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16. Abstract

This report gives the results of a study that evaluated methods and data for measuring the benefits of research projects. A simple procedure is outlined for using standard benefit-cost analysis, such as that developed in AASHTO's Manual on User Benefit Analysis and Charles Dale's procedure. First, the benefits must be calculated for each implementation unit, such as mile of highway, location, ton of asphalt, etc. Next, an estimate is made of the cost of each unit of implementation. Third, an estimate is made of the period of time over which the research results are expected to be implemented and the rate of implementation in terms of implementation units per year. An adjustment also can be made for the lag in time before implementation begins. These inputs are then used to estimate present worth of net benefits resulting from use of the research results. Several case studies based on research studies of the Texas State Department of Highways and Public Transportation are used to illustrate the method. These case studies demonstrate a very high return on research, but also show the need for development of better information using before-after studies of research implementation.

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A METHOD FOR EVALUATING

THE BENEFITS OF RESEARCH PROJECTS

by

William F. McFarland
Research Economist

Research Report 1137-1F
Research Study Number 2-10-85-1137
Benefits of Research

Sponsored by

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November 1988

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

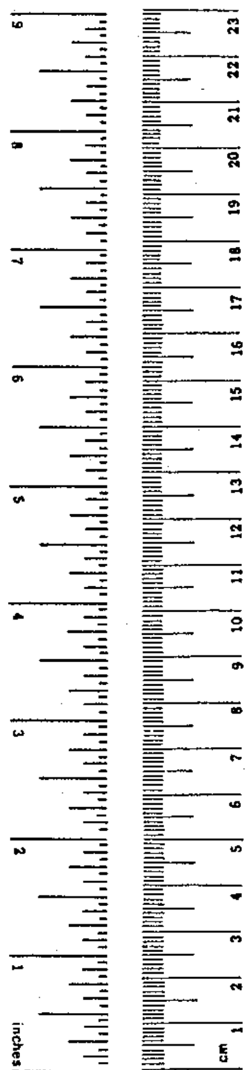
VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

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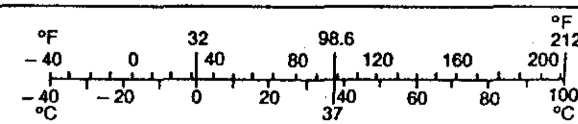

These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

PREFACE

The author is indebted to several individuals with the Texas State Department of Highways and Public Transportation for valuable advice on the way to approach the measurement of benefits of highway projects. He would especially like to thank Mr. Jon Underwood, Director of Research and Mr. David Hustace for their assistance throughout the project. Many helpful suggestions were made by the project advisory committee and the D-10 research staff, including Mr. Steve Golding, Mr. Bill Elmore (D-9), Ms. Tanya Pavliska (D-10R), Mr. H. Butler (D-5), Mr. C. Jett (D-6), Mr. L. Crawford (D-5), Mr. Jerry Daleiden (D-8), and Mr. Russell Cummings (D-18).

The author also is indebted to several individuals at the Texas Transportation Institute, including G. Sadler Bridges who assisted with developing this research project and Ms. Margaret Chui who assisted with analysis of accident data. Ms. Brenda Hazelwood and Ms. Wendy Heeder also assisted with the final report.

SUMMARY OF FINDINGS

This report gives the results of a study that evaluated methods and data for measuring the benefits of research projects. A simple procedure is outlined for using standard benefit-cost analysis, such as that developed in AASHTO's Manual on User Benefit Analysis and Charles Dale's procedure. First, the benefits must be calculated for each implementation unit, such as mile of highway, location, ton of asphalt, etc. Next, an estimate is made of the cost of each unit of implementation. Third, an estimate is made of the period of time over which the research results are expected to be implemented and the rate of implementation in terms of implementation units per year. An adjustment also can be made for the lag in time before implementation begins. The procedure uses these inputs to estimate present worth of net benefits resulting from use of the research results. These net benefits are then divided by the sum of research project cost and research division implementation cost to obtain a benefit-cost ratio for the research project.

The report also includes a discussion of historical and predictive studies. With either type of study, the objective is to measure the benefit of using the research results as compared to what the situation would have been if the research had not been implemented. Although this can never be known with certainty, with certain assumptions, estimates can be made. Historical studies are studies that are performed after implementation has been effected for several years and the effects of implementation can be based on actual results. For this type of study, the principal difficulty is in developing a good experimental design for measuring the benefits of the research. With predictive studies, the emphasis shifts to developing a good predictive model for predicting the effects of implementing research results. This report does not attempt to fully survey all of the types of predictive models that are available, but this could be a fruitful future research area.

Several case studies based on research studies of the Texas State Department of Highways and Public Transportation are used to illustrate the procedure. These case studies are divided into five types: (1) safety projects, (2) highway design and traffic control, (3) pavement design and materials, (4) cost saving designs, and (5) management and planning. Two projects are considered in each of categories (1) and (4) and one project is considered in the other three categories. It was not possible to include additional studies at this time, but it is recommended that research be continued in this area. The case studies demonstrate a very high return on research and implementation, as might have been expected since the chosen case studies all were known to have been successfully implemented. The case studies also show the need for development of better information using before-after studies of research implementation.

Table of Contents

I. INTRODUCTION

BACKGROUND AND OBJECTIVES

Estimates of the benefits of research studies are needed at several stages of the research program. Persons who monitor research projects are required to prepare estimates of the benefits of research studies after the studies are completed and at one year intervals for three years. Researchers are required to estimate the potential benefits of new research projects when they prepare proposals. Members of the Area Research Committees and members of the Department's Research Committee have to make judgments about the potential benefits of research studies when they rank and select studies for future research.

The objectives of this research project are to: (1) develop techniques for estimating the benefits of research projects, (2) make estimates of benefits of selected actual research projects, and (3) assist principal investigators in developing estimates of potential benefits of their research projects.

PREVIOUS RESEARCH

An extensive literature review revealed very few studies that developed estimates of the benefits of transportation research projects. The most extensive examples of calculating benefits for research projects that were found in the literature were the series published by the Transportation Research Board entitled "Research Pays Off" and specific unpublished reports prepared by technical coordinators of the State Department of Highays and Public Transportation (DHT).

Although there are only a few reported benefit-cost studies of research projects, there nevertheless is an extensive amount of literature dealing specifically with benefit-cost analysis of transportation alternatives. This literature includes recommendations for service lives, the discount rate, values of time, accident costs, and various formulas.

LIMITATIONS OF THE STUDY

One of the principal limitations of this study is that it emphasizes conventional benefit-cost analysis. This emphasis has a direct bearing on two important items. First, the enumeration of benefits is limited mainly to two types of benefits: (1) direct cost savings in the provision of transportation services, and (2) increases in motorist benefits, as measured by savings in travel time, vehicle operating costs, and accidents. Second, the measurement of motorist benefits follows conventional measurement techniques with whatever limitations are inherent in the current state of the art.

One difficulty in all benefit-cost studies is that there has not been general agreement on the unit costs or values for benefits. An example of this is the continuing disagreement on the cost of accidents, where many states continue to use National Safety Council values for accident costs even though the general consensus among economists is that these values are much too low for use in benefit-cost studies. Another item on which there is only limited agreement is the value of time. Perhaps as important is that methods have not been developed for evaluating the "cost of discomfort" for use in benefit-cost studies. Even though it is not possible to put many of the benefits in dollar terms, it is recommended that an attempt be made to list all benefits and disbenefits, and to quantify these where possible.

Another limitation of this study is that it is limited in geographic scope. The principal viewpoint taken in the report is to calculate benefits in Texas, since the benefits are measured for Texas and the research funding being considered is for Texas studies. This limited approach is not meant to be overly provincial but is pursued as a way to obtain preliminary results. In some cases where the Texas research appears to have had an impact on implementation elsewhere, these results may be mentioned but are not the primary subject of the analysis. This is not meant to infer that benefits outside Texas should not be considered in a more complete study but merely that this is a limited study.

It is difficult to isolate the benefits of specific research projects because research is intricately related to knowledge in general. It is virtually impossible to attribute a research finding to a single and simple cause. The research result is really a joint product of knowledge in existence at the beginning of the project and what is learned on the project, and there is <u>no</u> way to separate the influence of these two causal factors. Many kinds of knowledge enter into even the simplest of new research ideas. Nearly all new research developments use both basic and applied sciences.

It is always difficult to determine exactly how ideas were developed. Even the developers may not be aware of all of the influences on their final effort. Sometimes, if they write a history of their research we may begin to know some of the influences. However, this need not be of over-riding concern in this study. What is most important for this study is whether a research project led more or less directly to an implementation effort in Texas that resulted in benefits in Texas. This is the necessary condition to which must be added that the savings over time would not have taken place without the research project. It does not particularly matter for calculating a benefit-cost ratio of the type that is calculated whether the idea originated in the Texas research project or not. The only necessary condition is that the research and implementation effort for the research project; i.e., the spending of the Texas research money, led to results that would not otherwise have occurred. If the Texas spending leads directly to Texas results, then that is what matters for the analysis in this report.

There is no attempt, therefore, to give a complete history of each of the specific research innovations considered. It is considered sufficient for attributing benefits to a project if the project led directly (or, is expected to lead, in the case of predicted results) to implementable results and benefits in Texas, whatever the specific history of research on the innovation. A more complete history with the goal of estimating total societal costs and benefits of research might take into account these additional considerations.

Another limitation of the study is that detailed studies of the benefits and costs of individual research projects have not been made. For many projects, it is known that the results have been implemented, and from this it can be inferred that the benefit of implementation exceeded the implementation cost. For a more limited number of projects it is fairly clear that there were substantial benefits that resulted directly from the implementation effort. Noteworthy examples include the safety innovations such as breakaway sign supports, crash cushions, safety-treated culverts, safety-treated mailboxes, and breakaway luminaire poles, some of which are included in case studies in this report. However, for other research results, the full extent of implementation is not always known because no detailed records are kept.

II. GENERAL CONSIDERATIONS

HISTORICAL AND PREDICTIVE STUDIES

It is important to distinguish between historical and predictive studies for measuring the benefits of research. Historical studies are conducted after data is available on the benefits of implementing the research results, whereas predictive studies attempt to predict the future benefits of research before implementation. Technical coordinators of the Department typically must make predictive evaluations when they estimate benefits of projects soon after the research is completed and when little or no data are available on implementation. Each of these types of evaluations has its own set of estimation problems. One of the main difficulties in a historical study is to have a good experimental design for measuring the situation with and without implementation. Predictive studies must have some type of forecasting model, either explicit or implicit, for predicting future benefits of implementation. The predictive model must not only be able to estimate the benefits of implementing the research results in specific situations but must also predict the number of times that the research results will be used. There is not always a clear distinction between these two types of studies in the literature on the benefits of research and sometimes elements of historical data and predictive models are used.

Most often, however, results that are reported in the literature, such as in the Transportation Research Board's series entitled "Research Pays Off", are partial historical evaluations. That is, the findings of a research project have been implemented, and often are still being implemented on an on-going basis, but the benefit-cost ratio is presented for only the implementation to date. For example, something like the following is often found in the literature: "the project cost $150,000 and resulted in savings of over $1,000,000 in the first three years after the project ended." These are interesting results and there is no intent to be critical of this type of report. One important advantage of this type of approach is that the benefit estimates are more concrete and accurate than are those developed using a predictive approach. What is also needed, however, is further follow up on some of these studies and documentation of the results over time. Although this approach avoids speculative (future predicted) benefits, it must be viewed as only a partial estimation of total benefits.

In reports of technical coordinators, they typically are asked to predict all future benefits expected from implementation before any implementation has occurred, so their task is in many ways more difficult and sometimes almost impossible if a predictive model has not been developed in the course of the research. Sometimes, a trial implementation, a special study, or some measurements are made in the course of the research. Often, however, there is no opportunity to do full field testing. For a complete evaluation, an idea is needed of the variations expected in the field so that the technical coordinator can try to develop a model that can predict the outcome of implementation in the different circumstances that will be encountered in the field.

In some of the case studies in this report, historical data are used where available, but in other cases a deliberate attempt is made to develop predictive results even where more complete results on actual implementation is available. The reason for this is that the primary emphasis is on the development of procedures that can be used by technical coordinators when they must develop very preliminary predictive results, even when most of the information is based mainly on judgment. Historical studies probably are much more accurate than predictive studies, but a predictive approach is most often the type that technical coordinators take because historical data is not available.

CALCULATING BENEFITS OF RELATED PROJECTS

The following discussion is given to expand on the viewpoint of this study first presented in the introduction on the estimation of benefits of related research projects, either in one research program or in research programs in different states.

Assume that there are two states, each of which has several research projects, as listed in Table 1. A project is used to refer to a research project (with or without implementation) or simply an implementation effort if the research was performed in another state. Projects in State A are referred to as A-1, A-2, A-3, etc. and projects in State B are referred to as B-1, B-2, etc. Research cost refers to the direct research cost to the state. Implementation cost includes any cost to the research section for the implementation effort. Benefits are the present worth of future benefits net of any future state cost for using the results of the project. The comments column is used to show any project that used the results of a previous research project in the same state or another state. For example, the comment for Project A-4 is "Follows A-2"; this means that the results from project A-2 were critical to obtaining the results in Project A-4. The results of Project A-2 were not directly implemented but were used in Project A-4. The results from Project A-4 were implemented and are assumed to have given large benefits. Project A-5 is assumed to have used the results from Project A-4 and the results from A-5 were implemented for an additional net increase (not yet considering research or implementation costs)in benefits of $180. It is assumed that Projects A-6, A-7, and A-8 had no research cost in State A, but were adapted and implemented from research by Firm XYZ for A-6 and from State B for A-7 and A-8. The situation is similar for State B. State B's Project B-1 is

Table 1. Benefits and Costs for Two States for Assumed Research Projects.

STATE AND PROJECT	RESEARCH COST	IMPLEMENTATION COST	BENEFITS	COMMENTS
STATE A				
A-1	$30	$10	$200	
A-2	50	0	0	
A-3	100	30	45	
A-4	200	25	5000	FOLLOWS A-2
A-5	80	35	180	FOLLOWS A-4
A-6	0	40	150	FOLLOWS FIRM XYZ
A-7	0	50	300	FOLLOWS B-2
A-8	0	50	1800	FOLLOWS B-4
TOTAL	$460	$240	$7675	
STATE B				
B-1	$50	$20	$100	FOLLOWS A-5
B-2	100	30	150	
B-3	0	20	1200	FOLLOWS A-4
B-4	200	50	400	
TOTAL	$350	$120	$1850	

assumed to depend in a critical way on Project A-5 in State A but State B did additional research adapting the findings of Project A-5 to State B. Project B-3 in State B is a simple implementation with no research required in State B. State B simply implements the findings of Project A-4 from State A.

Given the above assumed relationships, it is possible to calculate several different types of benefit-cost ratios. First, the benefit-cost ratio for any single project can be calculated as a measure of the direct benefits within a state of that state's expenditures. For example, the benefit-cost ratio to residents of State A of Project A-1 is the benefit of $200 divided by the sum of research cost of $30 and implementation cost of $10, for a benefit-cost ratio of 5.0.

Second, it sometimes may be desirable to calculate the benefit-cost ratio of a group of related projects, especially where the results of one project are critical to another project. Examples of this for State A are A-2 and A-4 combined, or A-2, A-4, and A-5 combined. The benefit-cost ratio for the latter combination would be (0+5000+180)/(50+0+200+25+80+35) = 13.28.

Third, the total benefits in State A for research cost of $460 and implementation cost of $240 is $7675 for a benefit cost ratio of 10.96. Similar calculations can be made for State B.

Fourth, the calculation becomes slightly more complicated if the total return to research and implementation cost in State A is wanted. Here, allowance must be made for the benefits in State B from using the research results of State A. In making this calculation, two assumptions are made. First, it is assumed that the money that is used to apply State A research in State B would have returned only a rate equal to the discount rate used in making the calculation, had it not been used to apply State A's research. Second, it is assumed that the research in State A is absolutely critical (in a causal sense) to the effort in State B that results in benefits. Given these assumptions, Project A-4 (together with related preceding Project A-2) in State A not only "causes" the benefits in State A but also the net benefits from Project B-1 in State B. The net benefits from Project B-1 in State B that can be attributed to State A research would equal the net benefits of $1200 less State B's research and implementation cost of $20. Similarly, since Project B-3 is assumed to be causally related to Project A-5, the net benefits from it are attributed to State A's research program. This net benefit is $100-($50 + $20) or $30. There is no double counting as long as the calculation is being made from the viewpoint of a single state. All that is necessary is to establish causal relationships for final outcomes within each state. The total societal benefit-cost ratio from research in State A would be the benefit in State A of $7675 plus the net benefit in State B resulting from State A research amounting to $1210 ($1180 + $30) for a total of $8885.

Dividing this by the research and implementation cost of $700 for State A gives a total societal benefit-cost ratio for State A research of 12.69. A similar calculation for State B can be made taking into account that State A used State B results in two of their research projects (Projects A-7 and A-8). State B's societal benefit-cost ratio calculated in this way attributes the $2000 of net benefit in State A from Projects A-7 and A-8 to State B research, giving an overall societal benefit-cost ratio in State B of [1850 + (300-50) + (1800-50)]/470 = 8.19. Of course in many cases, a state would not be using another "state's research" but researchers on their projects would be using the results of knowledge generated throughout history, whatever the source. The procedure attributes the research benefits to the latest effort that "caused" the benefits to occur but also recognizes that other research often preceded the "causal" research.

The fifth and final calculation is for estimating the total return to the entire research of both states combined. Here, to avoid double counting, the benefits and costs in each state are added. In the example, benefits in State A of $7675 are added to benefits in State B of $1850 for a total of $9525. Total research and implementation cost is obtained by adding the $700 of State A to the $470 of State B for a total of $1170. The total societal benefit-cost ratio is $9525/$1170 or 8.14.

The preceding calculations ignore the cost of specific or general knowledge existing at the time of the research, except insofar as it is included in salary and library costs. So in effect, this type of calculation only works if a universal summation of all "research benefits" and "research costs" is made. This might be regarded as a mere technicality if it were not for the importance of recognizing that knowledge must be stored and many of the applied research findings that are implemented probably resulted at least in part from earlier basic research. This point is not unrelated to some criticisms of overemphasis on calculating benefit-cost ratios of research in the first place. The principal point being made here is that a reasonable calculation procedure can be outlined for calculating: (1) the return on a project or group of related projects, (2) the return within a state on the expenditures for research and implementation made within the state, (3) the total return to society (that is, including people in other states and countries) of the research and implementation expenditures within the state, and (4) the total societal return on all expenditures on research by all states.

III. BENEFIT-COST ANALYSIS OF RESEARCH

GENERAL PROCEDURE

It is recommended that the following steps be used to calculate a benefit-cost ratio for a research project:

1. Calculate benefits and costs for a typical implementation situation, i.e., for a typical project and location where the results might be implemented.

   a. Select service life.

   b. Calculate benefits, usually as benefits to motorists or reductions in department costs.

   c. Estimate cost to implement this typical project for which benefits are calculated.

2. Estimate net benefit per unit (e.g., mile of highway, location, ton, bridge, intersection, etc.).

   a. For a project that increases motorist benefit, the net benefit equals the increase in benefit minus the increase in department (project) cost, where all benefits are calculated in present worth terms over the life of the project.

   b. For a project that decreases department costs, estimate the reduction over the life of a typical project.

3. Estimate the number of units that will be implemented and the time period over which implementation is expected to take place.

4. Determine the cost of the research project and implementation cost.

5. Calculate the benefit-cost ratio for the research project by dividing the total actual or expected benefits by the sum of research and implementation costs.

BENEFITS AT A LOCATION

The first step in the evaluation process is to calculate the benefits at a typical location where the new research-generated idea or approach will be implemented. For this calculation, it is necessary to select an analysis period, a discount rate, and a technique for calculating reductions in agency and/or motorist (or user) costs.

Analysis Period

The analysis period should be a length of time sufficient to bring out the important costs and benefits being compared. This period may be the useful life of the improvement before it must be totally replaced or may be the length of time for which a traffic forecast is available and sufficiently trustworthy. For major highway improvements, this time period typically is 20 to 40 years. For minor improvements, it usually is 10 to 25 years.

Discount Rate

Several recent studies have recommended a relatively low real discount rate. The American Association of State Highway and Transportation Officials' Manual on this topic recommends a rate of three to five percent. Since most benefits of research are to typical consumers (motorists), it is appropriate to use a rate that reflects the trade-off between the present and the future for these consumers. For benefit-cost analysis using benefits expressed in constant, non-inflated dollars, as in this study, it is recommended that a five percent rate be used in calculating the benefits of research.

If the present worth of a series of benefits or costs is constant in each year, the present worth can be calculated using a uniform series present worth factor. If annual costs or benefits are not constant over time, the uniform series factors cannot be used. It sometimes is necessary to calculate the cost and benefit for each future year and discount each of these separately using the single payment present worth factor.

Technique for Calculating Motorist Benefits

Motorist benefits for the improved situation at this location using the new idea can be calculated as the reduction of the sum of the discounted present worth of motorist cost savings over the analysis period. Motorist benefits include reductions in vehicle operating costs, travel time costs, and accident costs:

$$TPWB = \sum_{t=1}^{N} PW_{i,t}(VOC_t + TC_t + AC_t) \quad (1)$$

where:

TPWB = total present worth of motorist benefits for the new research idea in one location where it is implemented, calculated over the analysis period.

N = length of the analysis period.

$PW_{i,t}$ = single payment present worth factor for a discount rate i and year t, $= 1/(1+i)^t$

VOC_t = the reduction in vehicle operating costs for the improvement using the new idea as compared to what the situation would have been without the new idea (the base condition).

TC_t = the reduction in time costs for the improvement using the new idea as compared to what the situation would have been without the new idea (the base condition).

AC_t = the reduction in accident costs for the improvement using the new research idea as compared to what the situation would have been without the new idea (the base condition).

Simplified Formula

If benefits or annual costs grow at a constant percent growth rate from year to year, then it is possible to simply calculate the annual benefits for the first year and for some future year, such as the last year during the analysis period, and use the following formula from the Red Book [18] to calculate the present worth of benefits for the entire analysis period.

$$TPWB = \frac{e^{(r-i)n}-1}{r-i}(B) \quad (2)$$

where:

TPWB = total present worth of benefits for the analysis period,

n = length of the analysis period,

i = annual discount rate,

B = annual benefits in year 1,

r = ln(a)/y where ln(a)is the natural logarithm of a, and a is the ratio of benefits in the y^{th} year to benefits in year 1, and y is the future year for which benefits are calculated. The period of the estimate y starts at the beginning of the first year and terminates at the end of the future year.

Where benefits are calculated for the first and last year of the analysis period, n and y in the above formula both equal the analysis period. A nomograph for making this simplification is given in Figure 1.

Use of this nomograph is the simplest way to estimate benefits over a long analysis where it is appropriate to assume that benefits grow at a constant annual rate, which results in exponential growth over time. This is certainly an appropriate assumption for evaluating the benefits of research from highway improvements, since traffic tends to grow in this way and benefits are often directly related to traffic. The analyst should consider estimating annual benefits at the beginning and end of the analysis period and using this nomograph to calculate total benefits.

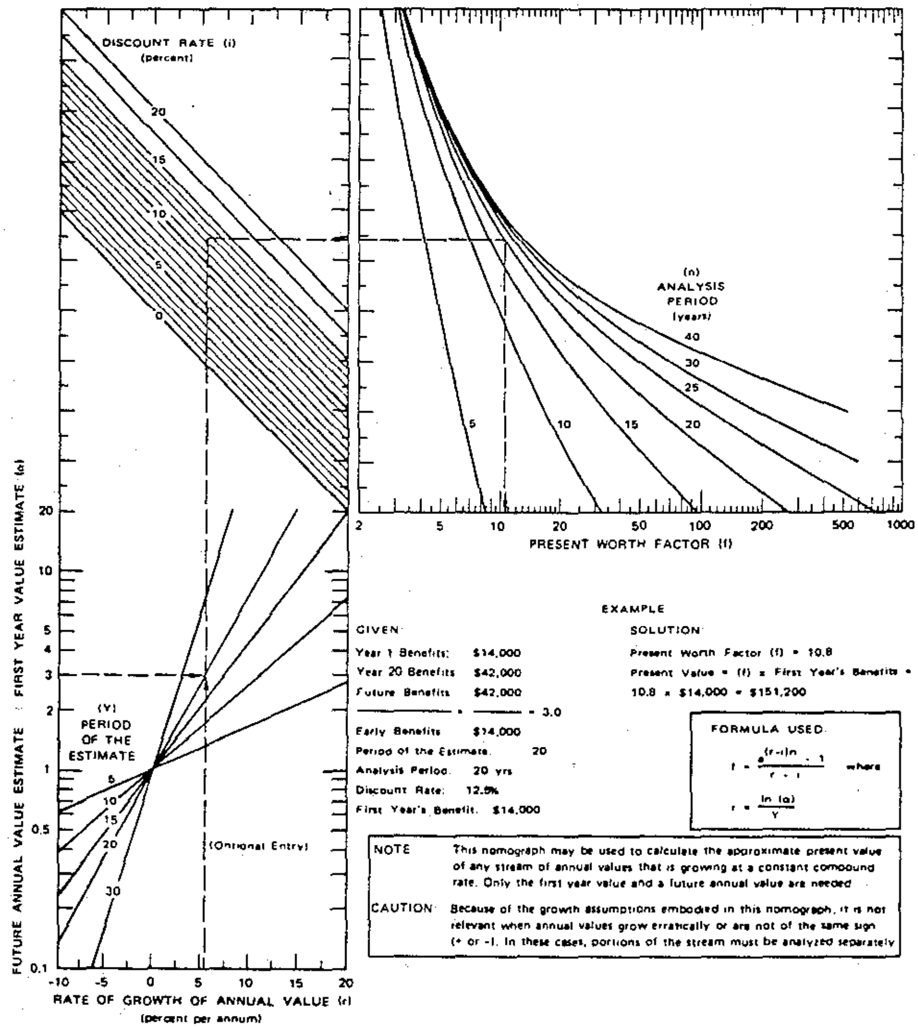

Figure 1. NOMOGRAPH FOR CALCULATING PRESENT VALUE FROM TWO ANNUAL VALUE ESTIMATES.

NET BENEFITS PER IMPLEMENTATION UNIT

Benefit-Cost Ratio

The benefit-cost ratio, B/C for the improved alternative relative to the base condition can be calculated as:

$$B/C = TPWB/\ (TPWC_A - TPWC_B) \tag{3}$$

where TPWB is the total present worth of benefits calculated using Equation (1), and $TPWC_A$ is the total present worth of cost for the improvement or "after" alternative and $TPWC_B$ is the total present worth of cost for the base or existing condition, the "before" improvement alternative. If this benefit-cost ratio is greater than one, then the research results should be implemented.

Net Benefits

The net benefits (or net present value) from implementing the research results at one location can be calculated as the difference between the present value of benefits and costs:

$$NB = TPWB - (PTWC_A - TPWC_B) \tag{4}$$

where NB is net benefits from implementation of the research results at one location and the other symbols are as previously defined. It may be desirable to further convert the net benefits to some standard measure, denoted as a highway unit, such as per lane mile, per ton, etc. depending on what units are used to estimate the number of units that will be implemented in each future year of the implementation period for which the research findings are assumed to be effective.

Savings in Agency Costs

Some research studies may yield research results that provide savings in agency costs but do not affect motorist benefits. The net benefits can be calculated with Equation (4) by simply setting TPWB equal to zero. Then the net benefits are calculated as the savings in agency costs, the total present worth of agency costs at a location before using the research results minus the total present worth of agency costs after implementing the research findings.

BENEFIT-COST RATIO FOR RESEARCH STUDY

The benefit-cost ratio of the project is calculated by dividing the total estimated project benefits by the research and implementation cost, using the following formula:

$$B/C = \frac{N \times K \times NB}{RC + IC} \quad (5)$$

where:

- B/C = the benefit-cost ratio for a research and implementation effort.
- N = the number of "highway units" or "implementation units" for which the research results are implemented.
- K = an adjustment factor (given below in Table 2) to account for the staged implementation of the project.
- NB = the net benefit per "highway unit" or "implementation unit" for which the research is implemented.
- RC = the cost of the research project.
- IC = the cost for implementing the results of the research project, which can be estimated as a given percent of RC.

An alternative formula that would be the benefit-cost ratio of the research project alone can be calculated by subtracting the implementation cost from the numerator instead of adding it to the denominator:

$$B/C = \frac{(N \times K \times NB) - IC}{RC} \quad (6)$$

where B/C is the narrowly-defined benefit-cost ratio for the research project and the other variables are as previously defined.

The K-factor in the above formula adjusts benefits for implementation over time. In this calculation, it is assumed that the research results are implemented uniformly over some implementation period at a uniform rate. Using a discount rate of five percent as recommended, the K-factor in the above formula is given in Table 2 for implementation periods with lengths of 1 through 20, 25, and 30 years. The above calculation assumes that the research benefits commence immediately after the project ends. If there is a lag before benefits commence, another adjustment should be made by discounting the numerator from the time that benefits commence back to the time the projects ends using a single amount present worth factor. For example, if implementation commences three years after the project ends, the numerator should be multiplied by the single amount present worth factor for three years and five percent [$= 1/(1.05)^3 = .86$]. A third type of adjustment also can be made on multi-year projects to bring research costs in early years of the project to present worth terms at the end of the project; for this adjustment, it is necessary to multiply each early year's cost by $(1.05)^n$, where n is the number of years from an early year's expenditure to the end of the project. For simplicity, this adjustment is typically ignored. This cost is at least partially offset by some projects giving benefits before the projects end. Examples of this in the case studies in Section IV of this report are the crash cushion project, the ramp metering project, and the roadside barrier project.

An alternative to using the K-factor is to simply calculate the benefits in each year of the implementation period and discount these back to the present using single amount present worth factors for each year.

MEASUREMENT OF EFFECTIVENESS

All types of benefits, or effectiveness, of a research study should be listed and, if possible, quantified. When this quantification is being planned, consideration should be given to using categories or measurement techniques that later can be used in a benefit-cost analysis. Otherwise, it may not be possible to develop an estimate of the benefit-cost ratio of the research project.

The best measures of effectiveness may not lend themselves to monetization. In these cases, the best that can be done may be to list and quantify the effectiveness. This may be the situation where the major benefits are reductions in motorist discomfort, reductions in air pollution, reductions in noise, etc.

Examples of some of the models that may be useful for predicting effectiveness are: (1) for prediction of number of accidents, encroachment-probability models and regression equations of accident rates; (2) for prediction of accident severity: full scale crash testing, pendulum tests, and severity indexes; (3) for new materials, special testing in the laboratory of materials and methods and trial field tests; and (4) for traffic and signalization studies, computer simulation can

Table 2. K-factor for Implementation Periods of Different Lengths.

Length in Years of Implementation Period	K-factor
1	1.00
2	0.98
3	0.95
4	0.93
5	0.91
6	0.89
7	0.87
8	0.85
9	0.83
10	0.81
11	0.79
12	0.78
13	0.76
14	0.74
15	0.73
16	0.71
17	0.70
18	0.68
19	0.67
20	0.65
25	0.59
30	0.54

sometimes be used in evaluating new techniques.

To be used in benefit-cost models, there is a need to predict the effectiveness of two types: (1) savings in agency costs, where the research results mainly represent a better way of accomplishing a given activity and (2) reductions in motorist costs. To be used in a benefit-cost analysis, the effectiveness must be measured in a format that fits available data for benefit estimation or a new approach for estimating dollar benefits must be developed. The data and approach outlined in this section of the report represent the standard approach used for calculating motorist benefits.

APPROACHES FOR ESTIMATING MOTORIST BENEFITS

The method recommended for calculating benefits is similar to that used in most standard benefit-cost analysis procedures. The specific procedure is similar to that in the revised Red Book [18] and is based on that outlined by Dale [21]. The procedure is summarized in Table 3.

The standard engineering-economy procedures for calculating time and vehicle operating costs use three basic categories (1) costs of traveling at uniform speeds, (2) costs of making speed changes, and (3) costs of idling while stopped. In addition, some studies sometimes require vehicle costs for traveling in other conditions, such as on horizontal curves, grades of various degrees, and pavements with different roughness measures. To develop standard values for time and vehicle operating costs, it is necessary to represent the vehicle stream by a combination of standard vehicle types, and then to develop weighted averages of these types for different situations. To facilitate making such calculations, this report develops weighted averages for rural and urban areas for the major categories of costs.

TIME AND VEHICLE OPERATING COSTS

The vehicle stream for rural and urban areas is represented by five vehicle types, with different percentages of each type as shown in Table 4. These percentages are used to develop weighted average values of time and vehicle operating costs for rural and urban areas in Texas.

The principal tables that usually are of interest are the following: (1) cost at uniform speeds in rural and urban areas, Table 5; (2) cost of making speed changes in rural and urban areas, Tables 6 and 7; and (3) cost of delay or idling, Table 8.

