(1-e^{-f_a L/5280(N_a)(v_a)}) + f_b(1-e^{-f_b L/5280(N_b)(v_b^*)}) + f_c(1-e^{-f_c L/5280(N_c)(v_c)}) + f_d(1-e^{-f_d L/5280(N_d)(v_d^*)}) \right]$$

B. Head-on exposure

1. Define approach velocities. These will be the same as for rear-end exposure calculated in the previous step.

2. Using these velocities and appropriate distances and flows, calculate head-on exposure:

$$E_{HO} = \frac{LT}{2640} \left[\frac{f_a f_c}{v_a} + \frac{f_b f_d}{v_b^*} \right]$$

C. Angle exposure

1. Define approach velocities:

The velocity on the non-stopped roadway (AC) is the free flow velocity.

The velocity on the stopped roadway (BD) is calculated using the following formula:

$$v_b' = v_d' = 0.83 \sqrt{w_{ac}}$$

2. Using these velocities along with the appropriate distances and flows, calculate angle exposure

$$E_A = \frac{T}{5280} \left[\frac{w_{ac}}{v_b'} + \frac{w_{bd}}{v_a'} \right] (f_a f_b + f_a f_d + f_b f_c + f_c f_d)$$

D. Single vehicle exposure

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

E. Sideswipe exposure

Sideswipe exposure only applies to the major non-stopped flow since the stop-controlled approaches will usually have only one through lane. If the major street has only one through lane, then $E_{SS} = 0$.

If the major street (approach A and C) has two through lanes, and the lane-by-lane velocities are approximately equal, then the sideswipe exposure for approach A is given by:

$$E_{SS}^{A} = \frac{Tf_1 f_2}{132 v_1} \quad .$$

where f_1 and v_1 are the inner lane flow and velocity and f_2 is the outer lane flow for approach A.

A similar measure can be developed for approach C using appropriate flows and velocities and the same formula. Total sideswipe exposure for roadway AC is the sum of these two measures.

If lane flows and velocities from a given direction are approximately equal, and if flows and velocities from approach A are approximately equal to flows and velocities from approach C, then the sideswipe exposure for the total intersection is given by:

$$E_{SS} = \frac{T}{528} \quad \frac{f_a^{\,2}}{v_a} + \frac{f_c^{\,2}}{v_c}$$

F. Total exposure at stop sign-controlled intersection (sum steps A-E)

$$E_{TOTMV} = T \Bigg[f_a\left(1-e^{-f_a L/5280(N_a)(v_a)}\right) + f_b\left(1-e^{-f_b L/5280(N_b)(v_b^*)}\right)$$

$$+ f_c\left(1-e^{-f_c L/5280(N_c)(v_c)}\right) + f_d\left(1-e^{-f_d L/5280(N_d)(v_d^*)}\right)$$

$$+ \frac{L}{2640}\left(\frac{f_a f_c}{v_a} + \frac{f_b f_d}{v_b^*}\right)$$

$$+ \frac{1}{5280}\left(\frac{w_{ac}}{v_b'} + \frac{w_{bd}}{v_a'}\right)\left(f_a f_b + f_a f_d + f_b f_c + f_c f_d\right)\Bigg]$$

$$+ (f_a + f_b + f_c + f_d) + \text{(Sideswipe exposure from E.)}$$

VI. Exposure Measures for Signal-Controlled Intersections

A. Rear-end exposure

Note: Rear-end exposure is calculated in a lane-by-lane manner. However, under the assumption that lane flows are approximately equal, rear-end exposure for a given approach and for the total intersection can be calculated as follows.

1. Define approach velocities:

   Assume percentage green time for a given approach is proportioned according to flows.

$$v_a^* = v_c^* = \frac{0.68 v_a L}{L + v_a d_a}$$

$$v_b^* = v_d^* = \frac{0.68 v_b L}{L + v_b d_b}$$

   where d_a and d_b are values for delay and can be extracted from the tables or the formula on the following pages.

2. Using these velocities and appropriate distances and flows, calculate rear-end exposure:

   For approach A:

$$E_{RE,A} = T \quad f_a(1-e^{-f_a L/5280(N_a)(v_a^*)})$$

   For the total intersection:

$$E_{RE} = T\left[f_a(1-e^{-f_a L/5280(N_a)(v_a^*)}) + f_b(1-e^{-f_b L/5280(N_b)(v_b^*)}) + f_c(1-e^{-f_c L/5280(N_c)(v_c^*)}) + f_d(1-e^{-f_d L/5280(N_d)(v_d^*)})\right]$$

Vehicle Delay Formula

The following formula was used in generating the vehicle delay tables on the following pages:[1]

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

where

c = cycle length (sec.)

s_{at} = saturation flow on approach A (veh/sec)

ASSUME $s_{at} = s_{bt} = 0.5$

Similarly for d_b

$$d_b = 0.9 \left[\frac{c\left(\frac{f_a}{f_a + f_b}\right)^2}{2\left(1 - \frac{f_b}{s_{bt}}\right)} + \frac{\left(\frac{f_a + f_b}{s_{bt}}\right)^2}{2 f_b \left(1 - \frac{f_a + f_b}{s_{bt}}\right)} \right]$$

[1]This formula was derived from Webster's expression for delay as given 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, p. 288.

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	100	200	300	400	500	600	700	800	900	1000	1100	1200
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

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	100	200	300	400	500	600	700	800	900	1000	1100	1200
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

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	100	200	300	400	500	600	700	800	900	1000	1100	1200
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	21.8	
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

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	100	200	300	400	500	600	700	800	900	1000	1100	1200
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

Flow (vph) on approach of interest

B. Head-on exposure

1. Define approach velocities:

The velocities used in the head-on exposure formulas will be free flow velocities which can generally be assumed to be equal to the respective speed limits; i.e.,

$$v_a = v_c = \text{average velocity on AC}$$

$$v_b = v_d = \text{average velocity on BD}$$

2. Using these velocities along with the appropriate distances and flows, calculate head-on exposure.

NOTE: Because of the complexity of the formula, head-on exposure will be presented in two parts -- exposure for roadway AC and exposure for roadway BD. The two components will then be summed to obtain total exposure.

Let $f_{tot} = f_a + f_b + f_c + f_d$

Head-on exposure on roadway AC:

$$E_{HO,AC} = \frac{T\ f_a f_c}{7200 f_{tot}} \left[f_{bd} \left(\frac{2c(f_{bd})}{f_{tot}} + (h+w_{bd}) \left(\frac{1}{v_a} + \frac{1}{1.22\sqrt{L}}\right) + \frac{2h+w_{bd}}{v_a} \right) + f_{ac} \left(\frac{c f_{bd}}{f_{tot}} + \frac{3(2h+w_{bd})}{v_a} \right) \right]$$

Head-on exposure on roadway BD:

$$E_{HO,BD} = \frac{T\ f_b f_d}{7200 f_{tot}} \left[f_{ac} \left(\frac{2c(f_{ac})}{f_{tot}} + (h+w_{ac}) \left(\frac{1}{v_b} + \frac{1}{1.22\sqrt{L}}\right) + \frac{2h+w_{ac}}{v_b} \right) + f_{bd} \left(c\left(\frac{f_{ac}}{f_{tot}}\right) + \frac{3(2h+w_{ac})}{v_b} \right) \right] ,$$

Total head-on exposure for the intersection:

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

C. <u>Angle exposure</u>

1. Define approach velocities

$$v'_a = \frac{(\text{green + yellow time}_a)}{c} v_a + \frac{(\text{red time}_a)}{c} (0.83) \sqrt{w_{bd}}$$

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

Assuming the signal timing is weighted by vehicle flows and $f_a = f_c$, $f_b = f_d$, then

$$v'_a = \frac{v_a f_a + 0.83 \sqrt{w_{bd}} f_b}{f_a + f_b}$$

$$v'_b = \frac{v_b f_b + 0.83 \sqrt{w_{ac}} f_a}{f_a + f_b}$$

2. Using these velocities along with the appropriate distances and flows, calculate angle exposure.

Let

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

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

= $1 - P_{r_a}$

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

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

= $1 - P_{r_b}$

Then

$$E_A = \frac{T}{5280} \left[\left(\frac{w_{ac}}{v'_b} + \frac{w_{bd}}{v'_a} \right) \left(f_a f_b + f_b f_c \right) \left(P_{g_a} P_{r_b} + P_{g_b} P_{r_a} \right) \right]$$

D. Sideswipe exposure

Assume adjacent lane flows and lane velocities on a given approach are approximately equal. Then calculate the sideswipe exposure for each approach with two through lanes as follows.

1. For the approach i, calculate the proportion of the total cycle length that is green for this approach (p_g), and the proportion that is red (p_r). These can be approximated by:

$$p_g = \frac{\text{Total approach flow for this approach plus opposing approach}}{f_{tot}}$$

$$p_r = \frac{\text{Total crossing flows}}{f_{tot}}$$

2. For the approach i, calculate sideswipe exposure as

$$E_{SS} = p_g \left(\frac{Tf_i^2}{528\ v_i} \right) + p_r \left(\frac{Tf_i}{2} \right)$$

3. To obtain sideswipe exposure for the total intersection, repeat steps 1 and 2 for each approach with two through lanes and sum all components.