Table 3. Procedural Guide and Data Sources for Estimating Highway User Costs, Fuel Consumption and Air Pollution, Based on Dale [21].

	ITEM	DATA SOURCE AND CALCULATION TECHNIQUE
1.	EVALUATION PROCEDURE	
	For each impact (e.g., vehicle operating cost, traveltime, fuel consumption, carbon monoxide emissions), multiply the measure of effectiveness (e.g., number of stops, hours of idling) by the unit impact value (e.g., vehicle operating cost per 1,000 stops, additional fuel consumption per 1,000 slowdowns, carbon monoxide emitted per 1,000 stops.	
2.	TRAFFIC DATA	
	A. Speed	By Observation
	B. Traffic Volume	D-10 Planning and Research
	C. Traffic Flow Data	
	a. Number of Stops	Equations or Special Study
	b. Number of Slowdowns	Speed or Delay Study
	c. Total Stopped (Idling) Delay	Equations or Special Study
	D. Traffic Accidents	Equations or Accident Records

	IMPACT	SOURCE OF UNIT COST OR CONSUMPTION RATE	CALCULATION TECHNIQUE
3.	HIGHWAY USER COSTS		
	A. Motor Vehicle Operating Costs, $		
	a. For Uniform Speed	Table A.4	Rate X Vehicle-Miles
	b. Additional Due to Stopping	Table A.13-A.14	Rate X Number of Stops
	c. Additional Due to Slowdowns	Table A.13-A.14	Rate X Number of Slowdowns
	d. Additional Due to Idling	Table A.29	Rate X Hours of Idling
	B. Vehicle Travel Time, Hours		
	a. For Uniform Speed	Uniform Speed	Vehicle-Miles/Uniform Speed
	b. Additional Due to Stopping	Table A.15-A.19	Rate X Number of Stops
	c. Additional Due to Slowdowns	Table A.15-A.19	Rate X Number of Slowdowns
	d. Additional Due to Idling	Traffic Study	Idling hours
	C. Traffic Accident Costs, $	Appendices B & C	Rate X Unit Costs
4.	FUEL CONSUMPTION, GALLONS		
	A. For Uniform Speed	Figure A.1	Rate X Vehicle-Miles
	B. Additional Due to Stopping	Zaniewski [5]	Rate X Number of Stops
	C. Additional Due to Slowdowns	Zaniewski [5]	Rate X Number of Slowdowns
	D. Additional Due to Idling	Zaniewski [5]	Rate X Hours of Idling
5.	AIR QUALITY IMPACT		
	A. Carbon Monoxide (CO) Emissions, pounds		
	a. For Uniform Speed	Figure A.1	Rate X Vehicle-Miles
	b. Due to Stops	Figure A.2	Rate X Number of Stops
	c. Due to Slowdowns	Figure A.2	Rate X Number of Slowdowns
	B. Hydrocarbon (HC) Emissions, pounds		
	a. For Uniform Speed	Figure A.1	Rate X Vehicle-Miles
	b. Due to Stops	Figure A.3	Rate X Number of Stops
	c. Due to Slowdowns	Figure A.3	Rate X Number of Slowdowns
	C. Nitrogen Oxide (NOX) Emissions, pounds		
	a. For Uniform Speed	Figure A.1	Rate X Vehicle-Miles
	b. Due to Stops	Figure A.4	Rate X Number of Stops
	c. Due to Slowdowns	Figure A.4	Rate X Number of Slowdowns

TABLE 4. Percentage of Vehicles by Type, for Rural and Urban Areas.

Type of Vehicle	Percent by Type Rural Areas	 Urban Areas
Passenger Cars	56.53%	69.99%
Pickups and Commercial Delivery Vehicles	27.81	22.24
Single-unit Trucks	4.78	3.13
Small truck-trailer combinations	1.04	0.62
Large truck-trailer combinations and busses	9.84	4.02
TOTAL:	100.00%	100.00%

Source: Texas State Department of Highways and Public Transportation, Division of Planning and Research (D-10), 1980.

TABLE 5. Dollars of Operating and Time Cost per 1000 Vehicle Miles at Uniform Speeds.

Uniform Speed (mph)	Dollars per 1000 miles Rural Roads	Urban Roads
10	$1,421.00	$1,312.48
20	762.71	706.31
30	554.15	511.49
40	453.03	416.01
50	401.25	367.15
60	376.09	343.87
70	370.80	338.02

Table 6. Dollars of Excess Operating and Time Cost of Speed Change Cycles, Excess Cost Above Continuing at Initial Speed, for Rural Roads in Texas, 1984.

Initial Speed (mph)	Dollars Per 1000 Cycles Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	$24.12						
20	47.97	21.89					
30	75.92	47.87	22.40				
40	109.02	79.52	50.95	23.54			
50	149.24	118.73	83.41	56.23	27.17		
60	206.35	172.39	136.59	89.75	64.89	31.51	
70	276.20	237.48	196.93	153.40	113.33	71.84	39.33

Table 7. Dollars of Excess Operating and Time Cost of Speed Change Cycles, Excess Cost Above Continuing at Initial Speed, for Urban Roads in Texas, 1984.

Initial Speed (mph)	Dollars Per 1000 Cycles Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	$20.71						
20	38.94	17.20					
30	59.51	36.65	16.69				
40	83.59	59.88	37.84	17.18			
50	111.42	87.11	63.05	39.80	17.51		
60	147.39	121.44	94.81	68.05	43.16	20.58	
70	191.66	163.54	134.45	103.65	75.54	48.20	26.08

Table 8. Dollars of Operating and Time Cost for Idling Delay, per 1000 vehicle Hours.

Type of Delay Cost	Dollars Per 1000 Vehicle Hours: Rural Roads	Urban Roads
Operating	$ 1,506.25	$ 1,471.45
Time	12,160.00	11,310.00
TOTAL	$13,666.25	$12,781.45

ACCIDENT COSTS

One of the major benefits of research is the reduction of accident rates and severities, resulting in reductions in accident costs. Although there is considerable disagreement on whether it is possible to put an economic value on reductions in numbers and severities of accidents, there nevertheless have been several recent studies that have calculated improved accident costs.

Accident costs typically have been calculated by estimating direct costs and indirect costs. Direct costs are defined as including the costs of property damage, medical and hospital expenses, and doctor expenses. Indirect costs include lost income, reduced earning capacity, and the cost of lost lives as estimated using a production or market approach, also called a willing-to-pay approach. The market approach for estimating the cost of a fatality attempts to estimate how much people actually pay to reduce their risk of death.

For benefit-cost analysis in Texas, it is recommended that a combination of NHTSA and market values be used. The combined values include the market value of the deceased's loss of life, \$257,000, plus NHTSA indirect cost to others of \$63,545, for a total indirect cost per fatality of \$320,545, in 1975 dollars. Using updated direct costs from Burke's study, NHTSA injury costs transformed to the A-B-C categories, Blomquist's market value for the cost of a fatality, and comprehensive accident records from five states, McFarland and Rollins developed accident costs for different categories of accidents. These values have been updated to 1987 and are given in Appendix B together with accident proportions for different types of accidents.

For estimating the cost of fixed obstacle accidents, accident costs have been related to an estimated severity index, and these costs are given in Appendix C. The costs for fixed object accidents can be used directly using the tables in Appendix C or by estimating a severity index for an obstacle and relating this index to costs.

Since many of the motorist costs are calculated in the case studies for years when research studies ended, sometimes in the 1960's, it is necessary to adjust values of time, vehicle operating costs, and accident costs for inflation. It is recommended that this be accomplished by using the consumer price index (CPI) and values for the CPI for the years 1960 through 1988 are given below in Table 9.

Table 9. Consumer Price Index (CPI), 1960-1988.

Year	CPI	Year	CPI
1960	88.7	1961	89.6
1962	90.6	1963	91.7
1964	92.9	1965	94.5
1966	97.2	1967	100.0
1968	104.2	1969	109.8
1970	116.3	1971	121.3
1972	125.3	1973	133.1
1974	147.7	1975	161.2
1976	170.5	1977	181.5
1978	195.4	1979	217.4
1980	246.8	1981	272.4
1982	289.1	1983	298.4
1984	311.1	1985	322.2
1986	328.4	1987	340.4
1988	354.2		

IV. CASE STUDIES

This chapter of the report presents case studies of selected research projects. An attempt was made to select projects of several different types that present different measurement problems.

SAFETY PROJECTS

This category includes different types of safety projects, which are some of the most impressive in terms of documented savings. There are two basic types of projects: (1) those that change the severity of accidents, with very little other effect; (2) those that change the accident rates, with very little other effect; (3) those that change both the severity and number of accidents, with very little other effects; and (4) those that not only affect accident rates and/or severities but also affect other motorist benefits.

BREAKAWAY SIGN SUPPORTS (Study 2-5-63-68)

A short history of the development of breakaway sign supports has been given by Ivey and Morgan [71]:

> Breakaway devices for rigid poles and posts along roadways were first considered in the later 1960's by the Road Research Laboratory of the Ministry of Transport in England. The slip base concept as applied to ground-mounted signs in the United States was originated by D. L. Hawkins of the Texas Highway Department in the mid-1960's. Hawkins became concerned by collisions with the large ground-mounted signs on the interstate system. The idea occurred to Hawkins when a Pitman safety bar broke on his sickle mower. The first feasibility test was conducted using a dump truck at the Highway Department District Office in Abilene during the summer of 1963. The slip base which is now standard on sign supports was subsequently developed by Hawkins, Olson, Rowan, and Edwards.

These research results had an influence on nationwide requirements that required breakaway sign supports on all federal-aid highways if the support was located within 30 feet of the highway. It is estimated that there are now over 100,000 breakaway signs in Texas alone. The original research was developed on Study 68 for a cost of about $80,000. Implementation in Texas began in about 1964.

The success of this research, development, and implementation effort depended on several items:

1. Recognition of a problem.

2. An initial idea.

3. Development and testing to develop an implementable design.

4. Initial implementation.

5. Adoption of a policy to put the research results into widespread use.

The following severity indices and average costs are estimated for breakaway and non-breakaway sign supports in rural and urban areas,based on Appendix C.

	Severity Index	Average Cost
Rural:		
Non-Breakaway	8.1	$35,900
Breakaway	2.0	12,400
Urban:		
Non-breakaway	8.1(high-speed urban)	$21,800
Breakaway	2.0(high-speed urban)	7,500

It might be noted that the breakaway severity indices are based on actual accident costs. The severity indices for non-breakaway sign supports are very similar to the actual costs for trees; since trees usually are farther off the roadway, which tends to result in less severe accidents, the estimated savings probably can be viewed as conservative. These costs for fatal and injury accidents are somewhat higher than those sometimes used because the study by McFarland and Rollins showed, with the data used to calculate the accident costs in Appendix B, that many very severe injuries occur in fatal accidents in addition to the fatalities and, also, the injuries in injury accidents with the more severe obstacles are much more serious than those with less severe obstacles. Therefore, breakaway devices result in more benefits than would be calculated simply with average injury costs.

It further is estimated, based on 1979 accident data that there are the following numbers of reported accidents with sign supports in Texas per year: rural areas, 2,000 accidents; urban areas, 6,000 accidents. However, in urban areas, it is assumed that only one-third of all accidents are affected by the breakaway design. It can further be presumed that there are many more unreported accidents as a result of breakaway sign supports. Therefore, it is reasonable to use these numbers as a preliminary estimate of the number of accidents affected per year by the results of Study 68, but it should be recognized that unreported accidents may increase the benefits by a factor of up to 2 (a factor of 2 would imply that half of the accidents with breakaway sign supports are not reported. Any possible overestimate of the severity index of non-breakaway supports almost certainly is more than offset by the existence of unreported accidents. A more complete analysis should attempt to resolve this unknown factor.

Using a saving of $23,500 per accident in rural areas and of $14,300 in urban areas together with 2,000 accidents in rural areas and 2,000 affected accidents per year in urban areas gives an annual savings of $47 million in rural areas and $28.6 million in urban areas, for a total annual savings of about $76 million in 1980 dollars. This number must be adjusted for inflation between the time Study 68 was completed and 1980. Using the consumer price index for adjustment, this estimate is divided by 2.61 to convert to 1965 dollars, giving about 29 million in 1965 dollars as the estimate of annual savings. However, implementation occurred over several years so it is assumed that benefits started at $6 million and grew by $6 million per year for another four years, giving $6 million in year 1, $12 million in year 2, $18 million in year 3, $24 million in year 4, and $30 million in years 5 through 30. The present worth of benefits in 1965 dollars of the 30 years of benefits equals about $407 million. (In 1988 dollars, the savings are about 3.79 times this amount or slightly over $1.54 billion for the 30 year implementation period from 1966 to 1996). The total savings nationwide are probably twelve to fifteen times this amount.

Net benefits are calculated by subtracting the cost of breakaway sign supports from the accident cost savings. Signs vary considerably in size and cost, with cost ranging from $100 to over $5,000. Using breakaway sign supports increases the initial cost by about 10 percent. It is assumed that the average cost of large highway signs is $1800 in 1965 dollars and that the average cost of the breakaway design represents ten percent of this cost, for an initial cost of $180 in 1965 dollars. It also is estimated that the repair cost for each time the sign is struck is $200 in 1965 dollars. Using the estimate of about 100,000 breakaway signs in Texas, the extra cost of making these signs breakaway is about $18 million in 1965 dollars. Assuming that this was phased in over a five year period, the cost per year would be $3.6 million per year. The present worth of this cost at the beginning of the program is estimated by multiplying $3.6 million by the uniform series present worth factor for five years and five percent, or 4.33, for a present worth cost of about $16 million in 1965 dollars. To this cost must be added the repair cost of 800 repairs in year 1, 1600 repairs in year 2, 2400 repairs in year 3, 3200 repairs in year 4, and 4000 repairs in succeeding years. At $200 per repair, this amounts to about $10.8 million in 1965 dollars. The total thirty year cost for initial cost and repair cost is estimated at about $27 million, for an average of about $270 per sign in 1965 present worth dollars. Subtracting this $27 million of cost from the estimated accident savings of $407 million gives a net savings of $380 million in 1965 dollars (or about $1.44 billion in 1988 dollars) for the 30-year implementation study period.

Dividing the estimated thirty-year net benefits of $380 million by the study cost of about $80,000 plus implementation costs estimated at $40,000 gives a benefit-cost ratio of 3,167.

CRASH CUSHIONS (STUDY 2-10-68-146)

The first crash cushions on Texas freeways were installed in Houston in October, 1968 [65]. Three concrete abutment gore locations were the scene of eight fatal accidents reported between September, 1965 and October, 1968. Modular crash cushions were installed at these three locations as well as two other gore positions in late October, 1968. Records show that there were thirteen accidents involving these installations in the following year through October, 1969 with no fatalities or serious injuries at any of these sites.

An in-depth study of steel drum crash cushions installed in Houston continued until March 12, 1971, when the 50th accident was recorded. At that time, there had been seven crash cushions installed on houston urban freeways. According to Hirsch and White [66], there were no police records on 31 of the 50 accidents. There were six accidents in which injuries were reported and one fatality occurred.

A later report by Hirsch et al. [67] documented the continued monitoring of vehicle impact attenuators in Texas. At the end of 1974, there were 135 installations in Texas, of which 117 were steel drum crash cushions, 14 were Fitch inertia barriers, and 4 were sand tire inertia barriers. A summary of the statewide accident data involving these impact attenuators during 1974 is shown in Table 10. During 1974, there were 180 impacts with the 135 installations. Of these 180 impacts, there were 73 known impacts on the noses of the attenuators and two known impacts on the side into the fish scales or redirection panels that had been added to the design. Of the two known side impacts, one resulted in the only fatality, which was the second fatality since 1968 at these locations. In this fatal accident, the vehicle made a side impact into the redirection panels and was redirected and struck concrete parapet walls on both sides of the highway and then overturned, resulting in the fatality. Marquis [68] continued to

Table 10. Summary of Accident Data with Vehicle Impact Attenuators in Texas, 1974*.

	Number of Installations	Impacts	Fatalities	Reported Injuries	Reported Property Damages
Texas Crash Cushion Steel Drums	117 (60 in Houston)	160 (81 in Houston)	1**	25 (10 in Houston)	96
Fitch Inertia Barrier	14	13	0	7	4
Sand Tire Inertia Barrier	4	1	0	0	1
Totals	135	174	1	32	101

* Courtesy of the State Department of Highways and Public Transportation, File D-18.

** Fatality resulted from angle impact into side of steel barrier VIA with redirection panels. Vehicle was redirected and struck concrete parapet wall on both sides of the highway, then overturned.

compile accident data with vehicle impact attenuators in Texas, and Table 11 is a summary of the accident experience that he summarized for the years 1974, 1975, and 1976.

In 1973, Viner and Boyer conducted an analysis of field accident data of vehicle impact attenuators reported by the states under the National Experimental and Evaluation Program Project No. NEEP-4, administered by the Office of Highway Operations, Federal Highway Administration. Analyses were made of 393 accidents at 188 installations of six types of attenuators. The analysis included data received through October, 1972 from 33 states, the District of Columbia, Puerto Rico, and Canada.

The available accident information was examined by Viner and Boyer to determine those events that would have resulted in death or serious injury had an impact attenuator not been in place. Accidents in which a rigid object would have been struck at speeds greater than 25 miles per hour (40km/hr) were considered to be such events. The authors noted that it was seldom possible to estimate the speed at which a vehicle struck the rigid object within plus or minus 10 miles per hour (16km/hr), and that their conclusions must be tempered by this consideration. They judged that 68 of the 393 reported accidents, or 17 percent, would have been likely to result in a fatality or serious injury if the impact attenuators had not been present. With the impact attenuators, the actual numbers were 5 fatalities and 12 hospitalizing injuries occurred in these 68 cases.

Viner and Boyer also tabulated the number of hit-and-run accidents. Fifty-two percent of all accidents were reported as hit-and-run. The authors also estimated that nine hit-and-run accidents may have resulted in death or serious injuries had the attenuator not been present. They also determined that there were 4.1 accidents per attenuator per year of exposure at the gore areas studied. Most of the installations included in the study were constructed in existing gore areas and in most cases the attenuator had been placed in front of the existing parapet nose. They noted that this reduces the area available in the gore vicinity and this is expected to increase the number of accidents.

A 1984 study by Griffin [85] estimated that crash cushions reduced fatalities by 78 percent and overall injuries by 27 percent. It was further estimated that A-level injuries were reduced by 67 percent, B-level injuries were reduced by 8 percent, and C-level injuries were reduced by 12 percent. Griffin further noted that:

> These findings are in good agreement with a study conducted by the Federal Highway Administration in 1973 [63]. In that study, 68 crash cushion accidents were judged to have resulted in deaths or A-level injuries had crash cushions not been present. Yet, of the 68

Table 11. Summary of Accident Data with Vehicle Impact Attenuators in Texas for the Years 1974, 1975, and 1976.

VIA	No. Installed	Known Impacts	Fatalities	Reported Injury	Property Damage
Texas Crash Cushion Steel Drums	165	430*	1	71	107
Fitch Inertia Barrier	62	32	0	9	10
Sand Tire Inertia Barrier	17	14	0	1	2
Totals	244	476	1	81	119

* Note: Nuisance impacts (generally 3 or less drums damaged) not included

accidents, only 5 resulted in deaths and 12 in A-level injuries. Thus, the estimated reduction in deaths and A-level injuries was 75 percent in that study.

In the Texas accident data reported on crash cushions, there is unfortunately little before-after information. Viner and Boyer do not resolve the question of the amount of reduction in fatalities since their study is based on several assumptions. Griffin's analysis depends on the extent to which the underpass and bridge end accidents match the gore type accident.

There is some indication that the gore abutment accidents are more severe and perhaps more like the accidents coded as underpass accidents on high-speed roadways. For example, the initial reported accidents in Houston resulted in 8 fatal accidents over a 37 month period. After the crash cushions were installed, there were 13 accidents with no fatalities or severe injuries in a 12-month period, and presumably there would have been more accidents per time period, not less. Assuming the same rate of accidents in the before period, there would have been about 40 accidents in the 37 month period. This gives a fatal accident percent of 20 percent. The category of accident giving this percent fatal in all of the obstacles in Appendix C is the rural "hit underpass" category, which is assumed to be hitting an abutment of bridge pier, with a percent fatal of about 16 percent, similar to the number derived above for the initial Houston data.

Also interesting in this respect is the use by California of an estimate of 15 percent fatal for gore abutments (before installing crash cushions)[87]. It is clear that the gore abutment accidents have two characteristics that are closely related to very severe accidents: (1) the object struck is large and very rigid, and (2) the object is very close to the roadway, leaving very little distance for slowing down, even if the driver foresaw a collision, which in many cases appears unlikely.

Based on this limited data, it is assumed that the average accident cost for unprotected gore abutments is similar to the rural underpass category of accident in Appendix C. This category of accident has the highest of all rural severity indices in Table C-17 with a 9.3, and an average cost of $126,500 in 1980 dollars. The rural bridge end accident has a severity index of 8.9 and an average cost of $65,800. The elevated gore abutment in urban areas was assigned a severity index of 9.3 but a cost of only $38,300. However, this includes abutments on city streets and probably is not indicative of the severity of accidents on freeways, many of which occur at night at relatively high speeds.

It was decided that a compromise would be made and a severity index for rural areas would be used but an index of only 9.1 instead of 9.3 would be used since the average speeds probably are somewhat lower on urban freeways than on rural roads. This gives an average cost of $83,820 from Table C-16 in Appendix C. The average cost of crash attenuators in urban areas is used as the after situation. This is rated in Table C-17 with an indicated Severity Index of 2.2 and an average cost of $9,900 in 1980 dollars. However this is for reported accidents only, and inclusion of unreported accidents would reduce this considerably; assuming unreported accidents average about $2,500 in damage and assuming about half of the accidents are not reported, the average cost of an accident with a crash cushion would be about $6,200, not including damage to the crash cushion. This gives an estimated saving per accident of about $77,600 in 1980 dollars. To convert to the time of research implementation, this is converted to 1968 dollars by multiplying by 0.4222 (or 104.2/246.8 from Table 10), giving an estimated saving per accident of $32,800 in 1968 dollars.

Table 12 shows the reported numbers of accidents with crash attenuators in urban areas of Texas for the years 1975 through 1987. Assuming a fifty percent reporting rate, and using the previously cited information as an indicator for the early years, the total number of accidents with crash cushions is estimated by year from 1968 through 1987 and is given in Table 13. The number of accidents is multiplied by $32,800 to estimate the accident cost savings in 1968 dollars, and this is also shown in Table 13. For the period of 1968 through 1987, total savings in accident cost are estimated to be about $150 million in 1968 dollars and about half a billion in 1988 dollars. Using a fifteen percent fatality percent for gore abutments, the number of lives saved to date would be about 700.

The first three steel barrel installations had a total cost of $10,750 for fabrication, site modification, and installation, for an average cost per site of $3,250 [65, p.2] Most of the cost resulted from having to modify the gore areas for the crash cushion. It was estimated that installations at newly constructed gore areas could be designed to accept the cushions at little additional cost. The cost for the crash cushion was very low, about $400 to $600 per site. The estimated average repair cost was estimated at $300 per hit.

For simplicity, it is assumed that all crash cushion costs occurred in 1968. Assuming that there are 400 installations of crash cushions at an initial cost of $3,250 in 1968 dollars and 4,579 accidents at $300 per accident for repair, the total cost of these installations is $2,673,700 in 1968 dollars. The net benefit in 1968 dollars is estimated at $150,191,200 minus $2,673,700, or about $147.5 million in 1968 dollars.

Using a research and implementation cost of $120,000 gives a benefit-cost ratio of $147.5 million/$120,000 = 1,229.

Table 12. Number of Reported <u>Urban</u> Accidents with Vehicle Impact Attenuators in Texas, by Most Severe Injury in the Accident, for the Years 1975-1987.

YEAR	PDO	C-INJ.	B-INJ.	A-INJ.	FATAL	TOTAL
1975	75	12	33	10	0	130
1976	63	6	26	4	0	99
1977	92	16	42	6	0	156
1978	84	11	41	9	0	145
1979	106	21	50	9	4	190
1980	109	16	52	14	6	197
1981	102	20	49	16	2	189
1982	85	12	36	11	2	146
1983	65	16	48	7	1	137
1984	80	16	52	10	6	164
1985	86	24	61	12	4	187
1986	96	22	40	10	2	170
1987	93	21	43	22	1	180
Total	1136	213	573	140	28	2090
Percent	54.4%	-------	44.3%	--------	1.3%	100%

Table 13. Estimated Number of Accidents and Accident Cost Savings from Crash Cushions, in Urban Areas of Texas, 1968-1987.

Year	Estimated Number of Accidents	Savings in Accident Costs, 1968 Dollars
1968	4	$ 131,200
1969	13	426,400
1970	26	852,800
1971	26	852,800
1972	50	1,640,000
1973	100	3,280,000
1974	180	5,904,000
1975	260	8,528,000
1976	198	6,494,400
1977	312	10,233,600
1978	290	9,512,000
1979	380	12,464,000
1980	394	12,923,200
1981	378	12,398,400
1982	292	9,577,600
1983	274	8,987,200
1984	328	10,758,400
1985	374	12,267,200
1986	340	11,152,000
1987	360	11,808,000
Total($1968)	4,579	$150,191,200
Total($1988)		$514,570,070

RAMP METERING (STUDY 2-8-61-24)

Study 24 in many ways was a project involving basic research and any attempt to measure the total benefits of this study cannot hope to fully capture the full benefits to later research efforts of Study 24. Nevertheless, there were substantial motorist benefits that resulted from the study and the study is a good example of a study where benefits measured in the course of the study make it possible to perform a fairly comprehensive evaluation of direct effects. The detailed calculations are given in Appendix A. The estimates are based on ramp metering costs and user costs that were applicable in the late 1960's since that is when the study costs were incurred and when the benefits to motorists commenced.

Net Benefit per Location (or Ramp)

The control system being evaluated has three levels of control: Level I - pretimed control; Level II - local actuated control; and Level III - system control. Each system has initial costs and annual maintenance and operating costs. The present worth of the initial costs and twenty years of maintenance and operating costs are given in Table 14. In calculating present worth, a discount rate of five percent is used. Each level of control results in savings in travel time, accidents, and vehicle operating costs.

Table 15 presents the estimates of total user costs for no control and for each level of control. The reduction in total user costs, relative to no control, is given in the third column and represents the estimate of total user benefits. Twenty-year benefits are calculated assuming that annual user benefits remain constant for each year of the analysis period.

Since all three levels of control have positive incremental net benefits, it would be justified to use Level III of control. However, since the Level III results are based on several assumptions and the estimates for Level II are based on detailed observations, it was decided to use the costs for Level III, since this was the system finally recommended, but to use the benefits for Level II, for a conservative estimate. Use of ramp metering may not be as beneficial on some freeways as on the Gulf Freeway, so this conservative approach probably is justified.

With these choices, the present worth of twenty-year costs is about $600,000 and the present worth of twenty-year benefits is about $3,900,000, giving a net benefit of about $3.3 million for ramp control on an 8-ramp section of the Gulf Freeway. This gives

Table 14. Present Worth of Twenty-year Total Cost for Central Digital Ramp Control System, by Level of Control.

Level of Control	Twenty-year Cost
Level I	$499,203
Level II	507,187
Level III	600,974

Source: Table D-10 in Appendix D.

Table 15. User Costs and Benefits, by Level of Control.

Level of Control	Total Annual User Costs	Total Annual User Benefits	Twenty-year Benefits
None	$1,750,039	$0	$0
Level I	1,547,573	210,466	2,622,800
Level II	1,443,171	314,868	3,923,900
Level III	1,396,767	361,272	4,415,900

Source: Tables D-26 and D-27 in Appendix D.

about $400,000 as the estimate of net benefits per controlled ramp.

Number of Locations (or Ramps)

The estimation of total benefits is made using a predictive approach. It is observed that Texas has several large cities, each of which has several radial freeways, so it appears reasonable (from the viewpoint of the late 60's, when these research results were completed) to assume that the equivalent of ten 8-ramp systems similar to the Gulf Freeway system analyzed in this case study would be implemented uniformly over the ten years after Study 24 was completed.

Benefit-cost Ratio

Adding an additional eight ramps in each year for 10 years means that net benefits (in present worth terms at the time they are implemented) of about $3.2 million would be added to total benefits in each year. The present worth of the ten additional systems is calculated by multiplying the uniform series present worth factor for ten years and a discount rate of five percent, which is 7.7217, by $3.2 million for a total of about $23.1 million. The total present worth of all benefits is estimated as the $3.3 million from the Gulf Freeway plus the present worth of these new systems, for a total of $26.3 million. Dividing this benefit estimate by the research and implementation cost of $340,000 gives a benefit-cost ratio for this research of 77.

PAVEMENT DESIGN AND MATERIALS

COMPUTERIZED PAVEMENT DESIGN (STUDY 2-8-62-32)

Significant implementable research results were obtained on Study 32 entitled "Extension of AASHO Road Test Results to Texas Conditions" [32], which was performed by a research team headed by Mr. Frank H. Scrivner working in close cooperation with Mr. James L. Brown of the Texas Department of Highways. Study 32 developed two principal outputs that were implemented: (1) a deflection equation for predicting the deterioration of flexible pavements over time with application of axle loads, and (2) a pavement design computer program using a life-cycle cost-effectiveness approach.

The deflection equation allowed the estimation of the performance of pavement materials proposed for use in a given area of the state from deflection tests made on existing highways containing similar materials and located in the same area of the state. The pavement design computer program had several innovative features. It was the first design procedure to make computer to compare a large number of pavement design alternatives on a cost-effectiveness basis.

The program compared a large number of initial designs, each of which had an optimized overlay strategy, on a life-cycle cost basis and included cost calculations for initial cost, overlay costs, maintenance costs, and user costs associated with overlay operations. The program used a cost-effectiveness procedure in the sense that all of the alternative design strategies (initial design together with optimum overlay timing and thicknesses) were predicted to maintain the pavement's serviceability index above a set level over the analysis period. An important innovative feature was the consideration of multiple performance periods (that is, multiple overlays) within the selected analysis period. Within constraints provided by the design engineer, numerous overlay strategies were evaluated.

Cost savings, in present worth terms over the life of the pavement, have been estimated to typically range from 10 to 30 percent in most cases, with much larger savings in some cases. The precise amount of savings in any particular case depends somewhat on the variety of materials available in an area but also is related to the ability of the program to consider many initial designs and overlay strategies that would not normally be considered without a computerized analysis.

This project also was the first of a group of studies that in a larger sense contributed to the research benefits calculated for this study. This brings up the question of exactly how to consider benefits of related research efforts. As was discussed in Section II, there are various ways to calculate benefit-cost ratios for related studies, depending on what is considered to be the sequence of studies and the causal factors in the overall implementation effort. No attempt is made here to fully address the larger problem by trying to calculate the total benefits for all of the studies combined. For example, one early addition to the program added a procedure for considering environmental effects on pavement design, especially the effects of swelling clay on optimal decisions. Explicit consideration of this factor brought out the importance of adding pavement thickness over time after initial roughness related to swelling clay had subsided, for savings in life-cycle costs. In Study 123 and later studies, the FPS program for flexible pavements was improved and a program was also written for rigid pavements. Mr. Brown and others developed a pavement overlay design program along the same lines as the overlay optimization routine in FPS-1. The Subroutine User in the initial program was the forerunner to several similar programs including the QUEWZ program for evaluating traffic handling strategies in work zones and another program used in Canada. A procedure for expanding the user calculations in FPS-1 to simultaneously consider the effects of pavement roughness on vehicle speeds and user costs throughout the life of the pavement was developed in Study 123 [13]. Although this procedure has not been used in Texas, it was implemented in Ontario [88] and in a study in Brazil funded by World Bank [89, 90]. Australia [91] later based their approach on the Ontario and Brazil models. This approach also is used in the user cost calculations of the Highway Performance Monitoring System, the World Bank's HDM-III computer program, and those used in pavement studies in Kentucky, Maryland, and elsewhere.

Research benefits for Study 32 are treated in a predictive approach wherein it is assumed that the program leads to a 20 percent savings in life-cycle costs in present worth terms, which is how the program calculates the costs. The initial cost typically represents about 60 to 70 percent of the life-cycle cost for flexible pavements so it is assumed that a pavement construction program with an initial cost of about $150 million would represent about $230 million. The program is assumed to be phased into use over a ten year period beginning at the end of the research project and it is assumed to be used on projects with a life-cycle cost of $20 million in the first year and this grows to $200 million in the tenth year and remains constant at $200 million for the remainder of the analysis period. The estimated benefits are summarized in Table 16.

The cost of Study 32 was $260,000 and the incremental cost of implementation cost is estimated at 40 percent of this cost or $104,000. The benefit-cost ratio for this research is estimated by dividing the estimated project benefits of $347 million by the research and implementation cost of $374,000. The resulting ratio is 928.

COST SAVING DESIGNS AND MATERIALS

EVALUATION OF ROADSIDE BARRIERS (2-18-84-333)

Research results sometimes give benefits by developing information that is used to avoid making a costly decision. For example, concern with small car impacts with roadside barriers led to the possibility of a mandate to install a more expensive system of guardrail in Texas. A research study of small car impacts with roadside barriers produced information that the existing design (the Texas roadside metal beam barrier) was equal or superior to the more expensive system being encouraged as a substitute. Therefore, the benefits of this research were costs avoided.

The critical data for analyzing this saving are as follow:

1. The research study cost $54,000.
2. The new design is estimated to cost an additional $3.00 per linear foot, as compared to the Texas roadside metal beam barrier.

Table 16. Calculation of Savings in Life-Cycle Costs from Use of Improved Pavement Design Program.

YEARS AFTER IMPLEMENTATION	LIFE-CYCLE COSTS OF PAVEMENTS	SAVINGS IN LIFE-CYCLE COSTS	PRESENT WORTH OF SAVINGS
1	$ 20 MILLION	$ 4 MILLION	$ 3.8MILLION
2	40 "	8 "	7.3 "
3	60 "	12 "	10.4 "
4	80 "	16 "	13.2 "
5	100 "	20 "	15.7 "
6	120 "	24 "	17.9 "
7	140 "	28 "	19.9 "
8	160 "	32 "	21.7 "
9	180 "	36 "	23.2 "
10	200 "	40 "	24.6 "
11	200 "	40 "	23.4 "
12	200 "	40 "	22.3 "
13	200 "	40 "	21.2 "
14	200 "	40 "	20.2 "
15	200 "	40 "	19.2 "
16	200 "	40 "	18.3 "
17	200 "	40 "	17.5 "
18	200 "	40 "	16.6 "
19	200 "	40 "	15.8 "
20	200 "	40 "	15.1 "

PRESENT WORTH OF 20-YEAR SAVINGS = $347.3 MILLION

Note: The present worth of savings is calculated by multiplying the savings in life-cycle costs in each year by the single amount present worth factor for that year. For example, in the tenth year, the savings in life-cycle costs of $40 million is multiplied by the present worth factor (for 10 years and a discount rate of 5 percent) of .6139 to obtain $24.6 million.

3. Approximately 2 million linear feet of roadside barrier is installed in Texas per year.
4. It is assumed that in the absence of these research findings, all of the new guardrails installed in Texas would have been of the more expensive design beginning two years from the time of the research project.
5. Even though the research indicated that the existing design might be not only equal but better than the new design, it is assumed in the analysis that the two designs are equal in effectiveness and only the guardrail costs are analyzed.
6. Since there is the possibility that new designs will be developed in the future, the relative conservative assumption is made of an effective life of these research findings of 20 years.

SAVINGS PER UNIT = $3/ LIN FT.
UNITS /YEAR = 2 MILLION LIN FT

NET BENEFITS PER YEAR = $3/LIN. FT. X 2 MILLION LIN. FT./YEAR
= $6 MILLION PER YEAR

TOTAL BENEFITS = USPW(15 YRS, 5%) X ($3/ LIN FT)
X (2 MILLION LIN FT /YR)
= 10.3797 ($3/L.F.)(2 MILLION L.F./YR.)
= $62.3 MILLION
B/C = $62.3 MILLION/$58,000 = 1,074.

HIGHWAY LIGHTING (STUDY 2-8-64-75)

Study 75, which had a cost of $279,000 had several implementable results. It was the critical research study in developing criteria and guidelines for continuous roadway lighting and high-mast interchange lighting in Texas. Especially important were the detailed experiments comparing different mounting heights, pole spacings, and other alternatives. The study also developed the effectiveness criteria for comparing these alternatives.

In addition to the detailed comparisons of continuous and interchange lighting, Study 75 also included special studies that were critical to lighting use and motorist safety. The study included development and testing of breakaway luminaire supports. The first slip-base for luminaire poles was developed on this study. The study also included vibration testing to help solve some of the problems encountered in the field with higher mounting heights, especially 50 feet or higher.

Study 75 had a large impact on lighting criteria at the national level and on the use of higher mounting heights and breakaway bases for luminaires. The present study will attempt only to calculate some of the possible savings from using higher mounting heights for continuous and interchange lighting.

Continuous Roadway Lighting

A detailed case study of the cost of continuous roadway lighting is included in Appendix E. In the appendix, costs are estimated for 40 and 50 feet mounting heights with different spacings and placements. One of the most important findings of Study 75 was that for multilane facilities, it is not possible to obtain a high level of effectiveness with the 30-foot, 250 or 400 watt luminaires that were in use at the time of the study. Conventional practice was to use fairly long spacings (150 feet or greater) and 30 foot mounting heights, resulting in motorists traveling from one puddle of light to another. The really critical finding was that this alternative was relatively unsafe and was undesirable from an operational standpoint. Research developed alternatives that were highly preferable. Median placement of units at higher mounting heights not only were more effective but also gave fewer units for vehicles to impact in accidents. (Later, with the development of concrete median barriers on which the units could be mounted, the safety increased even more - as opposed to the early placement in median guardrail.)

For this benefit-cost analysis, the costs from Table E-11 in Appendix E are assumed to be representative of the general cost of units at the higher mounting heights. It is impossible to make a clear comparison with the lower 30 or 35 foot mounting heights since the change in effectiveness is so great. Nevertheless, it can be assumed that the lower mounting heights would require placement in the median <u>and</u> on both sides of the roadway to provide a meaningful alternative for wide, urban freeways. Assuming this arrangement with 140 foot spacings would give about 38 units in the median with double arms and 76 units along both sides with single arms, for a total of about 114 units, as compared to 26 units for the 40 foot mounting height in the median and only 17 units for the 50 ft mounting height in the median.

Using the costs in Table E-11 with and ADT of 30,000, a 20-year analysis period and high maintenance costs, the total cost for the 40 and 50 foot mounting heights, respectively, are $99,600 and $88,300. The 30 and 35 foot mounting heights are estimated to cost about 60 percent as much per unit as the 40 foot mounting height, or $3,800 per unit. This gives a total cost per mile of about $433,000. The relative savings is about $333,000 for using the 40 foot mounting height and $345,000 for the 50 foot mounting height.

For this analysis, it is assumed that the present worth of savings over a twenty year analysis period is $300,000 in 1968 dollars. It further is assumed that an implementation period of 15 years is used and that 30 miles of urban freeway lighting is constructed per year at this cost saving. Using the K-factor from Table 2 for a 15 year period, the calculated benefits are equal to 30 miles per year, multiplied by 15 years multiplied by $300,000 per mile, multiplied by the K-factor, to account for implementation over 15 years, of .73, which gives the total estimated present value of benefits in 1968 dollars of $98,550,000.

Interchange Lighting

Tests on interchange lighting revealed that high-mast lighting could be used to replace continuous lighting within an interchange and provide savings in life-cycle costs. The reduced number of luminaire poles near the roadway also should result in substantial savings in accident costs. Table 17 shows the costs of three different systems: Design A, representing high-mast lighting; Design B, using 1,000 watt luminaires at 50-foot mounting heights; and Design C, using 400 watt luminaires at 40-foot mounting heights.

Summing the initial costs and the present worth of annual maintenance and operating costs gives the present worth of total twenty-year costs as follows:

Design A	$29,000 + $36,600 = $65,600	per interchange
Design B	$49,000 + $58,100 = $107,100	" "
Design C	$58,000 + $43,000 = $101,000	" "

This gives an estimated cost savings, not including accident savings from having fewer accidents with luminaire supports, of about $35,000 per interchange. This analysis needs to be expanded to include accidents and to resolve differences between the costs in this part of the study and the discussion of continuous roadway lighting. Also, it might be helpful to consider the savings relative to the 30 and 35 foot mounting heights. Nevertheless, for a preliminary estimate, it is assumed that a 15 year implementation period is used with 10 interchanges per year, for a total of 150 interchanges benefitting from the high-mast lighting cost savings.

Using $35,000 per interchange this gives $5,250,000 as the estimate of savings for the 15 year implementation period. Multiplying by the K-factor for 15 years of .73 gives total benefits in 1968 dollars of $3,832,500.

The total estimated savings equals the sum of the $98,550,000 from continuous lighting and the $3,832,500 from interchange lighting, for a total of about $102,400,000. The research project cost $279,000 and 40 percent is added for implementation costs for a total cost of $390,600. The benefit-cost ratio is 262.

Table 17. Initial, Maintenance, and Operation Costs for Three Alternative Interchange Lighting Designs.

(a) INITIAL COSTS

Design	Wattage	Number and Type of Units		Mounting Height	Spacing	Initial Cost
A	1000	1	10 flood-lights	150'		
		4	6 flood-lights	100'	>1000'	$29,000
B	1000	54	Type III	50'	300'	$49,000
C	400	70	Type III	40'	200'	$58,000

Note: The cost for the high-mast lighting installation is actual cost for the study site in about 1968 dollars. The other costs are based on unit costs at the time of the study.

(b) MAINTENANCE AND OPERATING COSTS

Design	Total Units	Wattage	Annual Costs	Twenty-year Costs
A	34	1000	$2,380	$36,600
B	54	1000	3,780	58,100
C	70	400	2,800	43,000

Note: The maintenance and operation costs are derived by using $40.00 per year for 400-watt and $70.00 per year for 1000-watt luminaires. The high-mast lighting is assumed in this study to be the same per luminaire as the design B luminaires.

MANAGEMENT AND PLANNING

PROJECT COMPLETION TIMES AND BIDDING STRATEGIES (Study 2-6-85-412)

The principal results of this study were: (1) developed new, higher estimates of engineering construction costs and motorists costs associated with delayed completion of construction projects, and recommended that these higher costs be used in setting liquidated damages and bonuses for early completion of projects; (2) developed new statistical equations for estimating the project completion time associated with different expected percentage overruns on completion times, and (3) developed a new procedure for evaluating the use of bonuses.

This final report includes statistical analysis of project completion times for various types of construction projects, costs to the highway agency and motorists of project overruns, as well as new strategies that can reduce delays and costs by reducing project completion times. The statistical analysis of project completion times produced equations relating project times to type of project and size of project. It was found that these equations gave roughly the same results as current procedures used by the department for estimating working days, so no general improvement in estimating accuracy would result from the use of these new equations, although some districts might find them useful as a double check on current procedures. One interesting result was that it was determined that the estimation process should not be viewed as trying to accurately predict the number of working days. Instead, it should be viewed as setting the number of days that will lead to a chosen percent of project overruns. This viewpoint was perhaps understood in practice, but was not explicitly recognized. Recognition of this fact helps to understand the real objective of the overall process which should be to get the project built at the minimum total cost.

The procedure for estimating working days has been partially implemented by being made available to the districts in the construction division's instructions for estimating working days. The equations for estimating the construction engineering costs also have been implemented as a way of planning and budgeting costs for projects of different types, even though this was not an objective of the research study.

This study analyzed several different highway contracting strategies and developed a new procedure for evaluating incentive/disincentive contracts. Most highway agencies currently award construction contracts to the qualified construction firm submitting the lowest bid in a sealed bidding process. An integral part of the contract is that the construction firm agrees to complete the project within a stipulated number of days, called contract days, that are set by the highway agency prior to bidding, or pay liquidated damages at a given rate for each day of overrun.

The liquidated damages rate per day, which is higher for more costly projects, generally follows guidelines developed by the American Association of State Highways and Public Transportation Officials (AASHTO). These standards were established mainly to cover extra construction engineering costs associated with project overruns.

Highway engineers currently estimate the number of contract working days using bar charts, statistical relationships, and historical data from similar projects. A major difficulty in setting contract days is that the estimating engineer does not know which firm will be low bidder and the firm's current workload and strategy for completing projects in different amounts of time. Since there is no way for the highway engineer to determine how much it will cost the winning contractor to reduce the project completion time, it is difficult to implement an optimal strategy with the current approach.

The improved approach for comparing alternative contracting strategies is to explicitly recognize all costs associated with project overruns and to determine which strategy minimizes these total costs. Total costs associated with a construction project include not only the construction cost, but also the highway agency's construction engineering costs for monitoring the construction work and the public's costs associated with driving in a construction zone versus on the improved highway.

With current contracting procedures, a construction firm might be able to complete a job in considerably less time than the contract working days at very little increase in construction cost. Often, the construction firm's increase in cost for completing the job earlier would be much less than the decrease in construction engineering costs plus motorists costs. However, with current procedures, the construction firm's only incentive for reducing project construction time is to reduce its construction cost.

The comparison of alternative bidding strategies showed how paying contractors a bonus per day for early completion would lead to earlier completion of projects and a reduction in total cost. Another strategy that would give comparable results and also would reduce the need to accurately predict working days would be to have contractors bid working days, combined with paying a bonus for early completion and charging liquidated damages for overruns. A third strategy that offers an improvement over current procedures but is not as good as the two preceding procedures is having contractors bid the number of working days together with charging liquidated damages for overruns, but not paying a bonus for early completion. This solution approaches the results of the first two strategies but does not provide the winning contractor an incentive for completing the project in less than the bid number of working days once the project is awarded. Therefore, the contractor may find ways of reducing the completion time as the project proceeds but will have no incentive to complete it earlier than the number of bidded days.

The daily bonus rate should be established to equal the daily liquidated damages rate, and each should equal the sum of the daily construction engineering cost and motorists' daily opportunity cost from not having the improved highway. The research report explains how payment of a daily bonus of this magnitude provides sufficient incentive for the construction firm to complete the project in the number of days that minimize total cost.

Figure 2 illustrates how costs are related to project construction time and how the improved strategy reduces construction time and lowers total cost. It was estimated that the combined strategy of bidding working days and paying an early completion bonus, coupled with a higher rate of liquidated damages, can reduce the total cost of many projects resulting in savings in total cost.

Even if current contracting procedures are used, the revised estimates of construction engineering cost and motorist opportunity cost developed in the study more accurately reflect the liquidated damages that result from project overrun. Charging liquidated damages at this higher rate should lead to earlier completion of projects. It is a very good strategy if used together with a policy of setting a very tight schedule on working days. In fact if liquidated damages were charged for all days required to complete the project, this strategy was shown to have similar results to the best strategies. However, this approach might be somewhat confusing to contractors unless it is explained very carefully. Therefore, all things considered, the best strategy probably is to have contractors bid working days, pay a bonus for early completion, and charge liquidated damages for overruns, using the higher rates for bonuses and liquidated damages.

Although it was estimated that use of this improved bidding procedure would lead to a reduction in total costs by millions of dollars per year, it was not possible to obtain a precise estimate because the contractors' costs of completing different types of projects in less time is not known to the researchers. Either of two procedures might be used to obtain a more precise estimate of the savings of using this new approach. One way would be to use the new approach on a selected group of projects and use the current procedures on a similar set of matched projects, and compare the results. It would be necessary to estimate not only construction costs but also the construction engineering costs and

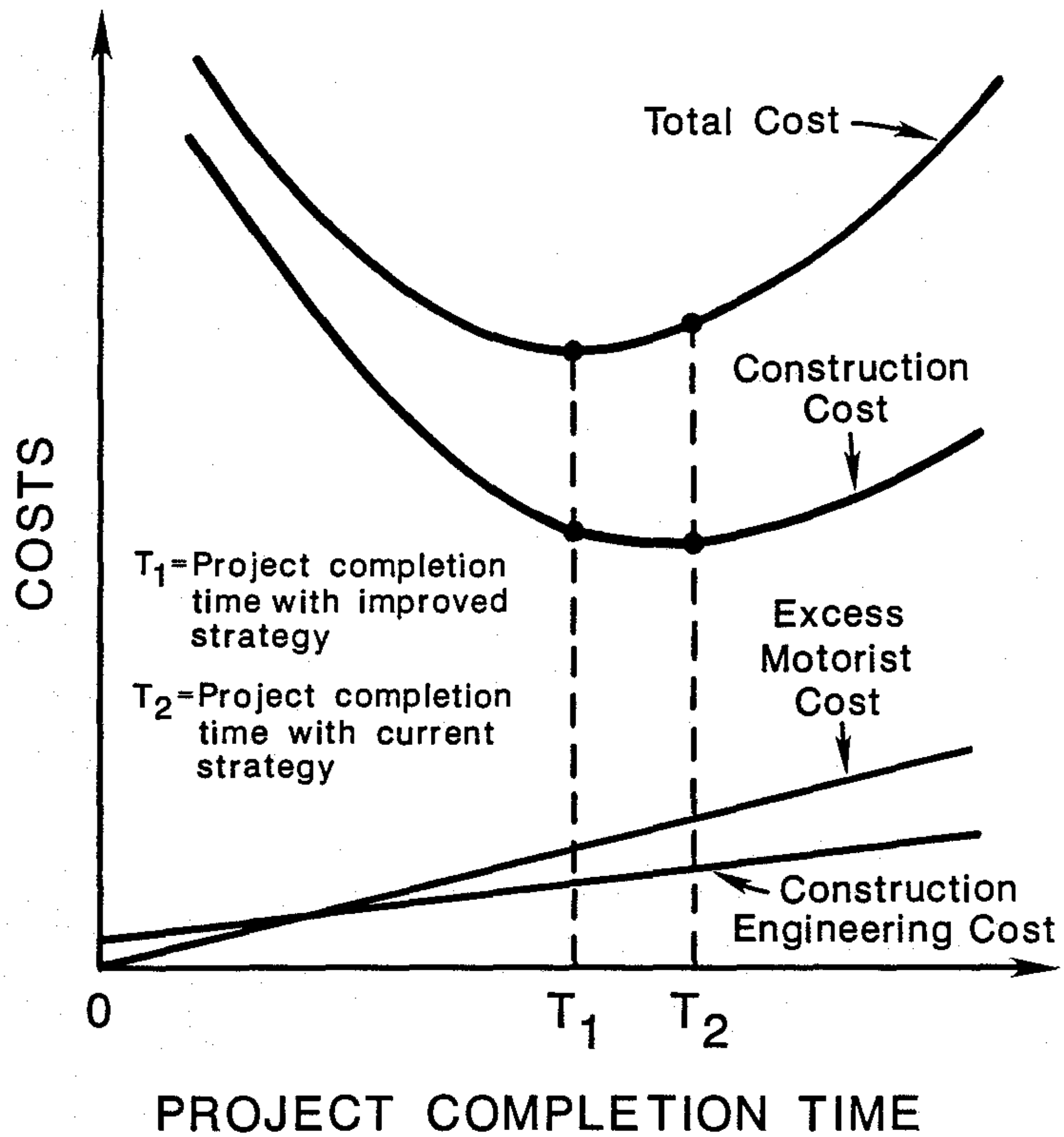

Figure 2. Cost Comparison of Improved and Current Strategies.

motorist cost reductions for early completion. It would be necessary to determine more precisely the long-term effects of the policy.

Another approach for estimating the benefits of the new procedure would be to obtain an estimate of the costs to contractors of completing construction projects earlier. This information could then be used together with the cost equations for construction engineering costs and motorist costs provided in the final research report.

One point that should be emphasized is that the construction costs of projects would increase. The savings result from paying contractors more per contract for earlier completion resulting in less construction engineering costs and motorist costs. The reduction in motorist costs are of two types. First, the reduced construction time means motorists have to travel through a construction zone for a shorter period. Second, the improved highway is available for use at an earlier date resulting in benefits. The net effect of these two types of effects is estimated for different types of situations in the research report on this study.

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Appendix A. VALUES OF TIME AND VEHICLE OPERATING COSTS

The standard engineering-economy procedures for calculating time and vehicle operating costs use three basic categories of time and vehicle operating costs: (1) costs of traveling at uniform speeds, (2) costs of making speed changes, and (3) costs of idling while stopped. In addition, some studies occasionally require vehicle costs for traveling in other conditions, such as on horizontal curves, grades of various degrees, and pavements with different roughness measures. To develop standard values for time and vehicle operating costs, it is necessary to represent the vehicle stream by a combination of standard vehicle types, and then to develop weighted averages of these types for different situations. To facilitate making such calculations, this report develops weighted averages for rural and urban areas for the major categories of costs.

Percent of Vehicles by Type

The vehicle stream for rural and urban areas is represented by five vehicle types, with different percentages of each type as shown in Table A-1. These percentages are used to develop weighted average values of time and vehicle operating costs for rural and urban areas in Texas.

Values for Travel Time

Several methods are available for estimating the value of time. The value of time for motorists typically is estimated by identifying situations in which motorists have trade- offs between travel time savings and other costs that can be calculated. Four methods, or models, of this type are: (1) land location and value, (2) route choice model, especially toll road versus alternate route, (3) mode choice model, including bus versus car, air travel versus car, and rail versus car, and (4) speed choice model.

In the land location and value model, a person often will pay more for land and a house if it is located near his place of work, other things being equal. The extra amount the person is willing to pay can be equated to the present value of future time savings and a value for time can be calculated.

Route choice models were used to develop some of the first willingness to pay values of time. These values were calculated by determining how much motorists would pay to use a toll road to save time. The value of time was calculated as being equal to the toll charge, less savings in vehicle operating costs and accident costs, divided by the savings in time. Although later studies used more sophisticated statistical techniques, this remained the type of tradeoff in route choice models. One of the more significant studies of this type is the study by Thomas and Thompson [33] that

Table A-1. Percentage of Vehicles by Type, for Rural and Urban Areas.

Type of Vehicle	Percent by Type Rural Areas	Urban Areas
Passenger Cars	56.53%	69.99%
Pickups and Commercial Delivery Vehicles	27.81	22.24
Single-unit Trucks	4.78	3.13
Small truck-trailer combinations	1.04	0.62
Large truck-trailer combinations and busses	9.84	4.02
TOTAL:	100.00%	100.00%

Source: Texas State Department of Highways and Public Transportation, Division of Planning and Research (D-10), 1980.

is used in the revised Red Book [18].

The modal choice model (e.g., see Lisco [42]) is similar to the route choice except, for example, the choice is between taking a car which costs more versus a bus which takes more time.

The fourth type of model is the speed choice model. The tradeoff in this model is that a person can travel at a higher speed and save time but has vehicle operating cost, accident cost, and speeding ticket cost increases with faster speeds, above a certain level. McFarland and Chui [25] recently used this approach and calculated values similar to updated values of the earlier studies by Thompson and Thomas and Lisco.

To develop estimates of the value of time, values are needed for each of the five vehicle types shown in Table A-2. These values are taken from McFarland and Rollins [31]. Using the percentages from Table A-1 for rural and urban areas, weighted average values of time are developed for rural and urban areas and are shown in Table A-2.

Derivation of Operating and Time Costs for Uniform Speeds

To derive vehicle operating costs for operation at uniform speeds on rural and urban highways in Texas, the vehicle operating costs by vehicle type from Table A-3, which are taken from Zaniewski [5], are multiplied by the proportions of vehicles by type from Table A-1. The weighted average values are given in Table A-4.

To derive the value of travel time per 1,000 miles, which is the traditional unit for stating such costs, for operation at uniform speeds on rural and urban highways in Texas, the values of time by vehicle type from Table A-2 are multiplied by the time that it takes to travel 1,000 miles. The resulting values of travel time, which are given in Table A-5, are multiplied by the vehicle proportions from Table A-1 to derive the values of time for rural and urban areas, which are given in Table A-6.

The overall operating and time cost for operation at uniform speeds, which is simply the sum of the values in Tables A-4 and A-6, is given in Table A-7.

Derivation of Operating and Time Cost for Speed Changes

To derive excess vehicle operating costs for different speed changes, the costs from Tables A-8 through A-12, by vehicle types, are weighted by the vehicle proportions in Table A-1. The resulting excess vehicle operating costs for rural and urban highways are given in Tables A-13 and A-14.

Table A-2. Values of Time for Rural and Urban Areas of Texas.

Vehicle Type	Value of Time Per Vehicle Hour [1]	Percent of Vehicles by Type Rural	Percent of Vehicles by Type Urban	Weighted Value of Time Rural	Weighted Value of Time Urban
Passenger Car	$10.22	56.53%	69.99%	$ 5.78	$ 7.15
Pick-up	12.43	27.81	22.24	3.46	2.76
Single-unit Truck	14.84	4.78	3.13	0.71	0.46
Small Combination Trucks	18.51	1.04	0.62	0.91	0.11
Large Combination Trucks	20.54	9.84	4.02	2.02	0.83
		Weighted Averages:		$12.16	$11.31

1. Values from W. F. McFarland and J. B. Rollins [3].

Table A-3. Vehicle Operating Cost for Operation at Uniform Speeds, in Dollars Per 1000 Miles, by Vehicle Type.

Uniform Speed (mph)	Passenger Car	Commercial Delivery or Pick-up	Type of Vehicle Single-unit Truck	Small Comb. Truck	Large Comb. Truck
10	$164	$147	$328	$491	$515
20	132	113	235	325	346
30	124	114	215	315	340
40	120	118	226	311	349
50	125	130	256	315	363
60	139	141	283	339	392
70	155	172	322	379	430

Source: Zaniewski et al. [5], pp. A-19, A-21, A-22, A-24, and A-25 for operation at zero grade highways.

Table A-4. Vehicle Operating Cost Per 1000 Vehicle Miles, at Uniform Speeds, in Dollars per 1000 Miles, for Weighted-Average Vehicles, Rural and Urban Highways in Texas.

Uniform Speed (mph)	Type of Highway	
	Rural	Urban
10	$205.06	$181.48
20	154.71	140.81
30	148.82	134.49
40	149.03	133.26
50	158.05	140.95
60	173.42	155.37
70	197.09	176.45

Table A-5. Value of Travel Time Per 1000 Vehicle Miles for Operation at Uniform Speeds, in Dollars Per 1000 Miles, by Vehicle Types.

Uniform Speed (mph)	Type of Vehicle				
	Passenger Car	Commercial Delivery or Pick-up	Single-unit Truck	Small Comb. Truck	Large Comb. Truck
10	$1,022.00	$1,243.00	$1,484.00	$1,851.00	$2,054.00
20	511.00	621.50	742.00	925.50	1,027.00
30	340.67	414.33	494.67	617.00	684.67
40	255.50	310.75	371.00	462.75	513.50
50	204.40	248.60	296.80	370.20	410.80
60	170.33	207.17	247.33	308.50	342.33
70	146.00	177.57	212.00	264.43	293.43

Table A-6. Value of Travel Time Per 1000 Vehicle Miles, at Uniform Speeds, in Dollars per 1000 Miles, for Weighted-Average Vehicles for Rural and Urban Highways, Texas.

Uniform Speed (mph)	Type of Highway Rural	Urban
10	$1,216.00	$1,131.00
20	608.00	565.50
30	405.33	377.00
40	304.00	282.75
50	243.20	226.20
60	202.67	188.50
70	173.71	161.57

Table A-7. Dollars of Operating and Time Cost, at Uniform Speeds, in Dollars per 1000 Vehicle Miles.

Uniform Speed (mph)	Dollars per 1000 miles Rural Roads	Urban Roads
10	$1,421.00	$1,312.48
20	762.71	706.31
30	554.15	511.49
40	453.03	416.01
50	401.25	367.15
60	376.09	343.87
70	370.80	338.02

Table A-8. Excess Vehicle Operating Cost for Speed Change Cycles, in Dollars per 1000 Cycles, Passenger Car.

Initial Speed (mph)	Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	2.8						
20	6.4	3.6					
30	11.0	8.2	4.7				
40	17.2	14.5	10.9	6.2			
50	24.6	21.9	18.1	13.6	7.4		
60	33.2	30.5	26.9	22.3	16.0	8.6	
70	45.6	42.8	39.2	34.6	28.3	21.0	12.2

Source: Zaniewski et al. [5], p. A-67, for medium-size passenger car.

Table A-9. Excess Vehicle Operating Cost for Speed Change Cycles, in Dollars per 1000 Cycles, Commercial Delivery Vehicles and Pickups.

Initial Speed (mph)	Speed Reduced To and Returned From (mph) 0	10	20	30	40	50	60
10	3.0						
20	7.1	4.1					
30	12.5	9.4	5.3				
40	19.5	16.4	12.5	7.0			
50	27.8	24.6	20.7	15.3	8.2		
60	38.7	35.7	31.7	26.1	19.1	10.9	
70	56.9	54.0	49.8	44.4	37.4	29.2	18.1

Source: Zaniewski et al. [5], p. A-69, for pickup truck

Table A-10. Excess Vehicle Operating Cost for Speed Change Cycles, in Dollars per 1000 Cycles, Single-Unit Trucks.

Initial Speed (mph)	Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	8.9						
20	24.0	15.2					
30	48.4	39.4	24.2				
40	80.8	71.9	56.5	32.3			
50	122.0	114.0	98.3	74.1	41.7		
60	168.0	159.0	145.0	120.0	88.1	46.2	
70	220.0	211.0	196.0	171.0	140.0	97.8	51.4

Source: Zaniewski et al. [5], p. A-70, for 2-axle single-unit truck

Table A-11. Excess Vehicle Operating Cost for Speed Change Cycles, in Dollars per 1000 Cycles, Small Combination Trucks.

Initial Speed (mph)	Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	20.8						
20	54.3	33.6					
30	102.0	81.5	47.7				
40	155.0	134.0	99.9	52.2			
50	221.0	200.0	167.0	119.0	66.9		
60	298.0	278.0	244.0	196.0	144.0	77.3	
70	386.0	365.0	332.0	284.0	232.0	165.0	88.0

Source: Zaniewski et al. [5], p. A-72, for 2-S2 truck semitrailer combination

Table A-12. Excess Vehicle Operating Cost for Speed Change Cycles, in Dollars per 1000 Cycles, Large Combination Trucks.

Initial Speed (mph)	Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	26.0						
20	74.2	48.1					
30	145.0	119.0	70.5				
40	221.0	195.0	146.0	76.5			
50	317.0	292.0	244.0	174.0	97.0		
60	426.0	400.0	351.0	281.0	205.0	108.0	
70	546.0	520.0	473.0	402.0	325.0	227.0	120.0

Source: Zaniewski et al. [5], p. A-73, for 3-S2 truck semitrailer combination

Table A-13. Excess Vehicle Operating Cost for Speed Change Cycles, in Dollars per 1000 Speed Change Cycles, Weighted-Average Vehicle for Rural Roads, Texas.

Initial Speed (mph)	Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	5.62						
20	14.60	8.99					
30	27.34	21.69	12.73				
40	42.36	36.78	27.75	15.06			
50	60.96	55.48	42.37	33.84	18.69		
60	82.56	77.02	68.01	45.30	40.23	21.53	
70	109.86	104.27	95.37	82.59	67.48	48.72	27.12

Table A-14. Excess Vehicle Operating Cost for Speed Change Cycles, in Dollars per 1000 Speed Change Cycles, Weighted-Average Vehicle for Urban Roads, Texas.

Initial Speed (mph)	Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	4.09						
20	10.13	6.05					
30	18.45	14.35	8.36				
40	28.75	24.72	18.67	10.31			
50	41.33	37.35	31.20	22.97	12.62		
60	56.09	52.07	46.04	37.69	27.34	14.71	
70	75.80	71.73	65.72	57.36	47.02	34.40	19.55

To derive the cost of excess travel time for speed change cycles, the excess hours of time for speed change cycles from Tables A-15 through A-19 which are based on Winfrey [4], are multiplied by the appropriate cost of time, by vehicle type, from Table A-2. The resulting time costs for speed changes are given in Tables A-20 through A-24. These tables are used together with the vehicle distributions from Table A-1 to derive the cost of excess travel time for rural and urban roads given in Tables A-25 and A-26.

The excess vehicle operating costs from Tables A-13 and A-14 are added to the excess time costs from Tables A-24 and A-26 to obtain the total costs for speed changes in Tables A-27 and A-28.

Costs of Delay or Idling

The vehicle operating cost associated with idling, based on values developed by the Federal Highway Administration [36], is given in Table A-29 for each of the five vehicle types. Weighted averages are developed using the distributions of vehicle types and these values are given in Table A-29 for rural and urban areas. The cost of time delay from idling is simply the weighted average cost for rural areas of $12.16 per vehicle hour and urban areas of $11.31 per vehicle hour. The vehicle operating costs and time costs are added to obtain the total cost of idling, given in Table A-30, and shown in terms of the cost per 1,000 hours of delay or idling.

The principal tables that are of interest usually are the following: (1) cost at uniform speeds in rural and urban areas, Table A-7; (2) cost of making speed changes in rural and urban areas, Tables A-27 and A-28; and (3) cost of delay or idling, Table A-30. However the analyst sometimes may wish to vary the vehicle distribution and this can be done with the data available in these tables. Figures A-1 through A-4 from Dale can be used to estimate pollution.

Table A-15. Excess Time for Speed Change Cycles, in Hours per 1000 Cycles, Passenger Cars.

Initial Speed (mph)	Speed Reduced From and Returned To (mph)						
	0	10	20	30	40	50	60
10	1.51						
20	2.49	0.93					
30	3.46	1.87	0.70				
40	4.42	2.81	1.52	0.51			
50	5.37	3.75	2.34	1.15	0.35		
60	6.31	4.67	3.14	1.78	0.78	0.21	
70	7.25	5.58	3.94	2.40	1.19	0.50	0.16

Source: Winfrey [4], p. 688, for 4-kip passenger cars

Table A-16. Excess Time for Speed Change Cycles, in Hours per 1000 Cycles, Commercial Delivery Vehicles and Pickups.