E. Single vehicle exposure

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

F. Total exposure at signal controlled intersection

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

CHAPTER 3
INTERCHANGE EXPOSURE

I. Overview and Introduction

The calculation of exposure for interchanges is complicated by the multitude of different layouts which exist (cloverleafs, partial cloverleafs, indirect ramps, diamonds, etc.). This makes it very difficult to develop a single measure for all types of interchanges. To overcome this problem, 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. Thru section prior to the exit ramp.
2. The exit ramp area.
3. The thru section between the exit ramp and the weaving section.
4. The weaving section.
5. The thru section between the weaving section and the entrance ramp.
6. The entrance ramp area.
7. The thru section following the entrance ramp.
8. The ramp proper.
9. Diamond type ramp terminals.

Figure 3.1 provides a schematic drawing of a full cloverleaf interchange showing each of the components. (A sketch of the diamond-type ramp terminals is given on page 53.) Included on the drawing are the various directional traffic flows required to calculate exposure both within segments (e.g., weave area) and across segments (e.g., total rear-end exposure for the entire interchange). Thus, for Section 1,

f_A = entering flow (vph) from A

f_{i1A} = inner (median) lane flow (vph) on A in Section 1 (prior to the exit ramp)

f_{TA} = thru flow (vph) on A in Section 1 (prior to the exit ramp)

f_{RA} = right-turning flow (vph) from A toward B

f_{LA} = left-turning flow (vph) from A toward D,   etc.,

will be used in the sections that follow.

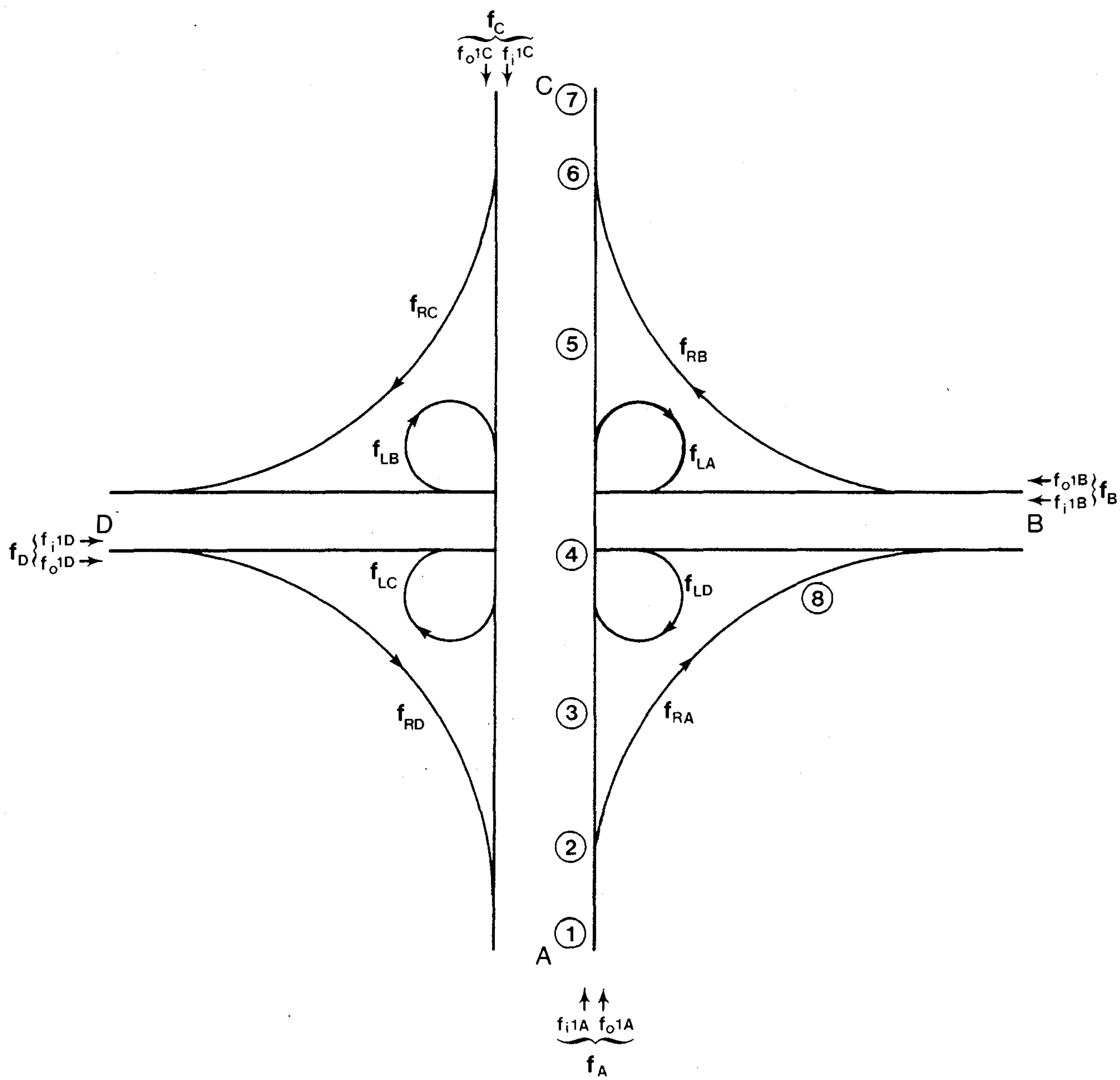


Figure 3.1. Components of a cloverleaf interchange.

Within each of these interchange 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, 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. This table presents a listing of the components and the accident types that are applicable for each given component.

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

	Accident Type				
Interchange Component	Rear-end	Side-swipe	Angle	Head-on	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

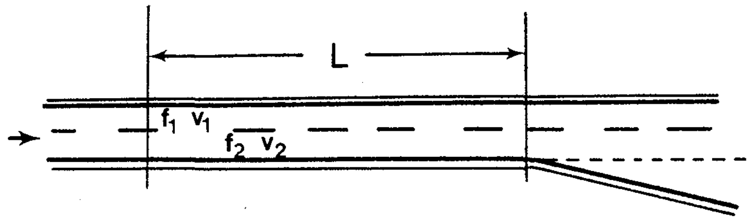
Each "X" in Table 3.1 represents a formula (measure of exposure) which has been developed. These measures of exposure are presented in the following pages. They can be used in two ways. First, the measures can be used separately by the user who desires to examine individual components for ranking purposes, to conduct a comparative analysis of components within a given interchange, or 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.

As the user will see, these individual measures can require complex computations, although most can be programmed on calculators. Otherwise, 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 (also spelled out in the text) which may or may not be true for the given interchange being analyzed.

The following pages each contain the series of formulas (including simplifications) for a given component. Developmental details are presented in the companion final report. All the formulas that are presented will cover the basic situation involving four thru lanes (two in each direction). Except for the head-on case which covers both directional flows, the specific formulas are designed for one direction of flow. This was done to allow the user to apply these formulas to the individual one-way components in any interchange configuration. However, the formulas can be modified to cover other cases.

II. 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

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

2. Sideswipe

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

3. Single vehicle

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

4. Head on

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.)

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

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

D. <u>Simplifications</u>

1. Rear end

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

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

2. Sideswipe

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

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) $f_1 = f_2 = \tilde{f}_1 = \tilde{f}_2 = .5f$

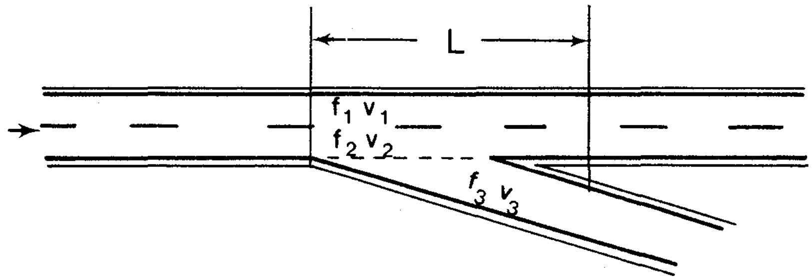
(2) Inner lane velocities = $v_1 = \tilde{v}_1$ = speed limit = s
Outer lane velocities = $v_2 = \tilde{v}_2 = 0.9s$

5. Total exposure (simplified)

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

III. 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)

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

2. Sideswipe

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

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

4. Head-on

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

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

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

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

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

(3) $\sigma_2 = 4$ mph

2. 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) $f_1 = \tilde{f}_1$; $f_2 = \tilde{f}_2$; $f_3 = \tilde{f}_3$ $f_1 = f_2 = f/2$

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

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

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

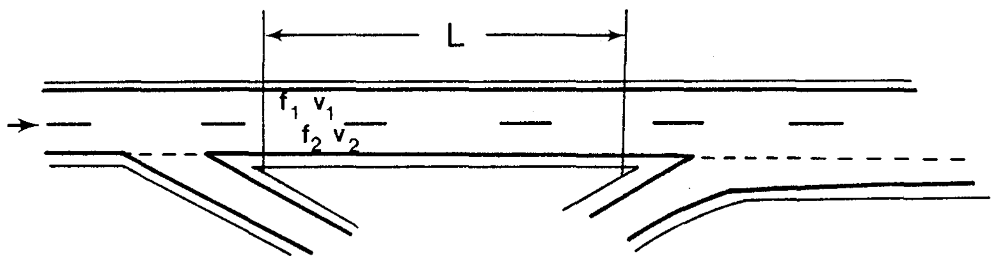
5. Total exposure (simplified)

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

Assumptions: All mentioned above.