Initial Speed (mph)	Speed Reduced From and Returned To (mph)						
	0	10	20	30	40	50	60
10	1.12						
20	1.93	0.86					
30	2.81	1.63	0.68				
40	3.78	2.50	1.42	0.57			
50	4.87	3.48	2.26	1.26	0.49		
60	6.15	4.67	3.28	2.07	1.11	0.43	
70	7.75	6.23	4.73	3.25	2.04	1.06	0.38

Source: Winfrey [4], p. 692, for 5-kip commercial delivery vehicles

Table A-17. Excess Time for Speed Change Cycles, in Hours per 1000 Cycles, Single-Unit Trucks.

Initial Speed (mph)	Speed Reduced From and Returned To (mph)						
	0	10	20	30	40	50	60
10	1.47						
20	2.93	1.23					
30	3.67	1.86	0.45				
40	5.87	3.84	2.18	0.83			
50	7.33	5.26	3.47	1.93	0.72		
60	8.80	6.81	4.94	3.27	1.83	0.72	
70	10.26	8.47	7.72	5.73	4.50	1.88	0.77

Source: Winfrey [4], p. 696, for 12-kip single-unit trucks

Table A-18. Excess Time for Speed Change Cycles, in Hours per 1000 Cycles, Small Combination Trucks.

Initial Speed (mph)	Speed Reduced From and Returned To (mph)						
	0	10	20	30	40	50	60
10	1.47						
20	3.19	1.19					
30	5.22	2.85	1.07				
40	7.76	5.24	2.96	1.16			
50	11.34	8.70	6.12	3.72	1.66		
60	17.47	14.29	11.18	8.18	5.30	2.56	
70	24.53	20.63	16.78	13.02	9.30	5.60	3.40

Source: Winfrey [4], p. 700, for 40-kip 2-S2 gasoline trucks

Table A-19. Excess Time for Speed Change Cycles, in Hours per 1000 Cycles, Large Combination Trucks.

Initial Speed (mph)	Speed Reduced From and Returned To (mph)						
	0	10	20	30	40	50	60
10	2.27						
20	4.76	1.71					
30	7.56	3.90	1.36				
40	11.09	6.99	3.66	1.36			
50	16.37	11.95	7.95	4.60	1.95		
60	27.94	22.10	16.55	11.44	6.92	3.10	
70	42.38	34.36	26.59	19.36	12.80	7.00	4.34

Source: Winfrey [4], p. 704, for 5-kip 3-S2 diesel trucks

Table A-20. Cost of Excess Time for Speed Change Cycles, in Dollars per 1000 Cycles, Passenger Cars.

Initial Speed (mph)	Speed Reduced From and Returned To (mph)						
	0	10	20	30	40	50	60
10	$15.43						
20	25.45	9.50					
30	35.36	19.11	7.15				
40	45.17	28.72	15.53	5.21			
50	54.88	38.33	23.91	11.75	3.58		
60	64.49	47.73	32.09	18.19	7.97	2.15	
70	74.10	57.03	40.27	24.53	12.16	5.11	1.64

Note: These values are derived by multiplying the value in Table 15 by $10.22 per vehicle hour

Table A-21. Cost of Excess Time for Speed Change Cycles, in Dollars per 1000 Cycles, Commercial Delivery and Pickups.

Initial Speed (mph)	Speed Reduced From and Returned To (mph) 0	10	20	30	40	50	60
10	$13.92						
20	23.99	10.69					
30	34.93	20.26	8.45				
40	46.99	31.08	17.65	7.09			
50	60.53	43.26	28.09	15.66	6.09		
60	76.44	58.05	40.77	25.73	13.80	5.34	
70	96.33	77.44	58.79	40.40	25.36	13.18	4.72

Note: These values are derived by multiplying the value in Table 16 by $12.43 per vehicle hour

Table A-22. Cost of Excess Time for Speed Change Cycles, in Dollars per 1000 Cycles, Single-Unit Trucks.

Initial Speed (mph)	Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	$21.81						
20	43.48	18.25					
30	54.46	27.60	6.68				
40	87.11	56.99	32.35	12.32			
50	108.78	78.06	51.49	28.64	10.68		
60	130.59	101.06	73.31	48.53	27.16	10.68	
70	152.26	125.69	114.56	85.03	66.78	27.90	11.43

Note: These values are derived by multiplying the value in Table 17 by $14.84 per vehicle hour

Table A-23. Cost of Excess Time for Speed Change Cycles, in Dollars per 1000 Cycles, Small Combination Trucks.

Initial Speed (mph)	Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	$27.21						
20	59.05	22.03					
30	96.62	52.75	19.81				
40	143.64	96.99	54.79	21.47			
50	209.90	161.04	113.28	68.86	30.73		
60	323.37	264.51	206.94	151.41	98.10	47.39	
70	454.05	381.86	310.60	241.00	175.80	103.66	62.93

Note: These values are derived by multiplying the value in Table 18 by $18.51 per vehicle hour

Table A-24. Cost of Excess Time for Speed Change Cycles, in Dollars per 1000 Cycles, Large Combination Trucks.

Initial Speed (mph)	Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	$46.63						
20	97.77	35.12					
30	155.28	80.11	27.93				
40	227.79	143.57	75.18	27.93			
50	336.24	245.45	163.29	94.48	40.05		
60	573.89	453.93	339.94	234.98	142.14	63.67	
70	870.49	705.75	546.16	397.65	262.91	143.78	89.14

Note: These values are derived by multiplying the value in Table 19 by $20.54 per vehicle hour

Table A-25. Cost of Excess Travel Time for Speed Change Cycles, in Dollars per 1000 Cycles, Weighted Average Vehicle for Rural Roads, Texas.

Initial Speed (mph)	Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	$18.50						
20	33.37	12.90					
30	48.58	26.18	9.67				
40	66.66	42.74	23.20	8.48			
50	88.28	63.25	41.04	22.39	8.48		
60	123.79	95.37	68.58	44.45	24.66	9.98	
70	166.34	133.21	101.56	70.81	45.85	23.12	12.21

Table A-26. Cost of Excess Travel Time for Speed Change Cycles, in Dollars per 1000 Speed Change Cycles, Weighted Average Vehicle for Urban Roads, Texas.

Initial Speed (mph)	Speed Reduced To and Returned From (mph) 0	10	20	30	40	50	60
10	$16.62						
20	28.81	11.15					
30	41.06	22.30	8.33				
40	54.84	35.16	19.17	6.87			
50	70.09	49.76	31.85	16.83	4.89		
60	91.30	69.37	48.77	30.36	15.82	5.87	
70	115.86	91.81	68.73	46.29	28.52	13.80	6.53

Table A-27. Dollars of Excess Operating and Time Cost of Speed Change Cycles, Excess Cost Above Continuing at Initial Speed, for Rural Roads in Texas, 1984.

Initial Speed (mph)	Dollars Per 1000 Cycles Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	$24.12						
20	47.97	21.89					
30	75.92	47.87	22.40				
40	109.02	79.52	50.95	23.54			
50	149.24	118.73	83.41	56.23	27.17		
60	206.35	172.39	136.59	89.75	64.89	31.51	
70	276.20	237.48	196.93	153.40	113.33	71.84	39.33

Table A-28. Dollars of Excess Operating and Time Cost of Speed Change Cycles, Excess Cost Above Continuing at Initial Speed, for Urban Roads in Texas, 1984.

Initial Speed (mph)	Dollars Per 1000 Cycles Speed Reduced To and Returned From (mph)						
	0	10	20	30	40	50	60
10	$20.71						
20	38.94	17.20					
30	59.51	36.65	16.69				
40	83.59	59.88	37.84	17.18			
50	111.42	87.11	63.05	39.80	17.51		
60	147.39	121.44	94.81	68.05	43.16	20.58	
70	191.66	163.54	134.45	103.65	75.54	48.20	26.08

Table A-29. Vehicle Operating Costs for Idling in Dollars Per 1000 Vehicle Hours.

Vehicle Type	Idling Cost Per 1000 Hours
Passenger Car	$ 1,349.49
Commercial Delivery/Pickup	1,734.47
Single-Unit Truck	2,753.00
Small Combination Truck	1,099.19
Large Combination Truck	1,199.19
Weighted Average:	
Rural Highways	$ 1,506.25
Urban Highways	1,471.45

Source: [6], p. IV-37

TABLE A-30. Dollars of Operating and Time Cost for Delay or Idling, per 1000 Vehicle Hours.

Type of Delay Cost	Dollars Per 1000 Vehicle Hours	
	Rural Roads	Urban Roads
Operating	$ 1,506.25	$ 1,471.45
Time	12,160.00	11,310.00
TOTAL	$13,666.25	$12,781.45

FIGURE A-1. FUEL CONSUMPTION AND EMISSIONS OF CARBON MONOXIDE, HYDROCARBONS, AND NITROGEN OXIDES FROM DRIVING 1,000 MILES AT VARIOUS SPEEDS (FOR LIGHT DUTY VEHICLES).

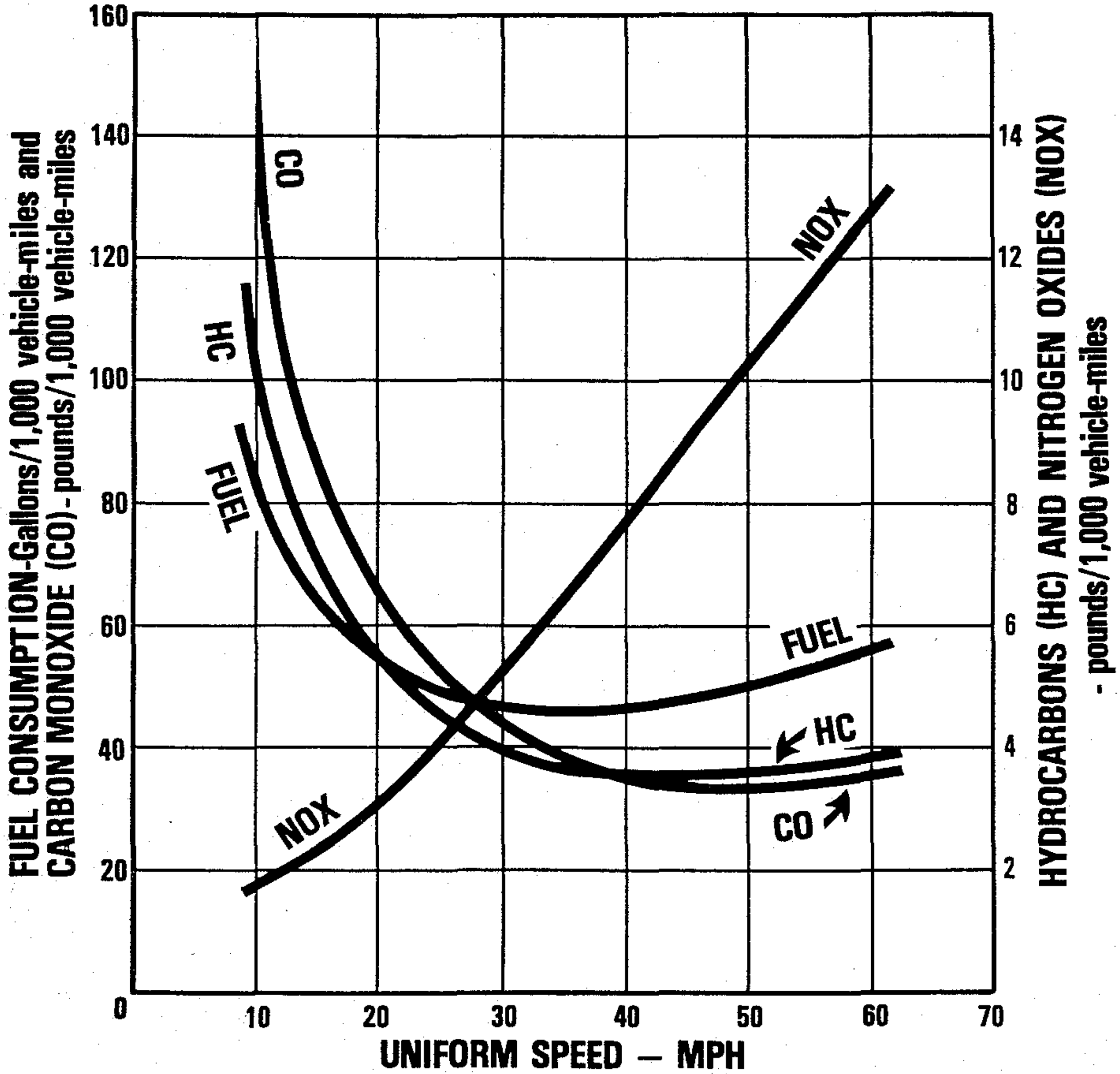


FIGURE A-2. CARBON MONOXIDE EMISSIONS FOR VEHICULAR SPEED CHANGES (FOR LIGHT DUTY VEHICLES).

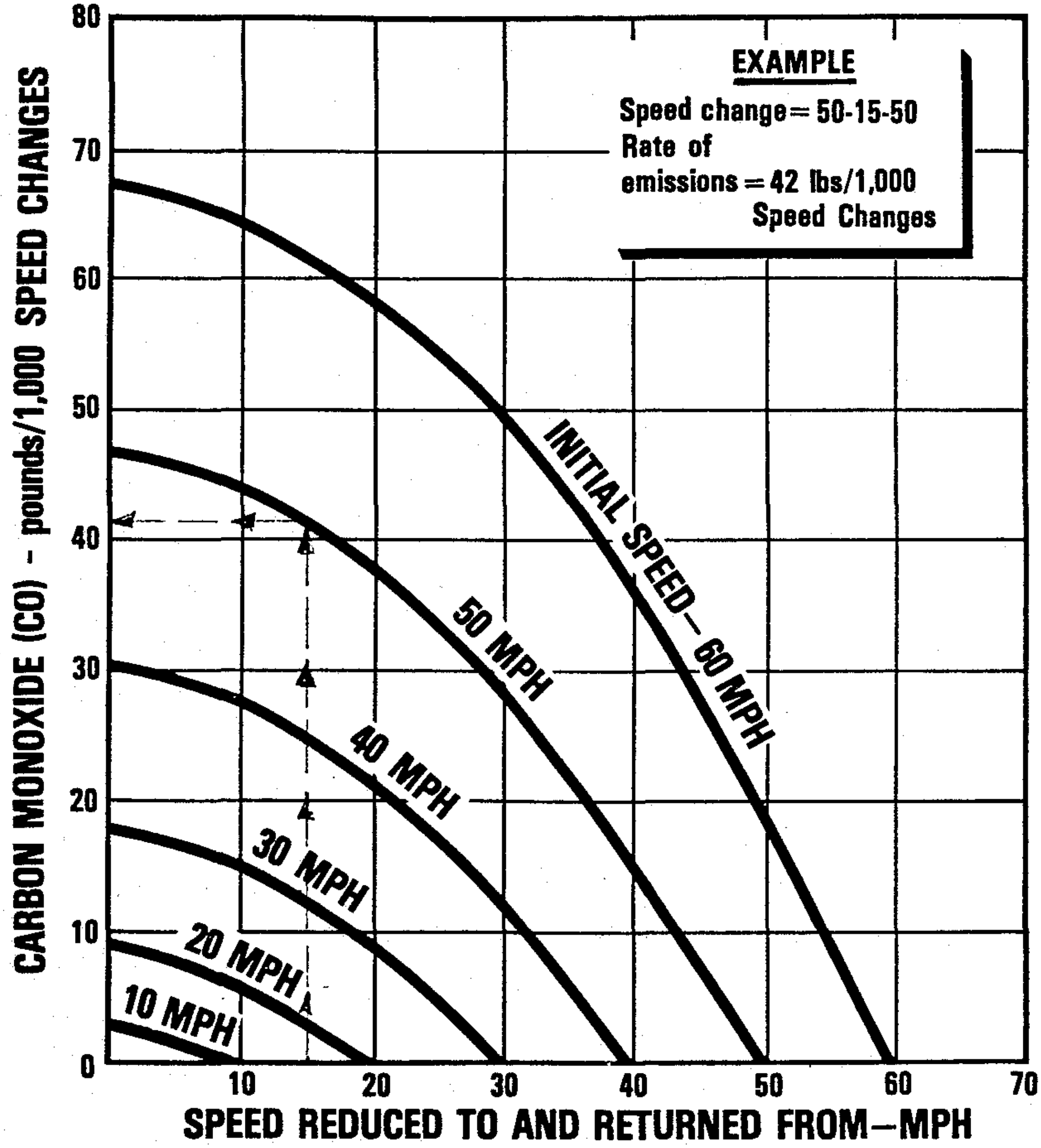


FIGURE A-3. HYDROCARBONS EMISSIONS FOR VEHICULAR SPEED CHANGES (FOR LIGHT DUTY VEHICLES).

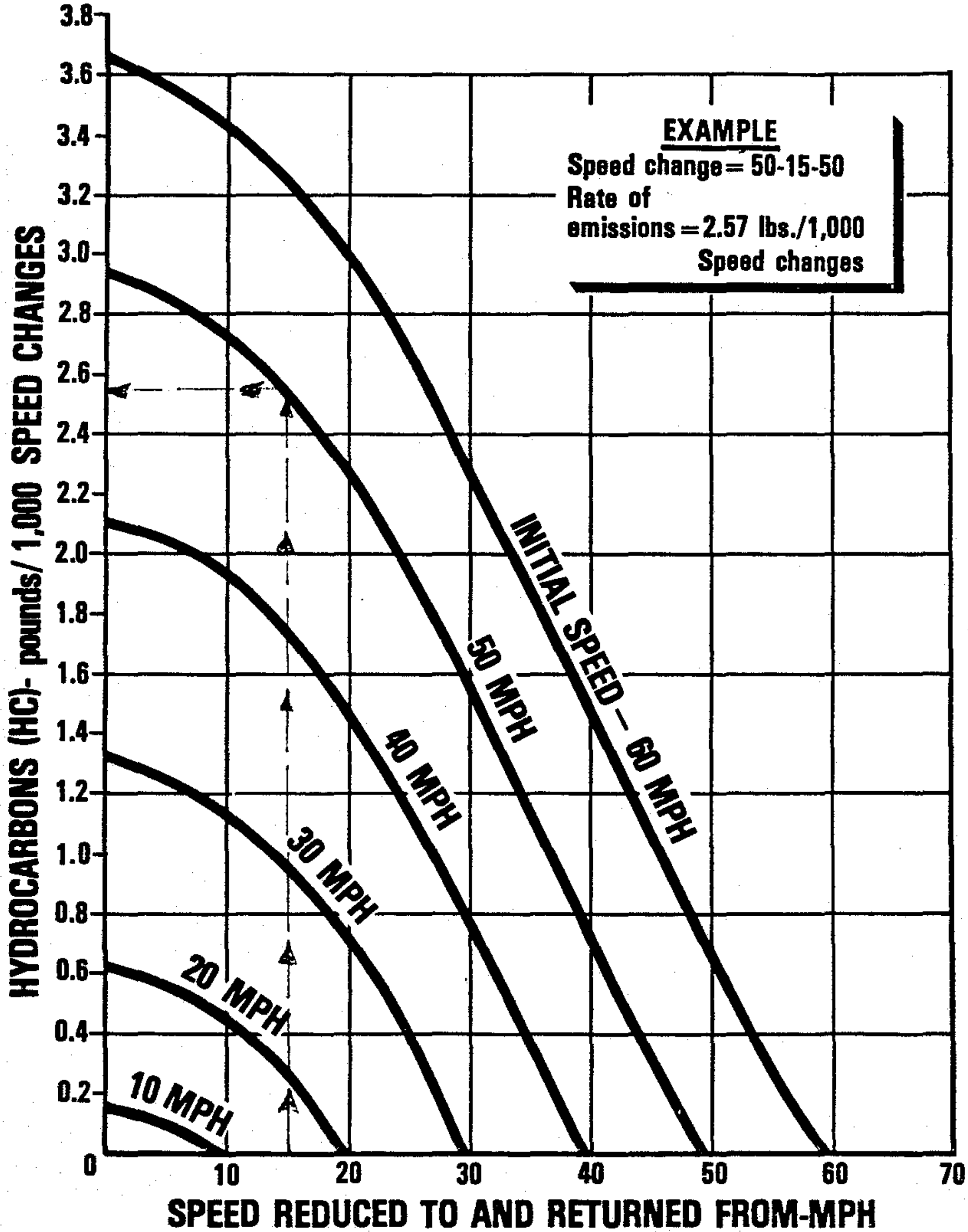
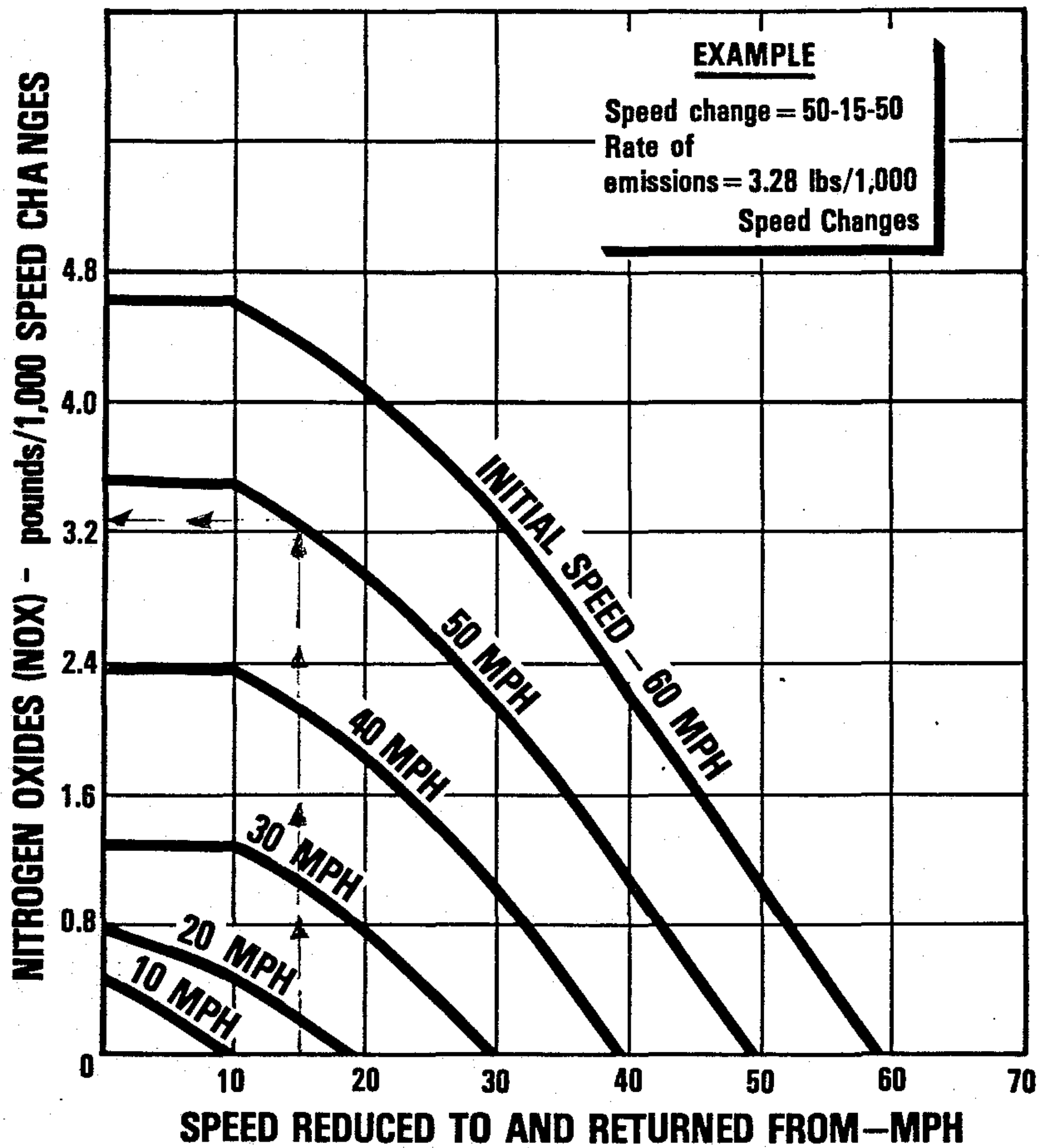


FIGURE A-4. HYDROCARBONS EMISSIONS FOR VEHICULAR SPEED CHANGES (FOR LIGHT DUTY VEHICLES).



Appendix B. ACCIDENT COSTS

One of the major benefits of research is the reduction of accident rates and severities, resulting in reductions in accident costs. Although there is considerable disagreement on whether it is possible to put an economic value on reductions in numbers and severities of accidents, there nevertheless have been several recent studies that have calculated improved accident costs.

Accident costs typically have been calculated by estimating direct costs and indirect costs. Direct costs are defined as including the costs of property damage, medical and hospital expenses, and doctor expenses. Indirect costs include lost income, reduced earning capacity, and the cost of lost lives as estimated using a production or market approach, also called a willing-to-pay approach. The market approach for estimating the cost of a fatality attempts to estimate how much people actually pay to reduce their risk of death.

Direct Accident Costs

Only one good source exists for calculating the direct accident costs for different categories of accidents by location, severity, type of accident, etc. This source is the group of state accident cost studies that were performed in Ohio, Illinois, Massachusetts, Utah, and New Mexico [46,47,48,49,50, and 51]. All of these detailed statewide studies determined direct accident costs for a one-year period in each state, following detailed procedures developed by the U.S. Bureau of the Public Roads in 1949 [52]. The extent to which these direct costs developed in the state studies are currently used in cost-effectiveness analysis is not completely known. It is known, however, that several states reported that they were using accident costs developed in "state studies" [53].] Direct costs as used in these studies are defined as:

> ... the money value of: damage to property, ambulance use, hospital and treatment services, value and settlements, and other miscellaneous items ... Such items as loss of future earnings of persons killed or permanently injured in accidents were excluded from the direct cost phase of the studies, except to the extent that damage awards of settlements made either in or out of court might have compensated for such losses. Expenditures also excluded from the direct cost phase of the studies were those made by public and private agencies to mitigate the economic burden of accidents and the overhead cost of automobile and certain other types of insurance [54].

There have been two other important studies (other than five state studies) that calculated direct accident costs. The first of these was a study of the Washington, D.C. area performed by Wilbur Smith and Associates [55]. This study mainly included urban and suburban accidents and also included calculation of some indirect costs. This Wilbur Smith study apparently was used by the California Department of Transportation to develop accident cost estimates for California, which, in turn, were updated and used by the Stanford Research Institute in the "revised Red Book" [18]. The California DOT at one time [56] had used direct accident costs from the Illinois accident costs study but later apparently switched to the Washington, D.C. area accident costs, presumably because they included some indirect costs.

The second study that developed direct (and indirect) accident cost estimates, other than the state studies, was that by the U.S. Department of Transportation [57]; these estimates sometimes are referred to as "NHTSA accident costs." The NHTSA accident costs are estimated by severity only, and, for use in cost-effectiveness studies, suffer from lack of estimates by the various cross-classifications of accidents. The NHTSA values provide the most comprehensive estimates of the cost of different types of injuries. Another widely-used set of estimates of injury costs for A, B, and C-type injuries is provided by the National Safety Council (NSC) [58]. The NSC values are not used in this report, since it is impossible to determine how their estimates are made or the accuracy of their estimates.

The NHTSA accident cost estimates are stated by severity as cost per fatality, cost per injury for five types of injuries, and cost per property damage only involvement. Thus, for fatalities and injuries, no estimate is given of cost per fatal or injury accident nor for fatal or injury involvement, and it is difficult to derive such costs from the NHTSA data. It appears, however, that some of NHTSA's cost items (e.g., property damage) per fatality actually are cost per involvement. Some of the NHTSA estimates also suffer from using samples of somewhat limited data; for example, the property damage estimates are based on damage to relatively new automobiles as shown by damage claims of insurance companies.

Burke [59] showed that the direct accident cost estimates developed in Massachusetts, Utah, New Mexico, and Illinois were statistically comparable and could be combined into one overall data base. Burke combined these state data bases and developed accident costs for the following cross classifications:

(1) Severity of accident
(2) Type of area (rural, urban)
(3) Type of vehicle (automobile, single-unit truck, combination truck)
(4) Type of accident (head-on, rear-end, fixed object, etc.)

All four data states were used to develop accident costs by the above cross-classifications. Additional cross-classifications were developed according to severity and vehicle type cross-classified against: (1) type of highway (for all states except Massachusetts), (2) highway system (Federal Aid Primary, Federal Aid Secondary, Nonfederal Aid, Local), (3) intersection control (stop sign, stop-go light, etc.), and (4) road characteristics (for Massachusetts and Illinois).

It is important to note that Burke's study is the only study, other than the individual state studies and the Washington, D.C. area study, that provides accident cost estimates for the types of cross-classifications needed in this research. Moreover, since Burke's study combined the results from four states, it is more comprehensive than any of the individual state studies and was used by McFarland and Rollins [3] to develop direct accident costs.

Indirect Accident Costs

Indirect accident costs of non-fatal injuries typically are considered to include production and consumption losses for the deceased and other losses to the deceased's home and family and to the community. The principal source for an estimate of these losses is the NHTSA report by Faigin [57], which includes calculations for five types of injury: minor, moderate, severe (not life threatening), severe (life threatening, survival probable), and critical (survival uncertain). NHTSA's values in 1975 dollars are given in Table B-1.

Since most states use "A-B-C" categories for injuries, the NHTSA values cannot be used directly to calculate injury costs from state accident records. McFarland and Rollins [31] showed, however, that national samples giving a cross-classification of A-B-C injuries versus NHTSA categories could be used together with the NHTSA injury costs to develop injury costs by A-B-C categories.

Indirect costs for fatalities include a cost or value for the deceased's loss of life and the indirect costs to others. Table B-2 shows these costs as calculated using three different approaches. Burke's value is representative of those approaches that include a cost to others for fatalities but include no cost *per se* for the value of a person's life to himself. The revised Red Book [18] and the National Safety Council [58] use similar values; see McFarland and Rollins [60] for a critique of this approach which omits the value of the person's life to himself. The NHTSA values include production losses, including the value of the individual's own consumption, to represent the cost of the lost life. The market value approach [31,60] uses market experiments showing how much people are willing to pay to reduce their risk of death. The specific value given in the table for the deceased's

Table B-1. Indirect Costs for Non-fatal Injuries, 1975 Dollars.

Injury Severity (MAIS)	Indirect Cost for Production/Consumption		
	Market	Home, Family and Community	Total
5 (Critical)	$126,650	$36,995	$163,645
4 (Severe 2)	55,520	16,660	72,180
3 (Severe 1)	1,645	425	2,070
2 (Moderate)	865	310	1,175
1 (Minor)	65	20	85
Overall Weighted Average	599	185	784

Table B-2. Indirect Cost of Fatalities, by Source.

Accident Type	Cost Per Fatality, by Source		
	Burke	NHTSA	Market-NHTSA
Deceased's Loss of Life	$ 0	$211,820	$257,000
Indirect Cost to Others	61,214	63,545	63,545
Total Indirect Cost	61,214	275,365	320,545

loss of life, $257,000, is based on Blomquist [61], whereas the other indirect costs are based on NHTSA's estimates.

In this study, it is recommended that a combination of NHTSA and market values be used. The combined values include the market value of the deceased's loss of life, $257,000, plus NHTSA indirect cost to others of $63,545, for a total indirect cost per fatality of $320,545, in 1975 dollars. These values were updated and used as estimates of the cost per fatality by McFarland and Rollins [31,60].

Using updated direct costs from Burke's study, NHTSA injury costs transformed to the A-B-C categories, Blomquist's market value for the cost of a fatality, and comprehensive accident records from five states (North Carolina, Alabama, Montana, North Dakota, and Texas), McFarland and Rollins developed accident costs for different categories of accidents. These values have been updated to 1987 and are shown in Tables B-3 through B-6. Accident proportions by severity from the five states combined data bases are given in Tables B-7 through B-10.

Table B-3. Average Accident Costs for All Accidents, by Severity, Type of Accident, and Type of Area, 1987 Dollars.

Accident Type	Severity: Fatal	Injury	PDO
Rural			
Multiple-vehicle	$941,400	$20,100	$1,800
Single-vehicle	746,500	17,100	1,700
All Rural	818,000	18,600	1,800
Urban			
Multiple-vehicle	819,200	12,200	1,200
Single-vehicle	719,000	13,600	800
All Urban	758,800	12,700	1,100

Table B-4. Average Accident Costs for Rural Multiple-vehicle Accidents, 1987 Dollars.

Accident Type	Severity		
	Fatal	Injury	PDO
<u>Intersection</u>			
Angle	$932,700	$19,700	$1,400
Head-on	915,700	34,800	2,400
Rear-end	862,500	16,500	2,000
Other	861,100	17,700	1,800
All	908,500	18,800	1,700
<u>Non-intersection</u>			
Angle	837,600	19,600	1,600
Head-on	1,025,500	38,500	2,400
Rear-end	859,900	18,000	2,000
Other	822,300	18,100	1,700
All	953,100	21,400	1,800
<u>All Rural</u>			
Angle	696,100	19,700	1,500
Head-on	1,020,600	38,100	2,400
Rear-end	860,300	17,600	2,000
Other	837,400	17,800	1,800
All Rural	941,000	20,100	1,800

Table B-5. Average Accident Costs for Urban Multiple-vehicle Accidents, 1987 Dollars.