IV. 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)

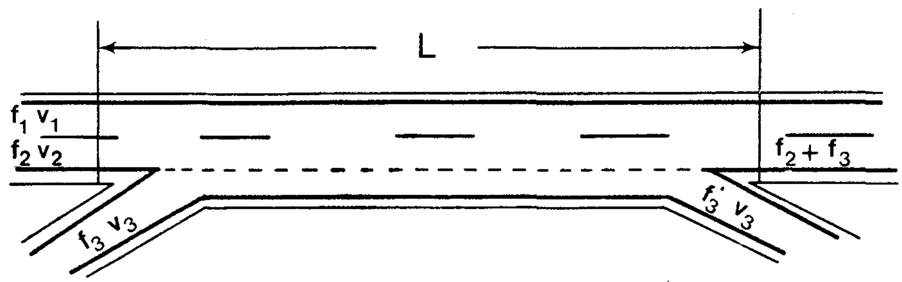
L = length of component (feet)

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 32-34 for details.

V. 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_{ilA}

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

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

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

2. Single vehicle exposure

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

3. Angle exposure

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

4. Sideswipe exposure

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

$$E_{HO} = \frac{LT}{5280} \left[f_1 \tilde{f}_1 (\frac{1}{v_1} + \frac{1}{\tilde{v}_1}) + f_1 \tilde{f}_2 (\frac{1}{v_1} + \frac{1}{\tilde{v}_2}) + f_1 \tilde{f}_3 (\frac{1}{v_1} + \frac{1}{\tilde{v}_3}) + f_2 \tilde{f}_1 (\frac{1}{v_2} + \frac{1}{\tilde{v}_1}) + f_2 \tilde{f}_2 (\frac{1}{v_2} + \frac{1}{\tilde{v}_2}) + f_2 \tilde{f}_3 (\frac{1}{v_2} + \frac{1}{\tilde{v}_3}) + f_3 \tilde{f}_1 (\frac{1}{v_3} + \frac{1}{\tilde{v}_1}) + f_3 \tilde{f}_2 (\frac{1}{v_3} + \frac{1}{\tilde{v}_2}) + f_3 \tilde{f}_3 (\frac{1}{v_3} + \frac{1}{\tilde{v}_3}) \right]$$

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

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

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

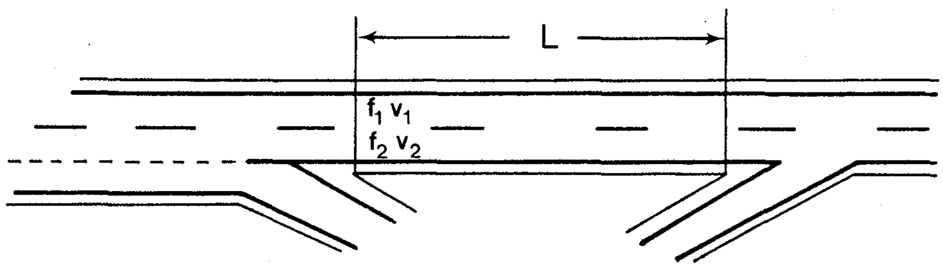
6. Total exposure (simplified)

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

Assumptions: All listed above.

VI. 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_{ilA}

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

f = total thru flow = f_1 + f_2

v_1 = inner lane average velocity (mph)

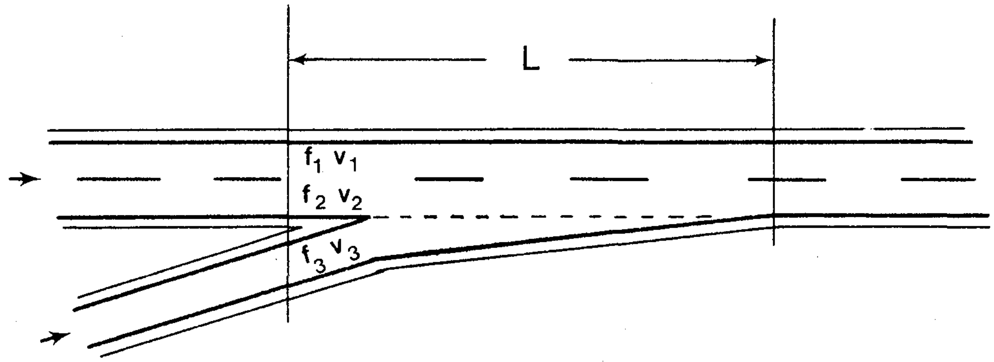
v_2 = outer lane average velocity (mph)

v = average velocity across all lanes (mph)
s = speed limit (mph)
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 32-34 for details.

VII. 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

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

2. Single vehicle exposure

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

3. Angle exposure

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

4. Sideswipe exposure

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

$$E_{HO} = \frac{LT}{5280} \left[f_1 \tilde{f}_1 \left(\frac{1}{v_1} + \frac{1}{\tilde{v}_1}\right) + f_1 \tilde{f}_2 \left(\frac{1}{v_1} + \frac{1}{\tilde{v}_2}\right) + f_2 \tilde{f}_1 \left(\frac{1}{v_2} + \frac{1}{\tilde{v}_1}\right) + f_2 \tilde{f}_2 \left(\frac{1}{v_2} + \frac{1}{\tilde{v}_2}\right) + f_3 \tilde{f}_1 \left(\frac{1}{v_3} + \frac{1}{\tilde{v}_1}\right) + f_3 \tilde{f}_2 \left(\frac{1}{v_3} + \frac{1}{\tilde{v}_2}\right) \right]$$

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

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

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

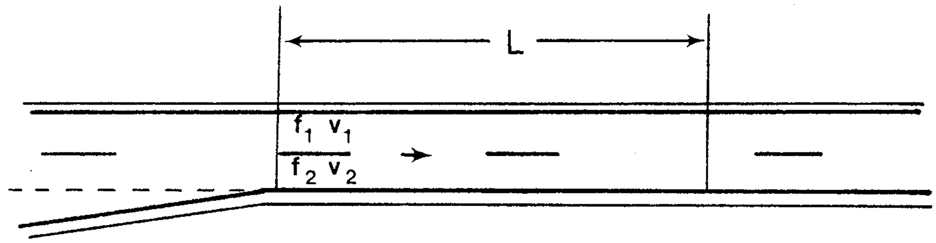
6. Total exposure (simplified)

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

Assumptions: All listed above.

VIII. 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)

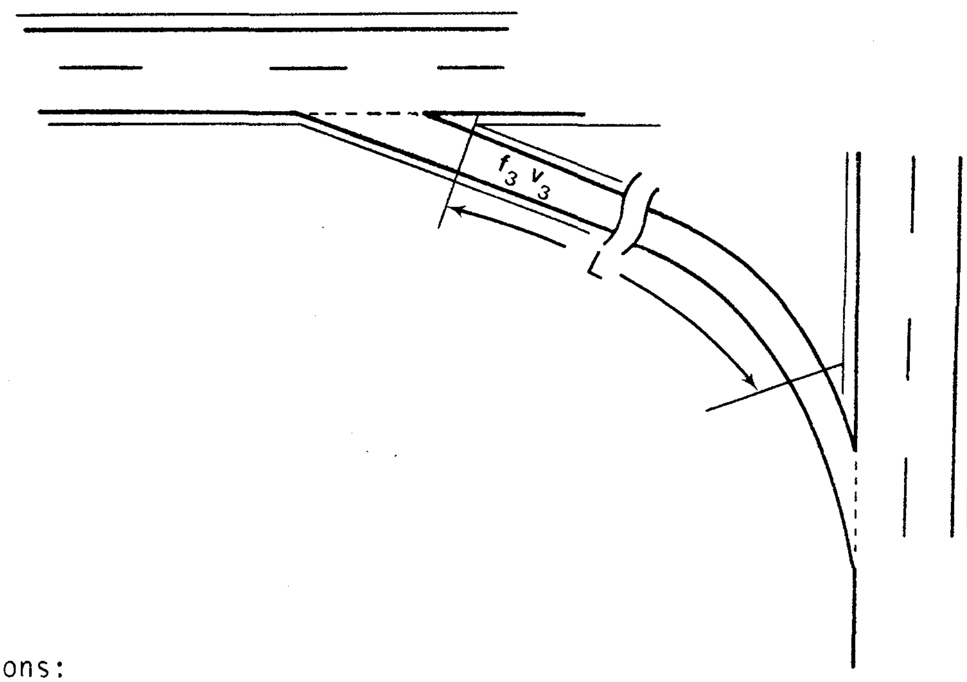
v_2 = outer lane average velocity (mph)

v = average velocity across all lanes (mph)
s = speed limit (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 32-34 for details.

IX. 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

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

2. Single vehicle

$$E_{SV} = Tf_3$$

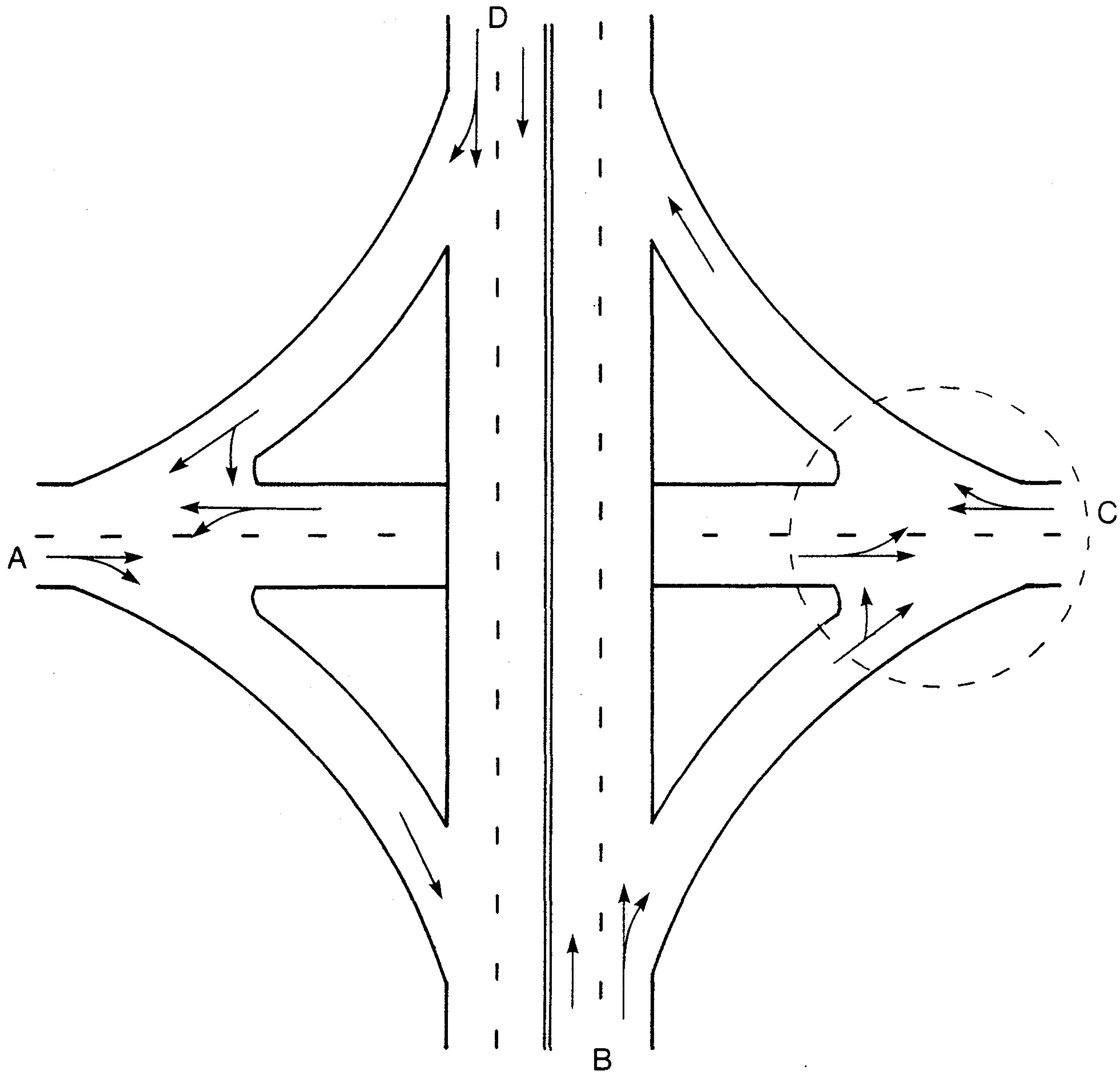
3. Total exposure

$$E_T = Tf_3 \left[2-e^{-f_3L/5280v_3}\right]$$

D. <u>Simplifications</u> -- None.

X. 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).

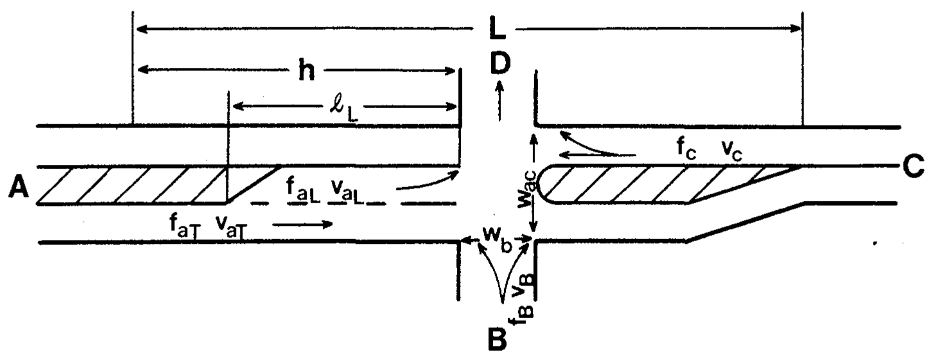


Since formulas for all other sections common to diamond and cloverleaf interchanges were presented in the preceeding pages, only the additional formulas for the ramp terminal areas will be presented here.

A. Assumptions: These diamond ramp terminals will be defined as intersections of widths "w" plus a distance equal to $\pm$ 150 ft.

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

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 no 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 (vph)
f_{a_T} = thru flow on approach A (vph)
f_{a_L} = left turning flow on approach A (vph)
f_c = total approach flow on approach C (vph)
f_b = total approach flow on approach B (vph)
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

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

2. Sideswipe

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

$$E_{SS} = 0$$

3. Single vehicle

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

4. Head-on

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

5. Angle (assuming $v_a = v_c$)

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

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

6. Simplifications

a. Rear-end

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

Assumptions:

$f_a = f_c = f$

$L = 350$ ft.

$h = 150$ ft.

$v_a = v_c = .9s_a$

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)

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

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

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

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

2. Sideswipe

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

3. Single vehicle

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

4. Head-on

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

5. Angle (assuming $v_a = v_c$)

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

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

1. Rear-end

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

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

4. Head-on

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

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

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

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

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. <u>Exposure for signal-controlled ramp terminals</u>.

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

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

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. 23-24.

2. Sideswipe

Sideswipe exposure is calculated assuming <u>adjacent</u> 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

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

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

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

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

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

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 MEASURES FOR HOMOGENEOUS SECTIONS OF HIGHWAYS

I. Introduction and Overview

The previous two chapters have concerned intersection points on the roadway systems. This chapter concerns exposure measures for non-intersection segments -- the homogeneous sections of two-lane and four-lane roadways where no access control exists. (For freeway-type four-lane roadways, the exposure formulas to be used are found in the Chapter 3 section concerning "Thru Segments Prior to Exit Ramps," page 32.) The following narrative is divided into two major divisions:

1. Exposure measures for sections of two-lane roadway.

2. Exposure measures for sections of four-lane roadway.

Just as with the other types of locations, the exposure measures here are based on and characterized by the major type of accidents that could possibly occur on these sections. In general, these accident types include:

1. Single vehicle accidents

2. Head-on collisions

3. Rear-end collisions

4. Driveway-related accidents

5. Sideswipe accidents (for four-lane segments only)

The theory and formulas for head-on and sideswipe crashes are the same as in the earlier chapters. However, two issues arise with respect to single vehicle, rear-end and driveway-related crashes. While these considerations are covered in more detail in the final report, the user of this manual should be aware of the points that follow.

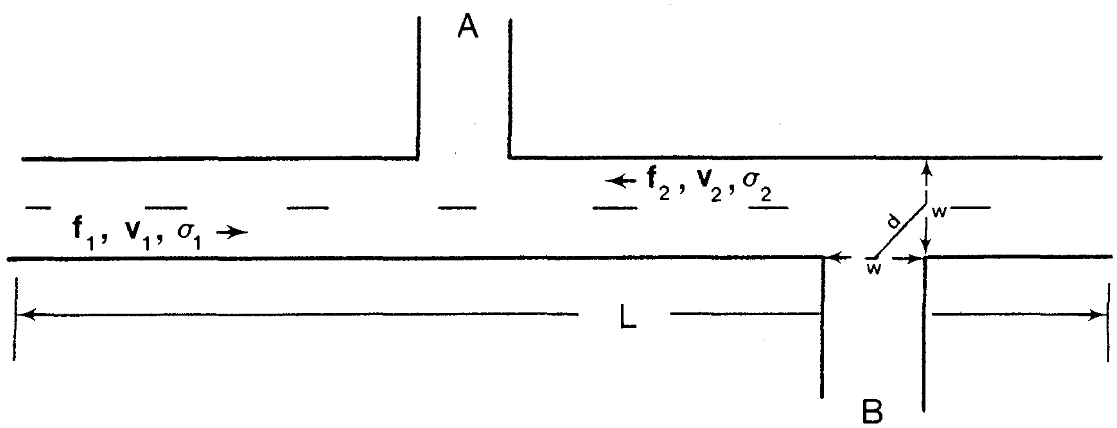
First, for long sections of roadway, the single vehicle and rear-end formulas used previously are not totally "additive" in nature, meaning that the exposure for a 10 mile segment would not exactly equal the exposure if this segment were broken into 40 quarter-mile segments and added. To overcome this, both single vehicle and rear-end exposure will be calculated on a "per-mile" basis and then multiplied by the total segment length. Rear-end exposure is again composed of a "following" component and a component based on possible passing maneuvers.