	Severity		
Accident Type	Fatal	Injury	PDO
Intersection			
Angle	$808,400	$13,200	$1,400
Head-on	886,600	15,900	1,600
Rear-end	778,700	9,500	1,000
Other	766,800	12,100	900
All	799,700	12,200	1,200
Non-intersection			
Angle	754,300	12,500	1,400
Head-on	921,000	19,300	1,500
Rear-end	754,800	10,900	1,000
Other	771,100	11,600	900
All	839,600	12,200	1,100
All Urban			
Angle	801,900	13,100	1,400
Head-on	917,900	18,400	1,500
Rear-end	760,100	10,300	1,000
Other	768,600	11,800	900
All Urban	819,200	12,200	1,200

Table B-6. Average Accident Costs for Single-vehicle Accidents, 1987 Dollars.

	Severity		
Accident Type	Fatal	Injury	PDO
Rural			
Animal	$715,300	$15,400	$1,400
Fixed/other Object	782,700	17,000	2,200
Parked Car	832,500	15,400	1,200
Pedalcycle	684,300	11,400	300
Pedestrian	674,900	16,900	100
RR Train	864,600	21,600	1,400
Overturn	740,000	18,600	2,000
Other non-collision	755,100	17,000	1,600
All Rural	746,500	17,100	1,700
Urban			
Animal	713,400	13,200	1,000
Fixed/other Object	742,700	15,500	1,000
Parked Car	741,900	10,100	500
Pedalcycle	689,600	10,900	300
Pedestrian	703,000	14,000	200
RR Train	852,700	11,400	2,700
Overturn	710,300	13,500	1,200
Other non-collision	671,900	12,100	1,200
All Urban	719,000	13,600	800

Table B-7. Accident Proportions for All Accidents.

Accident Type	Severity: Fatal	Injury	PDO
Rural			
Multiple-vehicle	0.0105	0.3022	0.6873
Single-vehicle	0.0232	0.4105	0.5663
All Rural	0.0160	0.3497	0.6343
Urban			
Multiple-vehicle	0.0023	0.2171	0.7806
Single-vehicle	0.0122	0.3456	0.6422
All Urban	0.0045	0.2458	0.7497

Table B-8. Accident Proportions for Rural Multiple-vehicle Accidents.

	Severity		
Accident Type	Fatal	Injury	PDO
Intersection			
Angle	0.0093	0.3693	0.6214
Head-on	0.0273	0.3791	0.5936
Rear-end	0.0025	0.3374	0.6601
Other	0.0040	0.2655	0.7305
All	0.0063	0.3244	0.6693
Non-intersection			
Angle	0.0089	0.2370	0.7541
Head-on	0.0781	0.4030	0.5189
Rear-end	0.0053	0.3562	0.6385
Other	0.0050	0.2120	0.7830
All	0.0137	0.2851	0.7012
All Rural			
Angle	0.0091	0.3170	0.6739
Head-on	0.0721	0.4001	0.5278
Rear-end	0.0044	0.3501	0.6455
Other	0.0046	0.2356	0.7598
All Rural	0.0105	0.3022	0.6873

Table B-9. Accident Proportions for Urban Multiple-vehicle Accidents.

	Severity		
Accident Type	Fatal	Injury	PDO
Intersection			
Angle	0.0025	0.2480	0.7495
Head-on	0.0038	0.2321	0.7641
Rear-end	0.0005	0.2357	0.7638
Other	0.0020	0.2131	0.7849
All	0.0020	0.2362	0.7618
Non-intersection			
Angle	0.0012	0.1280	0.8708
Head-on	0.0174	0.2855	0.6971
Rear-end	0.0017	0.2475	0.7508
Other	0.0016	0.1411	0.8573
All	0.0028	0.1884	0.8088
All Urban			
Angle	0.0022	0.2208	0.7770
Head-on	0.0132	0.2691	0.7177
Rear-end	0.0011	0.2419	0.7570
Other	0.0018	0.1793	0.8189
All Urban	0.0023	0.2171	0.7806

Table B-10. Accident Proportions for Single-vehicle Accidents.

	Severity		
Accident Type	Fatal	Injury	PDO
Rural			
Animal	0.0021	0.1004	0.8975
Fixed/other Object	0.0245	0.4070	0.5685
Parked Car	0.0055	0.2031	0.7914
Pedalcycle	0.0338	0.9343	0.0319
Pedestrian	0.1607	0.8350	0.0043
RR Train	0.0886	0.4072	0.5042
Overturn	0.0311	0.5124	0.4565
Other non-collision	0.0186	0.4338	0.5476
All Rural	0.0232	0.4105	0.5663
Urban			
Animal	0.0023	0.1691	0.8286
Fixed/other Object	0.0096	0.3620	0.6284
Parked Car	0.0016	0.1296	0.8688
Pedalcycle	0.0214	0.9680	0.0106
Pedestrian	0.0774	0.9133	0.0093
RR Train	0.0438	0.3802	0.5760
Overturn	0.0225	0.6056	0.3719
Other non-collision	0.0108	0.3839	0.6053
All Urban	0.0122	0.3456	0.6422

Appendix C. SEVERITY INDICES AND ACCIDENT COSTS FOR FIXED OBJECT ACCIDENTS.

Severity Index Approach Used in the AASHTO Barrier Guide

One of the most useful approaches for evaluating roadside safety improvement is the encroachment-probability approach presented in AASHTO's Guide for Selecting, Locating, and Designing Traffic Barriers [62], referred to throughout this appendix as the AASHTO Barrier Guide. The AASHTO Barrier Guide gives severity indices for numerous roadside hazards, such as bridge piers, guardrails, trees, utility poles, and culverts. These severity indices range from 0.0 to 10.0, with higher values representing more hazardous obstacles. The AASHTO Barrier Guide's coded listing of obstacles is reproduced here as Table C-1, and the severity index for each obstacle is reproduced as Table C-2. These severity indices were developed by a panel of experts based on their knowledge of these obstacles from crash tests and other information. These severity indices apply to high-speed facilities and are based on assumed impacts at high speeds, approximately (96.5 km/hr) [62, p. 157].

Similarly, accident costs for high-speed impacts are related to the severity index by using a different distribution of accident severities for each level of the severity index. At a severity index 0.0, all accidents are assumed to be property damage only (PDO) accidents. The percent of injury and fatal accidents increases for higher volumes of the severity index, reaching a level of 5 percent injury and 95 percent fatal at a severity index of 10. These percentages are shown in Table C-3, which also presents estimated accident costs for different severity index levels. These accident costs are based on costs of $200,000 per fatality, $10,000 per injury accident, and $700 per PDO accident, which are similar to 1975 NHTSA values. A graph of these costs taken from the AASHTO Barrier Guide is shown Figure C-1.

The purpose of this appendix is to use actual accident data to develop estimates of average accident costs that are related to the AASHTO Barrier Guide's severity index scale that are consistent with the other accident cost estimates presented in this report. These estimates are developed for three types of roadways: average rural, average urban, and high-speed urban. Based on these data, it also is recommended that some of the severity indices in the AASHTO Barrier Guide, such as those for trees and utility poles, be modified when used with the new cost curves developed in this appendix. In general, however, it appears that the severity indices presented in the AASHTO Barrier Guide are confirmed by the accident data developed in this study, although some modifications are needed to fit the accident cost curves derived in this study.

Table C-1. Obstacle Inventory Codes. (Source: Ref. 62, pp. 258 -260)

Identification Code	Descriptor Code
01. Utility Poles	(00)
02. Trees	(00)
03. Rigid Signpost	(01) single-pole-mounted (02) double-pole-mounted (03) triple-pole-mounted (04) cantilever support (05) overhead sign bridge
04. Rigid Base Luminaire Support	(00)
05. Curbs	(01) mountable design (02) non-mountable design less than 10 in (25.4 cm) high (03) barrier design greater than 10 in (25.4 cm) high
06. Guardrail of Median Barrier	(01) w-section with standard post spacing (6.25 ft or 1.91 m) (02) w-section with other than standard post spacing (03) approach guardrail to bridge--decreased post spacing (3.125 ft or 0.95 m) adjacent to bridge (04) approach guardrail to bridge--post spacing not decreased adjacent to bridge (05) post and cable (06) metal beam guardrail fence barrier (in median) (07) median barrier (CMB design or equivalent)
07. Roadside Slope	(01) sod slope (positive) (02) sod slope (negative) (03) concrete-faced slope (positive) (04) concrete-faced slope (negative) (05) rubble rip-rap slope (positive) (06) rubble rip-rap slope (negative)
08. Ditch (includes erosion, rip-rap runoff ditches, etc., but <u>not</u> ditches formed by front and back slopes	(00)

(continued)

Table C-1. Obstacle Inventory Codes. (Continued)

Identification Code	Descriptor Code
09. Culverts	(01) headwall (or exposed end of pipe culvert) (02) gap between culverts on parallel roadways (03) sloped culvert with grate (04) sloped culvert without grate
10. Inlets	(01) raised drop inlet (tabletop) (02) depressed drop inlet (03) sloped inlet
11. Roadway under Bridge Structure	(01) bridge piers (02) bridge abutment, vertical face (03) bridge abutment, sloped face
12. Roadway over Bridge Structure	(01) open gap between parallel bridges (02) closed gap between parallel bridges (03) rigid bridgerail--smooth and continuous construction (04) semi-rigid bridgerail--smooth and continuous construction (05) other bridgerail--probable penetration, severe snagging and/or pocketing, or vaulting (06) elevated gore abutment
13. Retaining Wall	(01) retaining wall (face) (02) retaining wall (exposed end)

14. Ditches

	Front Slope	Back Slope
(01)	6:1	6:1
(02)	6:1	5:1
(03)	6:1	3.5:1
(04)	5:1	6:1
(05)	5:1	5:1
(06)	5:1	3.5:1
(07)	4:1	6:1
(08)	4:1	5:1
(09)	4:1	3.5:1
(10)	3.6:1	6:1
(11)	3.6:1	5:1
(12)	3.6:1	3.5:1
(13)	3:1	6:1
(14)	3:1	5:1
(15)	3:1	3.5:1

(continued)

15. Crash Cushions (00)

Longitudinal Barrier End Treatment Codes

Beginning Treatment Codes

1. Not Beginning at Structure - Safety Treated
2. Not Beginning at Structure - Not Safety Treated
3. Beginning at Structure - Full-Beam Connection
4. Beginning at Structure - Not Full-Beam Connection

Ending Treatment Codes

1. Not Ending at Structure - Safety Treated
2. Not Ending at Structure - Not Safety Treated
3. Ending at Structure - Full-Beam Connection
4. Ending at Structure - Not Full-Beam Connection

Also, it should be noted that obstacles which are not of the longitudinal class have been designated code 0 for each end treatment.

Table C-2. Severity Indices. (Source: Ref. 62, pp. 261 - 264)

Identification Code	Descriptor Code	End Treatment Code Beginning	End Treatment Code Ending	Severity Index
1	0	0	0	7.1
2	0	0	0	3.0
3	1	0	0	4.7
3	2	0	0	7.2
3	3	0	0	7.2
3	4	0	0	7.2
3	5	0	0	8.1
4	0	0	0	7.5
5	1	0	0	2.4
5	2	0	0	4.1
5	3	0	0	3.7
6	1	1	1	3.7
6	1	1	2	4.0
6	1	1	3	3.6
6	1	1	4	4.5
6	1	2	1	5.6
6	1	2	2	5.7
6	1	2	3	5.3
6	1	2	4	5.7
6	1	3	1	3.3
6	1	3	2	3.3
6	1	3	3	3.3
6	1	3	4	4.6
6	1	4	1	4.5
6	1	4	2	4.7
6	1	4	3	4.5
6	1	4	4	5.0
6	2	1	1	3.9
6	2	1	2	4.2
6	2	1	3	3.8
6	2	1	4	4.7
6	2	2	1	5.8
6	2	2	2	5.9
6	2	2	3	5.5
6	2	2	4	5.9
6	2	3	1	3.5
6	2	3	2	3.5
6	2	3	3	3.5
6	2	3	4	4.8

(continued)

Table C-2. Severity Indices. (Continued)

Identification Code	Descriptor Code	End Treatment Code Beginning	End Treatment Code Ending	Severity Index
6	2	4	1	4.7
6	2	4	2	4.9
6	2	4	3	4.7
6	2	4	4	5.0
6	3	1	1	3.7
6	3	1	2	4.0
6	3	1	3	3.3
6	3	1	4	4.5
6	3	2	1	5.6
6	3	2	2	5.0
6	3	2	3	3.9
6	3	2	4	5.0
6	3	3	1	3.2
6	3	3	2	3.2
6	3	3	3	3.2
6	3	3	4	4.4
6	3	4	1	4.0
6	3	4	2	4.5
6	3	4	3	3.9
6	3	4	4	4.7
6	4	1	1	3.7
6	4	1	2	4.0
6	4	1	3	3.6
6	4	1	4	4.5
6	4	2	1	5.6
6	4	2	2	5.7
6	4	2	3	5.3
6	4	2	4	5.7
6	4	3	1	3.3
6	4	3	2	3.3
6	4	3	3	3.3
6	4	3	4	4.6
6	4	4	1	4.5
6	4	4	2	4.7
6	4	4	3	4.5
6	4	4	4	5.0
6	5	1	1	3.9
6	5	1	2	3.9
6	5	1	3	3.9
6	5	1	4	3.9
6	5	2	1	3.9
6	5	2	2	3.9

(continued)

Table C-2. Severity Indices. (Continued)

Identification Code	Descriptor Code	End Treatment Code Beginning	End Treatment Code Ending	Severity Index
6	5	2	3	3.9
6	5	2	4	3.9
6	5	3	1	3.9
6	5	3	2	3.9
6	5	3	3	3.9
6	5	3	4	3.9
6	5	4	1	3.9
6	5	4	2	3.9
6	5	4	3	3.9
6	5	4	4	3.9
6	6	1	1	4.4
6	6	1	2	4.4
6	6	1	3	4.4
6	6	1	4	5.0
6	6	2	1	5.6
6	6	2	2	5.7
6	6	2	3	5.3
6	6	2	4	5.7
6	6	3	1	4.0
6	6	3	2	4.4
6	6	3	3	4.0
6	6	3	4	4.6
6	6	4	1	4.5
6	6	4	2	4.7
6	6	4	3	4.5
6	6	4	4	5.0
6	7	1	1	4.2
6	7	1	2	4.2
6	7	1	3	4.2
6	7	1	4	4.2
6	7	2	1	4.2
6	7	2	2	4.2
6	7	2	3	4.2
6	7	2	4	4.2
6	7	3	1	4.2
6	7	3	2	4.2
6	7	3	3	4.2
6	7	3	4	4.2
6	7	4	1	4.2
6	7	4	2	4.2
6	7	4	3	4.2
6	7	4	4	4.2

(continued)

Table C-2. Severity Indices. (Continued)

Identification Code	Descriptor Code	End Treatment Code Beginning	End Treatment Code Ending	Severity Index
7	1	0	0	3.0
7	2	0	0	3.0
7	3	0	0	2.5
7	4	0	0	2.5
7	5	0	0	5.1
7	6	0	0	5.1
8	0	0	0	0.0
9	1	0	0	7.9
9	2	0	0	5.5
9	3	0	0	3.3
9	4	0	0	7.7
10	1	0	0	5.7
10	2	0	0	3.1
10	3	0	0	3.3
11	1	0	0	9.3
11	2	0	0	9.3
11	3	0	0	2.5
12	1	0	0	7.2
12	2	0	0	5.5
12	3	0	0	3.3
12	4	0	0	3.0
12	5	0	0	9.3
12	6	0	0	9.3
13	1	0	0	3.3
13	2	0	0	9.3
14	1	0	0	2.2
14	2	0	0	2.4
14	3	0	0	3.0
14	4	0	0	2.3
14	5	0	0	2.5
14	6	0	0	3.0
14	7	0	0	2.6
14	8	0	0	3.0
14	9	0	0	4.0
14	10	0	0	3.5
14	11	0	0	3.8
14	12	0	0	4.5
14	13	0	0	3.6
14	14	0	0	4.2
14	15	0	0	4.8
15	0	0	0	1.0

Table C-3. Severity Index and Accident Costs. (Source: Ref. 62, p. 165)

Severity Index	% PDO Accidents	% Injury Accidents	% Fatal Accidents	Total Accident Cost
0	100	0	0	$ 700
1	85	15	0	2,095
2	70	30	0	3,490
3	55	45	0	4,885
4	40	59	1	8,180
5	30	65	5	16,710
6	20	68	12	30,940
7	10	60	30	66,070
8	0	40	60	124,000
9	0	21	79	160,000
10	0	5	95	190,000

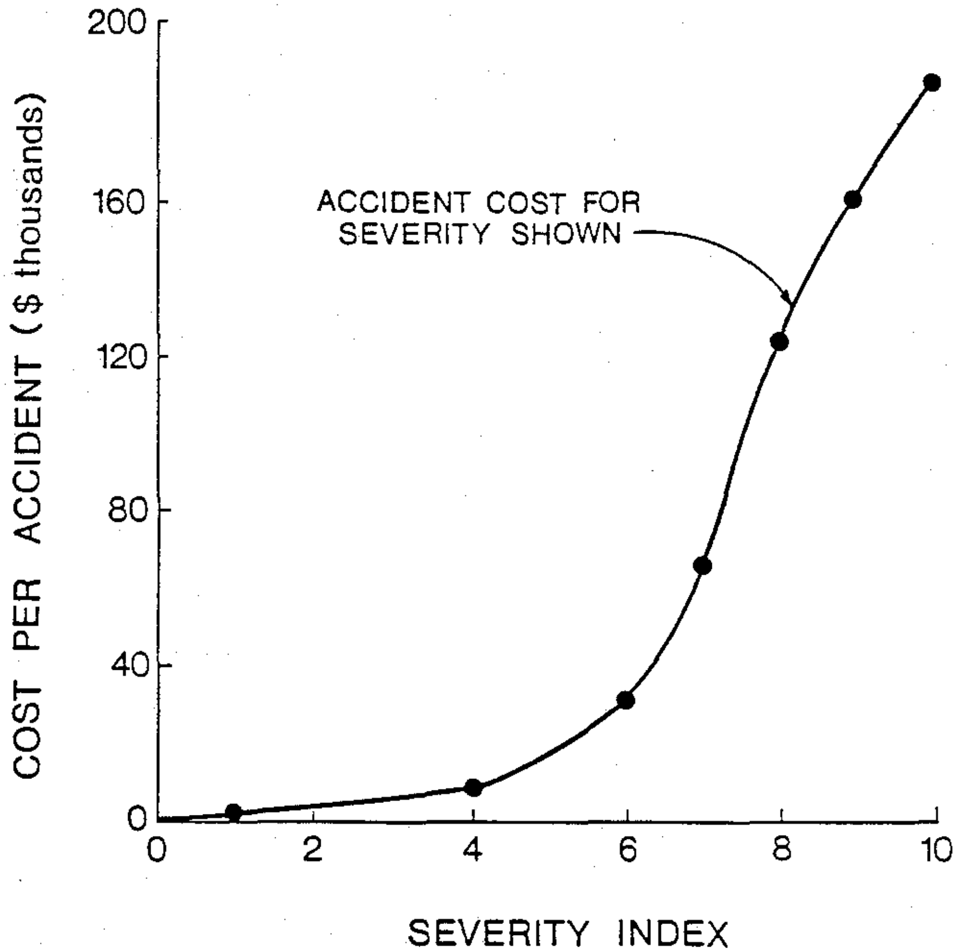


Figure C-1. Average Cost per Accident Related to Severity Index. Source: [62, p. 166].

Accident Costs for Roadside Obstacles

Cost per accident for different types of roadside obstacles are developed using the same method as that described for other accidents in Chapter III of the final report, Volume I. Tables C-4 and C-5 show the average numbers of fatalities and injuries by A-B-C type for fatal accidents in rural and urban areas, respectively, by type of obstacle hit. For example, it can be seen in Table C-4 that vehicles hitting underpasses (presumably bridge piers and abutments) in rural fatal accidents had an average of 1.45 fatalities, 0.30 A injuries, 0.10 B injuries, and 0.00 C injuries per fatal accident. Similar averages for A-B-C injuries in injury accidents are given in Tables C-6 and C-7 for rural and urban areas, respectively. The values in C-4 through C-7 are based on Texas accident data for 1978-79.

Indirect costs per accident are derived by multiplying the appropriate indirect cost per fatality or injury from Table C-8 by numbers of fatalities and injuries from Tables C-4 through C-7. Indirect costs per accident are added to the direct costs per accident from Table C-9 to derive the total cost per accident by severity and type of area. The percent of accidents by severity (fatal, injury, PDO) and number of accidents in the sample are shown in Table C-10 for rural accidents and in Table C-11 for urban accidents. As might be expected, the types of accidents with the highest percent of fatal and injury accidents in Tables C-10 and C-11 also are types with the highest numbers of fatalities and severe injuries per accident in Tables C-4 through C-7. To derive the indirect cost per accident, the number of fatalities and injuries by type from C-4 through C-7 are multiplied by the costs per injury and fatality from Table C-8. These indirect cost are added to the direct costs per accident from Table C-9 to derive the total cost per accident by severity and type of area, as shown in the first three columns of Tables C-12 and C-13. Using the proportions of accidents by severity from Tables C-10 and C-11, the average costs for different types of accidents, weighted across all severities, are derived and are shown in the last column in Tables C-12 and C-13.

The technique used to develop these costs in Tables C-12 and C-13 accounts for four sources of severity for more severe accidents: (1) higher percentages of fatal and injury accidents (Tables C-10 and C-11), (2) higher numbers of fatalities and more severe injuries for fatal accidents (Tables C-4 and C-5), (3) higher numbers of more severe injuries in injury accidents (Tables C-6 and C-7), and (4) higher indirect costs for A, B, and C injuries in fatal accidents than for the corresponding A, B, and C injuries in injury accidents (Table C-8). Because direct accidents costs were developed using State studies that did not differentiate between different types of fixed object/other object accidents, the direct costs that are used are the same for all

Table C-4. Fatalities and Injuries for A-B-C Categories, by Type of Obstacle, for Rural Fatal Accidents.

Type of Accident	Average Per Accident			
	Fatalities	A Injuries	B Injuries	C Injuries
Underpass	1.45	0.30	0.10	0.00
Bridge End	1.17	0.36	0.14	0.00
Traffic Signal Pole**	1.13	0.40	0.16	0.05
Tree	1.13	0.40	0.16	0.05
Culvert	1.14	0.60	0.17	0.07
Overturned	1.08	0.36	0.36	0.15
Guard Post or Rail	1.15	0.49	0.20	0.11
Side of Bridge	1.24	0.58	0.15	0.10
Luminaire Pole**	1.05	0.33	0.26	0.15
Curb**	1.05	0.33	0.26	0.15
Other Fixed Objects	1.06	0.25	0.13	0.04
Other Objects	1.20	0.35	0.20	0.05
Commercial Sign**	1.05	0.33	0.26	0.15
Utility Pole	1.05	0.33	0.26	0.15
Railroad Signal Pole**	1.00	0.36	0.09	0.00
Mail Box	1.00	0.36	0.09	0.00
Highway Sign	1.06	0.34	0.19	0.03
Construction Material	1.00	0.33	0.00	0.00
Fence	1.13	0.46	0.21	0.10
Railroad Crossing Gates	No fatal accidents			
Overhead Obstruction	No fatal accidents			
Attenuation Device	No fatal accidents			

* Based on 1978-79 Texas accident data.

** Because of small sample sizes, traffic signal poles values were assumed to be the same as trees; luminaire poles, curbs, and commercial signs were assumed to be the same as utility poles; railroad signal poles were assumed to be the same as mail boxes.

Table C-5. **Fatalities and Injuries for A-B-C Categories, by Type of Obstacle, for Rural Fatal Accidents.**

Type of Accident	Average Per Accident			
	Fatalities	A Injuries	B Injuries	C Injuries
Underpass	1.15	0.30	0.11	0.00
Bridge End	1.20	0.23	0.07	0.20
Traffic Signal Pole	1.13	0.38	0.13	0.13
Tree	1.13	0.19	0.20	0.03
Culvert	1.05	0.32	0.09	0.00
Overturned	1.05	0.28	0.25	0.14
Guard Post or Rail	1.09	0.28	0.19	0.15
Side of Bridge	1.10	0.24	0.08	0.03
Luminaire Pole	1.09	0.29	0.19	0.10
Curb	1.04	0.11	0.32	0.04
Other Fixed Objects	1.09	0.32	0.18	0.06
Other Objects	1.08	1.04	0.58	0.25
Commercial Sign	1.14	0.14	0.29	0.00
Utility Pole	1.10	0.16	0.19	0.09
Railroad Signal Pole**	1.05	0.25	0.10	0.10
Mail Box	1.00	0.13	0.13	0.00
Highway Sign	1.04	0.31	0.02	0.08
Construction Material	1.20	0.40	0.40	0.00
Fence	1.08	0.25	0.17	0.00
Railroad Crossing Gates**	1.05	0.25	0.10	0.10
Overhead Obstruction**	1.05	0.25	0.10	0.10
Attenuation Device**	1.05	0.25	0.10	0.10

* Based on 1978-79 Texas accident data.

** Since there were fewer than five fatal accidents for each of these types, the values were assumed to be as shown.

Table C-6. **Fatalities and Injuries for A-B-C Categories, by Type of Obstacle, for Rural Fatal Accidents.**

Type of Accident	Average Per Accident		
	A Injuries	B Injuries	C Injuries
Underpass	0.52	0.79	0.37
Bridge End	0.39	0.59	0.36
Traffic Signal Pole	0.42	0.50	0.67
Tree	0.38	0.68	0.33
Culvert	0.41	0.71	0.30
Overturned	0.33	0.70	0.42
Guard Post or Rail	0.33	0.66	0.37
Side of Bridge	0.33	0.71	0.37
Luminaire Pole	0.19	0.72	0.34
Curb	0.34	0.63	0.38
Other Fixed Objects	0.27	0.72	0.38
Other Objects	0.33	0.74	0.53
Commercial Sign	0.47	0.80	0.20
Utility Pole	0.30	0.68	0.37
Railroad Signal Pole	0.44	0.61	0.39
Mail Box	0.28	0.64	0.33
Highway Sign	0.25	0.66	0.35
Construction Material	0.37	0.66	0.37
Fence	0.27	0.68	0.38
Railroad Crossing Gates	0.00	0.50	0.50
Overhead Obstruction	0.00	0.75	0.25
Attenuation Device	0.00	1.00	0.00

* Based on 1978-79 Texas accident data.

Table C-7. Fatalities and Injuries for A-B-C Categories, by Type of Obstacle, for Rural Fatal Accidents.

Type of Accident	Average Per Accident		
	A Injuries	B Injuries	C Injuries
Underpass	0.32	0.69	0.30
Bridge End	0.38	0.69	0.27
Traffic Signal Pole	0.19	0.82	0.25
Tree	0.23	0.79	0.31
Culvert	0.27	0.73	0.28
Overturned	0.22	0.76	0.33
Guard Post or Rail	0.19	0.70	0.38
Side of Bridge	0.20	0.67	0.40
Luminaire Pole	0.16	0.77	0.32
Curb	0.22	0.65	0.32
Other Fixed Objects	0.20	0.73	0.36
Other Objects	0.20	0.73	0.43
Commercial Sign	0.15	0.80	0.33
Utility Pole	0.17	0.80	0.32
Railroad Signal Pole	0.29	0.83	0.24
Mail Box	0.16	0.78	0.33
Highway Sign	0.17	0.69	0.29
Construction Material	0.26	0.69	0.29
Fence	0.18	0.72	0.37
Railroad Crossing Gates	0.25	0.83	0.25
Overhead Obstruction	0.25	0.38	0.38
Attenuation Device	0.11	0.76	0.32

* Based on 1978-79 Texas accident data.

Table C-8. Indirect Cost per Fatality and Injury, by Type of Accident and Category of Injury, 1980 Dollars.

Type of Accident	Average Per Accident			
	Fatality	A Injury	B Injury	C Injury
Fatal	$471,781	$51,149	$10,516	$4,152
Injury	--	19,099	3,744	595

Table C-9. Direct Cost for Fixed Object Accidents and Overturned Accidents, by Rural and Urban Areas, 1980 Dollars.

Type of Accident and Area	Severity of Accident		
	Fatal	Injury	PDO
Fixed Object/Other Object			
Rural	$ 9,500	$4,100	$1,550
Urban	10,900	4,800	600
Overturned			
Rural	11,400	5,700	1,500
Urban	11,100	2,800	850

Table C-10. Rural Accident Frequency and Percent of Accidents by Severity.

Type of Accident	Number of Accidents	Percent of Accidents by Accident Severity		
		Fatal	Injury	PDO
Underpass	120	16.67%	43.33%	40.00%
Bridge End	678	10.18	41.74	48.08
Traffic Signal Pole	41	7.32	29.27	63.41
Tree	3,881	4.72	53.70	41.59
Culvert	2,410	3.36	57.68	38.96
Overturned	15,582	3.65	52.52	43.83
Guard Post or Rail	2,975	3.19	39.33	57.48
Side of Bridge	2,545	2.79	37.29	59.92
Luminaire Pole	185	2.70	36.76	60.54
Curb	112	2.68	28.57	68.75
Other Fixed Objects	5,739	2.33	49.99	47.67
Other Objects	951	2.10	31.02	66.88
Commercial Sign	46	2.17	32.61	65.22
Utility Pole	1,853	2.10	42.20	55.69
Railroad Signal Pole	55	1.82	32.73	65.45
Mail Box	683	1.61	35.87	62.52
Highway Sign	2,075	1.54	26.97	71.48
Construction Material	216	1.39	27.31	71.30
Fence	4,999	1.36	38.37	60.27
Railroad Crossing Gates	6	0.00	33.33	66.67
Overhead Obstruction	31	0.00	12.90	87.10
Attenuation Device	4	0.00	25.00	75.00

* Based on 1978-79 Texas accident data.

Table C-11. Rural Accident Frequency and Percent of Accidents by Severity.

Type of Accident	Number of Accidents	Percent of Accidents by Accident Severity		
		Fatal	Injury	PDO
Underpass	843	5.46%	50.30%	44.25%
Bridge End	497	6.04	48.29	45.67
Traffic Signal Pole	1,694	0.47	30.05	69.48
Tree	8,071	1.60	43.27	55.14
Culvert	1,424	1.54	54.21	44.24
Overturned	10,495	2.41	60.81	36.78
Guard Post or Rail	10,990	1.22	37.80	60.98
Side of Bridge	3,931	1.50	36.50	61.99
Luminaire Pole	7,843	0.87	40.12	59.01
Curb	3,051	0.92	40.68	58.41
Other Fixed Objects	10,978	0.75	39.94	59.31
Other Objects	2,661	0.90	27.32	71.78
Commercial Sign	660	3.64	35.91	60.45
Utility Pole	13,381	0.70	43.73	55.57
Railroad Signal Pole	189	1.06	30.69	68.25
Mail Box	1,047	0.76	27.03	72.21
Highway Sign	6,032	0.80	26.36	72.84
Construction Material	702	1.42	33.33	65.24
Fence	5,757	0.35	24.10	75.55
Railroad Crossing Gates	72	0.00	16.67	83.33
Overhead Obstruction	325	0.92	2.46	96.62
Attenuation Device	290	1.03	42.07	56.90

* Based on 1978-79 Texas accident data.

Table C-12. Total Cost per Rural Accident, by Severity, 1980 Dollars.

Type of Accident	Cost per Accident			
	Fatal	Injury	PDO	Average
Underpass	$710,000	$17,200	$1,600	$126,500
Bridge End	581,400	14,000	1,600	65,800
Traffic Signal Pole	565,000	14,400	1,600	46,600
Tree	565,000	14,100	1,600	34,900
Culvert	580,000	14,800	1,600	32,000
Overturned	543,100	14,900	1,550	28,300
Guard Post or Rail	579,700	13,100	1,600	24,600
Side of Bridge	626,200	13,300	1,600	23,400
Luminaire Pole	525,100	10,600	1,600	19,000
Curb	525,100	13,200	1,600	16,300
Other Fixed Objects	523,900	12,200	1,600	19,100
Other Objects	595,800	13,500	1,600	17,800
Commercial Sign	525,100	16,200	1,600	17,700
Utility Pole	525,100	12,600	1,600	17,200
Railroad Signal Pole	500,600	15,000	1,600	15,100
Mail Box	500,600	12,000	1,600	13,400
Highway Sign	529,100	11,600	1,600	12,400
Construction Material	498,200	13,900	1,600	11,900
Fence	568,800	12,000	1,600	13,300
Railroad Crossing Gates	--	6,300	1,600	3,200
Overhead Obstruction	--	7,100	1,600	2,300
Attenuation Device	--	7,800	1,600	3,200

Table C-13. Total Cost per Rural Accident, by Severity, 1980 Dollars.

Type of Accident	Cost per Accident			
	Fatal	Injury	PDO	Average
Underpass	$570,000	$13,700	$650	$38,300
Bridge End	590,400	14,800	650	43,100
Traffic Signal Pole	565,400	11,700	650	6,600
Tree or Shrub	556,000	12,300	650	14,600
Culvert	523,600	12,900	650	15,300
Overturned	524,000	10,000	900	19,000
Guard Post or Rail	542,100	11,300	650	11,300
Side of Bridge	543,100	11,440	650	12,700
Luminaire Pole	542,100	11,000	650	9,500
Curb	510,700	11,600	650	9,800
Other Fixed Objects	543,700	11,600	650	9,100
Other Objects	580,800	11,600	650	8,900
Commercial Sign	558,900	10,900	650	24,700
Utility Pole	540,400	11,200	650	9,000
Railroad Signal Pole	520,500	13,600	650	10,100
Mail Box	490,700	11,000	650	7,200
Highway Sign	518,000	10,900	650	7,500
Construction Material	601,700	12,500	650	13,100
Fence	535,000	11,200	650	5,100
Railroad Crossing Gates	520,500	12,800	650	2,700
Overhead Obstruction	520,500	11,200	650	5,700
Attenuation Device	520,500	9,900	650	9,900

accidents with a given severity and type of area (urban, rural). This may result in underestimating the direct costs for the more severe accidents and overstating the direct costs for the less severe accidents.

Relating Accident Costs to Severity Index

Several problems are encountered in estimating a cost curve as a function of the severity index from the costs in Tables C-12 and C-13. Most of the accident types shown in these two tables do not match the coded obstacles in Tables C-1 and C-2 from AASHTO Barrier Guide, because the former are averages over a wide range of conditions and thus lack the detail of the latter. For example, the AASHTO Barrier Guide lists numerous types of guardrails, whereas the accident data used in developing Tables C-12 and C-13 has the general category of "guard post or rail." Also, some obstacles such as a tree or a utility pole are similar in each listing, but accident records indicate a different severity code from that in the AASHTO Barrier Guide, as will be discussed more fully in the last section of this appendix.

However, some key accident types appear to be sufficiently similar in each listing to form the basis for deriving cost curves. Also, it is fairly clear that most costs fit within an array in much the same way as given in the AASHTO Barrier Guide. Specific accident types that appear similar in each listing are: (1) "underpass," which can be presumed to match with bridge pier or other codings that have a severity index of 9.3 in the AASHTO Barrier Guide, (2) "culvert," which appears to match with culvert headwall or exposed end of pipe culvert, with a severity index of 7.9 in the AASHTO Barrier Guide, and (3) "curb," which probably matches well with non-mountable curbs (5-02 and 5-03) in the AASHTO Barrier Guide that have an average severity index 3.9 (average of 3.7 and 4.1). Two curves, one for rural and one for urban, were fitted to these three points using the costs for underpass, culvert, and curb from Tables C-12 and C-13. The equations for these curves are used to estimate the cost curve between severity indices of 3.9 and 9.3 for rural and urban areas.

The lower part of each of the two curves was estimated by projecting two linear segments from the value given by the curves at the severity index of 3.9. The first segment was projected from the curve at 3.9 to a point represented by the cost of "highway signs" with an assumed severity index of 2.0. Highway signs are an obstacle having one of the lower average accident costs and also showing the desired relative consistency between rural and urban costs. It is assumed that most of these highway signs either are of breakaway design or are relatively small signs. The lowest segment of each curve from 2.0 down to 0.0 is obtained by projecting a line from highway sign cost at an index of 2.0 down to lowest railroad crossing gates, at an assigned index of 0.0.

The upper part of each of the curves, between 9.3 and assigned index of 0.0. The upper part of each of the curves, between 9.3 and 10.0 is estimated by assuming a linear function that changes at the same rate as does the estimated curve between 9.2 and 9.3. (This upper part of each the curves between 9.3 and 10.0 is hypothetical).

In summary, the curves are fitted between points given by average accident cost of : (1) railroad grade crossing gates, with an index assigned at 0.0, (2) "highway signs," presumed to be breakaway or relatively small signs, at 2.0, (3) curbs at 3.9, (4) culverts at 7.9, and (5) "underpass" (bridge pier, etc.) at 9.3. The curves are assumed to be linear between 0.0 and 2.0 and also (with a different slope) between 2.0 and 3.9. They are upward sloping at an increasing rate between 3.9 and 9.3 and then at a constant rate, which is hypothetical, between 9.3 and 10.0.

The specific estimating functions are presented in Table C-14 for "average urban." Also given Table C-14 is another category designated as "high-speed urban." This latter curve is developed as follows. Average costs for vehicles impacting roadside obstacles for "controlled access urban highways" are 22 percent greater than "average urban," and average costs for "other divided urban highways" are 36 percent greater than "average urban." Based on these percentages, a "high-speed urban" category was added, for which it is assumed that average accident costs are 29 percent above average urban for index values from 2.0 to 10.0. Since a 29 percent over average urban at a severity index of 0.0 would give a cost for high-speed urban that would be above the rural cost of $3,200 at 0.0 and to be linear between 0.0 and 2.0, reaching $9,680 at 2.0. The relative accident costs on which the high-speed urban curve is based are given as ratios in Table C-15, along with other ratios that the safety analyst may consider in assigning severity indices.

The three curves relating accidents with roadside obstacles to the severity index are plotted in Figure C-2 for index values up to 9.3. A detailed listing of costs for the average urban, high-speed urban, and average rural curves is given in Table C-16, with value from 0.0 to 10.0.

A summary of accident costs for average urban and rural from Tables C-12 and C-13 is reproduced in ascending order of costs in Table C-17, together with the indicated severity indices that match these costs, taken from Table C-16. As mentioned previously, the most severe type of accident in this listing is "underpass" which is presumed to be the notation used for vehicles striking bridge piers or retailing walls, each of which has the most severe rating of 9.3 in the AASHTO Barrier Guide. In Table C-17, the most severe urban accident (with an assigned index 9.4) is for bridge ends, assumed to include elevated gore abutments.

Table C-14. Summary of Equations Relating Average Accident Costs to Severity Index.

Range of Index	Equation*
Average Urban:	
0.0 to 2.0	$C = 2.700 + 2.400I$
2.0 to 3.9	$C = 4.973 + 1.268I$
3.9 to 9.3	$C = (.103287-.00001023I^{4})^{-1}$
9.3 to 10.0	$C = 37.374 + 40.3(I-9.3)$
Average Rural:	
0.0 to 2.0	$C = 3.200 + 4.600I$
2.0 to 3.9	$C = 8.368 + 2.016I$
3.9 to 9.3	$C = (.06588-.00007159I^{3})^{-1}$
9.3 to 10.0	$C = 120.56 + 218.7(I-9.3)$
High-Speed Urban:**	
0 to 2.0	$C = 3.0 + 3.34I$
2.0 to 10.0	129% of Average Urban

* C = average cost per accident, in thousands of dollars
I = severity index

** High-speed urban includes urban controlled-access highways and other high-speed urban highways.

Table C-15. Possible Adjustment Factors by Type of Roadway for Accidents Involving Roadside Obstacles.

Type of Roadway	Ratio of Average Accident Costs		
	Urban by Type to Average Urban	Rural by Type to Average Rural	Urban of Type to Same Rural Type
Average	1.00	1.00	0.45
Controlled Access	1.22	0.96	0.57
Other Divided	1.36	1.04	0.59
Undivided	0.90	1.00	0.40

* Developed from average costs for accidents with all roadside obstacles.

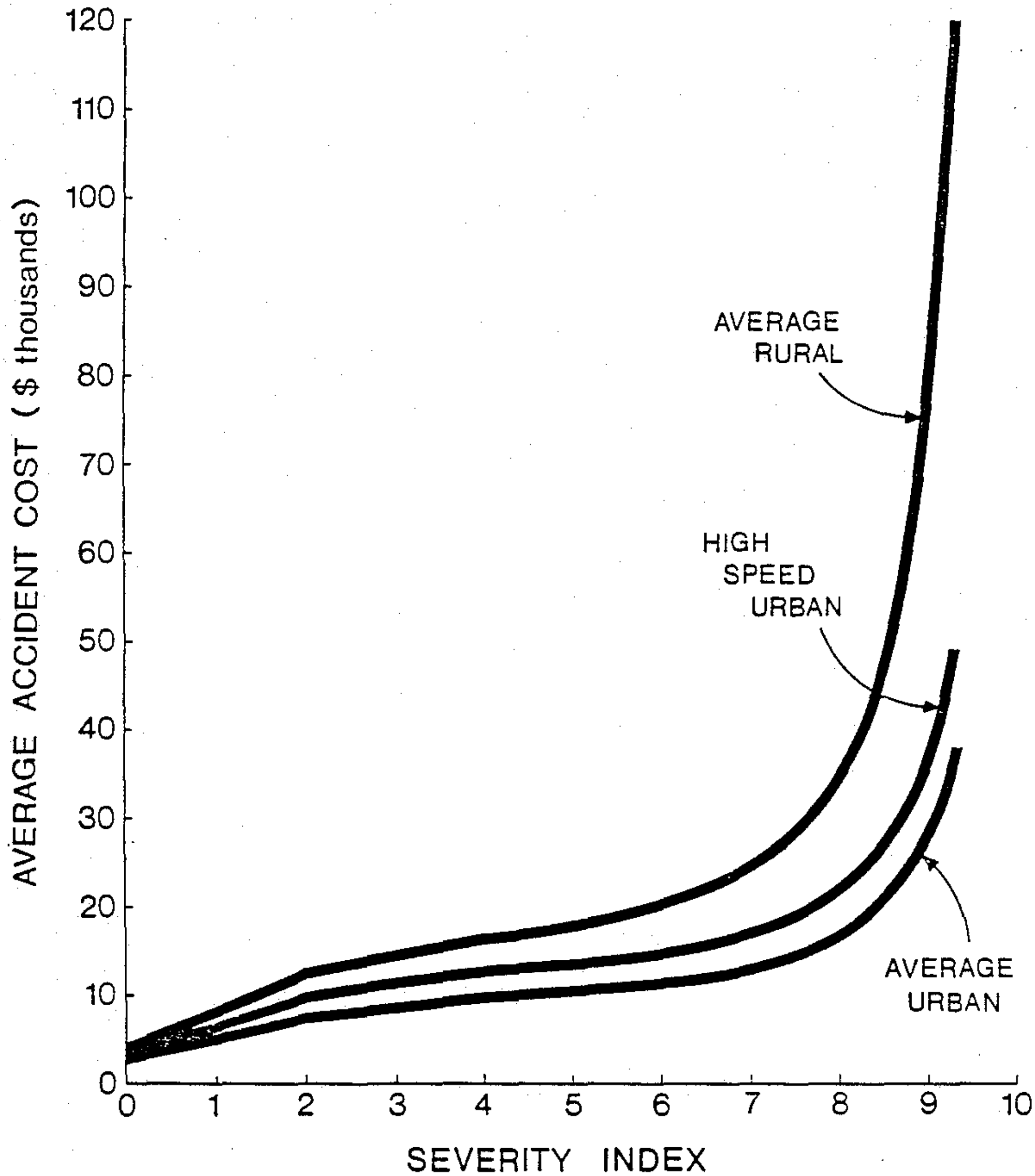


Figure C-2. AVERAGE COST PER ACCIDENT FOR RURAL AND URBAN ACCIDENTS RELATED TO SEVERITY INDEX.

Table C-16. Average Accident Cost Related to Severity Index, by Type of Roadway, 1980 Dollars.

Severity Index	Average Urban	High-Speed Urban	Average Rural
0.0	$2,700	$ 3,000	$ 3,200
0.1	2,940	3,330	3,660
0.2	3,180	3,670	4,120
0.3	3,420	4,000	4,580
0.4	3,660	4,340	5,040
0.5	3,900	4,670	5,500
0.6	4,140	5,000	5,960
0.7	4,380	5,340	6,420
0.8	4,620	5,670	6,880
0.9	4,860	6,010	7,340
1.0	5,100	6,340	7,800
1.1	5,340	6,670	8,260
1.2	5,580	7,010	8,720
1.3	5,820	7,340	9,180
1.4	6,060	7,680	9,640
1.5	6,300	8,010	10,100
1.6	6,540	8,340	10,560
1.7	6,780	8,680	11,020
1.8	7,020	9,010	11,480
1.9	7,260	9,350	11,940
2.0	7,500	9,680	12,400
2.1	7,640	9,860	12,600
2.2	7,760	10,010	12,800
2.3	7,890	10,180	13,000
2.4	8,020	10,350	13,210
2.5	8,140	10,500	13,410
2.6	8,270	10,670	13,610
2.7	8,400	10,840	13,810
2.8	8,520	10,990	14,010
2.9	8,650	11,160	14,210
3.0	8,780	11,330	14,420
3.1	8,900	11,480	14,620
3.2	9,030	11,650	14,820
3.3	9,160	11,820	15,020
3.4	9,280	11,970	15,220
3.5	9,410	12,140	15,420
3.6	9,540	12,310	15,630
3.7	9,660	12,460	15,820
3.8	9,790	12,630	16,030

(continued)

Table C-16. Average Accident Cost Related to Severity Index, by Type of Roadway, 1980 Dollars. (Continued)

Severity Index	Average Urban	High-Speed Urban	Average Rural
3.9	$ 9,920	$12,800	$16,230
4.0	9,930	12,810	16,310
4.1	9,960	12,850	16,410
4.2	9,990	12,890	16,510
4.3	10,020	12,930	16,620
4.4	10,060	12,980	16,730
4.5	10,090	13,020	16,850
4.6	10,130	13,070	16,980
4.7	10,170	13,120	17,110
4.8	10,220	13,180	17,250
4.9	10,270	13,250	17,410
5.0	10,320	13,310	17,570
5.1	10,380	13,390	17,740
5.2	10,440	13,470	17,920
5.3	10,500	13,550	18,110
5.4	10,570	13,640	18,310
5.5	10,650	13,740	18,530
5.6	10,730	13,840	18,760
5.7	10,810	13,940	19,000
5.8	10,900	14,060	19,260
5.9	11,000	14,190	19,540
6.0	11,110	14,330	19,840
6.1	11,220	14,470	20,150
6.2	11,340	14,630	20,490
6.3	11,470	14,800	20,840
6.4	11,610	14,980	21,230
6.5	11,760	15,170	21,640
6.6	11,920	15,380	22,080
6.7	12,100	15,610	22,550
6.8	12,280	15,840	23,060
6.9	12,480	16,100	23,610
7.0	12,700	16,380	24,200
7.1	12,940	16,690	24,840
7.2	13,190	17,020	25,540
7.3	13,470	17,380	26,300
7.4	13,770	17,760	27,120
7.5	14,100	18,190	28,030
7.6	14,460	18,650	29,030
7.7	14,850	19,160	30,130

(continued)

Table C-16. Average Accident Cost Related to Severity Index, by Type of Roadway, 1980 Dollars. (Continued)

Severity Index	Average Urban	High-Speed Urban	Average Rural
7.8	$15,290	$19,720	$ 31,340
7.9	15,760	20,330	32,700
8.0	16,290	21,010	34,220
8.1	16,880	21,780	35,930
8.2	17,530	22,610	37,870
8.3	18,270	23,570	40,090
8.4	19,100	24,640	42,650
8.5	20,050	25,860	45,640
8.6	21,130	27,260	49,160
8.7	22,380	28,870	53,370
8.8	23,850	30,770	58,510
8.9	25,580	33,000	64,890
9.0	27,650	35,670	73,050
9.1	30,180	38,930	83,820
9.2	33,340	43,010	98,690
9.3	37,370	48,210	120,560
9.4	41,400	53,410	142,430
9.5	45,430	58,600	164,300
9.6	49,460	63,800	186,170
9.7	53,490	69,000	208,040
9.8	57,520	74,200	229,910
9.9	61,550	79,400	251,780
10.0	65,580	84,600	273,650

Table C-17. Summary of Average Accident Costs with Indicated Severity Indexes.

Type of Accident	Accident Cost		Indicated Severity Index	
	Average Urban	Average Rural	Urban	Rural
1. Railroad Crossing Gates	$ 2,700	$ 3,200	0.0	0.0
2. Overhead Obstruction	5,700	2,300	1.2	0.0
3. Attenuation Device	9,900	3,200	2.2*	0.0
4. Construction Material	13,100	11,900	7.2	1.9
5. Fence	5,100	13,300	1.0	2.4
6. Highway Sign	7,500	12,400	2.0	2.0
7. Mail Box	7,200	13,400	1.9	2.5
8. Railroad Signal Pole	10,100	15,100	4.5	3.3
9. Curb	9,800	16,300	3.8	4.0
10. Utility Pole	9,000	17,200	3.2	4.8
11. Commercial Sign	24,700	17,700	8.9	5.1
12. Other Objects	8,900	17,800	3.1	5.1
13. Luminaire Pole	9,500	19,000	3.6	5.7
14. Other Fixed Objects	9,100	19,100	3.3	5.7
15. Side of Bridge	12,700	23,400	7.0	6.9
16. Guard Post or Rail	11,300	24,600	6.2	7.1
17. Overturned	19,000	28,300	8.4	7.5
18. Culvert	15,300	32,000	7.8	7.8
19. Tree	14,600	34,900	7.6	8.0
20. Traffic Signal Pole	6,600	46,600	1.6	8.5
21. Bridge End	43,100	65,800	9.4	8.9
22. Underpass	38,300	126,500	9.3	9.3

*This value was assigned using the curve for high-speed urban highways, since it is presumed that these attenuation devices mainly are crash cushions on freeways.

In general, the indicated severity index for urban areas is similar to that for rural areas, although there are notable exceptions. For example, "commercial signs" rates an 8.9 index in urban areas. This suggests that collisions with commercial signs in urban areas tend to occur at much higher speeds than the average urban accident and are even more costly than rural collisions with commercial signs.

Another obstacle with markedly different severity indices between urban and rural areas in Table C-17 is "traffic signal pole," with an index of only 1.6 in urban areas but 8.5 in rural areas. This also is probably explained by impact speed, with traffic signal poles in urban areas typically being hit on city streets at low speeds, whereas the 8.5 index is representative of rigid signal poles being hit at relatively high speeds in rural areas. This 8.5 rating probably also should be assigned to rigid sign posts and rigid luminaire poles (including steel) shoe base, aluminum shoe base, or steel transformer base) in rural or high-speed urban situations, especially if the obstacle is near the roadway.

Adjustment of Indicated Severity Indices

The indicated severity indices in the last two columns of Table C-17 are those that are "indicated" based on the listing of costs in Table C-16, which in turn are based on the equations given in Table C-14 and plotted in Figure C-2. These severity indices and related costs have several limitations. First, the direct costs that were used in deriving the accident costs varied by accident severity but not by type of obstacle within severity types. Therefore, direct costs vary by obstacle to the extent that different obstacles have different percentages of fatal, injury, and PDO accidents, but not according to the specific numbers of persons killed or injured by obstacle type within the specific fatal or injury accident category.

For example, in rural areas, an injury accident has assumed direct cost of $14,100 whatever the type of obstacle struck. This direct cost mainly includes the cost of vehicle damage and medical expenses. This direct cost undoubtedly is understated for the more severe accidents and is overstated for the less severe accidents within each accident severity type. For example, in rural areas, the number A and B injuries in bridge end injury accidents averages 0.98 per accident but in highway sign accidents averages only 0.24 per accident. Thus, it is easy to presume that the direct costs for the more severe injury accidents, or which bridge end accidents are representative, could be several thousand dollars more than the average $4,100, whereas the less severe injury accidents such as highway signs accidents probably are, say, one to two thousand dollars too high. This effect probably is most important within the injury accident category. It also probably is important in the more severe fatal accidents, where the medical costs of severe injuries can be large.

A second limitation is that several of the estimates are based on small samples. For the rural accidents, 10 estimates are each based on 216 or fewer accidents. These are railroad crossing gates (six accidents), overhead obstructions (31), attenuation devices (four), railroad signal poles (55), commercial signs (46), traffic signal poles (41), curb (112), construction material (216), luminaire pole (185), and underpass (120). The other 12 obstacle types are based on more than 600 accidents each.

To partially determine the extent to which small sample sizes in rural areas may have affected the assigned severity indices, another type of analysis, separate from estimation of accident costs, was performed. This second type of analysis consisted of determining the average numbers of fatalities and injuries of various types for all accidents by type of obstacle. These numbers are presented in Table C-18 for rural areas. The first column in Table C-18, for example, gives the number of fatalities and A injuries occurring in fatal and injury accidents divided by total (fatal, injury, and PDO) accidents. The second two columns are similar but also include B injuries in column 2 and B and C injuries in column 3. In Figure C-3, C-4, and C-5, the value in Table C-18 is plotted versus the "indicated" severity indices for rural areas from Table C-17.

These three figures are interesting for analyzing the effects of small sample sizes because they give average fatalities and injuries without the weighting implicit in accident cost calculations. In each figure, a curve was drawn that roughly fits the scatter of points, with emphasis on those points (the X's) that are based on more than 600 observations each.

One of the points that stands out in all three figures for being off estimated curves is number 20, that for traffic signal poles. Closer examination indicates that the estimated average accident cost for traffic signal poles was distorted by having 4 fatal accidents out of only 41 accidents. The values in Table C-18 and the three figures indicate that the severity of most traffic signal pole accidents in rural areas are more similar to, say commercial signs or "other fixed objects," rather than being the third most severe type of accident, as indicated by average accident cost. There are two possibilities. First, the large percent of fatal accidents may be mere chance, and all traffic signal poles in rural areas should be rated in, say, the 4.0 to 6.0 severity index range. Second, there may be some signal poles that should have very severe ratings in the high 8's or low 9's, while most other poles would be around, say, 4.0 to 5.0. This latter possibility would seem most plausible if there are some isolated,

Table C-18. Fatalities and Injuries Grouped in Various Ways and Divided by Total Accidents, by Type of Obstacle.

Type of Accident	Number Divided by Total Accidents		
	Fatalities Plus A Injuries	Fatalities Plus A & B Injuries	Fatalities Plus A,B,&C Injuries
Railroad Crossing Gates	0.000	0.167	0.333
Overhead Obstruction	0.000	0.096	0.129
Attenuation Device	0.000	0.250	0.250
Construction Material	0.120	0.301	0.403
Fence	0.126	0.388	0.536
Highway Sign	0.089	0.269	0.365
Mail Box	0.123	0.356	0.473
Railroad Signal Pole	0.182	0.382	0.527
Curb	0.134	0.313	0.420
Utility Pole	0.154	0.446	0.608
Commercial Sign	0.218	0.478	0.543
Other Objects	0.136	0.370	0.534
Luminaire Pole	0.119	0.384	0.508
Other Fixed Objects	0.164	0.524	0.718
Side of Bridge	0.174	0.441	0.581
Guard Post or Rail	0.183	0.450	0.599
Overturned	0.226	0.604	0.829
Culvert	0.296	0.709	0.885
Tree	0.279	0.653	0.834
Traffic Signal Pole	0.220	0.366	0.561
Bridge End	0.320	0.581	0.733
Underpass	0.517	0.875	1.033

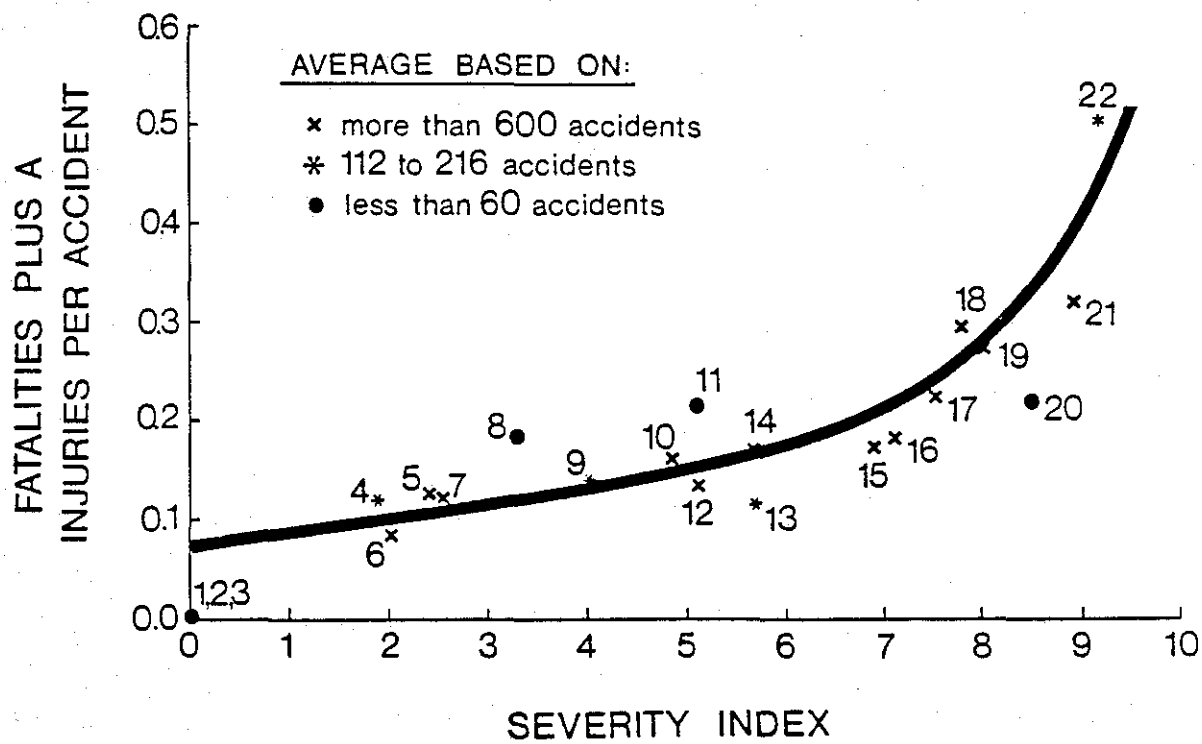


Figure C-3. FATALITIES PLUS A INJURIES DIVIDED BY TOTAL ACCIDENTS, RELATED TO SEVERITY INDEX, FOR RURAL ACCIDENTS. Source: Tables C-17 and C-18.

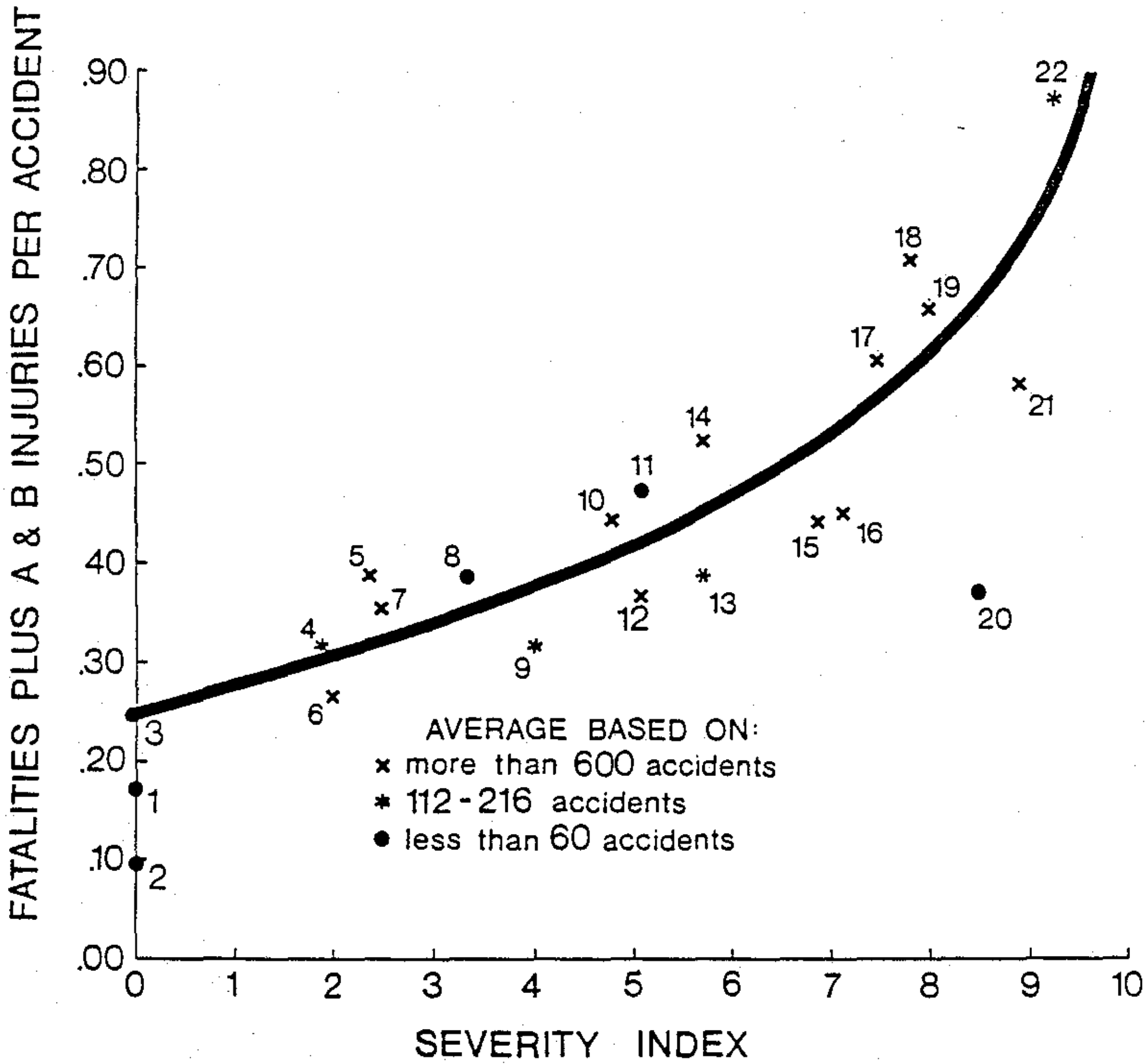


Figure C-4. FATALITIES PLUS A AND B INJURIES DIVIDED BY TOTAL ACCIDENTS, RELATED TO SEVERITY INDEX, FOR RURAL ACCIDENTS. Source: Tables C-17 and C-18.

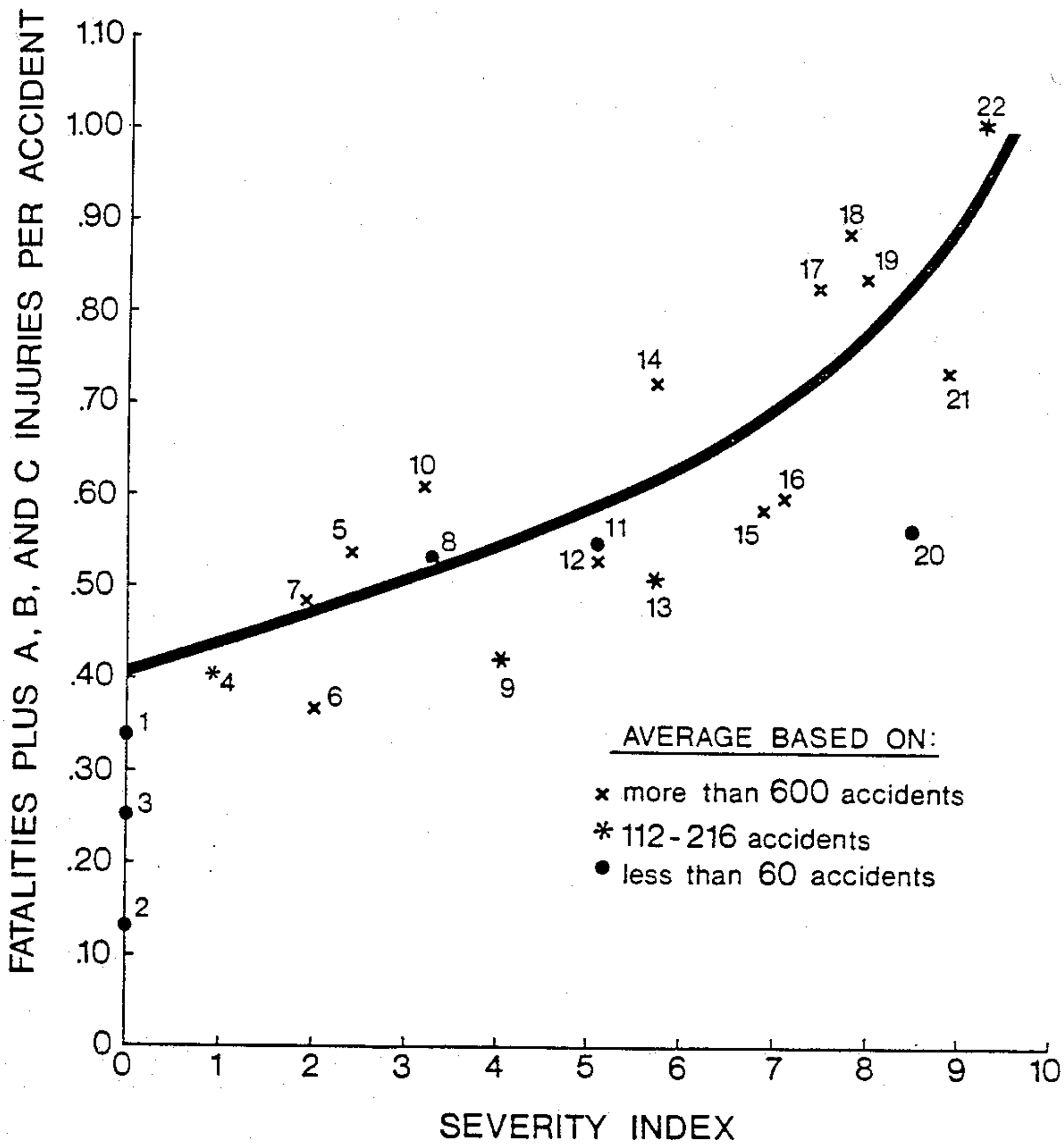


Figure C-5. FATALITIES PLUS A, B, AND C INJURIES DIVIDED BY TOTAL ACCIDENTS, RELATED TO SEVERITY INDEX, FOR RURAL ACCIDENTS. Source: Tables C-17 and C-18.

rigid signal poles near high-speed traffic lanes where they might be struck at high speeds. However, it appears that most traffic signal poles in rural areas should be given a rating averaging about 4.5 instead of the 8.5 assigned on the basis of small sample size average cost.