In addition, for the first time we are now considering exposure to driveway-related crashes. This is being treated as a special type of angle exposure and is included in this section because research has shown that three to twelve percent of all vehicle accidents in rural and urban areas involve vehicles entering from driveways. Driveway exposure formulas are presented for both two-lane and four-lane roadways. If one is studying a location with access control or a location otherwise free of side interference, this component of exposure should be deleted. The problem with this type of exposure is the requirement for an estimate of the volume (or percentage) of vehicles entering from driveways. Unfortunately, because no research exists to provide guidelines, the user will have to formulate and input his own estimates for these variables.

II. Exposure on Homogeneous Sections of Two-lane Highway

A. Assumptions

The following sketch depicts the necessary flows and velocities:



B. Definitions

f_1 = total flow in one direction (vph)

f_2 = total flow in opposite direction (vph)

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

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

v = average velocity of all vehicles (mph)

σ_1 = standard deviation of lane 1 speeds (mph)

σ_2 = standard deviation of lane 2 speeds (mph)

L = total length of segment (ft)

T = length of study period (hours)

N = average number of driveways per foot of section length

$= \frac{\text{number of driveways in the section}}{L}$

w = width of roadway (feet)

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

C. Types of Exposure

1. Rear-end

$$E_{RE} = \frac{LT}{L^*}\left[f_1(1-e^{-f_1L^*/5280v_1}) + f_2(1-e^{-f_2L^*/5280v_2})\right] + \frac{LT}{5280}\left[\frac{f_1^2\sigma_1}{v_1^2 - \sigma_1^2} + \frac{f_2^2\sigma_2}{v_2^2 - \sigma_2^2}\right]$$

where

$$L^* \begin{cases} L \text{ if } L < 5280' \\ 5280 \text{ if } L \geq 5280' \end{cases}$$

If opposing flows and velocities are approximately equal, and

$\sigma_1 = \sigma_2 = 4$ mph, then

$$E_{RE} = \frac{LT}{L^*}\left[f(1-e^{-fL^*/10560v})\right] + \frac{4LTf^2}{v^2 - 16}$$

2. Head-on

$$E_{HO} = \frac{LTf^2}{10560v}$$

3. Driveway

$$E_D = \frac{TNL\bar{f}f(0.69)\sqrt{w}}{5280} = \frac{TNL\bar{f}\,f\,\sqrt{w}}{7652}$$

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

$$E_D = \frac{Tp_d f^2\sqrt{w}}{7652}$$

4. Single vehicle

$$E_{SV} = LTf$$

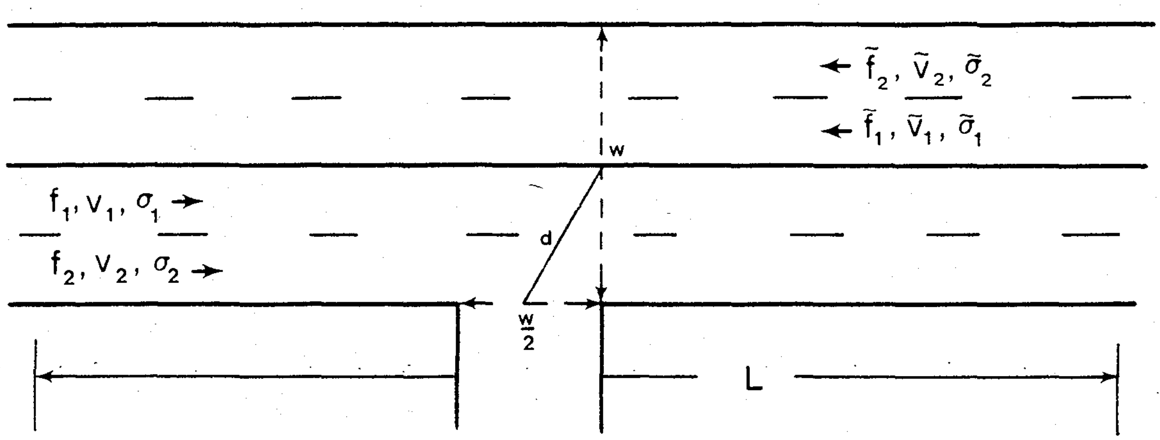
5. Total exposure

$$E_{TOT} = Tf\left[\frac{L}{L^*}\left(1-e^{-fL^*/10560v}\right) + \frac{4Lf}{v^2-16} + \frac{Lf}{10560v} + \frac{p_d f\sqrt{w}}{7652} + L\right]$$

III. Exposure on Homogeneous Sections of Four-lane Highways

A. Assumptions

The following sketch depicts the necessary flows and velocities:



B. Definitions

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

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

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

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

σ_1 = standard deviation of lane 1 speeds (mph)

σ_2 = standard deviation of lane 2 speeds (mph)

$\tilde{f}_1$, $\tilde{f}_2$, $\tilde{v}_1$, $\tilde{v}_2$, $\tilde{\sigma}_1$ and $\tilde{\sigma}_2$ are flows, velocities and speed standard deviations in the 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 = 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

$= \frac{\text{number of driveways in section}}{L}$

w = width of roadway (feet)

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

C. Types of Exposure

1. Rear-end

$$E_{RE} = \frac{LT}{L^*}\Big[f_1(1-e^{-f_1L^*/5280v_1}) + f_2(1-e^{-f_2L^*/5280v_2}) + \tilde{f}_1(1-e^{-\tilde{f}_1L^*/5280v_1}) + \tilde{f}_2(1-e^{-\tilde{f}_2L^*/5280v_2})\Big] + \frac{LT}{5280}\left[\frac{f_2^2\,\sigma_2}{v_2^2 - \sigma_2^2} + \frac{\tilde{f}_2^2\,\tilde{\sigma}_2}{\tilde{v}_2^2 - \tilde{\sigma}_2^2}\right]$$

where

$$L^* = \begin{cases} L \text{ if } L < 5280 \text{ ft.} \\ 5280 \text{ if } L \geq 5280 \text{ ft.} \end{cases}$$

If opposing flows and velocities are approximately equal, and $\sigma_1 = \sigma_2 = \tilde{\sigma}_1 = \tilde{\sigma}_2 = 4$ mph, then

$$E_{RE} = \frac{LTf}{L^*}(1-e^{-fL^*/21120v}) + \frac{LTf^2}{10560\,(v^2-16)}$$

2. Sideswipe: Assuming opposing lane flows and velocities are approximately equal.

$$E_{SS} = \begin{cases} \dfrac{TLf_1 f_2}{2640} \left| \dfrac{1}{v_2} - \dfrac{1}{v_1} \right| , & \text{if } \dfrac{(v_1 - v_2)L}{v_2} > 40 \\[2ex] \dfrac{T\, f_1 f_2}{66 v_1} , & \text{if } \dfrac{(v_1 - v_2)L}{v_2} \leq 40 \,. \end{cases}$$

3. Head-on

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

4. Driveway

$$E_D = \frac{TNL\bar{f} f (0.61) \sqrt{w}}{5280} = \frac{TNL\bar{f}\, f \sqrt{w}}{8656}$$

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

$$E_D = \frac{T p_d f^2 \sqrt{w}}{8656}$$

5. Single vehicle exposure

$$E_{SV} = TLf$$

6. Total Exposure

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

CHAPTER 5

EXPOSURE MEASURES FOR FIXED OBJECT COLLISIONS

I. Introduction

Crashes involving vehicles striking fixed objects along the roadway are studied for a number of reasons. Depending on the type of research question, the rates to be compared, and thus the exposure measures used, will differ. The three basic types of questions which arise include:

1. Research questions in which fixed object crashes are compared to other types of crashes at a location or series of locations.

2. Research questions in which two or more locations are compared on the basis of only the fixed object accident rates.

3. Research questions where two or more types of fixed objects are compared to determine which is more hazardous.

The first two of these questions are similar to the research questions in the preceding chapters in that they are "location-specific." Here, data will be collected either at one location or a relatively limited series of locations. The third question is different. Here the issue is not one of whether a fixed object crash is more hazardous than another type of crash or whether a given location is more hazardous in terms of fixed object crashes, but instead is a more general question asking which type of fixed object is more hazardous in an overall sense.

Since the first two questions require the same exposure measure, they will be covered together. The third question will be covered in later narrative.

II. Fixed Object Exposure for Location-Specific Research Questions

This section will cover the exposure measure and methods of comparing accident or injury rates for the first two types of research questions noted above. These questions are related to (1) a comparison of fixed object crashes to other types of crashes at a location or a series of locations, and (2) the question of comparing locations on the basis of fixed object crash rates. However, before the specific exposure measures are presented, an issue related to what is to be counted in the numerator requires some discussion.