Based on similar reasoning, from the values in Table C-18, especially those plotted in Figures C-3 and C-4, some of the other ratings could be adjusted up or down. For example, possibilities would be not to reduce the rating for luminaire poles but to increase the ratings for commercial signs and railroad signal poles.

It is implicit in accident cost calculations that the heaviest weight is given to the most severe accidents and injuries, especially fatalities and A injuries. Indeed, a severity scale based on Figure C-3 would be roughly the same as one based on accident costs. The safety analyst may wish to consider Table C-18 and Figures C-3, C-4 and C-5 in addition to Table C-17 in assigning relative severity indices, but emphasis should be placed on Figure C-3, especially if the sample size is fairly large, say, above 100 accidents.

Developing New Severity Indices

The ratios in Table C-18 and Figures C-3, C-4, and C-5 can be used to develop severity indices for roadside obstacles not included in the previous tables but for which data is available on fatalities and injuries per accident. For example, consider the accident data for different types of luminaire poles and bases from NCHRP Report 77 [2, p. 61] shown in Table C-19. These data are from accidents occurring in 1966 with lighting installations in the cities of Dallas, Fort Worth, San Antonio, Beaumont, and Houston and on the Dallas-Fort Worth turnpike. Thus, the accidents are a mixed sample of high-speed urban and rural accidents.

In this example, these accidents are compared to the curves derived for rural accidents. Table C-19 presents data on number of injuries by type for aluminum poles mounted on aluminum transformer bases and for steel poles on three different types of bases: aluminum transformer, steel transformer, and steel shoe. The aluminum transformer bases are breakaway bases, but the steel transformer and steel shoe are rigid and do not break away when hit.

Comparing the ratios from Table C-19 with the data in Figures C-3, C-4, and C-5, the tentative severity index ratings in Table C-20 are assigned. It is fairly clear, based on these limited samples, that aluminum poles on aluminum transformer bases should have a severity index around 0.0. The other ratings are not as clear, but based on knowledge that the steel poles on aluminum

Table C-19. Accident and Injury Data for Different Types of Luminaire Poles and Bases. Source: NCHRP Report 77 [92].

Pole	Base	No. of Accidents	Number of Injuries Per Accident, by Type		
			A	A+B	A+B+C
Alum.	Alum. Transformer	58	.034	.103	.224
Steel	Alum. Transformer	19	.158	.158	.263
Steel	Steel Transformer	37	.324	.405	.541
Steel	Steel Shoe	35	.400	.657	.657

Table C-20. Tentative Severity Ratings for Luminaire Poles and Bases.

Pole	Base	Tentative Severity Rating Based on Figure:		
		3	4	5
Alum.	Alum. Transformer	0	0	0
Steel	Alum. Transformer	5.5	0	0
Steel	Steel Transformer	8.5	4.6	4.1
Steel	Steel Shoe	9.0	8.4	6.4

transformer bases usually are breakaway, this configuration could be given a relatively low rating anywhere from 0.0 to 5.5. The small sample of only 19 accidents tends to support the use of Figure C-5, with a resulting index of 0.0, but the relatively large number of A injuries, when compared with data in Figure C-3, indicates that a higher severity index should be used. hence the higher value of 5.5 is assigned here, based on the limited sample in Table C-19.

The data on the two rigid bases indicate a high severity index, and the ratings in Table C-20, together with the knowledge that these bases are non-breakaway, could be used to assign values of, say, 8.5 to steel transformer and 8.6 to steel shoe. In summary, the following tentative ratings are suggested, based on use with the rural cost curve:

POLE TYPE	BASE TYPE	SEVERITY INDEX
Aluminum	Alum. Transformer	0.0
Steel	Alum. Transformer	5.5
Steel	Steel Transformer	8.5
Steel	Steel Shoe	8.6

The most uncertain of these values is that for steel poles on aluminum transformer bases. The evidence from the small sample of only 19 accidents is somewhat contradictory. The comparison with Figures C-4 and C-5 indicate that this configuration causes relatively few injuries per accident, but the comparison with Figure C-3 indicates that these injuries tend to be relatively severe, as compared to other obstacles. This possibly could be explained by this configuration being more severe with one subgroup of accidents, such as those involving small vehicles. Another possibility is that the indicated values may be affected by the sample covering different types of roadways. Therefore, more data is needed for determining a final severity index for steel poles mounted on aluminum transformer bases. This example illustrates that Figures C-3, C-4 and C-5 can be used to assign a severity index, but it also illustrates that a considerable amount of judgement must be used, especially if the sample sizes are relatively small.

Suggested Severity Indices

To facilitate the use of the accident costs as shown in Figure C-2 and Tables C-16 and C-17, Tables C-1 and C-2 (reproduced from the AASHTO Barrier Guide) were revised. The safety analyst should take these revised values only as a general guide and should consider the lateral distance form the travel lane to the roadside hazard when selecting a specific severity index. Especially for rigid objects such as elevated gore abutments, trees, bridge piers, non-breakaway sign posts, and non-breakaway luminaire poles (especially those mounted on a steel transformer base or any shoe base), distance from the roadway is an important variable in selecting a severity index. As a general guide, the following values are tentatively recommended for wide, rigid objects such as elevated gore abutments, bridge piers, and very large trees (say, 3 ft. or more in diameter):

Distance From Roadway	Severity Index
0 to 10 ft	9.0 to 9.4
10 to 20 ft	8.5 to 9.0
20 to 30 ft	7.5 to 8.5
30 to 40 ft	6.5 to 7.5
40 to 50 ft	4.5 to 6.5
50 ft or more	Less than 4.5

For rigid objects that are not as wide as presumed above, such as rigid sign supports, rigid luminaire poles, 1-2 ft diameter trees, and utility poles slightly lower values probably should be used, say, 0.1 lower than the values shown. This is because they are slightly less likely to be impacted in such a way that extreme decelerations result, because the possibility of a vehicle making a full head-on impact is slightly lower for narrow objects.

The above tentative severity index values as related to lateral distance are based mainly on: (1) the very large observed severity indices for elevated gore abutments and bridge ends, which are located near the roadway, and (2) the fact that the average observed severity index for trees is 8.0 in rural areas and for utility poles is only 4.8 in rural areas, the principal difference presumably being distance from the roadway, although some of this difference probably is accounted for by trees being more rigid. A more detailed inquiry into the effect of distance certainly is needed. The most that can be said for the above tentative values is that they are logical in the sense that encroaching vehicles often reduce speed as they increase lateral distance from the roadway. The revised values replacing the values in Tables C-1 and

C-2 are presented in Tables C-21 and C-22. These revised tables are very similar to Tables C-1 and C-2, which were taken from the AASHTO Barrier Guide, but have been revised to reflect the results of this report and also have been slightly changed to adjust to the revised accident costs recommended in this report. Also, some further adjustments were made in the values based on accident records where it was anticipated that a safety-treated obstacle would result in a higher percent of unreported, less-costly accidents. This type of adjustment was made for breakaway signs, breakaway luminaire poles, and crash cushions. The following discussion gives the reasoning behind the changes that were made.

Utility Poles - Value of 7.1 in the AASHTO Barrier Guide probably is too high and is adjusted downward to average values from accident records of 3.2 in urban areas and 4.8 in rural areas.

Trees - Value of 3.0 in the AASHTO Barrier Guide is too low. Average values from reported accidents are 7.6 in urban areas and 8.0 in rural areas.

Signposts - Values for rigid signposts are rated the same as in the AASHTO Barrier Guide. The value for average signposts in accident records was 2.0; this was reduced to 0.0 to account for a higher proportion of unreported accidents that is assumed to apply to breakaway signs.

Lumimaire Poles - Values for different pole-base combinations are assigned based on the special study reported above. However, the value of 5.5 from accident records for steel poles on aluminum transformer bases is adjusted downward from 5.5 to 3.5 to account for unreported accidents. The values for rigid luminaire poles are slightly higher than those in the AASHTO Barrier Guide.

Traffic Signal Poles - Values for rigid poles are based on accident records. It is assumed that any breakaway design would have a value of 0.0.

Railroad Signal Poles - Values for rigid poles are based on accident records. It is assumed that any breakaway design would have a value of 0.0.

Railroad Crossing Gates - Values are based on accident records.

Mail Boxes - Values for "average" mail boxes are based on accident records. It is assumed that the best safety-treated designs would have a value of 0.0.

Fence - Average values based on accident records are shown.

Curbs - Values from accident records are consistent with those in the AASHTO Barrier Guide, so those values are used.

Table C-21. Obstacle Inventory Codes. (Based on Table C-1, but with additional categories added)

Identification Code	Descriptor Code
01. Utility Poles	(00)
02. Trees	(00)
03. Signposts	(01) pole-mounted, breakaway base, safety treated (02) single-pole-mounted, rigid (03) double-pole-mounted, rigid (04) triple-pole-mounted, rigid (05) cantilever support, rigid (06) overhead sign bridge, rigid
04. Luminaire Poles	(01) aluminum pole, aluminum transformer or slip base, safety treated (02) aluminum pole, aluminum shoe base (03) steel pole, aluminum transformer or slip base, safety treated (04) steel pole, steel transformer base (05) steel pole, steel shoe base
05. Traffic Signal Poles	(01) breakaway base, safety treated (02) rigid base
06. Railroad Signal Poles	(01) breakaway base, safety treated (02) rigid base
07. Railroad Crossing Gate	(00)
08. Mailbox	(01) average, safety treated (02) average, non-safety treated
09. Fence	(01) average
10. Curbs	(01) mountable design (02) non-mountable design less than 10 inches (.254 m) high (03) barrier design greater than 10 inches (.254 m) high
11. Guardrail or Median Barrier	(01) w-section with standard post spacing (6 ft-3 in) (02) w-section with other than standard post spacing (03) approach guardrail to bridge--decreased post spacing (3 ft-1 1/2 in) (.95 m) adjacent to bridge

(continued)

Table C-21. Obstacle Inventory Codes. (Continued)

Identification Code	Descriptor Code
	(04) approach guardrail to bridge--post spacing not decreased adjacent to bridge (05) post and cable (06) metal beam guardrail fence barrier (in median) (07) median barrier (CMB design or equivalent
12. Roadside Slope	(01) sod slope (positive) (02) sod slope (negative) (03) concrete-faced slope (positive) (04) concrete-faced slope (negative) (05) rubble rip-rap slope (positive) (06) rubble rip-rap slope (negative)
13. Ditch (includes erosion, rip-rap runoff ditches, etc. --does not include ditches formed by front and back slopes)	(00)
14. Culverts	(01) headwall (or exposed end of pipe culvert) (02) gap between culverts on parallel roadways (03) sloped culvert with grate (04) sloped culvert without grate
15. Inlets	(01) raised drop inlet (tabletop) (02) depressed drop inlet (03) sloped inlet
16. Roadway under Bridge Structure	(01) bridge piers (02) bridge abutment, vertical face (03) bridge abutment, sloped face
17. Roadway over Bridge Structure	(01) open gap between parallel bridges (02) closed gap between parallel bridges (03) rigid bridgerail--smooth and continuous construction (04) semi-rigid bridgerail--smooth and continuous contsruction (05) other bridgerail--probable penetration, severe snagging and/or pocketing, or vaulting (06) elevated gore abutment

(continued)

Table C-21. Obstacle Inventory Codes. (Continued)

Identification Code	Descriptor Code		
18. Retaining Wall	(01) retaining wall (face)		
	(02) retaining wall (exposed end)		
19. Ditches		Front Slope	Back Slope
	(01)	6:1	6:1
	(02)	6:1	5:1
	(03)	6:1	3.5:1
	(04)	5:1	6:1
	(05)	5:1	5:1
	(06)	5:1	3.5:1
	(07)	4:1	6:1
	(08)	4:1	5:1
	(09)	4:1	3.5:1
	(10)	3.6:1	6:1
	(11)	3.6:1	5:1
	(12)	3.6:1	3.5:1
	(13)	3:1	6:1
	(14)	3:1	5:1
	(15)	3:1	3.5:1
20. Construction Material	(01) average		
21. Commercial Signs	(01) average		
22. Crash Cushions	(00)		

Longitudinal Barrier End Treatment Codes

Beginning Treatment Codes
1. Not Beginning at Structure - Safety Treated
2. Not Beginning at Structure - Not Safety Treated
3. Beginning at Structure - Full-Beam Connection
4. Beginning at Structure - Not Full-Beam Connection

Ending Treatment Codes
1. Not Ending at Structure - Safety Treated
2. Not Ending at Structure - Not Safety Treated
3. Ending at Structure - Full-Beam Connection
4. Ending at Structure - Not Full-Beam Connection

Also, it should be noted that obstacles which are not of the longitudinal class have been designated code 0 for each end treatment.

Table C-22. Severity Indices.

Identification Code	Descriptor Code	End Treatment Code Beginning	End Treatment Code Ending	Severity Index Urban	Severity Index Rural
1	0	0	0	3.2	4.8
2	0	0	0	7.6	8.0
3	0	0	0	0.0	0.0
3	1	0	0	4.7	4.7
3	2	0	0	7.2	7.2
3	3	0	0	7.2	7.2
3	4	0	0	7.2	7.2
3	5	0	0	8.1	8.1
4	0	0	0	0.0	0.0
4	1	0	0	8.4	8.4
4	2	0	0	3.5	3.5
4	3	0	0	8.5	8.5
4	4	0	0	8.6	8.6
5	0	0	0	0.0	0.0
5	1	0	0	1.6	8.5
6	0	0	0	0.0	0.0
6	1	0	0	4.5	3.3
7	0	0	0	0.0	0.0
8	0	0	0	0.0	0.0
8	1	0	0	1.9	2.5
9	0	0	0	1.0	2.4
10	1	0	0	2.4	2.4
10	2	0	0	4.1	4.1
10	3	0	0	3.7	3.7
11	1	1	1	4.0	4.9
11	1	1	2	4.3	5.2
11	1	1	3	3.9	4.8
11	1	1	4	4.8	5.7
11	1	2	1	5.9	6.8
11	1	2	2	6.0	6.7
11	1	2	3	5.6	6.5
11	1	2	4	6.0	6.9
11	1	3	1	3.6	4.5
11	1	3	2	3.6	4.5
11	1	3	3	3.6	4.5
11	1	3	4	4.9	5.8

Table C-22. Severity Indices. (Continued)

Identification Code	Descriptor Code	End Treatment Code Beginning	End Treatment Code Ending	Severity Index Urban	Severity Index Rural
11	1	4	1	4.8	5.7
11	1	4	2	5.0	6.2
11	1	4	3	4.8	6.0
11	1	4	4	5.3	6.5
11	2	1	1	4.2	5.4
11	2	1	2	4.5	5.7
11	2	1	3	4.1	5.3
11	2	1	4	5.0	6.2
11	2	2	1	6.1	7.3
11	2	2	2	6.2	7.4
11	2	2	3	5.8	7.0
11	2	2	4	6.2	7.4
11	2	3	1	3.8	5.0
11	2	3	2	3.8	5.0
11	2	3	3	3.8	5.0
11	2	3	4	5.1	6.3
11	2	4	1	5.0	5.9
11	2	4	2	5.2	6.1
11	2	4	3	5.0	5.9
11	2	4	4	5.3	6.2
11	3	1	1	4.0	4.9
11	3	1	2	4.3	5.2
11	3	1	3	3.6	4.5
11	3	1	4	4.8	5.7
11	3	2	1	5.9	6.8
11	3	2	2	5.3	6.2
11	3	2	3	4.2	5.1
11	3	2	4	5.3	6.2
11	3	3	1	4.5	4.4
11	3	3	2	4.5	4.4
11	3	3	3	4.5	4.4
11	3	3	4	4.7	5.6
11	3	4	1	4.3	5.2
11	3	4	2	4.8	5.7
11	3	4	3	4.2	5.1
11	3	4	4	5.0	5.9
11	4	1	1	4.0	4.9
11	4	1	2	4.3	5.2
11	4	1	3	3.9	4.8
11	4	1	4	4.8	5.7
11	4	2	1	5.9	6.8
11	4	2	2	6.0	6.9

(continued)

Table C-22. Severity Indices. (Continued)

Identification Code	Descriptor Code	End Treatment Code Beginning	End Treatment Code Ending	Severity Index Urban	Severity Index Rural
11	4	2	3	5.6	6.5
11	4	2	4	6.0	6.9
11	4	3	1	3.6	4.5
11	4	3	2	3.6	4.5
11	4	3	3	3.6	4.5
11	4	3	4	4.9	5.8
11	4	4	1	4.8	5.7
11	4	4	2	5.0	5.9
11	4	4	3	4.8	5.7
11	4	4	4	5.3	6.2
11	5	1	1	4.2	5.1
11	5	1	2	4.2	5.1
11	5	1	3	4.2	5.1
11	5	1	4	4.2	5.1
11	5	2	1	4.2	5.1
11	5	2	2	4.2	5.1
11	5	2	3	4.2	5.1
11	5	2	4	4.2	5.1
11	5	3	1	4.2	5.1
11	5	3	2	4.2	5.1
11	5	3	3	4.2	5.1
11	5	3	4	4.2	5.1
11	5	4	1	4.2	5.1
11	5	4	2	4.2	5.1
11	5	4	3	4.2	5.1
11	5	4	4	4.2	5.1
11	6	1	1	4.7	5.6
11	6	1	2	4.7	5.6
11	6	1	3	4.7	5.6
11	6	1	4	5.3	6.2
11	6	2	1	5.9	6.8
11	6	2	2	6.0	6.9
11	6	2	3	5.6	6.5
11	6	2	4	6.0	6.9
11	6	3	1	4.3	5.2
11	6	3	2	4.7	5.6
11	6	3	3	4.3	5.2
11	6	3	4	4.9	5.8
11	6	4	1	4.8	5.7
11	6	4	2	5.0	5.9
11	6	4	3	4.8	5.7
11	6	4	4	5.3	6.2

(continued)

Table C-22. Severity Indices. (Continued)

Identification Code	Descriptor Code	End Treatment Code Beginning	End Treatment Code Ending	Severity Index Urban	Severity Index Rural
11	7	1	1	4.5	5.4
11	7	1	2	4.5	5.4
11	7	1	3	4.5	5.4
11	7	1	4	4.5	5.4
11	7	2	1	4.5	5.4
11	7	2	2	4.5	5.4
11	7	2	3	4.5	5.4
11	7	2	4	4.5	5.4
11	7	3	1	4.5	5.4
11	7	3	2	4.5	5.4
11	7	3	3	4.5	5.4
11	7	3	4	4.5	5.4
11	7	4	1	4.5	5.4
11	7	4	2	4.5	5.4
11	7	4	3	4.5	5.4
11	7	4	4	4.5	5.4
12	1	0	0	3.0	3.0
12	2	0	0	3.0	3.0
12	3	0	0	2.5	2.5
12	4	0	0	2.5	2.5
12	5	0	0	5.1	5.1
12	6	0	0	5.1	5.1
13	0	0	0	0.0	0.0
14	1	0	0	7.9	7.9
14	2	0	0	5.5	5.5
14	3	0	0	3.3	3.3
14	4	0	0	7.7	7.7
15	1	0	0	5.7	5.7
15	2	0	0	3.1	3.1
15	3	0	0	3.3	3.3
16	1	0	0	9.3	9.3
16	2	0	0	9.3	9.3
16	3	0	0	5.5	5.5
17	1	0	0	7.2	7.2
17	2	0	0	5.5	5.5
17	3	0	0	6.3	6.3
17	4	0	0	6.0	6.0
17	5	0	0	9.3	9.3
17	6	0	0	9.4	9.3

(continued)

Table C-22. Severity Indices. (Continued)

Identification Code	Descriptor Code	End Treatment Code		Severity Index	
		Beginning	Ending	Urban	Rural
18	1	0	0	5.5	5.5
18	2	0	0	9.3	9.3
19	1	0	0	2.2	2.2
19	2	0	0	2.4	2.4
19	3	0	0	3.0	3.0
19	4	0	0	2.3	2.3
19	5	0	0	2.5	2.5
19	6	0	0	3.0	3.0
19	7	0	0	2.6	2.6
19	8	0	0	3.0	3.0
19	9	0	0	4.0	4.0
19	10	0	0	3.5	3.5
19	11	0	0	3.8	3.8
19	12	0	0	4.5	4.5
19	13	0	0	3.6	3.6
19	14	0	0	4.2	4.2
19	15	0	0	4.8	4.8
20	0	0	0	7.2	1.9
21	0	0	0	8.9	5.1
22	0	0	0	0.0	0.0

Guardrail or Median Barrier - A large number of different types of guardrails are listed in the AASHTO Barrier Guide with severity indices ranging from 3.2 to 5.9. The severity index for guardrail from accidents, on the other hand, averaged 6.2 in urban areas and 7.1 in rural areas. Based on the relationship between these average values from accidents, the values in the AASHTO Barrier Guide are used as basic values but are increased by 0.3 for urban guardrail and by 1.2 for rural guardrail, keeping the same relative values as in the AASHTO Barrier Guide.

Roadside Slope - No well-defined values were available from accident records, so the values in the AASHTO Barrier Guide are used.

Ditch - Same as comment for roadside slope.

Culverts - Values in AASHTO Barrier Guide and from accident record are consistent, so values in AASHTO Barrier Guide are used.

Inlets - Values from AASHTO Barrier Guide are used.

Roadway Under Bridge Structure - Values in the AASHTO Barrier Guide and from accident records are consistent so values from AASHTO Barrier Guide are used, except for bridge abutment with sloped face which is increased from the AASHTO Barrier Guide's 2.5 up to 5.5, since 2.5 appears too low for any rigid object near traffic lanes, based on the accident record results.

Roadway Over Bridge Structure - Values for gap between bridges are left as in AASHTO Barrier Guide. The value for elevated gore abutment for rural areas is left 9.3 but for urban areas is increased from 9.3 to 9.4, based on accident records for bridge ends. (It should be remembered, however, that a different accident cost curve is used for urban areas so even though the severity index is slightly higher for urban gore abutments, the cost still is lower than for rural areas.) For bridge rail, accident records indicate indices for "side of bridge" of 7.0 in urban areas and 6.9 in rural areas; and for "bridge end" accident records give 9.4 in urban areas and 8.9 in rural areas. Therefore, the AASHTO Barrier Guide's value of 9.3 for bridge rail that snags, pockets, etc., appears correct but the values of 3.0 to 3.3 for other bridge rails appear too low and are increased to 6.0 and 6.3 in both urban and rural areas.

Retaining Wall - The severity index for exposed ends is left at 9.3 as in the AASHTO Barrier Guide, but the retaining wall face is increased to 5.5 based on the same reasoning as for sloped faces for bridge abutments.

Construction Material - Accident records yielded an index of 7.2 in urban areas and 1.9 in rural areas. The value of 7.2 for urban areas probably is more appropriate for high speed freeways and is probably too high for lower speeds.

Commercial Signs - Values from accident records are used, 8.9 in urban areas and 5.1 in rural areas. Consider lateral distance as with other rigid objects.

Crash Cushions - Accident records yielded values above 0.0 for crash cushions but these included only reported accidents. Considering the high proportion of unreported accidents for crash cushions, the value is left at 0.0 in the AASHTO Barrier Guide.

Appendix D. FREEWAY RAMP CONTROL

Description of Control System

The control system that forms the basis for this case study is the ramp-metering control system on the Gulf Freeway in Houston, Texas. The section of the freeway that was controlled extended from the Reveille Interchange to the downtown-end of the freeway where traffic enters the downtown-street distribution system, at Dowling Street, near the central business district of Houston. The freeway had frontage roads in both directions, but these frontage roads were discontinuous at the locations of crossing railroads.

The main feature of the control system developed in this research study was the gap-acceptance method of merging control. Although three levels of sophistication are possible, control of vehicles merging at the entrance ramps is the basic ingredient of all the systems. These three levels of control are: (1) pre-timed control, (2) local actuated control, and (3) system control. With pre-timed control, the metering rate is preset and depends on the time of the day. Local actuated control uses metering rates that depend on the mainline traffic conditions in the vicinity of each ramp. System control uses a central computer to analyze traffic conditions on a section of the freeway and metering rates are set on the basis of overall traffic conditions.

Costs of Control Systems

Costs of control systems include the initial capital costs and the annual operating and maintenance costs over the useful life, assumed to be twenty years, of the systems. The salvage value of the equipment used for each system probably will be near, and is assumed to be, zero. As was mentioned previously, the cost of each system depends on the number of controlled ramps and whether these ramps are located on the inbound or outbound freeway. In the following presentation of costs, it is shown that there are some costs that are independent of, and some costs that depend directly on, the number of controlled ramps. All equipment costs include costs of designing and installing the equipment.

Initial Costs

At the first level of control, the analog satellite system requires at each ramp a gap and speed detector, a merge detector, a check-in detector, and a ramp signal, all of which cost $2,500 per ramp. Also required at each ramp is an analog controller that costs $4,000 per ramp, giving a total cost of $6,500 per ramp. At the second level of control, a queue detector is added and some parts are added to the controller for a total cost of $1,500 per ramp. At the third level of control, a central controller and detectors are added for the system entailing a cost of $11,000 which is independent of the number of ramps. Also, telemetry from the central controller to each local ramp controller is added and this, together with extra ramp detectors and adjustments to the local controllers, gives an additional cost for level three of $4,600 per controlled ramp.

When the digital satellite system, at the first level of control, is used, the detectors and signals are similar to those used with the analog satellite system, and likewise cost $2,500 per ramp. A local digital computer at each ramp adds a cost of $8,500 per ramp giving a total cost of $11,000 per controlled ramp. It is possible, however, to use this computer at an inbound-freeway ramp in the morning and also at a nearby outbound-freeway ramp in the afternoon. Thus, the extra cost of controlling a nearby ramp in the other direction is only $2,500 plus the cost of telemetry between the two ramps, which is estimated to be $1,000, for a total extra-outbound-ramp cost of only $3,500 per ramp. For the second level of control, a queue detector is added at each ramp and the controller remains unchanged, giving an additional cost of $500 per ramp, whether inbound or outbound. For the third level of control, a central computer and system detectors are added at a cost of $11,000 per ramp, which is independent of the number of ramps. Additional detectors, local computer equipment, and telemetry add $4,100 per controlled ramp.

At the first level of control using the central digital system, a single central digital computer is used and it cost $105,000 whatever the number of controlled ramps. There are additional costs per ramp of $4,100 for detectors, signals, cabinets, and telemetry from the central controller to the ramps. For level two additional detectors are added at the ramps at a cost of $500 per ramp. At level three the computer is expanded and system detectors are added at a cost of $2,000 per ramp.

The costs that have been discussed above are summarized in Tables D-1 and D-2. Table D-1 shows by level of control the incremental initial system costs which are independent of the number of controlled ramps. Table D-2 shows initial costs per ramp which are a function of the number of controlled ramps. Incremental as used in each of these tables, and other tables presented below, means the incremental cost above the immediately lower level of control. That is, the costs given for Level II are in addition to those for Level I, and similarly for Level III. Thus, the total initial system cost for a particular level is the sum of the costs at that level and lower levels.

<u>Annual Operating and Maintenance Costs</u>

In addition to the initial capital costs, there are annual operating and maintenance costs. These costs include the costs of office rental and wages and salaries for control personnel, both

Table D-1. Incremental Initial System Costs Which Do Not Depend on the Number of Controlled Ramps, by System and Level of Control.

Level of Control	Incremental Initial Cost, by System		
	Analog Satellite	Digital Satellite	Central Digital
Level I	$ 0	$ 0	$105,000
Level II	0	0	0
Level III	11,000	11,000	6,500

Table D-2. Incremental Initial System Costs Which Depend on the Number of Controlled Ramps, per Ramp, by System and Level of Control.

Level of Control	Incremental Initial Cost per Ramp, by System		
	Analog Satellite	Digital Satellite	Central Digital
Level I	$ 6,500	$ 11,000	$4,100
Level II	1,500	500	500
Level III	4,600	4,100	2,000

of which are independent of the number of controlled ramps, and maintenance and power and transmission costs which depend on the number of controlled ramps.

Office rental costs are assumed to be zero for Levels I and II of the analog satellite and digital satellite systems and $6,000 per year for the other two levels of these two systems and all levels of the central digital system. Wages and salaries for control personnel are assumed to be $5,000 per year for Levels I and II of the analog satellite and digital satellite systems; $10,000 per year for Levels I and II of the central digital systems; $15,000 per year for Level III of all three systems. The annual maintenance and power and transmission costs per controlled ramp are presented in Table D-3.

The present value of all annual operating and maintenance costs for a period of twenty years, discounted to the present using an interest rate of 5 per cent per year, are presented in increments by level of control in Tables D-4 and D-5. In Table D-4 are the costs that do not depend on the number ramps, i.e., the costs of office rental and control personnel. In Table D-5 are the costs that do depend on the number of ramps, i.e., the costs of maintenance and power and power and transmission.

Total Costs

Total system costs, including initial costs and the present value of annual costs, are the sum of the costs in Table D-1 and D-2 and Tables D-4 and D-5. The costs in these tables are incremental costs, presented in increments by level of control. In Tables D-6 and D-7 are presented the total system costs, given incrementally, as were the component costs in Table D-1, D-2, D-4, and D-5. In Table D-8 and D-9 are presented the total system costs, not on an incremental basis. In Table D-10 are shown the total and incremental costs for each of the three systems, at all three levels of control, when eight ramps are controlled. The analog satellite system is the least expensive at all levels of control when eight ramps are controlled, as can be seen by comparing the costs of the three systems in Table D-10.

Benefits of Control at Each Level

The benefits of control are estimated, as were costs, over a twenty-year analysis period, the assumed useful life of the control system. These benefits are reductions in user costs, which result from control, and include reduced vehicle operating costs. Benefits are estimated for one-direction control, with control of eight entrance ramps whatever the level of control. Also, benefits of control are estimated only for the peak-period (7:00 A.M. - 8:00 A.M.) of traffic, except for traffic accidents which are considered for an additional hour of control, that is from 7:00 A.M. to 9:00 A.M.

Table D-3. Incremental Annual Maintenance and Power and Transmission, per Ramp, by System and Level of Control.

Level of Control	Incremental Initial Cost per Ramp, by System		
	Analog Satellite	Digital Satellite	Central Digital
Level I	$ 1,440	$ 1,440	$1,625
Level II	125	40	40
Level III	165	275	90

Table D-4. Present Value of Twenty-year Incremental Annual Operating and Maintenance Costs Which Do Not Depend on the Number of Controlled Ramps, by System and Level of Control.

Level of Control	Incremental Initial Cost, by System		
	Analog Satellite	Digital Satellite	Central Digital
Level I	$ 62,311	$ 62,311	$199,395
Level II	0	0	0
Level III	199,395	199,395	62,311

Table D-5. Present Value of Twenty-year Incremental Annual Operating and Maintenance Costs Which Depend on the Number of Controlled Ramps, per Ramp, by System and Level of Control.

Level of Control	Incremental Annual Cost per Ramp, by System		
	Analog Satellite	Digital Satellite	Central Digital
Level I	$17,946	$17,946	$20,251
Level II	1,558	498	498
Level III	2,056	3,427	1,122

Table D-6. Present Value of Twenty-year Total System Costs Which Do Not Depend on the Number of Controlled Ramps, Presented Incrementally by Level of Control, by System.

Level of Control	Incremental Cost, by System		
	Analog Satellite	Digital Satellite	Central Digital
Level I	$62,311	$62,311	$304,395
Level II	0	0	0
Level III	210,395	210,395	68,811

Table D-7. Present Value of Twenty-year Total System Costs Which Depend on the Number of Controlled Ramps, Presented Incrementally by Level of Control, by System.