A. Accident or injury rates? In attempting to define appropriate exposure measures and thus appropriate rates to be used in answering these questions, an important consideration is whether or not one should be studying the accident rates (the rate at which a fixed object is struck) or severity rates (the rate at which people are injured in collisions with fixed objects). Depending on the nature of the research question, either criterion would be the more appropriate. (For a more detailed discussion of determining criteria, the reader should refer to page 31 of the Accident Research Manual referenced on page 3.)

If the research question being studied is more related to how many times a fixed object gets hit rather than how hazardous the fixed object is once it is struck, then the question will be answered with accident rates based on the number of fixed objects struck. If, on the other hand, the question is related to the severity of the fixed object collisions, then severity-related rates should be used. Here some frequency of injury divided by the potential number of injuries that could occur would form the most appropriate rate.

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 only one driver in each vehicle. The fact that one driver is in each vehicle also allows one to calculate severity-related rates based on the number of vehicles that strike. Thus, for example, a rate of fatal driver injuries per potential fatal injury is simply the number of fatal driver injuries divided by the number of vehicles that are involved.

B. General definition of 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 in a given section, then any vehicle passing by could potentially strike a fixed object. Hence, each vehicle represents a potential fixed object accident and must count as one exposure unit. This reasoning leads to the same definition of exposure for fixed objects as for total single vehicle accidents.

Thus fixed object exposure for location specific research questions is simply equal to the length of the time interval being studied multiplied by the number of vehicles that flow through the section per time interval. That is, for a section of roadway with total flow = f, the fixed object exposure would be:

$$E_{FO} = Tf$$

It should be noted that this definition of exposure does not include any measure of the number of fixed objects nor indication of their proximity to the highway. Further explanation of why this is true can be found on page 98 of the companion Final Report.

This definition is appropriate for use in analyzing a single section of highway or in comparing two or more sections of <u>equal lengths</u>. However, if sections of different lengths are to be compared, the analyst should calculate the number of fixed object crashes <u>per foot or mile of L</u>, and then divide by the above exposure measure in defining rates. Thus, the rate for each section would be

$$R_{FO} = \frac{a/L}{E_{FO}} \quad ,$$

where a is the total number of fixed object accidents (or injuries) in the section, L is the section length in miles, and E_{FO} is the exposure measure given above.

III. Exposure Measures for Comparing the Hazardousness of Fixed Objects

In the preceding section, the questions related to fixed objects concerned comparing fixed object crashes to other crashes or locations to locations. The sample used in those research questions would include either one location or a relatively small number of locations. In contrast, the general question of interest in this section is that of determining whether one type of roadside fixed object is more hazardous than some other type of fixed object. Answering this question could obviously be done by using data from a much larger sample of locations.

The following discussion of this type of fixed object exposure will contain (1) a brief description of the use of severity related rates rather than accident frequency related rates, (2) a description of the basic exposure measures for both point objects (trees, poles, etc.) and extended objects (guardrails, bridges, etc.), (3) a description of the two basic types of rates that should be formed using these exposure measures, and (4) a discussion concerning how and when to control for extraneous factors in the comparison of these rates. This will be followed by a series of five typical fixed object-related questions which may arise. This final section will also provide information regarding the specific exposure measure to be used and a corresponding specific rate to be used in the analysis.

A. Accident or Injury Rates

Just as above, the issue of defining appropriate exposure measures for use in comparing fixed objects is dependent on whether the objects are designed or placed to reduce the number of crashes or the severity of crashes. The answer will vary with the research question. (The user should review the more detailed discussion on pp. 74-75.) In this section, the exposure measure will usually be severity-related. Since driver injury of a certain class (minor, serious, fatal) is the recommended severity measure, the number of potential driver injuries (and thus the number of drivers/vehicles exposed) would be the most appropriate exposure measure. The specific measures proposed for the five often-asked research questions will be presented later in Section E.

B. Basic Exposure Measure for Point Objects

The basic exposure measure for point-type fixed objects (trees, poles, etc.) is a function of the interaction between the given type of fixed object and the number of vehicles (and thus drivers) which pass these fixed objects. For a given location i, the exposure for a given type of fixed object is:

$$E_{PFO} = Tf_i N_i$$

where

T = length of the study period (hours)

f_i = total traffic flow passing this type of fixed object (vph)

N_i = number of this type of fixed objects beside the roadway

For a series of locations, the exposure is simply the sum of the individual counts; i.e.,

$$E_{PFO} = T \sum_{i=1}^{s} f_i N_i$$

where

i = number of locations = 1,2,...s

C. Basic Exposure Measure for Extended Objects

In like fashion, the exposure measure for extended objects (guardrails, median barriers, bridge rails, etc.) is a function of the vehicle counts and the lengths of the objects. For a given location i,

$$E_{EFO} = T f_i L_{O_i}$$

where

T = length of study period (hours)

f_i = total traffic passing the object (vph)

L_O = length of the fixed object (ft.)

For a series of locations, the exposure measure is:

$$E_{EFO} = T \sum_{i=1}^{s} f_i L_{O_i}$$

where

i = number of locations = 1,2,...s

D. Controlling for Contributing (Extraneous) Factors

While the above discussion has provided the basic exposure measures, let us now expand this work to the measure which will be compared in most research -- the actual accident or driver injury rates to be used. (The reader should note that this discussion concerns the variables affecting the "likelihood" of a crash or injury rather than the "opportunity" -- an area which Chapter 1 indicated would not be stressed. However, this discussion of the control of these "likelihood" variables appears necessary in order to clarify the later treatment of specific research questions currently of interest. The reader is again urged to also consult other accident research texts.)

A major consideration in this development of rates for fixed object collisions concerns the questions of whether and how to "control" for other potential causes of the observed differences. These might include, for example, the type of location (curve or tangent), the distance of the fixed object from the edge of pavement (EOP), the speed of traffic, etc. The following rules are proposed for use here:

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 in nature (i.e., if one type of pole always is placed at a certain distance while a comparison type of pole is always placed closer to the EOP), then the differences should not 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.

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

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 homogeneous locations), the factors should be controlled for.

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

1. Grouping the objects by the levels of these extraneous factors and comparing rates within these different levels.

2. Adjusting 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 comparing these adjusted rates.

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

It appears that Approach 1 above is generally the most 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 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 formulated within various levels of these extraneous factors as in Approach 1, then the differences are accounted for.

E. Typical Research Questions

While it is not possible to enumerate all of the potential research questions related to comparing the hazardousness of fixed objects, the authors and FHWA have attempted to identify a series of basic questions which would represent the major types of research issues. These are presented below with a discussion of the appropriate rate to be used and a discussion of how to control for other factors.

Question 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)?

Consider first the problem of comparing two types of point objects. 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 equally far from the edge of the roadway. To address this question, we can examine driver 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. However, the high injury count could also result from the presence of more poles of the one type than of the other, or higher traffic flows past the one type, or any other situation resulting in more pole-vehicle interactions for that type of pole. In this case, it would seem that the overall accident rate per unit of exposure for each pole type would be given by

$$R = \frac{\sum_{i=1}^{s} di_i}{T \sum_{i=1}^{s} f_i N_i}$$

where

di_i = number of drivers injured to a certain degree at location i ($i = 1,2,\ldots s$).

T = length of the study period (hours)

f_i = total traffic flow passing this type of pole (vph)

N_i = number of this type of pole beside the roadway.

However, if the assumption of equal placements with respect to the roadway was not satisfied, then differing injury rates between pole types might simply be reflecting this differential placement. As indicated in Rule 3 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. The recommended 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' and all of the other type at 10' from EOP, no comparison should be made using this approach since the sample does not reflect reality of overall equal placements with respect to EOP).

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. Here 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 utility poles closer to the pavement versus those rates calculated for poles further away. 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 during the study period, T).

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

Now consider the problem of comparing types of similar extended fixed objects (e.g., two types of guardrails). In this case, the most appropriate rate for each type would be:

$$R_j = \frac{\sum_{i=1}^{s} di_i}{T \sum_{i=1}^{s} f_i L_{0_i}}$$

where

L_{o_i} = total length of extended object at location i (i = 1,2,...s)

and other variables are as defined on page 80.

Note that the exposure measure is as defined earlier. 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 (e.g., a guardrail) more or less hazardous than the object it protects (e.g., a culvert wall or a point object such as a tree)?

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 here 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.

Here 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, vehicle speeds, etc. should "match"). Here the most appropriate injury rates (within a given classification of injury) for culverts and guardrails, respectively, would be calculated as follows:

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

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

Note that 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. Even though the guardrail will be longer than the culvert, its length is defined by the need to protect the culvert. 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 five simply because the guardrail is five times longer than the culvert. This five-fold increase in length is required as part of the treatment and 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. Here, the rate for culverts would be calculated as above and the rate for guardrail 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,

$$R_g = \frac{\sum_{i=1}^{s} di_i}{T \sum_{i=1}^{s} f_i L_{0_i} / g_a}$$

where

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

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

As an 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 true since the end of a guardrail can be struck in more ways than the middle of the rail. For example, 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 is virtually impossible to obtain adequate data on only the first 50 feet of a given section of guardrail. Given these problems, it appears that one may be left with the latter formulation realizing that the calculated guardrail-section injury rate may be slightly conservative.

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 where the question concerns which type of object should receive higher priority for cleanup funding. Here the most appropriate rates in these comparisons are the injury rates calculated using the methods cited 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 of extended objects implies an assumption that a point object on the average is equal to one foot in width.)

CHAPTER 6

EXPOSURE MEASURES FOR VEHICLE TYPE RESEARCH QUESTIONS

The second, third and fourth chapters of the manual have concerned exposure measures which are specific to certain types of locations. The fifth chapter, concerning fixed objects, is slightly different but still is related to roadway hardware. 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 certain vehicle classes over an entire jurisdiction.

I. Exposure Measures for the Evaluation of Vehicle Specific Countermeasures

A. Introduction and Methodology

The first of the questions that often arises in this setting 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 runaway 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 flow which includes all other vehicles.

Because the individual exposure formulas for the three main location types have been developed and presented in the first three chapters, the modified formulas will not be repeated here. Instead a series of specific rules will be presented to aid the researcher in modifying the earlier formulas. These rules will each relate to one type of exposure (i.e., one type of accident). The procedure which should be followed for a specific research question involves the following three steps:

1. Determine the type of location where the evaluation is being conducted (i.e., intersection, interchange, non-intersection two-lane roadway, non-intersection four-lane roadway).

2. Determine the specific types of accidents (and thus exposure) which are of interest.

3. Modify the basic formulas (see Figure 1.1, page 8, for a guide to these formulas) using the following rules and calculate exposure.

Rule 1. Rear-end exposure. All rear-end exposure formulas are composed of the following two parts:

1. A portion which involves the calculation of the probability that a given pair of vehicles will be within distance L and thus have the opportunity of being involved in a rear-end crash.

2. A portion which involves faster vehicles passing slower vehicles and forming new pairs which have the opportunity of being involved in a rear-end crash.

Since the probability of being within the distance L is the same for a pair consisting of a vehicle from the class of interest (e.g., heavy truck) and another vehicle as it is for any two vehicles, the modification for the non-passing type of rear-end exposure involves reducing the incoming flow rate to that of the vehicle class of interest only. Therefore, for situations where passing is not possible (e.g., intersections), to calculate exposure to rear-end crashes, one should:

1. Calculate rear-end exposure for the total flow rate (as was done earlier).

2. To obtain the rear-end exposure for the special class, multiply the total rear-end exposure by p where

$$p = \frac{\text{flow rate for the special vehicle class}}{\text{total flow rate for all vehicles}}$$

For other situations where rear-end exposure involves both the non-passing ("pipeline") and the passing components (e.g., interchanges, homogeneous sections), exposure for the vehicle class of interest is calculated as follows:

1. Calculate the non-passing component and multiply by p as described above.

2. Calculate the passing component using the formulas provided earlier.

3. Multiply this passing exposure by the correction factor

$$\text{c.f.} = p\ (2-p)$$

   where, as above,

$$p = \frac{\text{flow rate for the special vehicle class}}{\text{total flow rate for all vehicles}}$$

4. Sum the non-passing and passing components to obtain total rear-end exposure for the special class.

Rule 2. Sideswipe exposure. By definition, exposure to sideswipe accidents is only allowed to occur on multi-lane roadways (with the faster lane flow overtaking the slower lane flow or with vehicles entering side-by-side) and at intersections (with the outer lane flow overtaking the left turn lane flow or vehicles entering side-by-side). The exposure measure is a function of these two lane flows and lane velocities. Modifying the basic formulas involves the following steps:

1. Calculate the sideswipe exposure for the total flow rate as was done earlier.

2. To obtain the sideswipe exposure for the special class, multiply the total sideswipe exposure by the correction factor

$$\text{c.f.} = p\ (2-p)$$

   where, as above,

$$p = \frac{\text{flow rate for the special vehicle class}}{\text{total flow rate for all vehicles}}$$

Rule 3. Head-on exposure. In all of the earlier formulas, the exposure to head-on crashes has been a function of total lane flows in a given direction multiplied by the opposing flow (lane by lane), and this product corrected by a velocity factor for each lane in each direction. Modifying this basic formula for use with a special vehicle class is again a two-step procedure; i.e.,

1. Calculate the head-on exposure for the total flow rate as was done previously.
2. To obtain the head-on exposure for the special class, multiply the total head-on exposure by the correction factor

$$\text{c.f.} = p\,(2-p)$$

where

$$p = \frac{\text{flow rate for the special vehicle class}}{\text{total flow rate for all vehicles}}$$

Rule 4. Angle exposure. Exposure to angle collisions is necessary in the following five situations: intersections, interchange merge areas, interchange entrance ramps, diamond ramp terminals, and locations where driveways enter urban and rural roadway segments. In all cases, the exposure is a function of the number of crossing vehicles which can enter a location (e.g., an intersection) while the given vehicle is travelling through the location. The modification of the basic exposure formulas requires the same two steps as in the calculation of overtaking and head-on exposure described above. Again these two steps are:

1. Calculate the angle exposure for the total flow rate as was done earlier.
2. To obtain the angle exposure for the special class, multiply the total angle exposure by the correction factor

$$\text{c.f.} = p(2-p)$$

where

$$p = \frac{\text{flow rate for the special vehicle class}}{\text{total flow rate for all vehicles}}$$

Rule 5. Single vehicle exposure. Exposure to single vehicle crashes is simply the sum of the individual flow rates multiplied by the length of the study period. Thus, to modify the previous formulas for special vehicle classes, substitute the special vehicle flow rates in place of the original total flow rates, or calculate single vehicle exposure as before and multiply by the correction factor p.

B. Example

Situation: A signing system, known as the Grade Severity Rating System, is designed to reduce heavy truck speeds on steep downgrades and thus to reduce runaway truck accidents. For evaluation purposes, the signs have been placed on an access-controlled four-lane divided downgrade of 7%. The average lane velocities on the downgrade side are 53 mph for the inner lane and 49 mph for the outer or curb lane. The downgrade is 5 miles long. The two-way ADT is 14,200 vpd with 7,680 in the outer lanes and 6,520 in the inner lanes. Approximately 18% of this flow is composed of heavy trucks.

First, convert ADT to hourly flows for one direction (assume 50-50 split)

Total lane flows	Truck flows
f_1 = 160 vph	f_{1t} = 29 tph
f_2 = 136 vph	f_{1t} = 25 tph

and then proceed through the following three steps.

Step 1. Determine type of location:

4-lane access-controlled segment (same as homogeneous sections of four lane roadway without driveways)

see page 32

Step 2. Determine types of collisions of interest:

Since runaway trucks can strike other vehicles or run off the road, we should study these accident types.

Rear-end exposure see page 32
Sideswipe exposure see page 32
Head-on exposure see page 33
Single vehicle exposure see page 32

Step 3. Modify the formulas and calculate exposure.

Given:

T = 1 year = 8760 hours
L = 5 miles = 26400 feet
f_1 = 160 vph
f_2 = 136 vph
f_{1t} = 29 tph
f_{2t} = 25 tph
$f_{1t} + f_{2t}$ = 18% of total flow

v_1 = 53 mph
v_2 = 49 mph
σ_2 = 4 mph (assumed)

Assume equal flows and velocities in opposing lanes

$f_1 = \tilde{f}_1$ = 160 vph
$f_2 = \tilde{f}_2$ = 136 vph
$v_1 = \tilde{v}_1$ = 53 mph
$v_2 = \tilde{v}_2$ = 49 mph
$\sigma_2 = \tilde{\sigma}_2$ = 4 mph

a. Rear-end exposure

Overall formula containing both non-passing and passing components:

$$E_{RE} = \frac{TL}{L^*}\left[f_1\ (1-e^{-f_1 L^*/5280 v_1}) + f_2\ (1-e^{-f_2 L^*/5280 v_2})\right] + \frac{TLf_2^{\,2}\ \sigma_2}{5280(v_2^{\,2} - \sigma_2^{\,2})}$$