Level of Control	Incremental Cost, by System		
	Analog Satellite	Digital Satellite	Central Digital
Level I	$24,446	$28,946	$24,351
Level II	3,058	998	998
Level III	6,656	7,527	3,122

Table D-8. Present Value of Twenty-year Total System Costs Which Do Not Depend on the Number of Controlled Ramps, by System and Level of Control.

Level of Control	Total Cost, by System		
	Analog Satellite	Digital Satellite	Central Digital
Level I	$ 62,311	$ 62,311	$304,395
Level II	62,311	62,311	304,395
Level III	272,706	272,706	373,206

Table D-9. Present Value of Twenty-year Total System Costs Which Depend on the Number of Controlled Ramps, per Ramp, by System and Level of Control.

Level of Control	Total Cost per Ramp, by System		
	Analog Satellite	Digital Satellite	Central Digital
Level I	$24,446	$28,946	$24,351
Level II	27,504	29,944	25,349
Level III	34,160	37,471	28,471

Table D-10. Twenty-year Total and Incremental Costs for Systems with Eight Controlled Ramps, by System and Level of Control.

System and Level of Control	Twenty-year Costs	
	Total	Incremental
Analog Satellite:		
Level I	$257,879	$257,879
Level II	282,343	24,464
Level III	545,986	263,643
Digital Satellite:		
Level I	293,879	293,879
Level II	301,863	7,984
Level III	572,474	270,611
Central Digital:		
Level I	499,203	499,203
Level II	507,187	7,984
Level III	600,974	93,787

The method used in calculating benefits is to calculate the benefits at each level of control for one year and to assume, generally, that benefits are the same in each of the twenty years.

The exceptions to this procedure are that it is assumed that the incremental benefits from Level III are zero for the first two years of control. These assumptions are made because even after the equipment is installed at these levels of control, there is a lag before enough control experience can be gained for one year at each level of control, benefits are calculated for different types of days. The numbers of days of each type at each level of control are multiplied by the daily benefits for each type of day to derive the yearly benefits.

The type of day depends on whether there is one or more accidents on the inbound freeway during the peak hour and whether the pavement is wet or dry during the peak hour. Thus, there are four types of days: (1) days with wet pavement and one or more accidents; (2) days with dry pavement and one or more accidents; (3) days with wet pavement and no accidents; and (4) days with dry pavement and no accidents. Days are divided into these four types because there are different numbers of accidents (and accident days) at the different levels of control, and, also, the effects of the accidents are not the same with dry pavement as with wet pavement.

The numbers of days of each type per year by level of control are presented in Table D-11. Only non-holiday week days are included in the analysis since holidays and Saturdays and Sundays do not have the same type of peak-hour inbound traffic as do non-holiday week days and control is not used on these days. It is assumed that in each year there are 252 non-holiday week days of which 54 have wet pavement and 198 have dry pavement, during the peak period; this corresponds to observations on the Gulf Freeway. The numbers of days of different types for no control and for Levels I and II of control are based on a previous study of the control operation on the Gulf Freeway [80]. The estimates, at these three levels of the numbers of accidents, average travel times per vehicle, vehicle volumes, and miles of travel also are based on the same two studies.

Freeway Travel Times

The major benefit to motorists of freeway control is reduced freeway travel time. Without control, there is congestion behind and in the vicinity of the entrance ramps to the freeway. This congestion is especially severe on days with accidents and on days when the pavement is wet or damp. By regulating the ramp volumes, control reduces the travel time of vehicles on the freeway. Also, with fewer days with accidents on the inbound freeway, travel times are further reduced by control. Table D-12 presents the average

Table D-11. Number of Days per Year by Type of Day for Each Level of Control.

Level of Control	Number of Days			
	Accident		Non-accident	
	Wet	Dry	Wet	Dry
None	21	68	33	130
Level I	12	40	42	158
Level II	10	32	44	166
Level III	8	25	46	173

Table D-12. Average Hours of Travel Time per Vehicle Trip on the Inbound Gulf Freeway, by Type of Day and Level of Control.

Level of Control	Hours Per Vehicle, by Type of Day			
	Accident		Non-accident	
	Wet	Dry	Wet	Dry
None	.45	.27	.33	.23
Level I	.39	.24	.30	.20
Level II	.37	.22	.27	.19
Level III	.35	.21	.26	.18

hours of travel per vehicle trip on the inbound freeway. Travel times are shown for each level of control for the four different types of days: (1) accident with wet pavement, (2) accident with dry pavement, (3) non-accident with wet pavement, and (4) non-accident with dry pavement. To derive the total hours of travel time per day, the average travel times in Table D-12 are multiplied by the numbers of vehicles using the freeway during the peak-hour of travel with Level II of control on days with no accidents. These volumes (number of vehicles) are 5,440 vehicles on days with wet pavement and 5,800 vehicles on days with dry pavement. These total hours of travel time per day are presented in Table D-13. To derive the annual travel time for all days of a particular type for each level of control, the travel times per day are multiplied by the numbers of days of each type, which were presented above in Table D-11. These derived travel times per year for each level of control are presented for each type of day, and for all peak-period days within a year, in Table D-14. To evaluate these travel times in dollars, it is necessary to know the value of travel time per vehicle hour for different types of vehicles and to know the proportion of such hours which is consumed by each type of vehicle. Since the proportions of hours consumed by different types of vehicles are not known, it is assumed that these proportions are the same as the proportions of vehicles using the inbound freeway during the peak hour of travel: passenger cars, .945; delivery vehicles, .029; single-unit trucks, .006; large trucks, .018; and buses, .002.

The values for travel time per vehicle hour for these same vehicle types are: passenger cars and delivery vehicles, $3.00; single-unit trucks, $3.90; large trucks, $6.50; and buses, $32.50. The weighted-average value of time based on the above proportion and values of time is $3.13 per vehicle hour. This weighted-average value of time of $3.13 per vehicle hour is multiplied by the hours of travel time in Table D-14 to derive the total value of travel time for a year of peak-period operation. These annual values of total travel time are presented in the last column of Table D-15. The values in this last column are the sums of the values in the other columns which are the values for each type of day. The vehicle operating cost for traveling 1,000 miles at different speeds is presented in Table D-17 for five types of vehicles. Also given in Table D-17, in the last column is the weighted-average vehicle operating cost for a composite freeway vehicle derived using the proportions of vehicles operating on the Gulf Freeway which were given above. Linear interpolation of these values is used to derive the vehicle operating costs for the speeds shown in Table D-16; the result is the average vehicle operating costs, for different types of days and levels of control, presented in Table D-18.

These costs are for the composite vehicle and in deriving them it is assumed that all vehicle types travel at the same average speed. This probably is a reasonable assumption since vehicle

Table D-13. Average Hours of Travel Time Per Peak Period on the Inbound Gulf Freeway, by Type of Day and Level of Control.

Level of Control	Hours Per Peak Period by Type of Day			
	Accident		Non-accident	
	Wet	Dry	Wet	Dry
None	2448	1566	1795	1334
Level I	2122	1392	1632	1160
Level II	2013	1276	1469	1102
Level III	1904	1218	1414	1044

Table D-14. Number of Hours of Peak-period Freeway Travel Time Per Year by Type of Day, and for All Days, by Level of Control.

Level of Control	Number of Hours Per Year, by Type of Day				
	Accident		Non-accident		All Days
	Wet	Dry	Wet	Dry	(Total)
None	51,408	106,488	59,235	173,420	390,551
Level I	25,464	55,680	68,544	183,280	332,968
Level II	20,130	40,832	64,636	182,932	308,530
Level III	15,232	30,450	65,044	180,612	291,338

Table D-15. Value of Peak-period Freeway Travel Time Per Year by Type of Day, and for All Days, by Level of Control.

Level of Control	Value of Time Per Year, by Type of Day				
	Accident		Non-accident		All Days
	Wet	Dry	Wet	Dry	(Total)
None	$160,907	$333,307	$185,406	$542,805	$1,222,425
Level I	79,702	174,278	214,543	573,666	1,042,189
Level II	63,007	127,804	202,311	572,577	965,699
Level III	47,676	95,309	203,588	565,316	911,889

Table D-16. Vehicle Operating Speeds in Miles per Hour, by Type of Day and Level of Control.

Level of Control	Average Operating Speed, mph			
	Accident		Non-accident	
	Wet	Dry	Wet	Dry
None	12.2	20.4	16.6	24.0
Level I	14.0	23.0	18.2	27.6
Level II	14.8	25.0	20.3	29.0
Level III	15.6	26.2	21.1	30.5

Table D-17. Vehicle Operating Costs Per Thousand Vehicle Miles, by Type of Vehicle and Speed.

Speed (mph)	Cost Per Thousand Miles by Type of Vehicle					
	Passenger Cars	Delivery Vehicles	Single-Unit Trucks	Combination Trucks	Buses	W'td. Average
10.0	$44.93	$49.49	$77.68	$134.42	$120.20	$46.96
12.5	41.82	46.31	72.86	120.80	110.11	43.65
15.0	39.73	44.15	69.62	111.79	103.41	41.42
17.5	38.21	42.55	67.37	105.64	98.84	39.81
20.0	37.09	41.39	65.90	101.46	95.81	38.63
22.5	36.23	40.58	65.09	98.68	93.89	37.74
25.0	35.63	39.95	64.73	97.06	92.92	37.12
27.5	35.19	39.55	64.76	96.29	92.64	36.68
30.0	34.91	39.32	65.11	96.27	93.02	36.41
32.5	34.79	39.24	65.75	96.94	94.00	36.31
35.0	34.76	39.29	66.60	97.97	95.10	36.31

Table D-18. Average Vehicle Operating Costs Per Thousand Vehicle Miles, by Type of Day and Level of Control.

Level of Control	Average Vehicle Operating Costs Per Thousand Vehicle Miles			
	Accident		Non-accident	
	Wet	Dry	Wet	Dry
None	$44.05	$38.49	$40.39	$37.37
Level I	42.31	37.62	39.48	36.67
Level II	41.60	37.12	38.52	36.52
Level III	41.03	36.91	38.24	36.39

maneuvering is not prevalent on freeways during peak-periods, and, as a result, little variation in average speed by vehicle type is to be expected. Multiplying these costs per thousand miles of travel under different conditions by the number (in thousands) of miles traveled gives the total vehicle operating costs per peak period, for the different types of days and levels of control.

These are shown in Table D-19. Multiplying these costs per day by the number of days of each type from Table D-11 gives the costs per year for days of different types which are in Table D-20. The values in the last column of Table D-20 are the sums of the costs for different types of days and, therefore, represent the estimates of total peak-period vehicle operating costs for a year, at different levels of control.

Freeway Accidents

In Table D-21 are the estimates of the numbers of accidents per year on the inbound freeway by pavement condition and level of control. The cost of these accidents is not known. However, a National Safety Council memorandum suggests that $600 is a reasonable value to use as the cost of an accident. Using $600 as the cost of an accident whatever the pavement condition or level of control together with the numbers of accidents from Table D-21, the annual cost of accidents for each level of control are estimated and are presented in Table D-22.

User Costs on Frontage Roads and Ramps

In addition to affecting freeway operations, control affects the costs of vehicles on the frontage roads and ramps. Observations indicate that the number of accidents on the frontage roads and ramps is the same for no control and for Level II of control. Since there is no reason to expect the number to be different for the other levels of control, it is assumed that accidents on the frontage roads and ramps are not affected by control.

Table D-23 presents estimates of the total hours of travel time for vehicles on the frontage roads and entrance ramps of the freeway. There is a slight increase in the amount of this time at Level I (over no control); but at Level II, there is a slight decrease because more sophisticated merging equipment reduces idle time at the entrance ramps. It is assumed that Level III is the same as Level I. The cost for this time on frontage roads and ramps is calculated by multiplying the numbers of hours of time by the value of time and idling per hour. The costs per hour for time and idling vehicle-operation are presented in Table D-24. The weighted-average cost of idling of $3.24 per vehicle hour is multiplied by the numbers of hours in Table D-23 to derive the total user costs per day for frontage roads and ramps. These per-day costs are multiplied by the numbers of days of different types

Table D-19. Total Vehicle Operating Costs Per Peak Period on the Inbound Gulf Freeway, by Type of Day and Level of Control.

Level of Control	Total Vehicle Operating Costs Per Peak Period by Type of Day			
	Accident		Non-accident	
	Wet	Dry	Wet	Dry
None	$1,311.68	$1,230.06	$1,202.69	$1,194.27
Level I	1,259.86	1,202.26	1,175.60	1,171.90
Level II	1,238.72	1,186.28	1,147.01	1,167.11
Level III	1,221.75	1,179.57	1,138.67	1,162.95

Table D-20. Total Peak-Period Vehicle Operating Costs, for the Inbound Freeway, Per Year, by Type of Day, and for All Days, by Level of Control.

Level of Control	Vehicle Operating Costs Per Year by Type of Day				
	Accident		Non-accident		All Days
	Wet	Dry	Wet	Dry	(Total)
None	$27,545	$83,644	$39,689	$155,255	$306,133
Level I	15,118	48,090	49,375	185,160	297,743
Level II	12,387	37,961	50,468	193,740	294,556
Level III	9,774	29,489	52,379	201,190	292,832

Table D-21. Number of Peak-Period Motor Vehicle Traffic Accidents Per Year by Pavement Condition and Level of Control.

Level of Control	Accidents Per Year by Pavement Condition		
	Wet	Dry	All
None	29	92	121
Level I	16	55	71
Level II	14	43	57
Level III	11	34	45

Table D-22. Cost of Peak-Period Motor Vehicle Traffic Accidents Per Year by Pavement Condition and Level of Control.

Level of Control	Accident Cost Per Year by Pavement Condition		
	Wet	Dry	All
None	$17,400	$55,200	$72,600
Level I	9,600	33,000	42,600
Level II	8,400	25,800	34,200
Level III	6,600	20,400	27,000

Table D-23. Total Hours of Time Per Peak Period on Frontage Roads and Ramps, by Pavement Condition and Level of Control.

	Total Hours by Pavement Condition	
Level of Control	Wet	Dry
None	200	190
Level I	210	200
Level II	190	180
Level III	210	200

Table D-24. Cost of Idling Per Hour, by Type of Vehicle.

Type of Vehicle	Cost of Idling Per Hour		
	Operating Costs	Time Costs	Total Costs
Passenger Cars	$0.11	$ 3.00	$ 3.11
Delivery Vehicles	0.13	3.00	3.13
Single-unit Trucks	0.20	3.90	4.10
Combination Trucks	0.22	6.50	6.72
Buses	0.20	32.50	32.70
Weighted Average	0.11	3.13	3.24

Table D-25. Value of Peak-Period Travel Time and Vehicle Operating Costs for Frontage Roads and Ramps, for One Year, by Pavement Condition and Level of Control.

Level of Control	Value by Pavement Condition		
	Wet	Dry	Total
None	$34,992	$121,889	$156,881
Level I	36,742	128,304	165,046
Level II	33,242	115,474	148,716
Level III	36,742	128,304	165,046

per year to derive the total annual user costs for frontage roads and ramps which are presented in Table D-25.

Total Benefits of Control

The total annual costs for each level of control are the sums of the costs in the last columns of Tables D-15, D-20, D-22, and D-25. These sums are presented in Table D-26. The total annual user costs are the totals of the user costs given in the last columns of Tables D-15, D-20, D-22, and D-25. The total annual user benefits are the reductions in total annual user costs, comparing each control level to no control.

The total annual user benefits are estimated as the reductions in user costs and also are given in Table D-26, in the last column. It is assumed that these annual costs are the same in each year of the twenty-year analysis period, except for the assumption that the incremental benefits of control are zero for the first two years at Level III. The present value of twenty-year benefits, calculated using an interest rate of 5 per cent per year, are given in Table D-27. These benefits at all levels of control are for eight controlled ramps and are for the inbound Gulf Freeway. In calculating the benefits for Level III, it is assumed that the incremental annual benefits are zero during the first two years. In discounting the annual benefits to the present, an interest rate of 5 per cent per year is used. All values for benefits are rounded to the nearest $100.

Table D-26. Total Annual User Costs and Benefits for One-direction Control by Level of Control.

Level of Control	Total Annual User Costs	Total Annual User Benefits
None	$1,750,039	$ 0
Level I	1,547,573	210,466
Level II	1,443,171	314,868
Level III	1,396,767	361,272

Table D-27. Present Value of Twenty-Year Total User Benefits for One-Direction Control, by Level of Control.

Level of Control	Total Annual User Benefits
Level I	$2,622,800
Level II	3,923,900
Level III	4,415,900

APPENDIX E. ROADWAY LIGHTING

The method used in this study is to determine the least costly of several alternatives that give the same level of effectiveness under certain stipulated conditions. The study is limited to continuous roadway lighting and also is limited in that only mounting heights of 40 feet and 50 feet are considered.

Alternatives and Measures of Effectiveness

Three effectiveness measures were used in selecting feasible alternatives: (1) a uniformity ratio of average illumination of not greater than 3 to 1; (2) a uniformity ratio of maximum illumination to minimum illumination of not greater than 6 to 1; (3) three different levels of average illumination: Level III, 1.25 horizontal footcandles, Level II, 1.00 horizontal footcandles, and Level I, 0.75 horizontal footcandles. There are, then, three levels of effectiveness or three design criteria, as summarized in Table E-1.

Table E-2 gives the five basic alternatives which are compared in the conclusions of the report. In the table, these alternatives are given letter designations which are used throughout this report. Table E-3 shows the illumination alternatives which give stipulated levels of effectiveness for roadways with different numbers of lanes. For a given number of lanes some alternatives meet more than one design criteria.

Cost Information

The initial and maintenance costs computed for the five alternate designs are based on information furnished by manufacturers and information taken from bids on projects in Texas. The accident cost information is taken from Texas accident reports. Table E-4 presents per-unit initial costs for lighting installations. Costs are given for 40-foot and 50-foot mounting heights with, respectively, 400-watt and 1000-watt luminaires. These costs are also given for single and double arms of 12-foot and 15-foot length. These costs include foundation and installation costs but do not include costs for duct cable, conduit, or service poles. Also, the costs are for galvanized steel poles on steel or aluminum transformer bases. Steel poles on steel shoe bases would cost about $40 less per unit. Aluminum poles would cost $150 to $250 more per unit. The cost of duct cable, conduit, and service poles is estimated at $3,400 per mile for installations placed in the median or on one side and at $6,500 per mile for installations which are staggered (alternating on each side) or opposite on two sides of the roadway.

Maintenance costs in Texas for power and luminary replacement are estimated to range from $50 to $70 per year per luminary for

Table E-1. Levels of Effectiveness By Design Criteria Level.

Effectiveness Measure	Effectiveness by Design Criteria Number		
	I	II	III
Average Illumination (ft-C)	.75	1.00	1.25
Uniformity, Average to Minimum	3 to 1	3 to 1	3 to 1
Uniformity, Maximum to Minimum	6 to 1	6 to 1	6 to 1

Table E-2. Description of Illumination Alternatives.

Letter Used To Designate Alternative*	Unit Placement	Luminaire Wattage	Mounting Height (feet)	Unit Spacing (feet)
A(M-40-200)	Median	400	40	200
B(O-50-300)	One-Side	1000	50	300
C(M-50-300)	Median	1000	50	300
D(S-50-260)	Staggered	1000	50	260
E(S-50-300)	Staggered	1000	50	300

Note: Alternatives A and C with median placement have double arms and two luminaires. The other alternatives have single arms and one luminaire.

* The letters and numbers in parenthesis refer to (Placement; Mounting Height in feet; spacing units in feet); M refers to units placed in the median; O refers to units placed on one side of the roadway; S refers to units which are staggered, alternating on opposite sides of the roadway.

Table E-3. Illumination Alternatives Which Meet Different Design Criteria For Roadways With Different Numbers Of Traffic Lanes.

Number of Traffic Lanes	Alternatives Meeting These Criteria by Criteria Number*		
	I	II	III
4	A,B	A,B	B
6	A,B,E	A,B	C,D
8	C,D	C,D	C
10	C	C	C

* For description of Criteria I, II, III, see Table E-1. For description of Alternatives A,B,C,D, and E, Table E-2.

Table E-4. Cost Per Illumination Unit By Pole Height, Number Of Arms, And Arm Length.

Number of Arms and Arm Length	Initial Cost Per Unit by Mounting Height and Wattage	
	40-foot, 400-Watt	50-foot, 1000 Watt
Single Arm:		
12-foot	$500	$625
15-foot	525	650
Double Arm:		
12-foot	575	725
15-foot	625	775

Note: Cost includes foundation and installation cost but does not include cost of duct cable, conduit, or service poles. Costs are for galvanized steel poles on steel transformer bases or aluminum transformer bases.

1000-watt luminaires and from $25 to $40 per year per luminary for 400-watt luminaires.

Accident costs for collisions of vehicles with lighting installations are taken from a report by Lazenby [93] and from the accident records collected by him. The accident information covers accidents with lighting installations in Beaumont, Dallas, Fort Worth, Houston, and San Antonio and on the Dallas-Fort Worth Turnpike.

Comparison of Alternatives

In making comparisons of the five illumination designs, those that meet the required effectiveness criteria are compared on a cost basis. The present value of costs for analysis periods of twenty and forty years are calculated using an interest rate of five percent per year. Two levels of maintenance costs, "low" and "high" are used. Also, two sets of accident costs are used, one set being based on an average two-way daily traffic of 10,000 vehicles and the other of 30,000 vehicles. In all of the calculations, salvage values are assumed to be zero.

Table E-5 presents initial costs per mile of roadway for the five designs with 12-foot and 15-foot arms. Table E-6 gives low and high maintenance costs per mile for analysis periods of twenty and forty years. Tables E-7 and E-8 give accident costs for analysis periods of, respectively, twenty and forty years. These accident costs are based on the cost per accident of $985 (for steel poles mounted on aluminum transformer bases) and assumptions regarding encroachment rates. Table E-9 gives the present value of the sum of initial and maintenance costs for the illumination designs but does not include accident costs.

Tables E-10, E-11, E-12, and E-13, are the same as Table E-9 except that they also include accident costs for units placed different distances from the edge of the roadway. As might be expected, the accident costs are lower the farther the distance the illumination units are located off the roadway.

In the first section of the appendix, three levels of effectiveness are defined. The highest of these levels is Level III, with an average illumination of 1.25 horizontal footcandles, followed by Level II, with 1.00 horizontal footcandles, and Level I with 0.75 horizontal footcandles. In Table E-3, the designs that meet these effectiveness criteria on roadways with different numbers of lanes are given. The following discussion compares on the basis of the costs shown in Tables E-10 through E-13, those designs which give a particular level of effectiveness on a specific roadway.

Table E-5. Initial Cost, By Type Of Designs, Per Mile Of Roadway, With 12-Foot and 15-Foot Arms.

Illumination Design	Arm Length (feet)	Number of Illumination Units Per Mile	Initial Costs Per Mile		
			Illumination Units	Other*	Total
A(M-40-200)	12	26.4	$15,180	$3,400	$18,580
"	15	26.4	16,500	3,400	19,900
B(O-50-300)	12	17.6	11,000	3,400	14,400
"	15	17.6	11,440	3,400	14,840
C(M-50-300)	12	17.6	12,760	3,400	16,160
"	15	17.6	13,640	3,400	17,040
D(S-50-260)	12	20.31	12,694	6,500	19,194
"	15	20.31	13,201	6,500	19,702
E(S-50-300)	12	17.6	11,000	6,500	17,500
"	15	17.6	11,440	6,500	17,940

* Includes costs of duct cable, conduit, and service pole.

Table E-6. Low and High Maintenance Costs For Different Illumination Designs, for Twenty-Year And Forty-Year Analysis Periods.

Illumination Design	Number of Luminaires Per mile	Maintenance Cost Per Mile Per Year		Present Value of Maintenance Cost Per Mile by Length of Analysis Period			
				20 Years		40 Years	
		Low	High	Low	High	Low	High
A(M-40-200)	52.80	$1,320	$2,112	$16,450	$26,320	$22,650	$36,240
B(0-50-300)	17.60	880	1,232	10,967	15,353	15,100	21,140
C(M-50-300)	35.20	1,760	2,464	21,933	30,706	30,200	42,280
D(S-50-260)	20.31	1,015	1,492	12,655	18,590	17,425	25,596
E(S-50-300)	17.60	880	1,232	10,967	15,353	15,100	21,140

Table E-7. Present Value of Accident Costs Per Mile For Different Illumination Designs, By Average Daily Traffic And Distance of Illumination Units From Traffic Lane, For An Analysis Period Of Twenty Years.

Illumination Design	Accident Cost by ADT and Distance of Units from Traffic Lane							
	ADT=10,000				ADT=30,000			
	10'	20'	25'	30'	10'	20'	25'	30'
A(M-40-200)	$14,485	$10,532	$7,291	$4,051	$43,454	$31,596	$21,874	$12,152
B(O-50-300)	4,861	3,511	2,430	1,346	14,583	10,532	7,290	4,050
C(M-50-300)	9,722	7,021	4,861	2,701	29,166	21,064	14,583	8,102
D(S-50-260)	5,524	3,989	2,767	1,533	16,571	11,968	8,300	4,598
E(S-50-300)	4,861	3,511	2,430	1,346	14,583	10,532	7,290	4,050

Table E-8. Present Value of Accident Costs Per Mile For Different Illumination Designs, By Average Daily Traffic And Distance of Illumination Units From Traffic Lane, For An Analysis Period of Forty Years.

Illumination Design	Accident Cost by ADT and Distance of Units from Traffic Lane							
	ADT=10,000				ADT=30,000			
	10'	20'	25'	30'	10'	20'	25'	30'
A(M-40-200)	$19,939	$14,499	$10,038	$5,577	$59,833	$43,498	$30,114	$16,730
B(O-50-300)	6,632	4,839	3,346	1,853	20,076	14,499	10,038	5,577
C(M-50-300)	13,384	9,661	6,692	3,724	40,152	28,999	20,076	11,153
D(S-50-260)	7,601	5,491	3,809	2,111	22,821	16,473	11,411	6,332
E(S-50-300)	6,692	4,839	3,346	1,853	20,076	14,499	10,038	5,577

Table E-9. Present Value of Initial And Maintenance Costs, Per Mile of Roadway, For Different Illumination Designs, By Length of Arms, Level Of Maintenance Costs, And Length Of The Analysis Period.

Illumination Design	12-ft. Arm(s)				15-ft. Arm(s)			
	Low MC		High MC		Low MC		High MC	
	M=20	M=40	M=20	M=40	M=20	M=40	M=20	M=40
A(M-40-200)	$35,030	$41,230	$44,900	$54,820	$36,350	$42,550	$46,220	$56,140
B(O-50-300)	25,367	29,500	29,753	35,540	25,807	29,940	30,193	35,980
C(M-50-300)	38,093	46,360	46,866	58,440	38,973	47,240	47,746	59,320
D(S-50-260)	31,849	36,619	37,784	44,790	32,357	37,127	38,292	45,298
E(S-50-300)	28,467	32,600	32,853	38,640	28,907	33,040	33,293	39,080

Note: MC signifies maintenance cost; M is the length, in years, of the analysis period. In calculating present values, an interest rate of five percent per year is used.

Table E-10. Present Value Of Initial, Maintenance, And Accident Costs, Per Mile Of Roadway, For Different Illumination Designs, By Amount Of Average Daily Traffic, Level of Maintenance Cost, And Length Of Analysis Period For Units With 12-Foot Arms, Placed Ten Feet From The Traffic Lane.

Illumination Design	ADT=10,000				ADT=30,000			
	Low MC		High MC		Low MC		High MC	
	M=20	M=40	M=20	M=40	M=20	M=40	M=20	M=40
A(M-40-200)	$49,515	$61,169	$59,385	$74,759	$78,484	$101,063	$88,354	$114,653
B(O-50-300)	30,228	36,192	34,614	42,232	39,950	49,576	44,336	55,616
C(M-50-300)	47,815	59,744	56,588	71,824	67,259	86,512	76,032	98,592
D(S-50-260)	37,373	44,220	43,308	52,391	48,420	59,440	54,355	67,611
E(S-50-300)	33,328	39,292	37,714	45,332	43,050	52,676	47,436	58,716

Note: MC signifies maintenance cost; M is the length, in years, of the analysis period. In calculating present values, an interest rate of five percent per year is used.

Table E-11. Present Value of Initial, Maintenance, And Accident Costs, Per Mile of Roadway, For Different Illumination Designs, By Amount of Average Daily Traffic, Level of Maintenance Cost, And Length of Analysis Period For Units With 15-Foot Arms, Placed Twenty Feet From The Traffic Lane.

Illumination Design	ADT=10,000				ADT=30,000			
	Low MC		High MC		Low MC		High MC	
	M=20	M=40	M=20	M=40	M=20	M=40	M=20	M=40
A(M-40-200)	46,882	57,049	56,752	70,639	67,946	86,048	77,816	99,638
B(O-50-300)	29,318	34,779	33,704	40,819	36,339	44,439	40,725	50,479
C(M-50-300)	45,994	56,901	54,767	68,981	60,037	76,239	68,810	88,319
D(S-50-260)	36,346	42,618	42,281	50,789	44,325	53,600	50,260	61,771
E(S-50-300)	32,418	37,879	36,804	43,919	39,439	47,539	43,825	53,579

Note: MC signifies maintenance cost; M is the length, in years, of the analysis period. In calculating present values, an interest rate of five percent per year is used.

Table E-12. Present Value of Initial, Maintenance, And Accident Costs, Per Mile of Roadway, For Different Illumination Designs, By Amount of Average Daily Traffic, Level Of Maintenance Cost, And Length Of Analysis Period With 15-Foot Arms, Placed Twenty-Five Feet From The Traffic Lane.

Illumination Design	ADT=10,000				ADT=30,000			
	Low MC		High MC		Low MC		High MC	
	M=20	M=40	M=20	M=40	M=20	M=40	M=20	M=40
A(M-40-200)	43,641	52,588	53,511	66,178	58,224	72,664	68,094	86,254
B(O-50-300)	28,237	33,286	32,623	39,326	33,097	39,978	37,483	46,018
C(M-50-300)	43,834	53,932	52,607	66,012	53,556	67,316	62,329	79,396
D(S-50-260)	35,124	40,936	41,059	49,107	40,657	48,538	46,592	56,709
E(S-50-300)	31,337	36,386	35,723	42,426	36,197	43,078	40,583	49,118

Note: MC signifies maintenance cost; M is the length, in years, of the analysis period. In calculating present values, an interest rate of five percent per year is used.

Table E-13. Present Value of Initial, Maintenance, And Accident Costs, Per Mile of Roadway, For Different Illumination Designs, By Amount of Average Daily Traffic, Level of Maintenance Cost, And Length of Analysis Period For Units With 15-Foot Arms, Placed Thirty Feet From The Traffic Lane.

Illumination Design	ADT=10,000				ADT=30,000			
	Low MC		High MC		Low MC		High MC	
	M=20	M=40	M=20	M=40	M=20	M=40	M=20	M=40
A(M-40-200)	40,401	48,127	50,271	61,717	48,502	59,280	58,372	72,870
B(O-50-300)	27,153	31,793	31,539	37,833	29,857	35,517	34,243	41,557
C(M-50-300)	41,674	50,964	50,447	63,044	47,075	58,393	55,848	70,473
D(S-50-260)	33,890	39,238	39,825	47,409	36,955	43,459	42,890	51,630
E(S-50-300)	30,253	34,893	34,639	40,933	32,957	38,617	37,343	44,657

Note: MC signifies maintenance cost; M is the length, in years, of the analysis period. In calculating present values, an interest rate of five percent per year is used.

For four-lane roadways, Design B meets criterion III; both Designs A and B meet Criteria II and I. In Tables E-10 through E-13 it is seen that Design B is always less expensive than Design A; therefore, Design B is for these conditions the preferred design. If, however, the illumination units for Design A are to be placed in a rigid median barrier, and the units for Design B are to be exposed on the side of the roadway, then for a relatively long analysis period and/or relatively high traffic volume, Design A is preferable. For example, Design A in a rigid median barrier is less expensive than Design B with exposed units placed ten feet from the edge of the pavement, for an average daily traffic of 30,000 vehicles, if the analysis period is forty years, or if the analysis period is twenty years, and low maintenance costs are assumed. (See Table E-9 and E-10).

For six-lane roadways Designs C and D meet the highest effectiveness criterion, Level III. Design D is less expensive than Design C, except for situations wherein, under Design C, units are to be placed in a rigid median barrier high average daily traffic is expected. For the lower effectiveness criteria at Levels II and I, Designs A, B, and E are also feasible, and Design B is the least costly of the alternatives.

For eight-lane roadways, Design C is the only design which meets the effectiveness criteria and, therefore, is the only feasible alternative for each of the three levels of effectiveness.

If it is anticipated that additional traffic lanes will be added, Design D would then give only Level II; if four lanes are added, Design D would not even meet the criteria for Level I. Thus, it can be seen that the flexibility of the design be considered when making comparisons.