1. Calculate the non-passing component

$$E_{RE,NP} = \frac{TL}{L^*}\left[f_1(1-e^{-f_1 L^*/5280 v_1}) + f_2(1-e^{-f_2 L^*/5280 v_2})\right]$$

$$= \frac{(8760)(26400)}{5280}\left[160(1-e^{-(160)(5280)/(5280)(53)}) + 136(1-e^{-(136)(5280)/(5280)(49)})\right]$$

$$= 12{,}251{,}200$$

2. Modify for truck exposure by multiplying by p = .18

$$E_{RE,NP,T} = (12{,}251{,}200)(.18) = 2{,}205{,}216 \text{ exposure units}$$

3. Calculate the passing component

$$E_{TR,P} = \frac{TLf_2^2\ \sigma_2}{5280\ (v_2^2 - \sigma_2^2)}$$

$$= \frac{(8760)\ (26400)\ (136)^2(4)}{5280\ (49^2 - 4^2)}$$

$$= 1{,}358{,}700$$

4. Modify for truck exposure by multiplying by

$$\begin{aligned} c.f. &= p(2-p) \\ &= .18(2-.18) \\ &= .328 \end{aligned}$$

$$E_{RE,P,T} = 1{,}358{,}700\ (.328) = 445{,}654$$

5. Sum to obtain total rear-end exposure for trucks

2,205,216 + 445,654 = 2,650,870 exposure units

b. Sideswipe exposure

1. Calculate sideswipe exposure for total flow

$$E_{SS} = \frac{TLf_1f_2}{5280}\left|\frac{1}{v_2} - \frac{1}{v_1}\right| \qquad \text{since } \frac{(v_1 - v_2)L}{v_2} = 2155 > 40$$

$$= \frac{(8760)\ (26400)\ (160)(136)}{5280}\left|\frac{1}{49} - \frac{1}{53}\right|$$

$$= 1{,}467{,}983 \text{ exposure units}$$

2. Modify for truck exposure by multiplying by

$$c.f. = p(2-p)$$

$$= .18(2-.18)$$

$$= .328$$

$$E_{SS,T} = .328\ (1{,}467{,}983) = 481{,}498 \text{ exposure units}$$

c. Head-on exposure

1. Calculate head-on exposure for the total flow

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

$$= \frac{(26400)(8760)}{5280}\left[(160)(160)(\frac{2}{53}) + 2(160)(136)(\frac{1}{53} + \frac{1}{49}) + (136)(136)(\frac{2}{49})\right]$$

$$= 150{,}245{,}907 \text{ exposure units}$$

2. Modify for truck exposure by multiplying by c.f. = .328:

$$E_{HO,T} = (.328)(150{,}245{,}907)$$

$$= 49{,}280{,}657 \text{ exposure units}$$

d. Single vehicle exposure

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

$$= (8760)(136 + 160)\ (.18)$$

$$= 466{,}733 \text{ exposure units}$$

e. Total exposure

$$E_{TOT,T} = E_{RE,T} + E_{SS,T} + E_{HO,T} + E_{SV,T}$$

$$= 52{,}879{,}758 \text{ exposure units}$$

II. Exposure Measures for Comparisons of Vehicle Types

A. Introduction

This section contains methods for calculating estimates of exposure for a fleet of vehicles belonging to different classes, and operating over an extended geographical area (e.g., statewide or nationwide estimates). The resulting exposure indices can be used with corresponding accident data to calculate accident rates by vehicle class. Exposure indices for single vehicle accidents and for two vehicle accidents are computed separately as are the corresponding accident rates.

B. Exposure to Single Vehicle Accidents

The exposure measure should indicate the extent to which vehicles of a given class are present on the area's roads during a fixed time period (e.g., vehicle miles or vehicle hours accumulated over time for the fleet of vehicles belonging to a given class).

Let

M_{v_i} = accumulated vehicle miles for vehicles belonging to class v_i (e.g., small cars, trucks, utility vehicles, etc.)

a_{1v_i} = number of single vehicle accidents involving vehicles of class v_i

Then the exposure to single vehicle accidents for vehicles of class v_i is given by

$$E_{1v_i} = M_{v_i}$$

while the corresponding single vehicle accident rate is given by

$$R_{1v} = \frac{a_{1v_i}}{M_{v_i}}$$

C. Exposure to Two-Vehicle Accidents

Exposure to two-vehicle accidents is a function of traffic density. Therefore, factors related to traffic density should, when possible, be taken into account. Such factors include:

1. Time of day
2. Day of week
3. Urban-rural
4. Highway class

The exposure measure for two-vehicle accidents should represent the extent to which vehicles of a given class are present on the area's roads with other vehicles of the same class and with vehicles of other classes during a fixed time period. Measuring this requires correctly combining vehicle miles accumulated by the different classes.

Case 1. No traffic density factors considered.

Let

$A_{2v_iv_j}$ = number of two-vehicle accidents involving one vehicle belonging to class v_i and one vehicle belonging to class v_j, where v_iv_j ranges over all distinct pairs of vehicle classes.

M_{v_i} = accumulated vehicle mileage for vehicles belonging to class v_i

The exposure index for two-vehicle accidents involving the vehicle in question (v_i) with other vehicles in the same class will be

$$E_{2v_iv_i} = M_{v_i}^2 \quad ,$$

the square of the total miles accumulated for this class (since each vehicle may strike all other vehicles).

In like manner, the exposure index for two-vehicle accidents involving vehicles of the class in question (v_i) with vehicles of another class (v_j) will be

$$E_{2v_iv_j} = 2M_{v_i} M_{v_j} \quad ,$$

with the factor "2" being included since all vehicles of class v_i can strike <u>and</u> be struck by all vehicles of class v_j. This type factor would be included for each class of other vehicle types involved in the study.

Thus, the total exposure index for two-vehicle crashes involving class v_i vehicles is

$$E_{2v_i} = E_{2v_iv_i} + \sum_j E_{2v_iv_j}$$

$$= M_{v_i}^2 + 2\, M_{v_i} \sum_j M_{v_j}$$

and the accident rate for vehicles in class v_i would be

$$R_i = \frac{\sum \text{all two-vehicle accidents involving vehicles of class } v_i}{E_{2v_i}}$$

<u>Example</u>: Consider the accident and vehicle fleet mileage for the three vehicle types shown in the following table:

Vehicle Type	Mileage	Single Vehicle Accidents	Two-Vehicle Accidents
Small car	M_S	A_S	A_{SS}
Large car	M_L	A_L	A_{SL}
Truck	M_T	A_T	A_{ST}
			A_{LL}
			A_{LT}
			A_{TT}

Single vehicle exposure:

$$E_S = M_S \ , \quad E_L = M_L \ , \quad E_T = M_T$$

Accident rates:

$$R_S = \frac{A_S}{M} \ , \quad R_L = \frac{A_L}{M_L} \ , \quad R_T = \frac{A_T}{M_T}$$

Two-vehicle exposure:

$$E_{SS} = M_S^2 \ , \quad E_{SL} = 2M_S M_L \ , \quad E_{ST} = 2M_S M_T \ ,$$

$$E_{LL} = M_L^2 \ , \quad E_{LT} = 2M_L M_T \ , \quad E_{TT} = M_T^2$$

Overall two-vehicle accident rates

$$R_{2S} = \frac{A_{SS} + A_{SL} + A_{ST}}{M_S^2 + 2M_S M_L + 2M_S M_T} \ , \qquad \text{for small cars;}$$

$$R_{2L} = \frac{A_{SL} + A_{LL} + A_{LT}}{2M_S M_L + M_L^2 + 2M_L M_T} \ , \qquad \text{for large cars; and}$$

$$R_{2T} = \frac{A_{ST} + A_{LT} + A_{TT}}{2M_S M_T + 2M_L M_T + M_T^2} \ , \qquad \text{for trucks.}$$

The following numerical example will provide further clarification.

The table below 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	$M = 1{,}000{,}000$	$a_T = 125$	$a_{LT} = 300$
			$a_{TT} = 100$

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 as follows:

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

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

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

$R_S = a_S/M_S = 250/2{,}000{,}000 = 12.5/100{,}000$

$R_L = a_L/M_L = 300/3{,}000{,}000 = 10/100{,}000$

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

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

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

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

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

$E_{LT} = 2M_LM_T = 6 \times 10^{12}$

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

Total two-vehicle exposure for small cars is given by

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

and similarly,

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

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

These final three expressions are then used as the denominators in the rate equations to give,

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

$$R_{2L} = \frac{1300}{27 \times 10^{12}} = 4.81/100 \text{ billion}$$

$$R_{2T} = \frac{700}{11 \times 10^{12}} = 6.36/100 \text{ billion} \quad .$$

Case 2. Traffic density factors included

Definitions: Suppose $D_1, D_2, \ldots, D_S$ are S density-related factors that are to be included in the two-vehicle exposure indices. Let the i-th factor have d_i levels and let $K = \prod_{i=1}^{S} d_i$ be the total number of combinations of levels of all factors. In practice S would usually be 1 or 2, and K would likely be no greater than 6 (e.g., D_1 = urbanization with levels urban and rural, D_2 = day of week with levels weekday and weekend so that S = 2, K = 4).

Calculating exposure indices for this situation requires information on mileage by vehicle class and accidents by vehicle class within each level. 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 two-vehicle accidents for each combination (pair) of vehicle classes. With these ingredients, single vehicle and two-vehicle accident rates can be calculated using the formulas in the previous section for each level (i.e., for each cell in the table). The total single vehicle exposure index for a given vehicle class v_i is then calculated by weighting (multiplying) each single vehicle cell rate by the mileage accumulated by this vehicle class within the cell divided by the total accumulated mileage for this class of vehicles. Thus, the weighting factor is

$$\frac{M_{v_i k}}{M_{v_i}}$$

where k is the level (cell) in question. These weighted rates are then summed to give the total single vehicle index.

In similar fashion, the total two-vehicle index for a given vehicle class is calculated by weighting each of the two-vehicle rates calculated in each cell by the total cell mileage for all classes divided by the total mileage for all classes, and the weighted rates are summed.

This method can also be expanded to calculating other rates (such as a total urban rate for small cars) using the same basic method. Details are provided in the comparison final report (Chapter 6, p. 114).

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 of the potential user one favor, and that is not to 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 represent 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.